UTS UNIVERSITY OF TECHNOLOGY SYDNEY

Waste to Paste

Sustainable and Circular Novel Material Composites for Explorative Prototyping in Product Design Practice.

by Saul Mazabow

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Doctor of Philosophy

under the supervision of

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Certificate of Original Authorship

I, Saul Mazabow, declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the Faculty of Design, Architecture and Building at the University of Technology Sydney.

This thesis is wholly my own work unless otherwise referenced or acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

This document has not been submitted for qualifications at any other academic institution.

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Abstract

This research focused on developing sustainable product design practices concerning exploratory prototyping. Exploratory prototypes, used to evaluate aspects of a design such as form and function, are typically made from non-recyclable materials such as polyurethane and thermoplastics, and finish their short lives in landfills.

This research contributes to ongoing experimental work focussed on developing novel material composites (NMCs) as a sustainable alternative to thermoplastics. This research aimed to develop and test a biodegradable prototyping material consisting of locally sourced, non-toxic industry waste and cellulose derivatives combined with a low-cost material extrusion (MEX) paste 3D printing system.

Conducted through product design practice using a research through design (RtD) approach, the research process was documented through a series of contextual portfolios (CPs). These portfolios captured the development of a 3D printable paste using brewer's spent grain (BSG) as a functional filler in a cellulose-based NMC. This paste and an open-source extruder and pneumatic paste delivery system aimed to reduce thermoplastic use.

The BSG-NMC paste and 3D printing system were refined and tested by printing prototypes like computer mice and gaming controllers. The resulting artefacts demonstrated the paste's effectiveness and durability, making it a viable, eco-friendly alternative to traditional thermoplastics in exploratory prototyping.

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Definitions of Terminology

3D	Three-Dimensional.
3D Printing	Three-dimensional printing, as ISO/ASTM 52900:2021(en) additive manufacturing — general principles — fundamentals and vocabulary.
ABS	Acrylonitrile butadiene styrene. A thermoplastic commonly used in 3D printing.
Alkalisation	The process of making something alkaline, the opposite of acidic.
AM	Additive manufacturing, also known as 3D Printing, is a group of technologies that create three-dimensional objects by building them layer by layer.
Bagasse	A solid by-product after sugarcane is crushed to extract juice.
Bed Adhesion	The ability of 3D printed components to stick to the build plate.
Binder	Binder materials can be viewed as the glue that holds the filler materials together. Binders work through either adhesion or cohesion, creating bonds through attraction through dissimilar modules binding their surfaces (adhesion) or binding through similar chemical molecular structures (cohesion).
Bridging	Occurs when a 3D printer is required to print between two points unsupported. In thermoplastic MEX printing, support material is not required for bridging distances under 10mm. Successful bridging can avoid the excessive use of support material.
BSG	Brewers spent grain is the beer brewing process's most significant solid waste output. BSG is what remains after the malting and mashing processes. BSG needs to be stored or used within five days of production to avoid microbial growth and spoilage.
CAD	Computer-aided design
Cellulase	An enzyme that degrades cellulose to glucose.
Cellulose	a polysaccharide, the main component that makes up plant cell walls. The most commonly occurring organic polymer. Commonly used in manufacturing clothes and paper.
CMC	Carboxymethyl cellulose, also known as cellulose gum, a white powder, is a cellulose derivative commonly used as a thickener, binder, emulsifier and film

	in food and therapeutic goods production. CMC is a food-safe ingredient that can be purchased cheaply online.
CNC	Computer numerical control. Machines controlled by computers.
Consumer Goods	Goods manufactured and designed to be bought by the average consumer (or households) for personal use.
Enzymatic Hydrolysis	A process in which enzymes are used to split chemical bonds in molecules.
Etherification	The dehydration of alcohol to form ethers. An ether is a class of organic compound with an oxygen atom bonded to two carbon atoms.
Explorative Prototyping	As defined by Hallgrimsson (2019). Explorative prototyping encapsulates all low-fidelity prototyping that is conducted during the infancy of design development. It encompasses prototyping, typically described as sketch and form prototyping, where a designer probes potential forms that engage with their design problem.
Extruder Assembly	A series of components that are responsible for moving and processing material. In thermoplastic 3D printing, these components typically include a stepper motor and driven train, a hot end, and a nozzle.
Filament	The material used in thermoplastic MEX printing. Typically, the filament is purchased in a spool of wired thermoplastics with a 1.75mm diameter. Filaments come in a range of colours and materials, such as ABS and PLA.
Flow Rate	The throughput of material from the extruder. Bed and layer adhesion and overall part quality.
Functional Filler	Filler materials are commonly used in industries like plastics and concrete mixing and are used to tailor the qualities of the material in aspects such as performance, appearance, cost and environmental impact.
Gantry	Regarding MEX 3D printers, the structure that supports and facilitates the movement of the printhead.
GHG	Greenhouse gas is a gas that absorbs infrared radiation emitted from the earth and reradiates it back, increasing surface temperature. Examples include carbon dioxide and methane.
Grape Marc	Also known as pomace, it is a solid by-product produced in winemaking.

Hemicellulase	An enzyme that modifies the structure of pulp fibres.
Hot End	A component within the extruder assembly that melts material for extrusion.
Layer Adhesion	The ability of newly deposited material to adhere to previously printed layers.
Logitech	A Swiss company which manufactures computer peripherals.
MEX	Material extrusion was previously defined as FDM (fused deposition modelling). A 3D printing process where three-dimensional objects are built layer by layer using a continuous flow of material through a nozzle and typically associated with consumer-grade and enthusiast 3D printers.
NMC	Novel material composites are new materials developed with two or more constituents. Many NMCs are designed, including organic industrial waste.
Over Hangs	Typically, it describes slopes that have an angle under 45 degrees. While these can be printed, results can be suboptimal, such as rough surface finishes. Usually, support structures are used to support the overhanging material and removed in postprocessing.
PLA	Polylactic acid, a renewable and popular thermoplastic used in 3D printing, is derived from corn starch. It can be composted in industrial settings.
Postprocessing	Process conducted after printing, where a part is prepared for its intended use case. Postprocessing includes processes such as removal of support material, sanding, puttying, painting, drilling, and more.
PS	Polystyrene foam
PU	Polyurethane foam
Slumping	Vertical shrinkage during drying.
Subtractive Manufacturing	Creating or manufacturing an object by removing material. Processes such as chiselling, sanding, milling and drilling. These can be performed by hand or by machine.
Support Inflation	Increases the size of support structures in the X- Y plane. Creates a wider net of support material for overhanging structures.
Support Material	Structures that are printed to support overhangs. These can have different settings to the main part, allowing for minimal material usage and easy removal.

Vermicomposting	The product of earthworm digestion and aerobic decomposition using the activities of worms at room temperature. The output is vermicast, which can be used as fertiliser.
Xbox	A US-based video gaming brand owned by Microsoft. They produce consoles, controllers, and games and host cloud gaming servers.
Z-Offset	The starting distance of the nozzle from the build platform. This can affect bed adhesion and layer adhesion.

1 Introduction

1.1 Context

The current climate crisis is well-documented as a multifaceted problem with no single answer or cure-all approach. It has widespread ramifications for our planet's ecosystems, and intergovernmental, industrial and localised changes are needed to mitigate its effects (OECD, 2020). An aspect of the crisis related to this research is how materials are utilised to manufacture the many and varied physical products that people use. Of particular concern is the large volumes of these physical products that are made using petrochemical polymers. It is well established that petrochemical polymers tend to outlive their intended use by hundreds of years, and can and are having long-lasting adverse effects on natural ecosystems and human health (Heinrich-Böll-Stiftung & Break Free From Plastic, 2020).

This research will focus on the discipline of product design, particularly prototyping, which is a central part of the product design process. The aim is to address the unsustainable prototyping practice where designers have traditionally used non-renewable and petrochemical-derived materials for short-lived prototypes exploring form, function, ergonomics and scale (Vasquez et al. 2020). While prototyping can be used as an investigative method during all stages of product design research and development, this research is particularly interested in the technologies and unsustainable material use in explorative prototyping, which typically occurs during the design process's infancy (Hallgrimsson, 2019). These practices can be reflected in the increased affordability and use of 3D printers as tools to rapidly produce explorative prototypes, which currently often use petrochemical polymers.

This research aims to shift situational expectations of materials, particularly around the use of petrochemical polymers in product design prototyping practice. Prototyping in product design plays a central role in both academic and industrial product design practice (Walden et al., 2018), where prototyping is an iterative practice exploring the physical embodiment of ideas for testing and refinement at all stages of product development (Mahtani et al., 2019). Through these innate prototyping processes, countless prototypes are generated at all stages of the design process (Lauff et al., 2018), which can lead to hundreds (Hustwit, 2018) and thousands (Dyson, 2001) of prototypes being produced by large firms, each exploring a new physical embodiment of a design.

In product design practice, firms traditionally have generated explorative prototypes through subtractive methods that utilise petrochemical-based materials such as polystyrene and

polyurethane foams (Hallgrimsson, 2019; McElroy, 2016b). Explorative prototypes are generated to investigate a multitude of factors that present themselves through the design process, such as form, function, ergonomics, scale, and aesthetics, and are used as platforms that build towards a singular design goal (Hustwit, 2018; Lauff et al., 2018). The prototypes generated are often used once for evaluation and then stored for later comparison or disposed of. While fundamental to the successful development of products, the materials used in prototyping are often unsustainable, and their single-use nature is a significant factor affecting the overall sustainability of developing new products. Commonly used foams such as polyurethane (PU) are recyclable; however, reports show that more than 50% of PU waste goes to landfill (Kemona & Piotrowska, 2020), and other popular foams, such as polystyrene (PS), are not recyclable (Marten & Hicks, 2018).

3D printing technologies, particularly material extrusion (MEX), have become significantly more affordable, accessible and reliable, allowing product designers to integrate their use into explorative prototyping practices (Wohlers et al., 2022). MEX printing traditionally has used thermoplastics such as PLA and ABS; however, researchers have identified issues with these, such as their prolonged lifespan concerning their use case, difficulties in recycling, and possible harmful environmental effects during printing (Mikula et al., 2021; Peng et al., 2018). Researchers from various disciplines have considered these issues and proposed ways to combat the overall environmental impact of these materials. Researchers have identified PLA, which is compostable in industrial settings, as a suitable medium for adding functional filler materials derived from waste resources (Kariz et al., 2018; Liu et al., 2019; Stoof et al., 2017; Zhao et al., 2016). However, if not disposed of correctly, these materials create a new waste stream due to their organic matter content, creating more difficulties in recycling (Narancic et al., 2018; Purkiss et al., 2022).

Researchers from a broad range of disciplines, such as the sciences, engineering, and design, have been developing sustainable novel material composites (NMCs) for MEX as possible sustainable substitutions for petrochemical polymers (Faludi et al., 2019; Rael & San Fratello, 2018; Sauerwein, 2020). NMCs have been developed incorporating underutilised organic waste from local industries such as grape marc, bagasse, orange peels, and coffee grounds in NMC pastes and filaments for MEX 3D printing ((Rael & San Fratello, 2018; Sauerwein; Wang et al., 2022)), and have been exploring potential use cases for their materials or comparing them to more established materials such as PLA and ABS (Faludi et al., 2019; Liu et al., 2019; Milosevic et al., 2017).

There is a clear need to develop NMCs from underutilised localised organic waste resources and identify potential and meaningful cases for these materials without comparing them to established

and refined thermoplastics. It is hypothesised that through transparently shared systematic and thorough enquiries, NMCs could be developed more broadly with functional use cases. This research aims to create transparent, accessible and repeatable processes for developing and assessing functional use cases of NMCs utilising local organic waste, lowering the barrier to entry for NMC development for product designers and potentially creating further knowledge-sharing cultures and more sustainable materials for use in practice and production.

1.2 Research Questions

Three research questions were created as anchor points for this research. The research questions were designed to be answered sequentially, where the findings from each question become the foundational knowledge required to begin answering the next. Further, the transition between each question is a point of reflection for the researcher to assess the outcomes of findings and plan future investigations.

1. What is involved in identifying, sourcing, managing and preprocessing a sustainable waste material suitable for development into a novel material composite (NMC) for material extrusion (MEX) 3D Printing?
2. What is involved in generating 3D forms for product designers using MEX 3D printing and NMC?
3. To what extent can MEX Printing of NMC support the physical prototyping requirements of product designers?

1.3 Methodological Approach

This research is situated within the context of product design practice and emergent novel material development. The practice-based aspects of the research utilise a research-through-design (RtD) approach, an iterative solution-focused process where designers probe their way through unknowns towards a desired outcome. The RtD process is documented within a contextual portfolio (CP) practice (Sadokierski, 2019), where planning, action, documentation, and reflection cycles are used to synthesise, share and progress practice-based research. RtD and CP practices are complementary in that the CPs help designers capture, analyse and share research-through-design practice, creating a framework for extracting and sharing the embedded knowledge in artefacts generated in practice.

1.4 Research Significance

This research is conducted for product designers by a product designer, aiming to create more sustainable practices through localised material development for use in prototyping processes. This will be addressed through several approaches.

First, the literature review challenges the notion of material usage and functional expectations. Fundamentally, designers' and consumers' functional expectations of materials have been aligned with highly developed petrochemical polymers, which have well-documented effects on the environment and human health. While sustainable alternatives are continually being produced and refined, their use is still often overshadowed by comparison to significantly more developed petrochemical polymers, possibly reducing their public perception, implementation in meaningful use cases, and further development. This research argues that sustainable NMC development should avoid comparisons with longstanding materials and look for use cases suitable to the material's capabilities. Furthermore, it is argued that through the development of an NMC, the characteristics and suitable use cases for the material will be apparent.

Next, through a research-through-design process, the research develops and demonstrates a ground-up approach to NMC paste extrusion 3D printer development, aiming to find practical use cases for both within product design practice. This process is separated into three sections: material, process, and application, and these are addressed sequentially in the research questions.

The research documents and reflects on the process of identifying potential organic waste resources for use in an NMC. This transparent and repeatable process demonstrates a potential approach designers can take in identifying waste outputs from local industries. The research presents workflows and processes for translating research from other disciplines and implementing them in the context of a design studio or firm, particularly around safe material handling and processes. Finally, a process that incorporates tools and processes relatable to product design practice is presented for developing preliminary NMCs utilising organic waste as functional filler material.

Further, the research presents processes for developing, refining and identifying functional use cases for NMCs and affordable paste-extrusion MEX printers. This process was developed through an RtD approach documented through CPs, where the process of acting was documented and used for critical reflection to plan further action. The culmination of this process was the development of a 3D-printable cellulose-based NMC utilising locally sourced waste material and modified consumer-grade 3D printing hardware. Furthermore, through the iterative development processes where the

paste, paste delivery system, extruder design and 3D printer were continually developed, potential use cases for the material were identified and tested.

Lastly, the developed system and paste are presented as suitable for explorative prototyping in product design practice. Three forms, computer mice, an Xbox controller, and kurrajong seedpods were printed and tested. The experimentation process explored factors that affect explorative prototype fidelity, such as speed of production, the complexity of forms, postprocessing capabilities such as sanding, and dimensional accuracy. The system and paste thus developed act as a proof of concept and example, demonstrating and guiding designers through material identification, processing, NMC development and printer configuration. It is envisaged that the workflows presented and systems designed could serve as sustainable rapid explorative prototyping systems in education, hobbyist, professional and academic product design settings.

1.5 PhD Structure

Following this introductory chapter, the research is structured as follows:

Chapter 2, Literature Review, provides an in-depth review of the problem space, positioning the contextual approach to be undertaken through the research. First, it introduces product design prototyping practices and describes their importance and the central role prototyping plays in product design practice in academic and professional contexts. Further, traditional and current prototyping practices and techniques, particularly around material use, are reviewed regarding their sustainability and environmental effects. Next, the environmental impact of petrochemical-derived materials used in prototyping is discussed. Then, additive manufacturing (AM) is reviewed regarding its growth and now inseparable integration into product design practice, particularly regarding the technology's benefits to practice and its effects on the environment. Last, current efforts by scientists, engineers, and designers to develop NMCs utilising organic waste resources such as extrudable paste and filament feedstock for AM are reviewed and assessed. The results, which described the need for more transparent and situationally targeted materials rather than overall petrochemical polymer replacements, formed the foundational knowledge and direction for the practical investigations undertaken in later chapters.

Chapter 3, Methodology, describes the methodological approach used to address the three research questions. First, research-through-design (RtD) is introduced as the overarching methodological approach. Next, complementary methodologies such as annotated portfolios and action research are reviewed. Then, contextual portfolios (CPs) are introduced as a complementary and supportive

approach to the practice-based RtD approach. Examples of RtD documented and synthesised through CPs are presented, describing the workflow of capturing, sharing and synthesising results of RtD with CPs.'

Chapter 4, Experimentation, is split into three sections, each documenting and analysing the processes undertaken to answer individual research questions. The investigation is undertaken sequentially, in that the findings from the first question became the foundational knowledge used in the second, and so on.

4.1 Research Question One describes the systematic process of identifying, sourcing, managing and processing local organic waste resources into NMCs. Brewers spent grain (BSG), the most significant and underutilised solid waste output of breweries, was sourced locally, stored, and processed based on material scientists' reports. A manually extricable preliminary cellulose-based NMC was developed using BSG as a functional filler.

4.2 Research Question Two continued the findings from research question one and explored the development of the NMC, a paste delivery system and a 3D printer configuration for use in explorative prototyping in product design practice. The NMC was developed into a consistently extrudable paste that could reliably and predictably build 3D organic shapes. A pneumatic paste delivery system utilising off-the-shelf components was developed, which could reliably deliver the NMC paste to a custom 3D printed extruder design mounted to a consumer 3D printer.

4.3 Research Question Three explored the extent to which the NMC paste and 3D printing system could support the needs of product designers conducting explorative prototyping. A series of gaming mice and controllers and Kurrajong seedpods were printed, exploring the system's ability to fulfil the functional prototyping needs of product designers. It was shown that the paste and 3D printing system could fulfil the needs for explorative prototyping in product design, such as rapid printing of organic shapes with infill and support materials using consumer hardware and software. Further testing explored the dimensional accuracy of printed components and postprocessing needs and capabilities of models for further refinement of prototype fidelity.

Chapter 5, Discussion, analyses the findings and results from experimentation and synthesises approaches for further development and implementation of similar paste extrusion systems in product design practice. Moreover, processes undertaken and findings from the experimentation are extrapolated and analysed, such as the material identification and selection process, barriers to entry to NMC development, initial NMC development, and building and configuring a paste-

extrusion 3D printing system. Further, the relationships between components and material regarding successful extrusion are discussed, and potential applications for similar systems are analysed.

Chapter 6, Conclusion, summarises the processes undertaken in the research. First, the context and purpose of the research are reiterated with support from the literature review. Then, the methodological approach is reiterated. Next, the research questions are restated, followed by summaries of the processes and findings of all chapters. Then, the research's methodological, empirical and theoretical findings are presented. Finally, recommendations for future research are suggested to align with the themes of material, processes, and applications of the three research questions.

Last, in the **Appendix** is the catalogue of all 223 contextual portfolio documents. All experiments conducted during the research process are presented, including synthesis documents that summarise and reflect on groups of experiments.

2 Literature Review

2.1 Product Design

In general, the practice of the product designer follows an iterative process consisting of stages relating to problem identification, concept development, testing and refinement. This iterative process, shown in Figure 2.1, has been adapted and represented in many different formats, yet the fundamental process of a designer using a prototype as a research generator and tool remains a central concept (Ashby & Johnson, 2013, p. 14; Cuffaro & Zaksenberg, 2013, p. 29; Swann, 2002, p. 53; Ulrich & Eppinger, 2008, p. 9). This research is concerned with the continued development of product design practice, specifically exploring ways to promote more environmentally sustainable prototyping practices for designers while they design products. This is viewed as an essential milestone in the progression of product design practice, moving away from using petrochemical plastics for prototyping to more environmentally sustainable materials. This evolution is enabled by the digitisation of designs, consumer and designer awareness of global issues, and on-demand manufacturing supported by additive manufacturing technologies (Bürdek, 2015; Diegel et al., 2016).

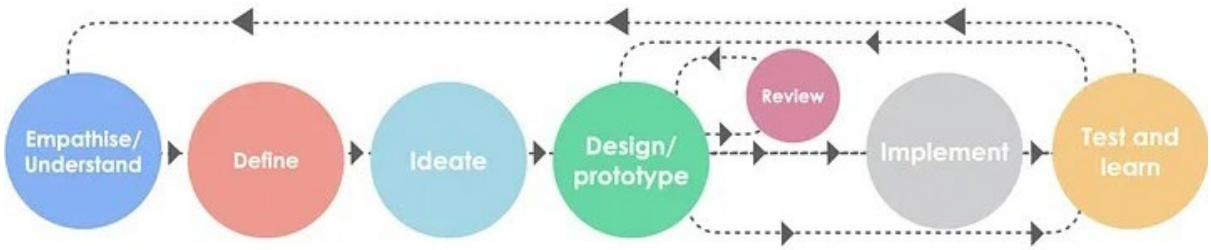


Figure 2.1 Product design process. Adapted from McConnell (2020).

Since the second industrial revolution, the industrial designer has been concerned with the design of functional, mass-manufactured products (Hendry & Dumas, 1988; Muratovski, 2016; Schon, 2016; Tjalve, 2015; Valtonen, 2005). This period marked a transition from craft-based design and production to industrialised processes harnessing new machinery and materials, an evolutionary process that has heavily influenced modern design (Bürdek, 2015). Product design as a profession evolved alongside the industrial and social developments of the times, where designers implement new technologies, materials and social focus into their practice in an ever-evolving attempt to create items that benefit society (see Figure 2.2) (Bürdek, 2015; Cuffaro & Zaksenberg, 2013, p. 13).

The practices and methods of designers utilised to develop products also affect the environment. This is apparent within the product refinement and prototyping phases, where product designers explore and develop a design's physical form and functions. Traditionally, prototyping practices

involved subtractive methods, such as sketch modelling with foam, woodworking, generating cardboard prototypes, clay modelling, and CNC machining (Hallgrimsson, 2012; McElroy, 2016a). Though effective, traditional subtractive prototyping is inefficient, as much material is wasted in the subtractive process; further, commonly used materials such as polyurethane and polystyrene foam can adversely affect the environment. Polyurethane foam causes environmental harm from the way it is manufactured to end-use cases due to poor disposal and recycling practices (Gadhave et al., 2019; Kjeldsen & Scheutz, 2003; Skleničková et al., 2022; Thomas et al., 2018, pp. 17-29).



Figure 2.2 Michael Thonet's No. 14 (The Vienna Coffee House Chair), 1859, Germany. The No. 14 chair is the most mass-produced and sold chair in human history. The Thonet chair consists of six wood pieces, ten screws and two nuts and is shipped unassembled to save space in transportation (Thonet, 2023).

2.2 Prototyping

Central to product design, prototyping processes can play essential roles in both academic and industrial product design processes (Walden et al., 2018). Though computer-based and digital technologies have experienced rapid improvement and development during the 21st century, some argue that physical prototyping (prototypes made by hand) provides designers and users with unmatched physical and tangible details that cannot be scrutinised or examined in digital environments (see Figure 2.3) (Hallgrimsson, 2012). McElroy (2016a) similarly argues that prototypes are the physical embodiment of the development of ideas, whose purpose is to be tested, analysed, reflected upon and refined through self-analysis and user feedback.



Figure 2.3 Explorative foam prototypes of hair dryers developed by designer Ariane Prin. The models were designed to address findings from interviews and observations of professional hairdressers. (Core Jr, 2010)

In their seminal discussion, Wensveen and Matthews (2014) analyse the various roles that prototypes can embody during different modes of design practice. They argue that prototypes can serve as an experimental component in formalised research processes or as a means of inquiry for data collection within a design project, and that a prototype can be a research archetype that physically embodies the culmination of a design research process. These roles can overlap, where a prototype generated within an academic design project can serve as an experimental component of practice and a physical embodiment of the culmination of a design research process (Dunn, 2017; Stappers, Sleeswijk Visser, & Keller, 2015).

Product designers employ prototyping as a mode of enquiry into a design's physical aspects, where designers and users can physically examine the form, function, and styling of a design in three-dimensional space (Camburn et al., 2017; Hallgrimsson, 2012). Within prototyping practice, the fidelity of a prototype often depends on the means of enquiry for which the prototype is intended (Hallgrimsson, 2019; Trudeau, 1995). Product fidelity has been defined differently by researchers and practitioners. Both Hallgrimsson (2019) and McElroy (2016b) categorise prototyping as high-fidelity and low-fidelity prototypes. Low-fidelity prototypes, also known as mock-ups and explorative prototypes (Augustin, Augustin, & Coleman, 2011; Milton & Rogers, 2017; Säde, 2001; Thomas et al., 2011), are generally rough and are generated quickly, made from cheaper and easy-to-manipulate material like form core, foams, paper, cardboard (Hallgrimsson, 2019). Explorative prototypes encompass prototyping investigations such as sketch, form, massing, and other low-fidelity prototypes and are used for faster iterative prototyping cycles, such as rapid form development, initial ergonomic testing, and user feedback on button placement (see Figure 2.4).



Figure 2.4 Explorative prototype of the "Cantilevered Plywood Chair" built using cardstock at 1:1 scale. Smaller prototypes and sketches can be seen in the background (Kleemola, 2012).

High-fidelity prototypes are models used to accurately determine a design's final appearance and functionality (Hallgrimsson, 2019). Usually, high-fidelity models, such as appearance models (as seen in Figure 2.5) are produced using higher quality and end-use materials such as timbers, composite materials, and alloys, and may be produced using advanced machinery like CNC machines and commercial 3D printers (Milton & Rogers, 2017). High-fidelity prototypes will often have careful attention paid to their minute details and will be a highly accurate 1:1 scale representation of a finished product, but may not be functional. These prototypes can often be found at trade fairs, on display at corporate offices or shop windows, and used in demonstrations with prospective customers.

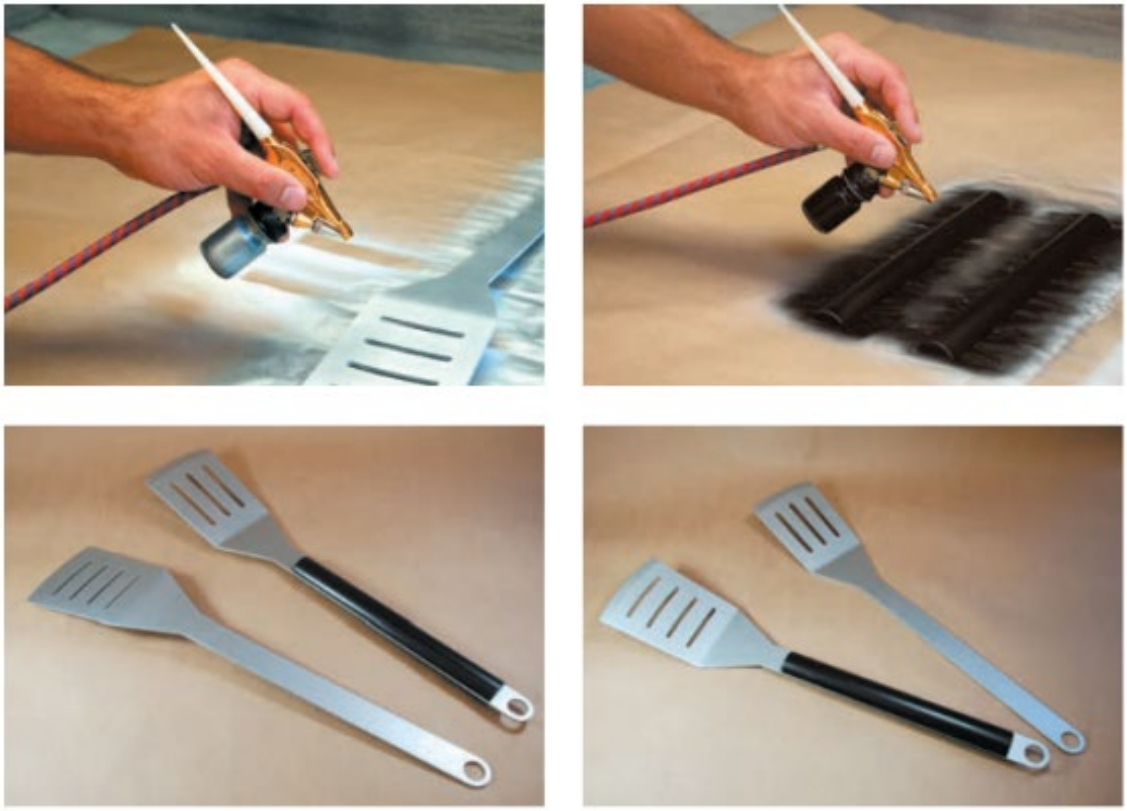


Figure 2.5 "An appearance model of a barbecue spatula was made from acrylic sheet and an extruded plastic pipe. Metal was simulated with metallic paint and the rubber handle was simulated with flat paint (rubber appears flat). The focus here was to study and communicate." (Hallgrimsson, 2019, pp. 148-149)

Fundamentally, effective prototyping plays a role in positively impacting a product's lifecycle. Prototyping allows the designer to improve a product through reflection and analysis of iterations; effective prototyping within a research and development process can result in well-rounded products that provide users with extended periods of use.

However, aspects within product design prototyping practices are not always sustainable; these include the materials used and the methods of generating prototypes. While traditionally, prototypes have been produced through subtractive methods such as manual or machine-controlled processes (Camburn et al., 2017; Hallgrimsson, 2012; Wohlers et al., 2022), the rise in the performance ability, accessibility and affordability of additive manufacturing (AM) technologies (also known as 3D printing) has given designers alternative options to the traditionally subtractive practices (as seen in Figure 2.6) (Beaman, Bourell, & Wallace, 2014; Gardan, 2017; Garmulewicz et al., 2018; Wohlers, 2022; Wohlers et al., 2022). Due to its increasing affordability, accessibility, and versatility, AM has become an integral part of product design practice.

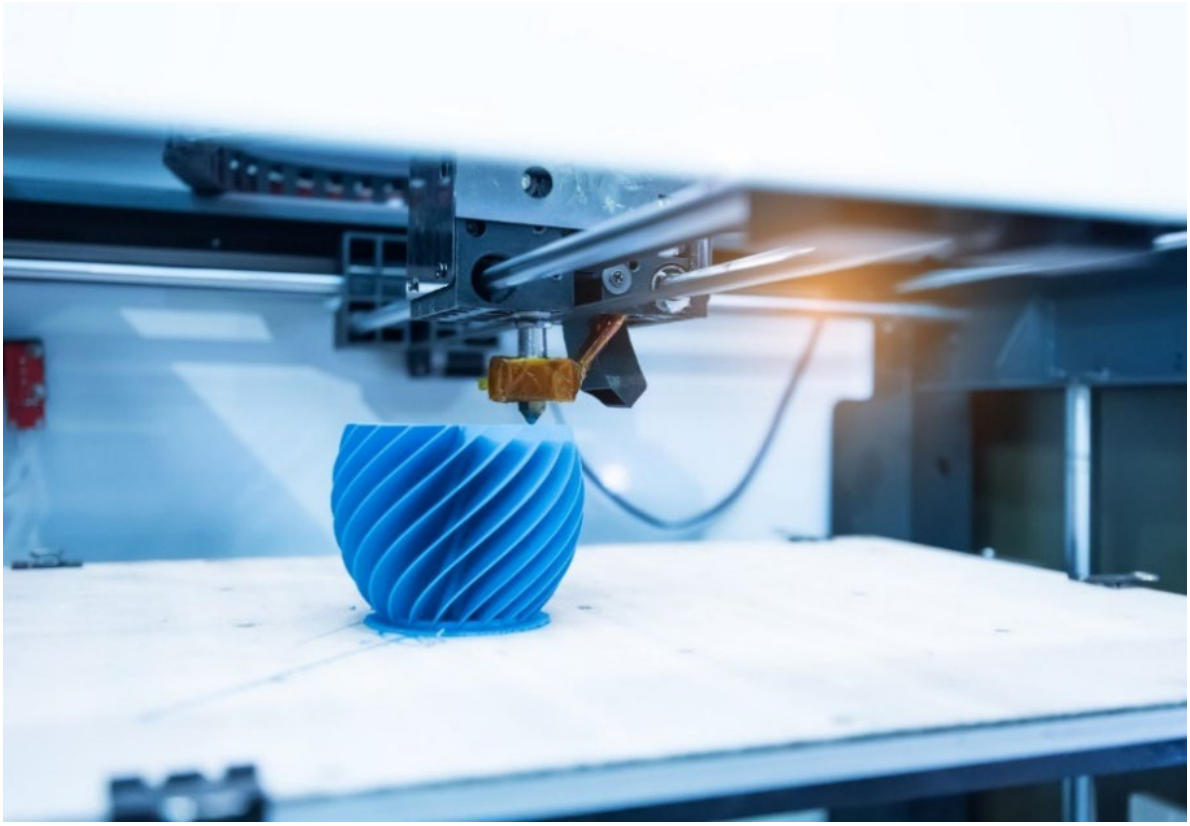


Figure 2.6 A close-up shot of a MEX (material extrusion) 3D printer printing a vase-shaped model (Xiaoliangge, 2016).

2.3 Additive Manufacturing

This research focuses on a particular type of 3D printing called material extrusion (MEX); in this process, a 3D printer constructs models by depositing material along a set of coordinates defined by software, gradually building a 3D model layer by layer (see Figures 2.7-2.9). Since the early 2000s there has been a significant uptake of AM technology in a wide variety of industries, such as the automotive, medical, dentistry, product development, manufacturing (such as tooling) and fashion industries, and the benefits of additive manufacturing are well documented (Wohlers et al., 2022).





Left to right
Figure 2.7 Delta 3D Printer, the AnyCubic Kossel Plus (AnyCubic, 2023).
Figure 2.8 Cartesian 3D printer, the Original Prusa i3 MK3S+ (3d Printing Gear, 2023).

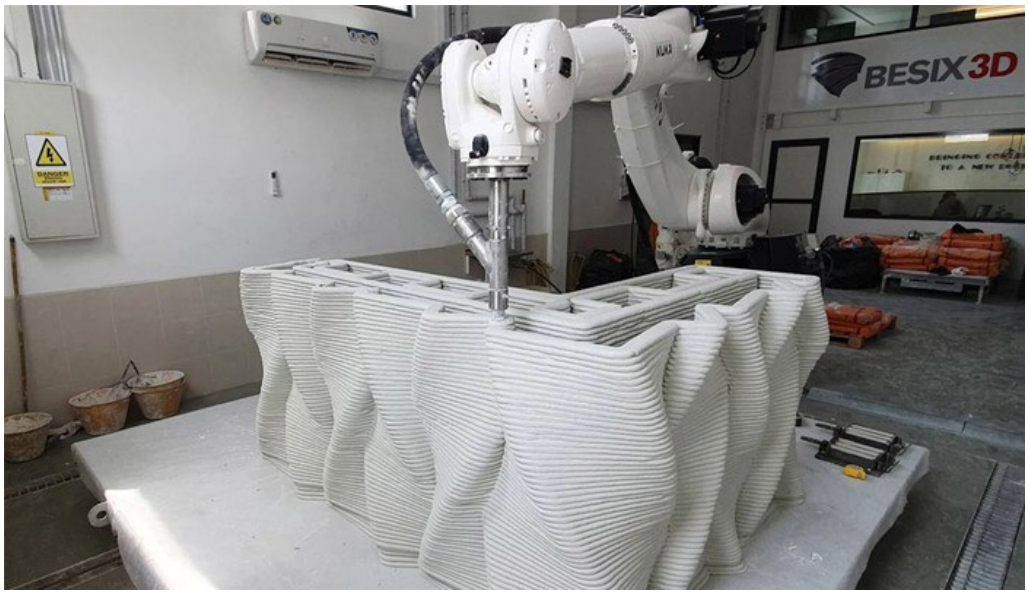


Figure 2.9 A Robotic arm with a custom extruder, The KR QUANTEC arm was equipped with a nozzle to extrude concrete for the Besix3D Comapn (KUKA, 2022).

Of particular relevance to product design and this research, AM enables rapid localised prototyping (see Figure 2.10), as well as distributed manufacturing enabled through cloud and digital storage, less resource consumption, DIY and maker small-scale local production processes, and novel material development and testing (Despeisse et al., 2017; Garmulewicz et al., 2018; Mehrpouya et al., 2021; Ngo et al., 2018; Niaki, Torabi, & Nonino, 2019; Rognoli et al., 2015; Sathish, Vijayakumar, & Krishnan Ayyangar, 2018; Sauerwein, 2020; Sculpteo, 2020a; Smith et al., 2020; Unruh, 2018; Wohlers Associates, 2020). AM technologies have many benefits compared to traditional manufacturing technologies. Many of these advantages, such as complex and lightweight part manufacturing, distributed production and lessened resource consumption, allude to lessened environmental impact; however, environmental issues are still associated with AM technologies. Peng et al. (2018) state that "energy and material consumption represent the main resource consumption" in AM processes (p. 696). Peng et al. continue to state that though waste output from manufacturing with AM can reduce manufacturing waste by up to 90%, waste is still generated from printed support structures, failed prints, and non-recyclable materials used in the AM production process. Kellens et al. (2017), a co-author of Peng et al., as well as Rejeski, Zhao and Huang (2018), argue that though AM may have a higher environmental impact caused by increased energy consumption in part production, the functional improvements to AM manufactured parts may compensate for the difference.



Figure 2.10 Students at Burg Giebichenstein University of Art and Design Halle (2014) participate in a paste 3D printing workshop with artist Jonathan Keep. Many MEX AM technologies are desktop-sized, allowing for transportation and use in the home and professional environments. MEX technologies have become increasingly affordable and open source, allowing for modification and exploration into applications beyond thermoplastic-based printing.

Some AM produces harmful pollutants and emissions during feedstock manufacturing, printing processes and attempted recycling (Gebler, Schoot Uiterkamp, & Visser, 2014; Kellens et al., 2017; Ngo et al., 2018; Pakkanen et al., 2017a; Peng et al., 2018; Rejeski, Zhao, & Huang, 2018). MEX printing traditionally uses filament spools of thermoplastic polymers derived from fossil fuels (Figure 2.11). Some of the most popular thermoplastic polymers used in MEX printing are acrylonitrile butadiene styrene (ABS), high-density polyethylene (HDPE), polylactic acid (PLA), polyethylene terephthalate glycol-modified (PET-G), thermoplastic polyurethane (TPU), and nylon (Ford & Despeisse, 2016; Ngo et al., 2018; Pakkanen et al., 2017a; Peng et al., 2018). All these materials, except for PLA, are produced using resources derived from fossil fuels, which negatively affect the environment during extraction.



Figure 2.11 Various coloured spools of thermoplastic 3D printing filaments (LuchschenF, 2018).

Studies have also shown that MEX printing can release harmful emissions during the printing process. Stephens et al. (2013) and Mendes et al. (2017) found that printing with PLA and ABS releases ultrafine particles into the air and categorised both materials as high emitters within a $45m^3$ office space. Sigloch et al. (2020) investigated the emissions released from a 3D printing pen device and found that additives to filaments can result in worse emissions and increased geometric mean diameter of particles released. Azimi et al. (2016) measured the release of volatile organic compounds from various parings of desktop 3D printers and materials. They found that the primary volatile organic compound released in ABS prints was styrene, which is toxic and carcinogenic (National Center for Biotechnology Information, 2022b). In contrast, the bioplastic PLA prints released the benign particle of lactide (National Center for Biotechnology Information, 2022a).

There is a contradiction between the benefits of MEX printing and its negative impact on the environment. While MEX printing is mainly used for and enables cheap rapid prototyping for numerous industries (Sculpteo, 2020b), it also uses, generates, and potentially creates difficult-to-recycle plastic waste (Figure 2.12). Though it has been shown that plastic waste from AM processes can be recycled (Cruz Sanchez et al., 2020; Pakkanen et al., 2017a), these processes require the user to sort their own material and recycle it with expensive speciality equipment or find a recycling centre themselves (shopplaywood, 2019) (Figure 2.13). Real-world applications such as recyclability through curb-side waste collection are not yet achievable or are poorly regulated (Hunt et al., 2015; Jones, 2022). Furthermore, the most common plastics used in 3D printing, ABS and PLA, are classified as type 7 'other' plastics, which, if labelled correctly, is a classification of material that is not commonly recycled (Figure 2.14) (Hardin, 2021; Hossain et al., 2022). In efforts to try to steer AM towards its perceived sustainability potential, researchers have identified the need to implement sustainability-based guidelines, methodologies and training within the 3D printing industry (Malik et al., 2022; Peng et al., 2018).





Left to right
Figure 2.12 3D-printed waste filament in various colours (shopplaywood, 2019)'
Figure 2.13 Felfil Evo Filament Extruder (Felfil, 2023)

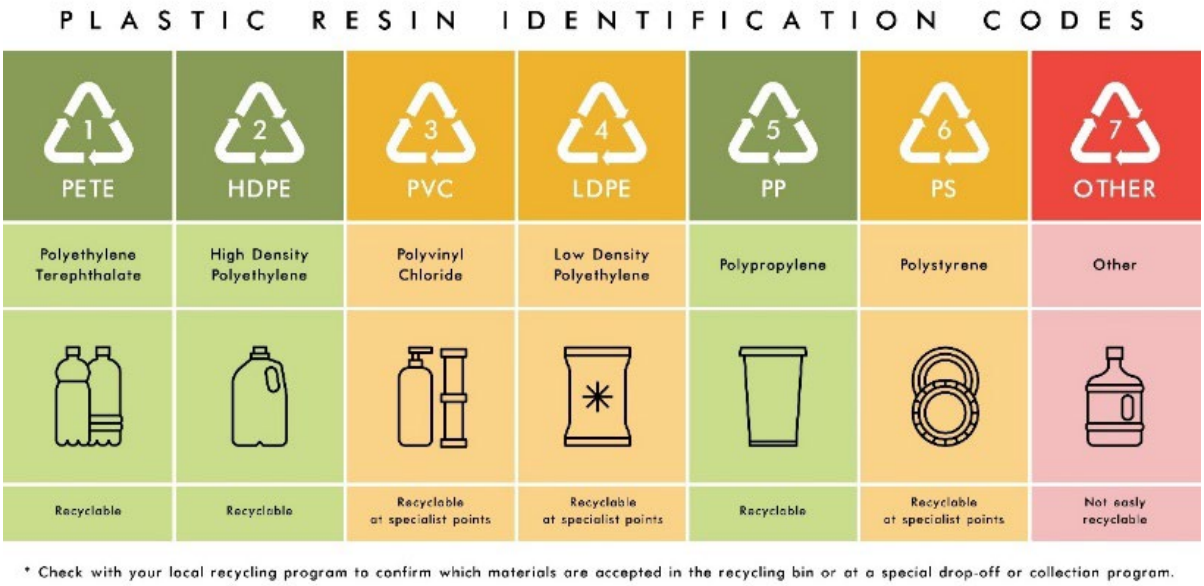


Figure 2.14 Plastic recycling codes based on ASTM D7611/D7611M-21 "Standard Practice for Coding Plastic Manufactured Articles Resin Identification". Image from Adobe Stock, shopplaywood (2019)

2.3.1 The Maker Movement

Since the early 2000s, AM technologies have become increasingly popular in many industries due to their benefits over subtractive manufacturing. While industrial and professional 3D printers have consistently improved to fill the needs of industry, there has been a trickle-down effect in functionality, increasing the capabilities of consumer and budget-friendly 3D printers, particularly those in the Material Extrusion (MEX) categorisation (Aliverti et al., 2015; Blikstein, 2013). Many benefits that have enabled the adoption of AM for professional use cases can be applied to home or hobbyist users, such as cheaper access to technology, enabled localised production, digitised parts and digital design tools, online sharing communities, and freely shared knowledge online in written and video formats (Aliverti et al., 2015; Browder et al., 2019; Fisher, 2022). The popularity of AM for hobbyist groups has supported and resulted from the development of online communities featuring repositories and guides (Browder et al., 2019). One such group that has experienced tremendous growth due to the affordability and capability of AM technologies and IOT (internet of things) is the maker movement (Aliverti et al., 2015; Browder et al., 2019; Rognoli et al., 2015).

The maker movement consists of communities (broadly online) of enthusiasts from diverse backgrounds and interests who engage in democratised play, tinkering and creation (Dougherty, 2012). Over the past two decades, the maker movement has experienced continued growth in popularity and engagement and has entered the mainstream (Browder et al., 2019; Make et al., 2022), evidenced by increasing attempts to captivate and train younger generations in maker skill sets (Halverson & Sheridan, 2014) and the increase of academic institutions opening maker spaces on university and school campuses (see Figure 2.15) (Mounde, 2020; Nay, 2020). This sentiment is echoed by Harness (2022), who outlines the proliferation and establishment of the maker movement into the mainstream as shown by maker spaces, also known as ‘Fab Labs’, becoming prominently featured in community centres, schools and libraries (pp. 14-21). Maker Spaces have entered the lives of regular consumers, where makers are flocking to online marketplaces to sell their handmade, homemade, small batch and digital products to consumers through online marketplaces like Etsy and Amazon Marketplaces.



Figure 2.15 Columbia University's School of Engineering Makerspace @ Columbia is an innovative hub for interdisciplinary invention (Yablon, 2020).

As discussed in 2.1 *Product Design*, product designers have evolved alongside the trends and technologies of the times, creating period-relevant products for consumers (Bürdek, 2015). Through this evolution, the product designer became more focused on developing products and less involved in the physical creation and manufacturing of the products they designed. The maker movement has enabled designers to take agency over the entire design and manufacturing process. The proliferation of affordable MEX 3D printers, in combination with the tinkering approach of the maker movement, has enabled makers and product designers to focus on a holistic approach to product development processes (Fisher, 2022), including the development of new sustainable materials used within the product design process and to manufacture products.

While not new, significant developments overlap between the maker movement, additive manufacturing, design, science, manufacturing industries, and sustainability researchers regarding the development of sustainable novel materials (Karana et al., 2015). Traditionally, after development, a novel material will take decades to reach a point of successful commercial application (Maine et al., 2005); however, material developers have begun to introduce new materials to designers soon after development in an attempt to find practical applications for their material (Karana et al., 2015). The designer tends to ask questions relating to potential applications of materials rather than more rigid performance-based questions from scientific perspectives, a notion reflected in the playful and inquisitive intersection of novel materials, design, and the maker

movement (Rognoli et al., 2015). Parisi, Rognoli and Sonneveld (2017) proposed *material tinkering* as an experiential educational tool enabling designers to better understand novel and existing materials through a hands-on approach. Material tinkering strongly represents the differences in prototyping methodology in novel material design, separating the work between designers, makers, and scientists, all of whom contribute uniquely to the interdisciplinary intersection of novel material design.

2.4 Sustainability

The unparalleled danger of the global climate change situation is well documented. Policymakers and intergovernmental groups such as the United Nations (UN) and The Intergovernmental Panel On Climate Change (IPCC) are now actively involved in attempts to mitigate global temperature increases. Intergovernmental agreements like the *Paris Agreement* (UN, 2022) and scientific collaboration such as the *AR6 Synthesis Report: Climate Change 202ss2* (IPCC, 2022) outline and demonstrate collective pressure and urgency in response to the increasingly obvious signs of climate change.

In response to the climate change crisis, countries are exhibiting varying levels of adoption and success in creating more sustainable economies. Of particular importance are the growing global concerns about reducing greenhouse gas (GHG) production, circular economy adoption and reduction of waste (OECD, 2020). Discussions have been presented that suggest the concerns of the OECD are relative and reactive to one another; they argue that higher use of fossil fuels is tied to increased economic activity, reinforcing global reliance on fossil fuels and the subsequent production of GHGs (de Coninck et al., 2018; Heinberg, 2018; Næss & Høyer, 2009; Wu et al., 2018).

Some human activities negatively affect the environment as an ancillary cause of the generation of excessive GHG. Intergovernmental bodies like the IPCC have identified modern mass manufacturing and its inherent unsustainable processes as significant contributors to climate change by generating GHGs and other pollutants and toxins (IPCC, 2022; Schumer et al., 2022). Without considerable intervention to mitigate the production of GHGs and changes to producer and consumer behaviours and relationships, today's manufacturing industries will continue to cause significant and long-lasting environmental impacts (Aljazeera, 2021; Starr, 2016).

As noted by Azoulay et al. (2019), Heinrich-Böll-Stiftung and Break Free From Plastic (2020), Intergovernmental Panel on Climate Change [IPCC] (2022), Kaza et al. (2018) and OECD (2020), solid waste generation and waste management are serious issues affecting the environment (Figure 2.16). While the production of some materials, like polymers, directly correlates to GHG emissions through the use of fossil fuels for energy and feedstock, there are also ramifications in that the environment caused by these materials exists beyond their intended lifecycle (Hoornweg & Bhada-Tata, 2012; Kaza et al., 2018; Shen et al., 2020).



Figure 2.16 "Workers risk their health for little pay rummaging through the trash" at the Gonio Landfill in Georgia (Bertrams, 2021).

2.5 Polymers

Both naturally occurring and artificial polymers are of central interest to sustainability issues. Artificial polymers (also known as plastics) are ubiquitous in our everyday life. Heinrich-Böll-Stiftung and Break Free From Plastic (2020) foreshadow the issues associated with the unavoidability of non-biodegradable plastic products and their long-lasting effects on the climate in their introduction to *Plastic Atlas:*

> At this point in modern life, we touch plastic more than we touch our loved ones. Plastic is everywhere; it is in our air, our water, and in our soils. It is the vehicle for globalisation, and the epitome of unregulated late stage capitalism – a system that externalises cost to people and the environment for the sake of profit. (p. 6)

The traditional lifecycle of plastic is one of unmatched versatility, but it also causes contamination and environmental damage, leaving near-permanent damage to the environment (see Figure 2.17). Moreover, all stages of the plastic lifecycle have been shown to have a detrimental effect on human health, contributing to cancers, obesity and diabetes, fertility and developmental issues (Azoulay et al., 2019; Heinrich-Böll-Stiftung & Break Free From Plastic, 2020; Wang et al., 2020).



Figure 2.17 Waste plastic bottles and other types of plastic waste at the Thilafushi waste disposal site (Abdulraheem, 2015).

Furthermore, plastic products are commonly discarded in landfills or waste streams, where they can take hundreds of years to degrade, affecting natural ecosystems (WWF, 2021). As seen in Figure 2.18 and Figure 2.19, if not recycled, everyday objects such as plastic bags, plastic water bottles, and toothbrushes will live in and continually affect our environment for hundreds of years (WWF, 2021).



Figure 2.18 The Great Pacific Garbage Patch, It's estimated that between 1.15 to 2.41 million tonnes of plastic are entering the ocean each year (The Ocean Cleanup, 2019).



Figure 2.19 Emissions from fossil fuel refinement (Geisler Fotopress, 2019).

It is estimated that nine billion, two hundred million metric tonnes of plastic have been produced since 1950, with production reaching three hundred and sixty million metric tonnes in 2019 (Heinrich-Böll-Stiftung & Break Free From Plastic, 2020; Plastics Europe & European Association Of Plastic Recycling and Recovery Organisations, 2021). In their Report *Plastic Atlas* Heinrich-Böll-Stiftung and Break Free From Plastic (2020) estimate since 1950, only six hundred million metric tonnes of plastic have been recycled (around 6.5%), with four hundred million metric tonnes being discarded or incinerated after recycling, leaving only two hundred million metric tonnes still in use.

Both municipal and industrial material recycling and waste management practices are being implemented globally for a wide range of materials. However, the effectiveness of these practices varies from country to country and from local council to local council. Waste management has improved with varying success through legislation in various locations. Germany, the world's most proficient recycler of municipal solid waste at 67% (OECD, 2022), is an example of successful legislative implementation, such as the Packaging Act, where the producer is responsible for recycling and recovery of packaging, and the Green Dot System, allowing correctly labelled packaging to be collected by both public and private waste managers (see Figure 2.20) (Igini, 2022).



Figure 2.20 Waste management bins in Berlin, Germany. White Glass, Coloured Glass, Paper and Cardboard, Plastics, Compost, Residual Waste (left to right) (Berliner Stadtreinigungsbetriebe, 2023)

As mentioned above, plastic polymers have unrivalled versatility. Over the last century, plastics have been fine-tuned to suit many highly efficient mass production processes, such as injection moulding used to create casings for our appliances and vacuum forming for a wide range of packaging applications. This suitability for mass production means that plastics are purchased and used in large quantities, making them very cost effective. Its low cost and suitability for mass production have made the industry heavily reliant on plastics, and challenging this convention is proving difficult.

2.6 Mass Production

Manufacturers and consumer goods play a fundamental role in supporting modern society's function, with highly visible products and infrastructures such as automotive, textiles, electronics, appliances and household goods being manufactured, distributed and sold locally and internationally on massive scales. However, the cycle of product development through to manufacturing, use, and end-of-life is leaving significant trails of damage to the planet beyond the intended aim of supporting human civilisation (Hamilton & Feit, 2019; Panagiotopoulou, Stavropoulos, & Chryssolouris, 2022; Shen et al., 2020).

These systems of mass production are designed to support the increasing demands of modern society, which in turn places further demands on the environment. For example, automotive manufacturing causes significant waste and emissions during manufacturing and use, with reports of manufacturers underreporting their emissions (Bonaccorsi, Ferraro, & Manassé, 2022). It has been estimated that a car's total emissions of GHG through its lifecycle are similar to those released during manufacturing (Hirz & Nguyen, 2022). Communications devices have grown exponentially in importance, capabilities and demand in recent decades, resulting in significant growth in e-waste production (see Figure 2.21) (Forti et al., 2020). The industry accounts for roughly 1.4%–5.9% of global GHG emissions, of which consumer devices cause 31% (Singh & Ogunseitan, 2022).



Figure 2.21 Men selecting electronic waste from used cellular phones at a workshop in the Bantar Gebang area, Bekasi, West Java (Greenpeace, 2017)

Many agents affect the mass production process, filling and overlapping roles responsible for all stages of development and production, such as market research, concept generation, product development, preparation for manufacturing, marketing and distribution. The product designer has traditionally played the role of the aesthetic driver; however, the profession and practice of product design have become more widely implemented within the production process (Bürdek, 2015; Cuffaro & Zaksenberg, 2013). Focusing on modern product designers' workflow, this research is developing new processes and materials to enable environmentally friendly prototyping and product development practices. The product designer has traditionally been initially involved with many of the processes from design development through to manufacturing of the goods (Bürdek, 2015); however, a niche group of product designers has shifted away from focusing on manufacturing and manufacturability to a focus on research and development of new processes and materials for product design practice.

2.7 Novel Material Development by Designers, Engineers and Scientists

The following section discusses the differences in the approaches to novel material development by designers, engineers and scientists. These categorisations are archetypal and approximate, based on traditional disciplinary approaches associated with the work of professionals in each field.

Environmentally conscious designers and makers have begun to develop products and materials that address many of the environmental concerns of the modern consumer. Of particular interest to this research is the work of designers who are formulating, designing and manufacturing sustainable novel materials (Camere & Karana, 2018; Faludi et al., 2019; McLean, 2018; Rael & San Fratello, 2018; Sauerwein & Doubrovski, 2018). Like some in the additive manufacturing community, who freely share their designs and printer schematics online (Jones et al., 2011; Keep, 2020; Kintel, 2022; MakerBot Industries LLC, 2022; StoneFlower3D, 2022), communities of material designers and makers are also sharing their material 'recipes' freely (Figure 2.22) (Garmulewicz & Corbin, 2018; Kääriäinen et al., 2020a; MaterialsDesignMap, 2024).

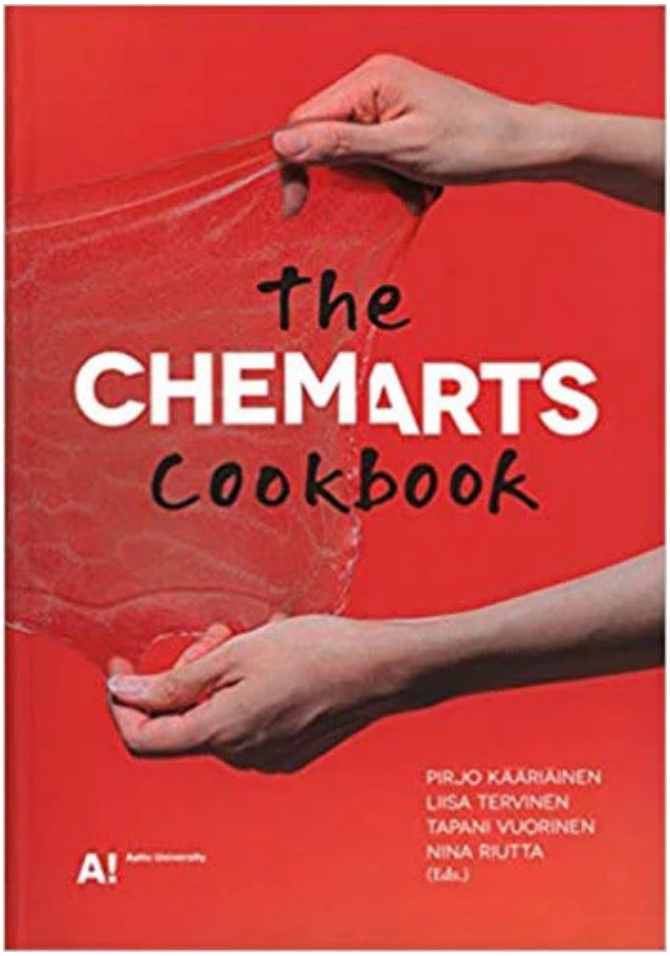


Figure 2.22 The Chemarts Cookbook cover. A free-to-download PDF (or purchasable hardcover) featuring recipes for novel material creation and play (Kääriäinen et al., 2020b).

In response to growing societal awareness of the dangers and issues associated with petrochemical materials used to manufacture products, designers, engineers and scientists are increasingly engaging with novel material research. While researchers from these disciplines are interested in creating new materials for the dual benefit of humans and the environment, designers, engineers and scientists communicate their material selection process in contrasting ways, using distinct language and reasoning to communicate their motivations for identifying, selecting and experimenting with novel material composites. This notion is well defined in the seminal work of Professor Nigel Cross in his book *Engineering Design Methods: Strategies for Product Design:*

> In an experimental research study, Lawson (1984) compared the ways in which designers (in this case architects) and scientists solved the same problem. The scientists tended to use a strategy of systematically trying to understand the problem, in order to look for underlying rules which would enable them to generate an optimum solution. In contrast, the designers tended to make initial explorations and then suggest a variety of possible solutions until they found one that was good, or at least satisfactory. The evidence from the experiments suggested that scientists problem-solve by analysis, whereas designers problem-solve by synthesis; scientists use 'problem-focused strategies' and designers use 'solution-focused strategies'. (2008, p. 21)

Through a review of novel material research, the apparent differences in the methodological approaches and transparency of results between disciplines become apparent; when approaching the same problem or working in similar problem spaces, a designer explores multiple possibilities on their way through to a solution, while scientists and engineers work towards solving a defined problem. These disciplinary differences are innate and embedded in their respective practices; however, adopting and embracing cross-disciplinary knowledge and methodological approaches could be beneficial for developing sustainable materials designed for positive, broader ecological impacts.

In journal articles detailing novel material development, scientists and engineers plainly and transparently described their sourcing, material preparation, testing methodology and workflow in their reports of experimentation (see 2.7.1 Scientific and Engineering Based Research). Their work is pragmatic in that it is published to share knowledge and assist others on similar journeys. In contrast, designers have their work published in online magazines (such as Core77 and Dezeen), news articles and through their social media and online portfolios. Their work takes an alternative

but equally pragmatic approach, following sensuous effects and human meaning rather than transparent descriptions of mixtures, sourcing procedures, performance results and procedural approaches.

2.7.1 Scientific and Engineering Based Research

A noticeable trend in scientific and engineering-based explorations in novel materials is using sustainable and reclaimed materials as functional fillers. These materials, such as sugarcane bagasse, are mixed with petrochemical or plant-derived biodegradable polymers to create cheaper or seemingly more environmentally friendly materials (Girdis et al., 2016; Kariz et al., 2018; Liu et al., 2019; Zhao et al., 2016). These mixed source materials result in difficult-to-recycle waste streams, as when the organic matter is mixed with virgin plastic material, the recycling possibilities for the end product become more complex while spoiling virgin plastic materials. Many of these materials are publicised using greenwashing tactics, such as the broad declaration of their biodegradable qualities (Kariz et al., 2018; Tran et al., 2017); however, the conditions of biodegradability are rarely explicitly shared with consumers. Materials such as PLA cannot decompose in domestic settings; instead, the material needs specific high-temperature processing facilities to degrade fully (Narancic et al., 2018; Weng et al., 2013).

While scientists and engineers are experimenting with sustainable functional filers in composites, some of their testing methods are skewed through their tests that compare thermoplastics to novel material composites. Plastics have been in development for over 100 years and are universally known as incredibly versatile and high-performance materials. Comparing a newly developed sustainable novel material to a highly developed thermoplastic (like ABS) will constantly show higher performance qualities for the ABS. However, while plastics are highly versatile, their negative impact on the environment during manufacturing, in use, and after disposal is well documented (*see 2.5* Polymers). The design of novel materials is a broader industry-based answer to the issues of plastics, and perhaps the lower performance qualities of novel sustainable materials indicate less permanent and more sustainable materials. Designers, scientists and engineers are working within this space to design sustainable materials; however, performance-based comparisons between material categories are a disservice to sustainability efforts.

In their aim to improve the environmental impact of AM, Faludi et al. (2019) review, develop and test various novel material paste extrusion recipes for MEX. They assess recipes published by Rael and San Fratello (2018), von Hasseln (2017) and Ganter and Storti (2011) and introduce an array of novel formulations. Their testing compares these novel materials to standard acrylonitrile butadiene styrene (ABS) through the criteria of a life cycle assessment (LCA), assessing the cost of production, accuracy, and ease of printing as well as the strength of the material. Faludi et al.'s methodology and results demonstrate the importance of a structured analysis of novel materials' mechanical properties. For example, in their pecan shell flower and sodium silicate paste, the LCA results show a

75% reduction in energy consumption in printing, an 82% reduction in material environmental impact, and a 50% reduction in production cost. Faludi et al., like many other researchers, structure their performance testing based on standardised tests for synthetic polymers (ASTM D638-14 Type IV dog bone), where they compare ABS filament to their "pecan" novel material. This research proposes an alternative material development approach where NMCs are developed based on properties that become evident in the development cycle and not through comparison or standardised testing.

Liu et al. (2019) researched the effect of the orientation of tensile strength on biopolymers printed on MEX printers. The researchers created biopolymers consisting of processed and raw sugarcane bagasse with PLA. Results showed that a mix of 6% processed sugar cane bagasse and PLA has the second-best performance compared to virgin PLA filaments. All mechanical tests conducted were based on standardised plastic performance tests such as ISO 527 (see Figure 2.23), meaning the results are based on the performance of virgin plastic composites. Milosevic, Stoof and Pickering (2017) investigated the performance of a natural fibre-reinforced polypropylene (PP) for MEX printing. Filaments were made using a mix of hemp or harakeke (also known as New Zealand flax) and preconsumer recycled PP. Both hemp and harakeke were preprocessed in an alkali treatment to further purify the organic material for mixing with PP. Like Liu et al. (2019), the tensile tests performed (ASTM D638-10, similar to ISO 527 shown in Figure 2.23) are designed for virgin plastics and point to negative performance from the novel material examples.

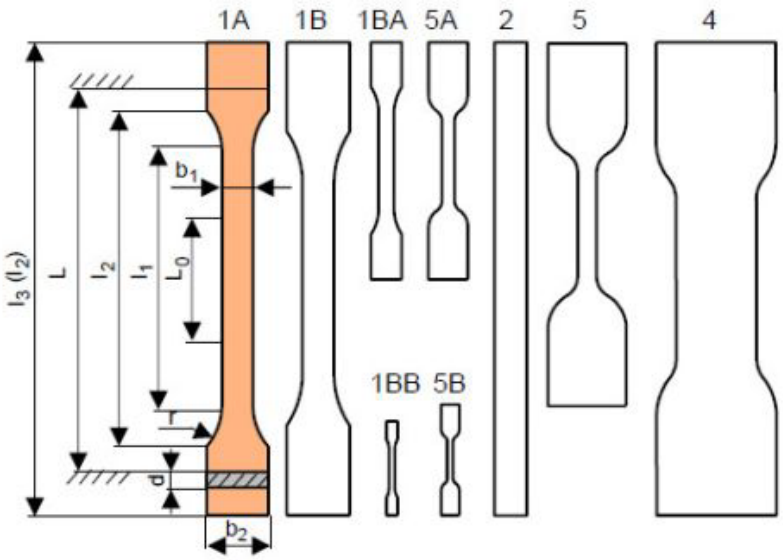


Figure 2.23 ISO 527, similar to ASTM D638, is a tensile test that provides data on a specimen's tensile strength (load) and elasticity. The specimens used are commonly referred to as a "dog bone" but can be in various shapes and scales, as shown in the figure (Polymer Service GmbH Merseburg, 2023).

Girdis et al. (2016) examined the use of organic waste material from local industries as a functional filler in a MEX filament. The Australian-based researchers compare their mixture of ABS plastic and ground macadamia nutshells against mostly unspecified store-bought filaments, some containing organic content. The researchers claim their 19% macadamia nut and ABS filament is 25% stronger than commercially available 30% wood fibre and PLA filament; however, this result does not consider that their novel material filaments contain different virgin plastics in different quantities and their associated performance qualities. Osman and Atia (2018) attempted to develop a cost-effective filament ABS incorporating the natural waste material of rice straw. Like Faludi et al. and Girdis et al., Osman and Atia compare their rice straw ABS mixture to virgin ABS through ATSM standard tests for virgin plastics, showing favourable results for the virgin material examples. Furthermore, though the authors succeeded in developing a cheaper material, a 15% rice straw content ABS filament would be 10% cheaper per kilogram than virgin ABS; the filament produced is now contaminated and cannot be recycled with other ABS.

Similar to Girdis et al. and Osman and Atia, Tran et al. (2017) investigate the implementation of industry by-products as a functional filler within 3D printing filaments. Tran et al. developed a cocoa shell and biodegradable polycaprolactone (PCL) filament. Tran et al. separate their work from similar papers by conducting experimentation that is fair to all materials tested; they explore the 3D printability of their material. The researchers tested factors such as the materials' thermal performance and layer adhesion and concluded their testing by printing 3D printing benchmark tests (see (Creative Tools, 2020)). Zhao et al. (2016) created a MEX filament consisting of PLA, bamboo, polyethylene glycol and synthesis plant ester. The mixture has a ratio of 5 parts of PLA to 2 parts of powdered bamboo and showed promising results in use cases on existing 3D printers. The significance of Tran et al. and Zhao et al.'s work is in their deviation from comparing novel materials with well-refined thermoplastics to evaluating the performance and identifying areas of improvement for a novel material composite. These studies acknowledge that novel material composites cannot serve as total plastic replacements and investigate the performance qualities to find avenues where a novel material can be utilised and excel in its implementation.

2.7.2 Design-Based Research Approach

Some studies in product design focus on artistic expression and formal possibilities, often motivated by a desire to better understand the potential of emerging sustainable materials and processes. Architect Ronald Rael and designer Virginia San Fratello combine their practices through their Emerging Objects Corporation, where they conduct experimental design work beyond the traditional realms of architectural practice. Rael and San Fratello navigate their experimental design practice by investigating novel material design with the influence of a material's traditional use and origins, and they express their findings through computational design processes and AM production. Their work develops novel filaments, paste, and powders manufactured from diverse sources of materials and binders. In their practice, they have worked with cement (2011), clay (2017) and, more recently, the studio has been upcycling agro-industrial and consumer waste materials such as salt, coffee, tea, wine, sawdust, rubber bioplastic and sand (2018). The studio explores and embraces the origins of their materials as they create evocative designs 'from the ground up' (2018, p.9), such as a meta-series of coffee, tea and wine cups, all 3D printed using a paste developed from the relevant industry; that is, a teapot and cups printed from tea-based paste and so on (Figure 2.24).



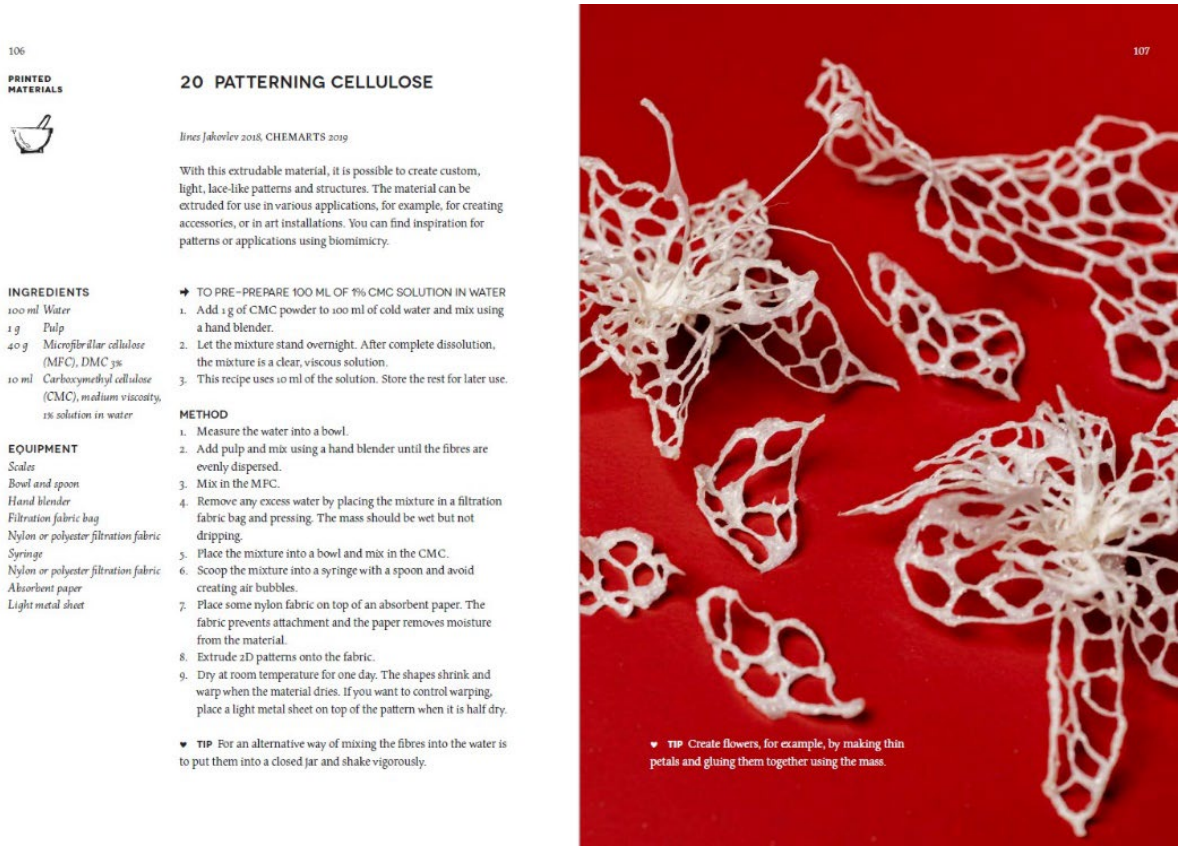
Figure 2.24 The Utah Teapot by Rael and San Fratello. The teapot design, by Dr Martin Newell, has become a semi-standard reference model in rendering software (Torrence, 2006). Emerging Objects 3D printed the set from powdered tea and sweetener using powder-based 3D printers. The teaspoon's volume contains the exact amount of one teaspoon (Rael & San Fratello, 2015).

Sauerwein and Doubrovski (2018) and Sauerwein et al. (2020) investigate the intersection between AM and the circular economy by creating a circular reprintable material for AM with inputs from local waste streams. Sauerwein, a product designer, uses a research-through-design (RtD) approach that uses prototyping for knowledge generation in her investigation. In the two-part study, Sauerwein et al. developed a circular additive manufacturing material using localised waste and mussel shells mixed with sodium alginate, and printed using a modified MEX printer for paste extrusion (Figure 2.25). The mussel shell print was compared with other organic filler materials in the same alginate mix, such as eggshells, walnut shells and cacao shells. The significance of Sauerwein et al.'s research is the transparency in the material selection and mixing process and the intent to design reprintable material for 3D printing.



Figure 2.25 Sauerwine's 3D printed mussell shell composite vessel. The material consists of equal parts water to sugar, mixed with crushed mussel shells (Sauerwein, 2023).

Recipes similar to those used by Rael and San Fratello and Sauerwein et al. are offered by the open-source online recipe database Materiom, founded by Garmulewicz and Corbin in 2018; similar materials can be found in *The CHEMARTS Cookbook,* as shown in Figure 2.26 (Kääriäinen et al., 2020a). Although there has been some quantitative research into the performance of these materials when used in AM, further evaluation of the structural properties and sustainability credentials of these novel materials is needed before they can be implemented in mainstream production cycles.



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PRINTED MATERIALS

20 PATTERNING CELLULOSE

Iines Jakovlev 2018, CHEMARTS 2019

With this extrudable material, it is possible to create custom, light, lace-like patterns and structures. The material can be extruded for use in various applications, for example, for creating accessories, or in art installations. You can find inspiration for patterns or applications using biomimicry.

INGREDIENTS

100 ml Water
1 g Pulp
40 g Microfibrillar cellulose (MFC), DMC 3%
10 ml Carboxymethyl cellulose (CMC), medium viscosity, 1% solution in water

EQUIPMENT

Scales
Bowl and spoon
Hand blender
Filtration fabric bag
Nylon or polyester filtration fabric
Syringe
Nylon or polyester filtration fabric
Absorbent paper
Light metal sheet

→ TO PRE-PREPARE 100 ML OF 1% CMC SOLUTION IN WATER

1. Add 1 g of CMC powder to 100 ml of cold water and mix using a hand blender.
2. Let the mixture stand overnight. After complete dissolution, the mixture is a clear, viscous solution.
3. This recipe uses 10 ml of the solution. Store the rest for later use.

METHOD

1. Measure the water into a bowl.
2. Add pulp and mix using a hand blender until the fibres are evenly dispersed.
3. Mix in the MFC.
4. Remove any excess water by placing the mixture in a filtration fabric bag and pressing. The mass should be wet but not dripping.
5. Place the mixture into a bowl and mix in the CMC.
6. Scoop the mixture into a syringe with a spoon and avoid creating air bubbles.
7. Place some nylon fabric on top of an absorbent paper. The fabric prevents attachment and the paper removes moisture from the material.
8. Extrude 2D patterns onto the fabric.
9. Dry at room temperature for one day. The shapes shrink and warp when the material dries. If you want to control warping, place a light metal sheet on top of the pattern when it is half dry.

♥ TIP For an alternative way of mixing the fibres into the water is to put them into a closed jar and shake vigorously.

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♥ TIP Create flowers, for example, by making thin petals and gluing them together using the mass.

Figure 2.26 Recipe 20, Patterning Cellulose, The CHEMARTS Cookbook; "With this extrudable material, it is possible to create custom, light, lace-like patterns and structures. The material can be extruded for use in various applications, for example, for creating accessories or in art installations. You can find inspiration for patterns or applications using biomimicry." (Jakovlev, 2019)

Other designers are creating material composites for works that draw public attention to the space of novel material design. Some of these designs, utilising waste materials' social draw, generate difficult-to-recycle materials through their mixture of organic materials with plastics. Carlo Ratti Associati's (2019) *Feel the Peel* installation, shown in Figure 2.27, generates cups for orange juice that are 3D printed with a mixture of orange peels and PLA plastic. Similarly, Figure 2.28 shows the furniture and artifacts of Natasa Perkovic, which are also produced from a mixture of PLA and reclaimed palm oil (Hitti, 2020). The works from Carlo Ratti Associati and Perkovic draw attention to underutilised waste generated in various agricultural industries and generate minimalist products. Whilst it can be argued that the mixture of organic waste matter and PLA can create difficult-to-recycle waste streams (Narancic et al., 2018; Weng et al., 2013), installations such as 'Feel the Peel' and designs like Natasa Petkovic's chair raise public awareness regarding novel material development, and are an important stepping stone in the process of broader public acceptance of everyday products consisting of organic waste material.



Figure 2.27 Figure 2.28 Feel the Peel Installation: Bioplastic cups from orange peels (Giorgetti, 2019).



Figure 2.28 Nataša Perković makes textured furniture from palm oil byproducts: A chair 3D printed using a mix of PLA and palm oil tree fibre micro powder (Takano, 2020).

Companies like Model No. (2023) sell 3D printed products under 'plant-based polymers'. Similar to Carlo Ratti Associati's *Feel the Peel* installation, they mix reclaimed organic materials with PLA, boosting public awareness of sustainable materials with possibly circular and sustainable lifecycles. Whilst the use of mixed material composites, such as PLA and organised waste matter, can have positive effects on consumer appreciation and adoption of sustainable products, transparency in the end-of-life process for these composites is important. Companies such as Krill Design (2023a) sells 3D-printed lemon, coffee and orange designs without indicating what bioplastic they use (Figure 2.29). Whilst important stepping stones within the process of increasing consumer understanding and appreciation of sustainable materials, Carlo Ratti Associati, Perkovic, and Model No., Krill Design's selling point of biodegradability could be more transparent to enable consumers to safely dispose of products correctly. Many businesses are utilising the strong marketing ability of sustainable materials and products to attract environmentally conscious consumers; however, not all of these businesses are genuinely transparent about the sustainable qualities of their products and material (Schmuck et al., 2018).

To avoid the suitability issues of the past and many current practices, such as the lack of transparency in production and material use, employing greenwashing tactics for marketability, and comparison with established thermoplastic materials through standardised testing, those developing and manufacturing novel materials need to be realistic about their material's performance expectations and environmental impact and identify scenarios for their material to succeed.

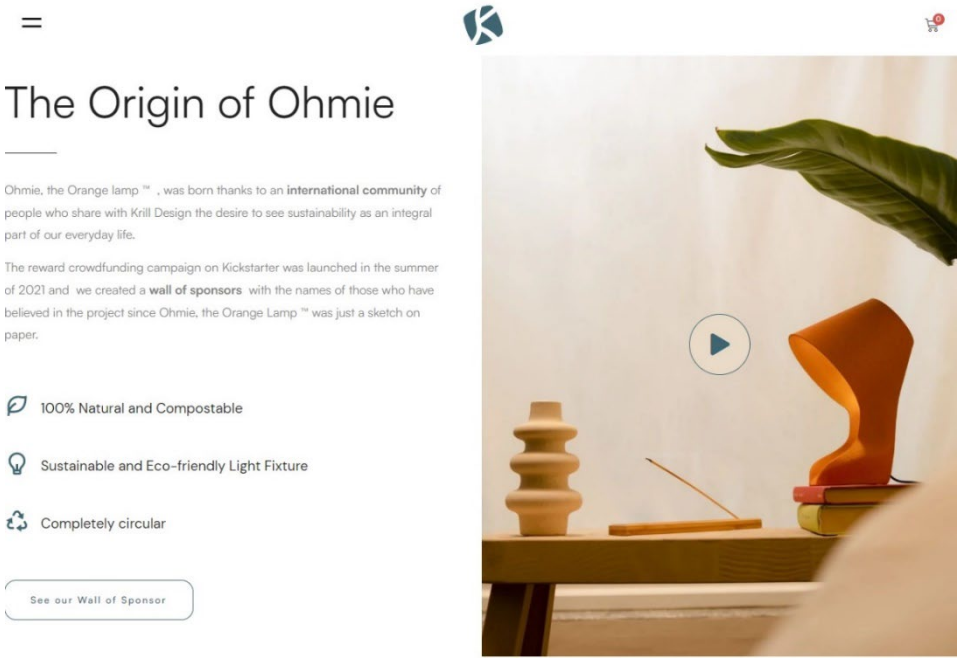


Figure 2.29 "The Origin of Ohmie". Krill Design claims circular economy, composability and sustainability without providing evidence or detail of what materials comprise their composite (Krill Design, 2023b).

2.7.3 Novel Material Development

This research aims to demonstrate pathways for novel material development and use that are sustainable and meaningful. As discussed, novel material development is a relatively new area of study and an important piece of sustainability research investigated by many different disciplines. However, to avoid the sustainability mistakes and oversights of the past, earlier intervention and the implementation of best practices should be applied to develop novel materials.

A literature review explored and analysed trends that could impact novel material composites' successful development and implementation. Though there are fundamental differences in the research practices of designers, scientists and engineers, their interest in novel material design suggests a collective understanding of the importance of developing more sustainable materials. Additionally, similarities in the identification and selection processes of waste materials can be seen between disciplines, where site locality plays a role in selecting a material. While designers, scientists and engineers may describe their material selection processes differently, with varying amounts of detail, their proximity to their chosen material remains site-specific in that the material is produced or is a result of industrial processes in their country of research. (see Appendix Table A).

How designers, scientists and engineers share their results has traditionally been different. While designers tend to share a final result supported by curated images and some supporting information on their processes, scientists and engineers will publish journal articles that describe their entire processes in detail. Scientists and engineers describe their research background, sourcing, processing, methodology, as well as their experimentation and results in great detail (See Faludi et al., 2019), while designers doing similar work tend to show their final work with limited information describing their process (see Rael & San Fratello, 2018). Unfortunately, some businesses, designers, scientists and engineers use greenwashing tactics for marketing their products without further clarifying their material's true construction (see Krill Design, 2023a). Though commercialisation is needed in many instances, those developing novel materials should be transparent and inclusive rather than joining a race for commercialisation and monetisation. This process will only harm the environment further through incorrect waste management of materials (Bulut et al., 2021; Enck & Dell, 2022; Zhang, 2022).

As discussed in *2.7*, Novel Material Development by Designers, Engineers and Scientists, the novel materials created by designers, scientists and engineers are still unrefined compared to well-established consumer materials such as plastic; however, this has not stopped researchers from continually comparing novel materials' performance to their highly refined plastic (petrochemical

and biobased) alternatives. Though researchers are generating meaningful insights into developing novel materials, testing a newly developed and unrefined material against a well-established champion of material versatility (Andrady & Neal, 2009) will ultimately lead to skewed results. For novel materials to be more widely accepted and adopted, standardised testing should be developed for novel materials that aim to find the practical use cases for materials rather than their comparison to plastics. This can be particularly useful in the case of single-use or short-lifecycle products, where a plastic material may live in the environment for hundreds of years after it has been discarded (Heinrich-Böll-Stiftung & Break Free From Plastic, 2020; WWF, 2021).

2.8 Summary

Central to product design practice and research is the prototyping process, which provides the designer with insights into various factors relating to their design. As with the practice of designers, prototyping methods have evolved with technological advancement and societal expectations towards products. In response to the sustainability crisis, some designers have turned to producing sustainable designs and materials; however, some aspects of traditional product design practice are still unsustainable. This research is a response to aspects of unsustainable prototyping practices, in which the materials currently being used can have adverse effects on the environment. The research will propose methods for generating sustainable alternative materials that can be used with existing prototyping technologies, like additive manufacturing.

Since the Industrial Revolution, the role of product designers has shifted through varying levels of involvement within product manufacturing. The rise of neoliberalism has influenced product design (Ansari, 2018; Jullier, 2019; Stern & Siegelbaum, 2019), partially moving the disciplinary focus away from low-quantity craft production to mass manufacturing of cheaper products (Stern & Siegelbaum, 2019; Bürdek, 2015). More recently, product design has been shifting back to craft manufacturing, a process enabled by consumer awareness, digitisation of designs, and on-demand manufacturing supported by additive manufacturing technologies (Bürdek, 2015; Diegel et al., 2016). The transition has also enabled the product designer to focus on user-centred, customised and low-quantity design rather than design for mass manufacturing.

An important aspect within the practice of product design, explorative prototyping processes can play an essential role in both academic and industrial product design processes (Walden et al., 2018; Wensveen & Matthews, 2014). While designers have traditionally produced prototypes through subtractive manufacturing methods, additive manufacturing technologies are becoming increasingly accessible to product designers to assist in prototyping practices. Although there have been dramatic improvements in digital technologies, physical prototyping provides designers and users with unmatched physical and tangible details in a design process (Hallgrimsson, 2012; McElroy, 2016a). Effective prototyping within a research and development process can result in well-rounded products that provide users with extended periods of use.

Additive manufacturing (AM) is a popular rapid prototyping tool for product designers. AM has many benefits over traditional subtractive manufacturing, including distributed and localised manufacturing and prototyping, cloud and digital storage, access to libraries of open-source parts, less material consumption, low cost for entry, and the ability to modify and control printers to the

operator's needs (Despeisse et al., 2017; Garmulewicz et al., 2018; Wohlers et al., 2022). While many scholars argue that AM has a lessened environmental impact than subtractive manufacturing, AM still impacts the environment through factors such as energy (Peng et al., 2018), and the impact popular thermoplastic materials used in 3D printing have on the environment (Gebler, Schoot Uiterkamp, & Visser, 2014; Kellens et al., 2017; Ngo et al., 2018).

Additive manufacturing can be attributed to some of the success in the revival of the maker movement and DIY (Do-It-Yourself) design (Dilberoglu et al., 2017). Many factors that have enabled the adoption of AM within the broader industry have similarly influenced the growth of the maker movement (Fisher, 2022). The maker movement has inspired and given increased manufacturing control to DIY makers, who are further enabled through immediate access to information and creative dialogue through the internet. The maker movement has evolved into subcategories of DIY makers who share common interests, some of which are areas of interest which align with academic and industry research, such as novel sustainable material design.

Environmentally conscious makers, designers, scientists and engineers have begun exploring sustainable novel material design processes. While researchers and practitioners investigate the creation of sustainable novel materials that use locally sourced waste material as functional fillers, each discipline conducts its research and shares its results differently. While scientific research excels in sharing rigorous and transparent research processes, they consistently implement standardised plastic performance tests to evaluate their novel materials, which sets the novel material at a consistent performance disadvantage during testing (Faludi et al., 2019; Girdis et al., 2016; Liu et al., 2019; Milosevic, Stoof, & Pickering, 2017). Designers explore artistic expression and formal possibilities in their research and practices, focussing on creating social awareness for their creations and brand recognition with the attachment to sustainable initiatives (Carlo Ratti Associati, 2019; Hitti, 2020; Krill Design, 2023a; Model No., 2023). However, there are designers and scientists whose work explores the generation of novel material composites with aims to generate useful materials that address fundamental sustainability, such as circular economy, waste material utilisation and effective and transparent testing processes (Kääriäinen et al., 2020a; Rael & San Fratello, 2018; Sauerwein, 2020; Sauerwein & Doubrovski, 2018; Tran et al., 2017; Zhao et al., 2016).

There is a clear need to develop novel materials within modern and future societies. However, like many innovations before, early intervention through policy and standards is needed to provide safe, sustainable avenues for future growth (Peng et al., 2018; Sauerwein et al., 2019). Notwithstanding the lack of policies and standardisation, there are still promising signs of the effective development

of sustainable novel materials shown through many disciplines, academic publications, designs, artistic work, and businesses. Trends have appeared within published works from multiple disciplines, showing that novel material designers recognise that various levels of conformity are needed to generate sustainable novel material. As seen in the work of Sauerwein and Doubrovski (2018), if a systematic enquiry process is applied to the entire material design and development processes, the novel materials generated can be designed beyond simple plastic replacements and can function as a material waste offset value in circular economy settings.

2.9 Research Questions

The research questions generated for this research serve as platforms for both investigating and synthesising a process for developing a novel material composite for practical use in localised situations. This research aims to use locally sourced waste to generate a plastic replacement material that functions within the prototyping processes of product designers. The material generated provides an example of a novel material composite being utilised as a functional material within established practices as well as a way to implement underutilised waste materials from the industry as replacements for petrochemical plastics in some scenarios.

1. What is involved in identifying, sourcing, managing and preprocessing a sustainable waste material suitable for development into a novel material composite (NMC) for material extrusion (MEX) 3D printing?
2. What is involved in generating 3D forms for product design explorative prototyping using MEX printing and NMCs?
3. To what extent can MEX printing of NMCs support the physical explorative prototyping requirements of product designers?

3 Methodology

This research is situated within the context of product design practice and emergent research and practices in sustainability. The research focuses on creating a locally sourced, sustainable, novel material composite (NMC) for use in additive manufacturing technologies (AM). More specifically, the research documents the development of an NMC that can be used to satisfy a product designer's needs for explorative prototyping as part of the design process. The practice-based aspects of the research utilise research-through-design (RtD), an iterative solution-focused process where designers probe their way through unknowns towards a desired outcome. The RtD process is documented using aspects of action research, such as critical diary-inspired documentation, incorporated within a contextual portfolio (CP) practice.

The research questions generated for this research are primarily investigated through an RtD approach (see *3.1*). While research questions 2 and 3 are investigated through RtD, research question 1 utilises a hybrid literature review (Xiao & Watson, 2019) to build a knowledge base that underpins the subsequent investigation of the material selection process, and the practical RtD-based enquiries into the initial material preprocessing and NMC paste creation. The hybrid literature was structured based on a meta-ethnography approach (Noblit & Hare, 1988), and further analysis was conducted through a thematic synthesis (Thomas & Harden, 2008), which follows three stages of reviewing and 'coding' data, organising data into themes, and developing analytical themes for further investigation. In this hybrid review format, key stages revolved around interpreting themes between interdisciplinary and interindustry sources.

3.1 Research through Design

RtD was introduced by Frayling (1994) as an approach that supports the knowledge generated during the practical elements of design practice. RtD has evolved alongside and with design practice to become a widely accepted methodological approach, which has been refined by many scholars such as Bowers (2012), Galdon and Hall (2022), Koskinen, Binder and Redström (2008), Stappers (2007), and Zimmerman, Forlizzi and Evenson (2007). The RtD approach incorporates and embraces the practice-based aspects of a designer's process, such as prototyping. While the articulation of the results from RtD can be different, the artifacts and prototypes generated have proven to be valuable contributors to knowledge within and beyond their initial experimentation.

The definition and implementation of RtD have evolved substantially since Frayling's paper was first published (1994). A significant contributor to the evolution and adoption of RtD as a recognised

research methodology was the collaboration between designers and researchers from the human-computer interaction (HCI) discipline. While no clear definition of the outputs of RtD was agreed upon by scholars, trends began to appear in their writing about what constitutes an RtD practice. Zimmerman, Forlizzi and Evenson (2007) expand on Frayling's work, stating, "Design artefacts are the currency of design communication" (p. 496), and describe the process of RtD as:

> ….[in] an active process of ideating, iterating, and critiquing potential solutions, design researchers continually reframe the problem as they attempt to make the right thing. The final output of this activity is a concrete problem framing and articulation of the preferred state, and a series of artifacts – models, prototypes, products, and documentation of the design process. (p 497)

Koskinen, Binder and Redström (2008) agree and expand on Zimmerman et al.'s discussion, stating that the knowledge generated through design practice is embedded within the artefacts created during the design process. Koskinen et al. progress on previous definitions that frame the design process as a method of proposing possible solutions to desired futures. Koskinen et al. argue that the intangible knowledge generated through a designer's practice is rooted within the artefacts created to examine the questions proposed in the research process. Similarly, Gaver (2012) states that design is generative in that it is concerned with creating "*what might be*" (p 940) and "new realities" (p. 941) and states that the expression of the application of design skills within the artefacts textually will enable the broader application of the embedded knowledge (see *3.3).* More recently, Galdon and Hall (2022) state that design is a transformational practice through the prospective thinking of designers and the abductive reasoning of the practice. The practice of designers and research of RtD scholars converge through practise-based and theoretical knowledge embedded in the artefacts and prototypes generated through practice; it is through the sharing of this embedded knowledge that enables RtD to be an effective academic knowledge contributor.

3.2 Action Research

Within discussions exploring the application of RtD in formal research contexts, action research (AR) has been proposed as a methodology that would aid RtD practitioners in documenting and synthesising their process and results through an established methodological approach (Archer, 1995; Frayling, 1994; Pedgley, 2007; Swann, 2002). AR is a practical multidisciplinary approach that can be effectively applied to RtD and other practice-based research methodologies through similarities in their approaches, such as their cyclical, iterative and reflective natures (Brandt, 2004; Kemmis, 2009; Muratovski, 2016; Pedgley & Wormald, 2007; Swann, 2002). An AR approach enables

practice-based disciplines to conform to criteria that are prevalent and expected by the broader research community, such as being knowledge-directed, systematically conducted, and transparent in its approach to conducting research (Archer, 1995; Pedgley & Wormald, 2007). AR is a broadly accepted approach and is recognised as a formal research methodology in diverse fields, including design (Brandt, 2004; Kemmis, 2009; Muratovski, 2016; Swann, 2002), nursing (Holter & Schwartz-Barcott, 1993), education (Heigham & Croker, 2009), psychology (Kidd & Kral, 2005) and more.

Traditionally, product designers are trained to follow a practice-based design approach (Glanville, 2014; Swann, 2002), where the process of designing is iterative, as designs evolve through reflective processes during action (Schon, 2016); a research and practice process that is coherent with AR methodology. Swann argues that an "Action research methodology provides a ready-made scaffold for a systematic research method that could be easily understood and adopted by designers in the translation of their professional practices into acceptable academic and public discourse" (2002, p. 61). The benefit of pairing RtD research and AR is particularly evident in cases where the "final outcome is undefined" (p. 58). Swan states that the "implicit process[es]" within a design practice can "become explicit" (p. 58) through the systematic documentation and reflection used in action research methodology.

Within the RtD methodological approach applied in this research, AR plays a fundamental role in influencing the documentation and analysis of experiments conducted during the research. AR provides a formal documentation process that complements RtD processes, enabling the knowledge translation and transfer from artefacts, prototypes and design research processes into perceptible and transferrable formats. AR complements the iterative cycle of traditional design practice by applying further analytical and documentation-based layers over the action and reflection-based practices in RtD practice.

Within the field of design research, researchers have been constructing tools and methods independent of AR that enable designers to express the embedded knowledge within the artefacts and prototypes generated in the practices while also enabling designers to display and present the artefacts to audiences as designed pieces. Examples include annotated portfolios (see *3.4*) (Gaver & Bowers, 2012), contextual portfolios (see *3.5*) (Sadokierski, 2019), and reflective design documentation (Dalsgaard & Halskov, 2012).

3.3 Annotated Portfolios

While AR and RtD can seamlessly integrate for greater expression of RtD for scholarly contribution (Swann, 2002), scholars within the RtD and HCI communities have been developing new methods and tools to be utilised for the realisation of RtD as an established methodological approach. Pedgley (2007) proposed criteria enabling RtD as a scholarly endeavour, stating that reflection, analysis, theorising and methodological transparency are paramount in research practice. Pedgley and Wormald (2007) extend on their previous work, proposing the 'design diary' (akin to techniques in AR) as activities enabling the sharing and synthesis of results. Dalsgaard and Halskov (2012) propose a novel tool for rigorous documentation within the design process, promoting increased reflection about the events within a design process and generating transmissible data from the design process to new viewers.

While acknowledging the need for designers to produce more mature outputs than physical designs, Gaver and Bowers (2012) argue that further labelling or prescription to a more systematic methodological framework could jeopardise the fundamentally unorthodox nature of designers' work. The pair propose annotated portfolios as a means for designers to convey the "varied, multifaceted, and heterogenous" (p. 43) layers of their design and process to various audiences. As shown in Figure 3.1, this is done by carefully annotating curated images of the design; the image choice, layout, annotations and placement, and where the annotated portfolio is published are all at the designer's discretion.



Figure 3.1 Annotated Portfolio of the 'Photostroller' by Gaver and Bowers (2012)

Annotated portfolios can be a limited information transfer medium, as the designers' choice of what information and images to include may be biased and limited. The chosen medium to display the annotated portfolio may not have enough space or, thematically, may not allow the designer to include the whole 'design journey', a process which, if reflected on stringently, may include much more information that would appeal to a greater audience. Gaver and Bowers' initial representations of the annotated portfolio reflect full-page magazine spreads, only showing a single image of a final design with curated textual annotations spaced around it. Though seminal in its implication for capturing and sharing knowledge beyond the profession of design research, the annotated portfolio format has shortcomings regarding the comprehensive sharing of RtD processes and results. Design researchers such as Sadokierski (2019) have developed more scholarly and formal progressions from the annotated portfolio, such as the contextual portfolio (CP), enabling more thorough documentation which encapsulates more of the design research process.

3.4 Contextual Portfolios

The contextual portfolio (CP) is a tool developed by Dr Zoe Sadokierski (2019), expanding on the annotated portfolio model first introduced by Gaver and Bowers (2012). Sadokierski aligns her framework with Bowers and Gaver, stating that the CP documents' layout and overall visual and textual choices may be aligned to suit the appropriate audience or context. However, she does recommend that a contextual portfolio should have the following:

- High-quality images (or recordings) of experimentation and artefacts
- A project overview,
- A contextual review aimed at situating the project within the appropriate literature
- Documentation and reflection of iterative design practice (p.6).

The CP framework expands upon annotated portfolios' ability to communicate design research to broader audiences while conforming to the criteria needed for design processes to contribute as a scholarly endeavour (Glanville, 2014; Pedgley & Wormald, 2007; Stappers, Sleeswijk Visser, & Keller, 2015). The model provides an adaptable and approachable yet comprehensive workflow and documentation format that outputs rigorously documented but easy-to-interpret results for other practitioners and non-practitioners. Sadokierski demonstrates a use-case for her proposed CP framework through her own work 'Endgame' (see Figure 3.2 on the following page), stating, "I show how 'research data' drawn from my Critical Journaling practice is used to produce Contextual Portfolios, in order to present the research in different contexts" (p. 1). Sadokierski states:

> The 'Contextual Portfolio' aims to communicate explicitly the scholarly research within an RtD project. Using 'research data' from the Critical Journal, it is a synthesis document drawing together research aims, key insights from literature and design precedents, iterative design processes, and self and peer critique. (Sadokierski, 2019, p. 6)

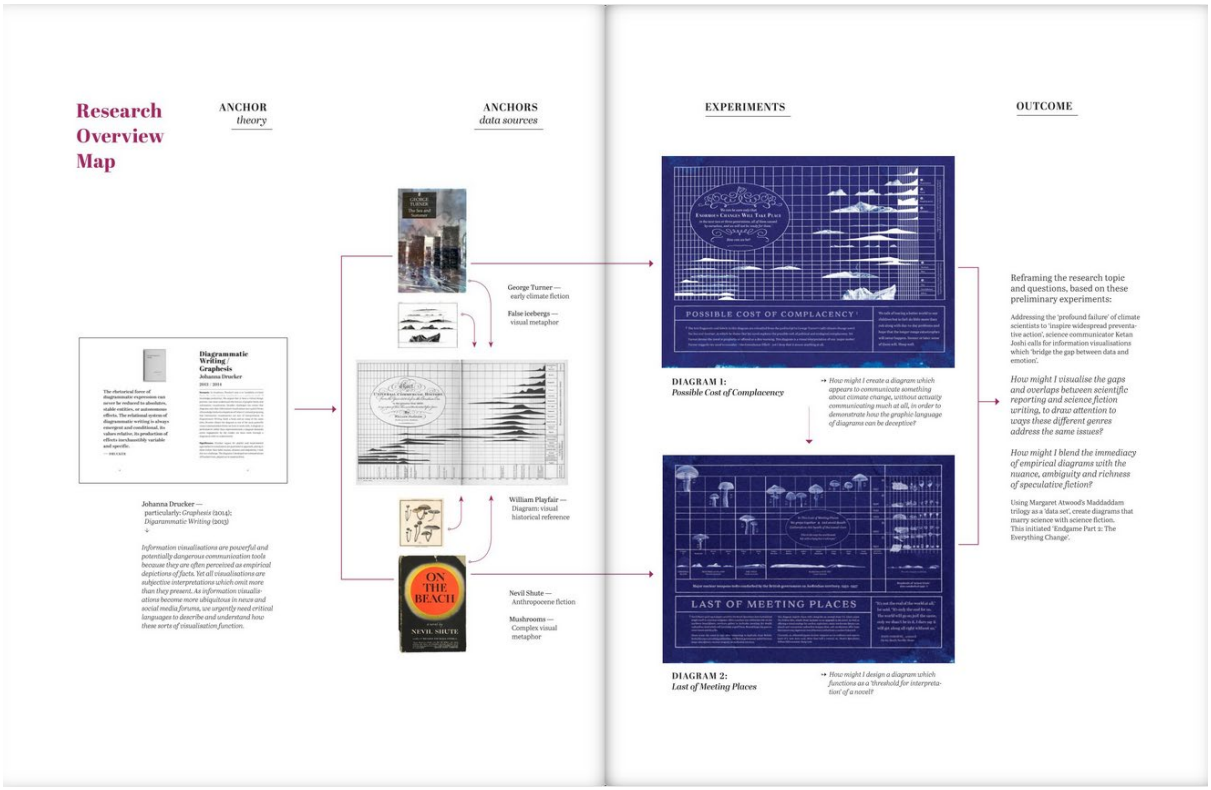


Figure 3.2 Research Overview Map, Contextual Example in 'Endgame' By Sadokierski (2019).

Sadokierski presents an account of her development of the CP documentation method, first starting as a purposefully 'unfinished' process document to accompany exhibited works, then evolving to a print-on-demand book featuring more contextual development such as peer critique and more clearly defined research questions. The finalised CP document contains three key sections of information:

[1] A*nchors*, where seminal information that informs the process is recorded and reflected.

[2] E*xperiments,* featuring evidence-based iterative design development and an

[3] *Outcome,* a section for further critical reflection based on the process undertaken.

CP's enable the documentation and sharing of an RtD approach as scholarly research by including critical reflection, rigid shared documentation, transparency, and direct referencing to relevant seminal texts for inspiration and development (Sadokierski, 2019). The CP's structure is supported through the implementation of Hamilton and Jaaniste's (2010) research exegesis model, which follows the written structure of [1] introduction, [2] situating concepts, [3] precedent of practice, [4] researchers' creative practice and [5] a conclusion. The research exegesis model subscribes to similar criteria proposed by Archer (1995), Glanville (2014), and Pedgley and Wormald (2007) in outlining the requirements of practice-led research to contribute as scholarly endeavours.

This research utilises CPs as a documentation method and medium for critical reflection on RtD practice. Through their expansion on annotated portfolios, CPs are a means for recording, organising, reflecting, and sharing the processes of experimentation and results of an RtD practice within academic and broader communities. While annotated portfolios provide readers with a glimpse into the theory within a design or design process, CPs provide a comprehensive view into a practice or research process. The CP format provides practitioners with scaffolding to collate and share the knowledge generated through individual and collective experimentation processes within an RtD practice and express them as a cohesive group of combined research outputs.

Within this research, CPs are utilised per experiment and logged through a numerical system to enable easy sorting and access to data. The three information fields of the CP, [1] anchor (theory), [2] experiments, and [3] outcome (reflection), allow for: [1] detailed insights into the foundation of the experimentation; [2] images and description of the experiment; and [3] critical reflection on the outcome of the experiment (with reference to the anchor, previous experiments and descriptions of future experiments). The implementation of CPs to record the rapid prototyping process and fast-paced experimentation within this research is supported by the initial 'unfinished' state of recording described by Sadokierski (2019). The unfinished documents are processed digitally, combined with images and video recordings of experimentation, numbered along with the artefact from the corresponding experiment and sorted digitally for future sharing. The formatting of the CP allows for digital (web-based and digital documents) and physical sharing of results, such as in a book, printed out for discussion, or paired with the corresponding artefact for display.

3.5 Contextual Portfolios as a Synthesis Document for AR and RtD

As discussed above (3.4), a contextual portfolio is a synthesis document used to critically document and explicitly communicate design processes in a scholarly manner. CP documents provide a framework that aids in the amalgamation and sharing of the processes evident in design research processes, such as the RtD approach implemented in this research. Each CP has three sections: [1] anchors, [2] experiments, and [3] outcome. The CP format is further adapted to this research as a cataloguing tool, allowing readers to follow the experimentation process chronologically or to navigate to specific CPs or series of experiments.

An example of a CP is provided below in Figure 3.3 (see the full page spread on the following page), which will be used as an example to expand on the types of information documented in the three sections of a CP. The CP documents the first paste mixing experiment conducted in the experimentation processes while answering research question 1. The CP is named PASTE_001_001, noted on the bottom right of the page, signifying the first paste made in the first series of paste-mixing experiments. As per the CP framework, the document is divided into three labelled columns: anchor, experiments and outcome.

ANCHOR

Small batch paste mix of:

20g finely Ground Brewers Spent Grain (BSG)

14g of Carboxymethyl cellulose (CMC)

14g of Microfibrillated Cellulose (MFC)

15g of Water.

inspired by Jakovlev, I. (2019).

Recipe 20 Patterning Cellulose

in Kääriäinen et al. (2020), the CHEMARTS Cookbook, p. 106.

In initial tests, materials were mixed into a paste and extruded by hand through a syringe

onto an acrylic surface to test flow behavior, self-adhesion and ability to self-support.

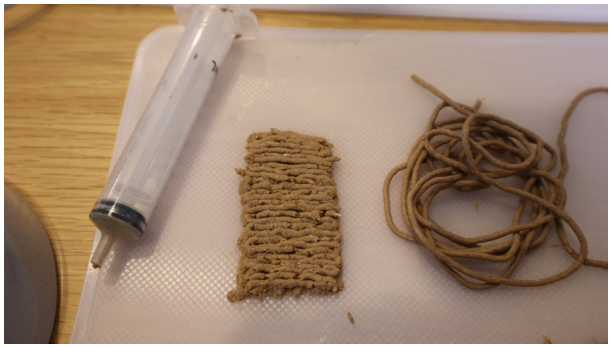
Faludi et al., (2019), p .7

EXPERIMENTS









Material was mixed with a handheld stick mixer and 'nutribullet' blender. Both devices struggled to evenly mix the cellulose with each other and the BSG. Additional water was needed to mix dilute and mix the materials.
The final paste felt like fibrous playdough, with a little less structural rigidity and easier to stick to skin. It was able to hold some hand formed shapes.
The material was packed into a pharmacy bought 5ml syringe and was easy to extrude without significant force on the plunger.
Small cylindrical towers were hand extruded, as well as a flat slab representative of a traditional MEX 3D printing infill pattern. The material was also applied too the exterior of a shot glass to test its moulding capabilties.

OUTCOME

Manual syringe extrusion worked successfully after the 'guess and check' process of paste mixing. Small portions of the ingredients were added until a satisfactory paste was mixed. MFC was difficult to break up and spread evenly into the mix, so I either need to remove this material from the mix or find a more consistent and stronger way to blend the ingredients. Though a good starting point, I feel that the mixing ratios will need to be altered to scale up the mix for larger batches.

Figure 3.3 Contextual Portfolio PASTE_001_001. This CP documents the first paste mixing experiment which was conducted in research question 1.

PASTE_001_001 uses two anchors, featured in the leftmost column, which creates the foundational knowledge base from which the experimentation process can build; the first is the ingredients used in the recipe with reference to the source of the recipe's inspiration, Recipe 20, Patterning Cellulose, by Jakovlev (2019) featured in the *CHEMARTS Cookbook* (Kääriäinen et al., 2020a, pp. 106-107). Jakovlev's recipe was adapted due to its described extrudable nature and its use of only processed cellulose derivates. The second anchor is a quote from Faludi et al. (2019), who adopted recipes for NMCs from other studies and tested and developed them for MEX 3D printing. Faludi et al. describe their methods for material testing, which helped them determine whether a recipe was ready for more advanced development for 3D printing: "In initial tests, materials were mixed into a paste and extruded by hand through a syringe onto an acrylic surface to test flow behaviour, self-adhesion and ability to self-support" (p. 7).

The middle column, experiments, features images, video (on a web-based CP) and text detailing the experimentation processes. As discussed in *3.3* Annotated Portfolios*,* the medium and layout of the document are crucial determining factors dictating the type of content that can be displayed in a shared document. In the print version of the CP document generated for this research, it was decided that a maximum of four images would be displayed per CP due to layout limitations. Web-based or digital versions could display many more images and include videos. The images featured in PASTE_001_001 depict key moments in the experimentation process, such as the set-up of the mixing station, paste loaded into a syringe for manual extrusion testing, the first extruded line, and artefacts that were manually extruded into shapes mimicking the layer creation process of a MEX 3D printer. The images are accompanied by text describing the experimentation process in depth, such as the home appliances used to mix the paste, what the paste felt like to the touch and how it felt to manipulate it manually.

The outcome section, the rightmost column, is home to critical reflection. In the context of PASTE_001_001, this section describes how the paste mixture was changed through a trial-and-error process after initial difficulties mixing the ingredients with home appliances and manual extrusion. There is also a reflection on the material choices, such as discussing the difficulties of separating and mixing microfibrillated cellulose (MFC) evenly with home appliances. Finally, the reflection concludes by acknowledging that though this paste was successfully extruded, it was envisaged that it would need further alteration to successfully 3D print.

3.6 Delimitations and Limitations of Scope

An essential process in all research projects is defining the scope of the research. The scope of this research has been defined by identifying approach-based delimitations and methodological limitations, which create boundaries for the action undertaken and reporting conducted. Delimitations define the scope of a research study, established by the researcher's choices regarding what to include and exclude. These boundaries help focus the study, making it more manageable and pertinent to the research objectives. Limitations concern factors affecting the validity and reliability of the study. They are inherent aspects of the research design and methodology that are beyond the researcher's control but impact the study's findings. Consequently, limitations influence the study's internal and external validity and are viewed as potential weaknesses. Delimitations and limitations are embedded in RtD practice, where a practitioner's approach is inherent in their action (delimitation) and can require qualitative interpretation through artefacts and qualitative reporting (limitations).

Delimitations

This research aimed to create a transparent and repeatable process that assists product designers in developing sustainable and biodegradable paste extrudable NMCs. A crucial aspect of the material design was meaningfully upcycling locally sourced and underutilised organic industrial waste within the NMC without the implementation of greenwashing tactics. Further, a key focus in NMC design was transparency in the biodegradability of the material, with a focus on using bioderived materials in the NMC recipe. Through this scope, it was intended that similarly inspired materials could be developed locally within similar domestic settings without negative environmental impacts on material development.

Further, the scale of production and related processes were of central consideration in the development process. The development processes focused on using domestic and consumer products to lower the barrier to entry in NMC development and increase the repeatability of the developed processes by product designers. Through this lens, the materials used, recipes generated, tools developed, and machinery used were developed through and in product design practice for use in product design practice.

The material testing and development goal was to create an environmentally friendly NMC suitable for a short life cycle in product design explorative prototyping practices. The development process follows RtD, finding functional possibilities through explorative practice and reflection rather than

standardised testing. This approach allows for open-ended material development, aligning with the research goal to create sustainable alternative materials rather than thermoplastic replacements.

The components and systems designed, such as extruders and paste-delivery systems, are designed to be open-source and compatible with consumer 3D printers, meaning files and schematics are available freely, and off-the-shelf componentry should be used when needed. The extruder assembly and paste delivery system were designed and are shared in ways that allow product designers to easily replicate the designs in professional, educational and hobbyist settings. The open-source design is intended to enable product designers in rural and remote areas to replicate the processes and system, enabling remote development of NMCs utilising possibly underutilised organic waste.

Limitations

The main limitation of this study comes primarily from the focus on developing the material, processes, and systems for more sustainable explorative prototyping and the lack of quantitative and professional-based reflection to support the results. While the material, process, and systems could output sustainable 3D-printed explorative prototyping forms printed in a biodegradable NMC, in-field testing and evaluation by professionals were not conducted to verify the results. Instead, the results show a viable proof-of-concept documented from material identification to the output of sustainable explorative prototypes that are adaptable to the needs of professionals.

3.7 Processes

This section comprehensively outlines the ingredients, equipment, tools, machines and processes employed and developed in the research. Section *3.7.1* describes the paste mixing processes, listing the equipment and ingredients used to make the final paste recipe 'PASTE_004_012', and the mixing and testing processes used to create the BSG-NMC paste. *3.7.2* provides an overview of the tools, equipment, and machines used to assemble the paste delivery system, extruder assembly, and the 3D printer. Last, section *3.7.3* comprehensively describes the processes developed and used for 3D printing, documenting, and postprocessing BSG-NMC paste prototypes.

3.7.1 Paste Mixing

The following is based on the creation of PASTE_004_012, the final paste used in this research.

Paste Mixing Equipment

- Gloves
- Cling wrap
- Kitchen scale
- Mixing bowls (Pyrex)
- Measuring cups
- Rubber spatulas
- Spoons
- 40 mesh sieve
- Stick blender (Kenwood Triblade XL with puree attachment)
- 5ml syringes for manual extrusion testing can be purchased from pharmacies and online
- Resealable containers for storage. Several are needed (for dry grain, powders, wet binders, pastes)
- Refrigerator
- Dehydrator (Benchworks 32V-CUD) or oven. This is used to dry BSG after receiving and for drying parts.
- Grain mills (or coffee grinders), high-powered and larger-capacity ones, can be purchased from Amazon cheaply.
- *Optional:* A Starr Instruments FGD-1000N digital forge gauge mounted to an FGD-Stand (manually controlled stand) was used for more advanced compression testing. A

rudimentary rig using a recycled glass jar and a cap made from a piece of form ply with a syringe-sized hole was used to hold syringes under pressure from the gauge.

Ingredients

- Brewers spent grain (BSG) sourced from 4 Pines Brewery
- Carboxymethyl cellulose (CMC) which can be purchased online
- Methylated spirits
- Vegetable glycerin

Mixing Processes

Before mixing:

- Mix a 6% CMC solution (by weight percentage): Slowly add CMC powder to water while mixing with a stick mixer. *The best results were found with a whisk attachment to a stick mixer.* The solution should be left overnight to set and kept in the refrigerator between uses.
- Dry, grind and sieve BSG. BSG was dried using a dehydrator at 50-60 degrees. Then, it was ground using a grain mill and filtered through a 40-mesh sieve. *A coffee grinder can be used in place of a grain mill.*

Method

1. Measure dried and ground BSG into a large bowl,
2. Then add the 6% CMC solution, followed by the glycerin, and lastly, methylated Sirits.
3. Thoroughly mix with a gloved hand or spatula. Mix until all liquid has been absorbed.
4. Then, continue mixing with a stick mixer.
    a. *Some stick mixers, such as the puree attachment for the Kenwood Triblade XL, have holes for material to escape under force. Paste consistency can be gauged by the stringing behaviour of material escaping during mixing.*
5. Once thoroughly mixed, the paste can be manually tested for extrudability by loading it into a 5ml syringe. *Gauge paste extrusion by how easily it leaves the syringe under force and the consistency of the string/noodle/ that extrudes*. *It was found that the syringe loaded with PASTE_00_012 could compress under 1.5kg of force (by balancing small weights on the syringe).*
    a. Further testing can be performed with a digital force gauge. All results should be recorded for comparison in future tests.

6. Wrap paste tightly in glad wrap and store it in a refrigerator overnight before use. *This allows any excess moisture to be fully absorbed by the mixture, reducing cracking during drying.*
7. Before use, retest paste extrusion via the 5ml syringe method; finetune if needed.
    a. If finetuning is needed, add more ingredients (and record amounts) and repeat mixing. More BSG (filler) makes the paste denser, and more CMC (binder) makes the paste more fluid (easier to extrude).

3.7.2 3D Printer, Paste Delivery System, and Extruder

The following describes this research's equipment, final system, and processes developed and used to address research question three.

Equipment List

3D Printer (PRINTER_002_002)

- Creality Ender 3 V2 flashed with "Professional Firmware" by Miguel Risco-Castillo.
- Official Creality Ender 3 Direct Drive Upgrade Kit (mainly used for E-Plate)
- Ender 3 Dual Z Axis upgrade kit
- CR-Touch auto-leveling kit
- Silicone bed leveling mounts
- 0.5mm sheet metal beds (cut from a single large sheet)
- Small bulldog clips to hold metal beds to the printer
- Heat gun
- Fishing wire (print removal from metal bed)
- Steel mesh (used in drying to allow better airflow around part)

Paste Delivery System (PASTEDELIVERY_002_002)

- Chicago Hush 30 air compressor (cheaper options available)
- Spring balancer (0.5kg-1.5kg)
- C-stand (or other suitable mode of holding Spring balancer above printer)
- Carabiners and string/rope
- Custom-made (laser cut) acrylic collar for securing 500cc cartridge to spring balancer (see Appendix D)
- Air hoses x2

- Nitto fittings for hoses
- Air regulator
- 500cc clear PVC cartridge, purchased from Eazao (https://www.eazao.com/product/500cc-cartridge/)
- Metal back cover for the paste cartridge, purchased Eazao (https://www.eazao.com/product/500cc-cartridge-air-pressure-cap/)
- 1/8 inch BSP to 10mm push fit connector (from metal black cover to entry hose)
    - Or 1/8 inch BSP to Nitto plug fitting
- 1/4 inch BSP to 19mm hose barb
- 19mm ID clear PVC wire reinforced hose
- Hose clamps for 19mm ID hose

Extruder (EXTRUDER_003_002)

- 3D print of the extruder body (Appendix D): this *needs some accuracy for thread in the base for nozzles*
- 3D printed 1.75mm nozzle (Appendix D). Uses 1/4 inch BSP thread to screw into extruder body
- 560mN.m NEMA17 stepper motor (which uses a 4-pin Dupont connector)
- 1 x 40x10x10 12v fan for cooling stepper motor, may need wires extended
- 12v power supply, powers cooling fan
- 4 x 30mm M3 threaded rod
- M3 Threaded hex spacers
- Flexible beam coupling 5 x 6.35 mm
- Sutton tools 8 x 160mm 2 Cut SDS plus masonry drill bit – *used as auger, cut to size.*
- 3D printer or laser cut collar as an auger shank

Extruder Mount (EXTRUDER_003_EXTRUDERMOUNT2)

- Mount body (Appendix D), which can be 3D printed in PLA
- 2 x 40x10x10 12v fans (uses the same power as cooling fan for stepper motor)
- Uses the same screws as those used for mounting the direct drive hot end and extruder
- 2 x M3 threaded hex spacers

3.7.3 Processes for Printing and Postprocessing

1. First, models are prepared in Simlpyf3D. This included setting changes such as flow rate, infill type, and percentage and manually editing support structures. Models were exported as gcode to MicroSD cards or saved to file for later use.
2. Print contextual portfolio (CP) numbers (eg PRINT_001_001) and settings are written on loose A3 paper which is used for sketch notes and reflection.
3. If necessary, the extruder mount is added to the e-plate using preexisting screws and mounts.
4. Paste (mixed as discussed above) is removed from the refrigerator and rolled out to remove air bubbles. Retesting extrusion behaviour is also recommended (as discussed above).
5. Then, the paste is loaded into the cartridges with a spatula or by hand. When full, the cartridge is repeatedly tapped (not on the same table as the printer) to remove air pockets. *Larger pockets were removed by using a dowel to mix material around.*
6. The air compressor is turned on.
7. The plunger is then inserted into the cartridge and pushed with a thumb or dowel to extrude 10mm of material. This primes the nozzle before loading to avoid air bubbles.
8. The printer is then turned on, and the auto mesh building function is run, which also activates the stepper motors and can identify if the bed needs manual or digital levelling.
9. Then, the cartridge back plate (with Nitto or push fit attached), spring balance mounting collar, 1/4 inch 19mm hose barb and 19mm ID PVC reinforced hose are attached. The hose is secured with two hose clamps.
10. Then, the hose is attached to the extruder body and secured with hose clamps.
11. The 3D-printed nozzle is then screwed into the extruder body.
12. The cartridge is then mounted to the spring balancer using carabiners (which are attached to the spring balancers by rope).
13. By now, the auto-mesh building function should be complete, and the extruder body can be pulled from the spring balancer and mounted to the extruder mount with M3 threaded rod and hex spaces. The spring balancer should support the cartridge, and the printer should support the weight of the extruder.
14. Next, the 3D-printed spacer is pushed onto the auger shank. The auger is then attached to the beam coupling and stepper motor. *A permanent marker has been used to mark the perfect placement points, particularly for the alignment of the coupling to the stepper motor shaft. Having a tight seal between the paste entry point of the extruder and the coupling section can help prevent the paste from escaping, which can be messy and ruin prints.*

15. The auger and stepper motor are then mounted to the top of the extruder body using threaded rods and threaded hex spacers.
16. Next, air tubing is connected to the metal back plate of the cartridge (using either a push fit or Nitto fittings).
17. Connections are then double-checked, especially the hose between the cartridge and extruder.
18. Air is then released at 2 BAR (29 PSI), and the flow of paste from the cartridge to the extruder is monitored. Usually, paste comes out quickly, not touching all sides of the hose, followed by a much slower mass of paste touching the hose's full width.
19. A 0.5mm sheet metal plate is mounted to the print bed using bulldog clips.
20. Once paste reaches the extruder inlet, a priming print is run from the SD card. This print, a 150 x 150 x 5 mm rectangle with one bottom layer, has several functions and is usually run multiple times:
    a. First, it primes the auger and nozzle with material; this can sometimes take a few minutes, depending on the paste and pressure.
    b. Once the material is extruding, it allows the calibration of extrusion and line width. This is controlled through the z-offset, which is calibrated live using the printer's onboard control screen*.*
    c. Careful attention is paid to the line width of the first layer, using the z-offset and air pressure to try to create lines that touch without overflowing into each other and lines that are not extruding so much that they are flowing over the nozzle.
21. Once print extrusion is consistent, the priming print is stopped, and the prints created in step 1 can be started.
22. Prints required little monitoring (in research question 3) and were checked occasionally for air bubbles forming in the hose or cartridge, material escaping through the coupling (remedied via air lowering air pressure), and material build-up on the nozzle. Notes are taken on the same A3 paper as in step 2.
23. Once prints are completed, the air pressure is noted (if more prints are to follow) and then turned off (to avoid material leakage).
24. Notes regarding print quality, artefacts, and print time are taken.
25. The completed print is then removed from the printer while still on the 0.5mm sheet metal bed, which is then photographed in a light booth. If required, weight is also recorded (with the weight of the bed subtracted later).

    a. *Once the build plate has been cleared, a new sheet metal bed can be added, and new prints started. Pressure can be applied to the paste delivery system.*

26. Then, the finished print is crusted with a heat gun. *Careful attention is made not to overheat the part, which can cause artefacts such as delamination of external layers.*
27. Prints are then removed from the sheet metal by slowly sliding tensioned fishing wire under the print.
28. Prints are then placed on steel mesh and placed in a dehydrator at 50-60 degrees.
29. Prints are checked daily to monitor drying. Dry prints are strong enough to be handled by hand and cannot decompress under pressure (such as pushing with a finger). *Drying time is affected by the print size, density, and water content.*
30. Once deemed dry, prints are photographed in a light booth and measured. Notes are recorded on the same A3 sheet as step 2.
31. Postprocessing and storage:
    a. Prints can be post-processed via hand or machine sanding, drilling, glueing and puttying.
    b. Prints can be coated with 6% CMC gel and dehydrated overnight for added moisture protection; these can be for display or storage.
    c. Prints can be stored in airtight containers with silica gel for added protection if desired.
32. Once printing has concluded,
    a. The air pressure is turned off.
    b. All components are disassembled to be cleaned with soap and hot water (excluding electronics.
    c. Paste from the cartridge and hose can be reused: paste from the cartridge can be extruded using the plunger and air pressure, and paste from the hose can easily be extruded by first removing the plunger from the cartridge, then attaching the hose back to the cartridge, and allowing low-pressure air to flow through.
    d. Paste should be refrigerated in airtight containers, preferably shrink-wrapped.
33. Print disposal and reuse:
    a. Prints can be vermicomposted in domestic worm farms,
    b. Ground back to poweder and reused in paste mixing formulation (this requires more finetuning but has been proven to work).

4 Experiments

The investigations and experiments conducted to answer the three research questions will be presented separately. This is due to the sequential nature of the research questions, where the findings from one question become the foundational knowledge for the next.

What is involved in identifying, sourcing, managing and preprocessing a sustainable waste material suitable for development into a novel material composite (NMC) for material extrusion (MEX) 3D printing?

Research question 1 is an enquiry into gathering the underlying knowledge and information required to commence a project to create a novel material composite. Research question 1 and its outputs outline the questions a designer may face during the preparation and early phases of designing a novel material. The investigation requires the designer to gather and analyse action data from quantitative and qualitative sources; for this, the designer must analyse and choose a material for investigation. Additionally, research question 1 asks the designer to understand the composition of their sourced material so that they can safely handle and store the material during and between experimentation. Finally, the question asks the designer to begin the research through design (RtD) process as they create a novel material composite recipe.

What is involved in generating 3D forms for product designers using material extrusion (MEX) 3D printing and novel material composites (NMC)?

Research question 2 follows an RtD approach, documented and reflected through contextual portfolios (CP). The question progresses from the results in research question 1 into advanced material refinement, 3D printer modification and configuration, material benchmarking and recipe alteration. Research question 2 follows an iterative cycle of making, analysing, and reflecting documented through a contextual portfolio format. The outcome of research question 2 is a refined material and printing process for the final experimentation process of the research.

To what extent can MEX printing of NMCs support the physical prototyping requirements of product designers?

Research question 3 progresses from the findings in research questions 1 and 2 and explores the process of identifying applications for a novel material composite. The experimentation follows the same RtD approach documented through a CP as research question 2 and explores the development

of a novel material composite for additive manufacturing rapid prototyping processes in product design practice.

4.1 Research Question 1

4.1.1 Introduction

What is involved in identifying, sourcing, managing and preprocessing a sustainable waste material suitable for development into a novel material composite (NMC) for material extrusion (MEX) 3D printing?

Research question 1 asks the researcher to gather and assess secondary qualitative and quantitative information and synthesise this into actionable procedures for sourcing, preprocessing, and developing novel material composites utilising waste materials. First, through the literature review, the current landscape of designers, engineers and scientists who are generating novel material composites (NMCs) was outlined. After identifying a trend indicating geographical connections between the researcher and their chosen waste resource, an investigation began exploring possible waste resources for the research. A review of potential sources for organic waste material identified the Australian agricultural sector as a significant producer of potentially underused organic waste. This involved generating a report which aided in evaluating Australian agricultural industries and their organic waste outputs. A selection criterion that valued the availability and accessibility of waste resources was developed, which ultimately led to the selection of brewer's spent grain (BSG), a significant and underutilised waste output from breweries, to be the subject of this research. A literature review was then conducted, outlining current use cases and attempts by designers, engineers, and scientists to upcycle BSG. This review also outlined the preparatory steps needed to source, preprocess and store BSG before experimentation. Lastly, a preliminary proof of concept extrudable paste was developed by adapting the recipe structure and workflows from other researchers. The paste utilising organically derived and biodegradable materials, such as cellulose derivatives and water, was documented using contextual portfolios (CPs), confirming BSG as a capable functional filler in a cellulose-based paste.

4.1.2 Context

The material choices available to a researcher or practitioner vary in accordance with constraints, availability and context. As discovered in the literature review, framed through an archetypal and approximate view, engineers and scientists are more transparent than product designers when sharing their selection and sourcing processes, whereas some designers share information in more opaque formats to support green marketing narratives. In part, this research aims to create a bridge between the transparency of engineers and scientists and the practice-based RtD workflows of product designers working in NMCs, to create accessible and approachable material identification, sourcing, preprocessing and development of NMCs for product design practice. This research was conducted and developed through the RtD approach, where the findings of action begin to construct the foundation of the processes. The goal is to create an approachable and replicable process for product designers and others interested in NMC development, enabling the rapid development of NMCs in urban and rural contexts.

This project differs from many product design experimental projects in that the aim is not to follow an abstract material selection and design process, but to provide a guideline for other designers that will be conducted under a planned approach that critically analyses and transparently shares the material selection. To begin the material search, understanding the workflow, reasoning, and findings of other product designers who were developing NMC for AM was critical. Appendix A1 was developed as part of the preliminary NMC literature review process. It maps the researchers' chosen material sourcing locations against the geographical location of each practitioner, which created a system to identify trends in material sourcing processes, secondary and other materials used in the novel material composite mixing process, and the type of 3D printing technology the material was designed to be used with.

While not all product designers shared their NMC development process, their material selection and location give insight into the local nature of NMC development, and those who have published an account of their experimental practice developing and using novel materials in an AM production process rarely recount clear reasoning for choosing a particular material to work with. Those who do discuss reasons for their choice of materials primarily cite opportunistic reasons such as geographic availability (Milosevic, Stoof, & Pickering, 2017), existing knowledge of biological properties (Zhao et al., 2016), and decisions driven by research questions relating to their particular project (Rael & San Fratello, 2018). This research adapts these reasonings into aspects of the material identification and selection criterion, particularly the local nature of material sourcing.

Material Identification Process

The material selection process began based on the literature review and Appendix A1 findings, particularly regarding the geographical relationship between the author and material location. Fundamentally, this process was inspired to create a clear linear connection between the material selection process and the research, which could be transferred into other NMC development projects. This research is being conducted at the University of Technology Sydney, New South Wales (NSW), Australia. As seen in Figure 4.1, NSW covers an area of 800,400 square kilometres, of which 647,900 square kilometres, or around 81% of the state, is occupied by agricultural land (Department of Agriculture Water and the Environment, 2020a). Forty-one percent of the state's gross agricultural revenue comes from livestock, focusing on cattle, calves, wool, sheep and lambs (Australian Bureau of Statistics, 2020).

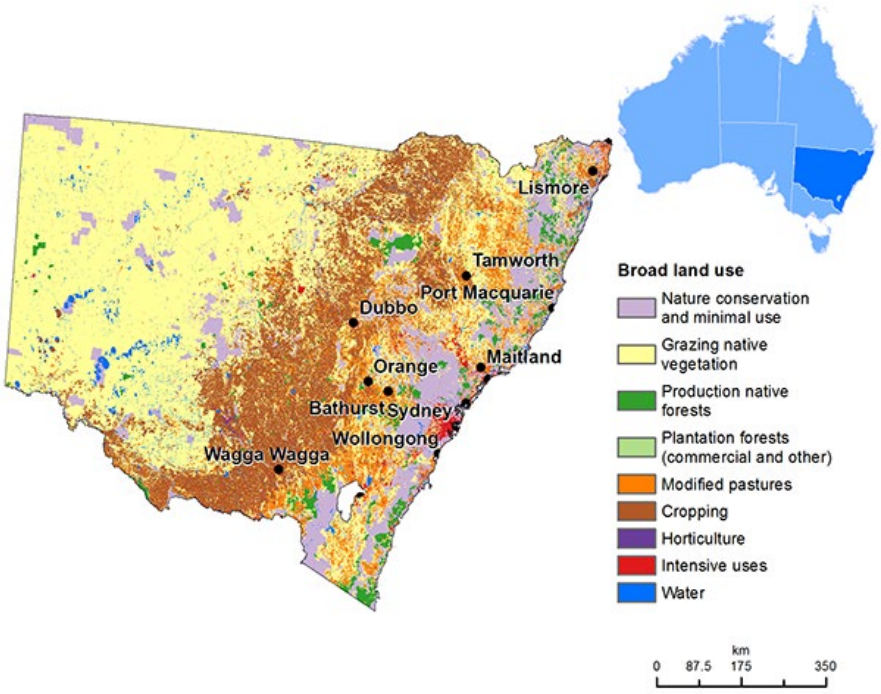


Figure 4.1 Broad land use in New South Wales (Department of Agriculture, 2020)

Waste Report

Initially, the Australian National Waste Report by Pickin et al. (2022) was reviewed as a potential source of information on local organic waste resources. The report is generated every two years and focuses on core waste, which is defined as "materials generally managed by the waste and resource recovery sector, comprising solid non-hazardous materials and hazardous waste including liquids." (p. 1). Table 4.1 shows a categorised list of materials identified as 'core-waste' in the report.

Waste categories	Waste types included in this category
Ash	Residues of coal-fired power generation (bottom ash and fly ash).
Building and demolition materials[8]	Asphalt; bricks, concrete and pavers; ceramics, tiles and pottery; plasterboard and cement sheeting; uncontaminated soil, sand and rock; rubble.
Glass	Glass from food and beverage containers; other glass.
Hazardous[9]	Acids; alkalis; inorganic chemicals; reactive chemicals; paints, resins, inks and organic sludges; organic solvents; pesticides; oils; food-derived organic wastes (K100, K110 and K200); other putrescible or organic waste (K140 and K190); organic chemicals; contaminated soils; asbestos contaminated materials; other soil/sludges; clinical and pharmaceutical; tyres[9]; other miscellaneous; unclassified hazardous wastes.
Metals	Iron and steel; aluminium; other non-ferrous metals.
Organics	Food, garden organics, timber, sawdust, biosolids and other organics. Excludes: • paper, cardboard, textiles, leather and rubber (included in separate categories) • except where specified, hazardous organic wastes (incl. as hazardous waste).
Paper and cardboard	Cardboard, polymer-coated paperboard, newsprint and magazines, office paper.
Plastics	PET (1), HDPE (2), PVC (3), LDPE (4), PP (5), PS (6), certified compostable plastics, other (7).
Textiles, leather and rubber (excl. tyres)	Textiles; leather and rubber (excluding tyres).
Unclassified materials	Materials that cannot be classified, usually because of uncertainty about composition
	[8] This category was previously referred to as ‘masonry materials’. During development of the Australian Standard for Waste and Resource Recovery Data and Reporting it was determined that this is inaccurate as some components are not masonry related. ‘Building and demolition materials’ do not include all materials that arise from the C&D stream. [9] Tyres are hazardous due to fire risks. In some parts of the report, tyres are addressed separately from hazardous wastes because they are a major waste material and are subject to specific export regulations.

Table 4.1 Core-waste categorisations, adapted from Table 1 in "National Waste Report 2022" Pickin, J et al.(2022). National Waste Report 2022. E. The Department of Climate Change, the Environment and Water, & Blue Environment Pty Ltd, p. 2.

These core-waste categories are considered to be generated from the following streams: "municipal solid waste (MSW) from households and council operations; commercial and industrial (C&I) waste; and construction and demolition (C&D) waste." (PIckin et al., 2022, p. 3). The report estimates that in 2020-21, Australia generated 75.8 million tonnes (Mt) of waste, with the two highest categories of waste being 25.2 Mt of building and demolition materials and 14.4 Mt of organics. Overall, the report shows an increase in waste to landfill of around 3% since the 2016-17 report (p. 37) and a stagnation in the recycling percentage of waste generated, which remains around 63% for all waste types (p. 41).

In line with research question 1, there was a need to identify information within the report related to novel sustainable materials. As outlined above, the report states that of Australia's annual generation of 75.8 Mt, 14.4 Mt of the total waste is 'organics'. The report outlines organics in section 9.7 (p. 46). Section 9.7 describes a total (of core and non-core) organic waste at 48.4 Mt (an 18.4 Mt increase from the 2016-17 report). Core materials (14.4 Mt of total waste) come from the MSW, C&I and C&D sectors, while the rest is from non-core organics. However, between sections, the report alters what is classified as organics. In earlier sections, core organics are considered food waste, garden organics, and timber, excluding paper, cardboard, textiles, rubber, leather, and hazardous organics. Section 9.7 discusses organics more broadly, covering core organics and hazardous waste materials, including biosolids, grease trap sludge and waste from abattoirs and tanneries. They also outline 'non-core' organic wastes from agriculture and fishers, such as manure, sugarcane bagasse, cotton gin trash, and fisheries. The change in what is included in this category between graphs and sections makes it difficult to follow their comparisons, and the reasoning behind this choice is not stated.

Finding readily available information on organic waste in New South Wales through reports such as the *National Waste Report* was challenging; scarce details are provided on the types of waste industries are producing, and the categorisations of types of waste, such as core and non-core, are not easy to differentiate. Further, little information is provided detailing the current processes to handle and possibly recycle the various waste resources.

4.1.3 Material Identification Process

Based on the preliminary findings in 4.1.2, a new direction was charted for identifying possible organic waste resources. Where the *National Waste Report* provided a comprehensive 'zoomed-out' (macro) overview of waste generation and management in Australia, this research needed to construct a more zoomed-in (meso and micro), local and focused analysis of large state-based agricultural producers and their associated organic waste. Doing so would generate a detailed understanding of local production, their waste outputs, and how those are being processed.

Data was collected from local, state, national and international sources to develop a dataset that could be used to identify suitable industries and waste outputs for use in the study. On a macro level, international export data was used to identify significant Australian producers and their locations and areas of production in NSW. At the meso level, geographically accessible industries related to larger agricultural producers were assessed for their production, land use, location and organic waste products. At a micro level, the waste products were researched regarding their production, physical contents, chemical constituents, percentage of waste, and current use cases.

While the material search was filtered through several criteria developed to generate a baseline understanding of significant agricultural industries operating in NSW, Australia, the final selection was based on two key criteria. The most critical criterion was the distance of production from the university campus for the convenience of collection and relationship building. Another key consideration was assessing the current cases of organic waste and evaluating whether the use of the waste product in the study would improve the lifecycle of the waste and not add additional negative impacts to the generation of the material.

Data Gathering and Analysis

After an initial review of the Australian agricultural industry, five industries were selected for a more thorough review: barley, grape, hemp, sugarcane, and wheat. These industries were selected based on preliminary assessments; each offers unique research opportunities. As shown in Table 4.2, barley and wheat were selected based on their significant contributions to the Australian economy. Grape production has less economic impact than barley and wheat but fuels the Australian wine industry, which ranks fifth globally in terms of export by volume (OIV, 2022). Industrial hemp, a smaller industry compared to the others selected, was reviewed due to the significant global growth in industrial hemp farming and Australia's global standing as a producer (Burton et al., 2022;

Jefferies, 2022). Last, sugarcane was also selected based on insights into the commercial manufacturing viability of bagasse, its more prominent solid waste output (Ajala et al., 2021).

	Barley	Grape	Hemp	Sugarcane	Wheat
Production Rank	2nd	15th	5th	10th	5th
Production (t)	14,377,284	1,228,829	12,600	28,669,280	36,237,477
Area used (Ha)	5,094,527	112,077	1,340	336,003	12,728,252
Export Rank	2nd	17th	28th	34th	3rd
Export Value (USD)	2.98 b	307.7 k	330 k	320 k	11.34 b

Table 4.2 Australian global production rank, output, area use and export value of barley, grape, hemp, sugarcane and wheat crops. Data sources: Australian Bureau of Agricultural and Resource Economics and Sciences [ABARES] (2023), Food and Agriculture Organization of the United Nations [FAO] (2024), and US Department of Agriculture (2024).

Building on the findings of Table 4.2, the investigation continued exploring localised industrial uses of outputs from barley, grape, and wheat production. Hemp and sugarcane were excluded from further searches. Hemp (Narrabri, NSW) and sugarcane (Grafton, NSW) were excluded due to the significant distance of crop production from Sydney (500+ kilometres; see AgriFutures Australia (2024) and Australian Bureau of Statistics (2021)). With the possible list of agriculture industries narrowed to barley, grape and wheat, the research transitioned to identifying hyperlocal industries utilising outputs from their harvesting.

In NSW, farmers produced 120,300 kilotons of wheat (ABARES, 2024b), the second-most of any state behind Western Australia. While a portion of this wheat is exported, wheat is used locally to produce flour and cereals in NSW. Examples include the Malinda flour mill (located 300km from UTS), Malindra Group's largest facility contributing to their 1 million tonnes output per annum, equal to 1/6th of NSW flour output (Malindra Group, 2024). Another large user of wheat and flour is the longstanding Kellogg's factory in Botany (<10kms from UTS), producing 42 million kilograms of cereal per annum, some using wheat flour such as Nutri-grain and All-Bran Wheat Flakes, Fruit Loops, Just Right Special K, Sultana Bran (Kellogg (Aust.) Pty. Ltd, 2024a, 2024b). Ultimately, wheat and wheat processing by-products (such as kernels, germ, and bran) were ruled out as potential organic by-products for use in this research, as they are rich in nutritional compounds and are readily reintroduced back into both human and animal food chains in the form of cereals (Galanakis, 2018).

While grapes generally can be eaten raw (dried or fresh) and are used to produce table grapes, wine, juice, and jam, data for state-based production is only readily available for wine grapes. Making 12.7 million hectolitres, Australia is the world's 5th largest producer of wine (OIV, 2023). NSW is

Australia's second-largest producer of wine grapes by state, producing 355,083 tonnes of grapes (Australia, 2024). As shown in Table 4.3, there are 484 wine producers in NSW, some within 120 km of UTS. Roughly 20% of the total weight of grapes used in wine production is output as grape marc, which consists of seeds, stalks and skins (See Table 4.3).

	Beer	Wine
Number of Producers	137	484
Area Used (Ha)	x	34,000
Distance from UTS	<3 kms	120 kms (Souther Highlands)
Organic Waste Products	Brewers Spent Grain, Hot Trub, Spent Yeast	Grape Marc

Table 4.3 NSW local industries and their organic waste products.

NSW farmers produced 35,600 kilotons amount of barley (ABARES, 2024a). Locally, barley is used to produce malted barley, cereal, and whisky. As shown in Table 4.3, a hyperlocal use of barley is in beer production, which is accessible within 3 km of UTS. Australia has a large brewery industry, producing the 24th largest quantity of beer at 1,745 million L (BarthHaas GmbH & Co. KG, 2023). Breweries have three main organic waste products: brewers' spent grain (BSG), hot tub, and spent yeast, each with its own waste recovery or upcycling strategies (see Table 4.4).

	BSG > 85%	Hot Trub > 6%	Spent Yeast (<15%)	Grape Marc
Source	Formed in mashing process	Boiling process	Recovered from sedimentation	Recovered from 20% of input volume
Contains	Barley husk and seed coat	Insoluble protiens, wort, hops and malt particles	Residual Yeast	Skins, Stalks, Seeds, Moisture, Organic Acids, and Polyphenols
Composition	30% Hemicellulose, 21% Cellulose, 11% Lignin, 21% Protien, 8% Lipids, 10% Starch	40-70% Proteins, 1-4% Lipids, 20-60% Cacrbohydrates, 5-10% Polyphenols	40% Crude protein, 59% Carbohydrates, 1% Lipids	20.8% Cellulose, 12.5% Hemicellulose, 13.8% Tannins, 18.8% Proteins, 13.8% Ash
Current Uses	70% used for animal feed, 10% of biogas, disposed, composted, human diet, functional filler in NMCs, isolation of constituents	Mixed with BSG or spent Yeast for animal feed, Soil conditioner, fertiliser, bioprocesses for essential oil	Animal Feed, Flavour enhancer, nutritional suppliment, biofuel, used in Vegemite	Animal Feed, Biofuel, Soil, Composted, Biochar,

Table 4.4 Overview and analysis of organic waste products from breweries and vineyards (Avramia & Amariei, 2021; Muhlack, Potumarthi, & Jeffery, 2018; Santos & Martins, 2024; Zeko-Pivač et al., 2022).

Based on the findings from Table 4.4, it was noted that there are substantial waste products from both wineries and breweries. The most substantial solid waste products, grape marc from vineyards and BSG from breweries, are obtained at roughly 20% of the total weight of production, and both

contain relatively large portions of cellulose (Muhlack, Potumarthi, & Jeffery, 2018; Nyhan et al., 2023; Zeko-Pivač et al., 2022). Through a review process, it was found that both BSG and grape marc are being investigated and used in similar upcycling. Through this review process (BSG presented below, and grape marc in Appendix A1), BSG was selected as the functional filler material for the NMC development in this research. BSG was selected over grape marc due to its geographical accessibility from the university campus, abundance in production, and currently limited functional use cases beyond animal feed and fuel production.

4.1.4 Brewers Spent Grain

Introduction

BSG, the most abundant solid waste from beer production, makes up 85% of all residues generated in beer production and is removed relatively early in production. It is a solid heterogeneous material mainly containing barley and grain husks, which are lignocellulosic biomass and are rich in proteins (20-30%), fibre (30-70%), lipids, vitamins, and minerals. Through their calculations of reported mean values of chemical constituents in BSG, Zeko-Pivač et al. (2022, p. 5) found that BSG contains mainly hemicellulose (30.60% ± 9.78), cellulose (21.42% ± 4.81), lignin (11.41% ± 6.76) and proteins (20.93% ± 2.38), with smaller contents of lipids, ash, starch and arabinoxylan (with large variance). BSG is rich in polysaccharides, mainly cellulose, which, when isolated, can be used in many applications ranging from medical and pharmaceutical to the construction and textile industries (Aravamudhan et al., 2014; Singh & Singh, 2013). Cellulose, isolated or used as part of a cohesive bond with cellulose-based binders, can be processed further and is a highly versatile tool in creating feedstocks for 3D printing (Dai et al., 2019).

Researchers, particularly scientists, have identified BSG's potential as a value-added waste resource. BSG is an abundant and underutilised waste resource with the potential for significant upcycling by isolating its desirable chemical constituents. It is a readily available and underutilised local waste resource with chemical properties identified as beneficial in creating biocomposites. Further, it has been utilised in various design contexts, such as furniture and packaging; however, within these designs, BSG was used as a filler material held together by other substances and was not processed beyond drying and shredding.

Proximity

According to the Independent Brewers Association (2021), New South Wales had the most breweries of any state in Australia, with 114, 22 more than Victoria. A map search for "brewery near me" shows how accessible breweries are within Sydney CBD (Figure 4.2). These breweries range in size and scale; however, all could be potential sources for brewer's spent grain, hot trub and spent yeast.

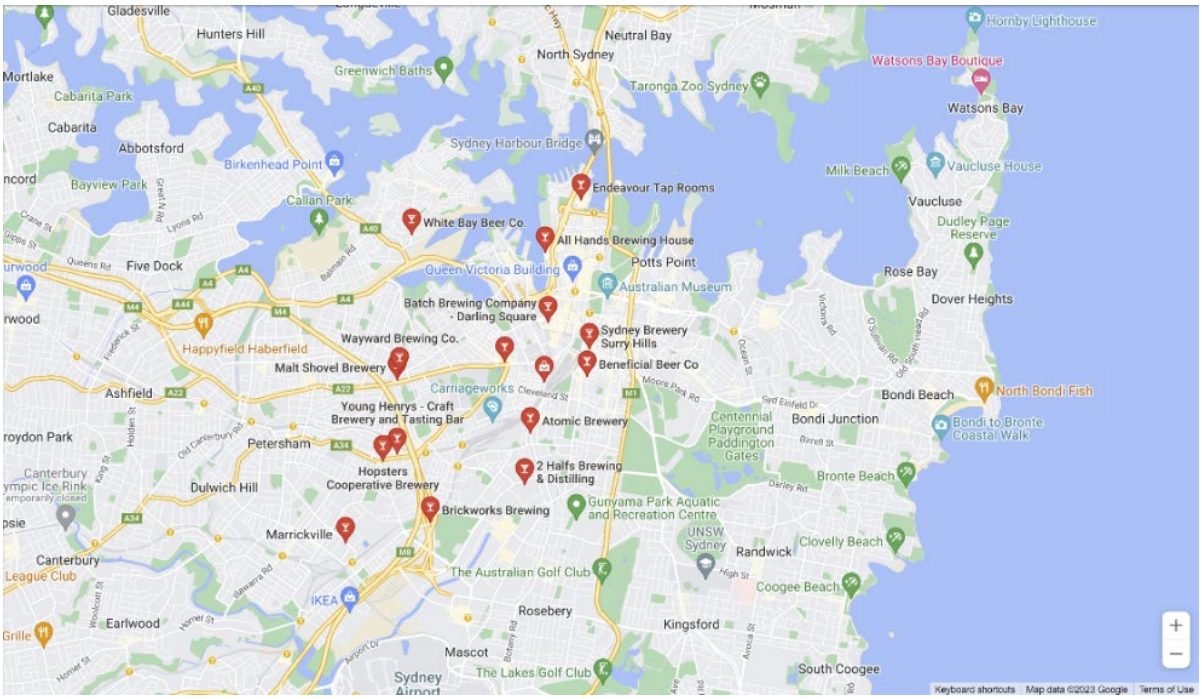


Figure 4.2 Google Maps shows results for the query "brewery near me".

Directly opposite the UTS campus in Ultimo and behind the international design award-winning Central Park Mall are heritage-listed buildings that used to be home to the Carlton United Brewery (CUB). First home to the Gadigal people of the Dharug Nation, Chippendale was established in 1819 (Pollon & Healy, 1988). It was developed into an industrial area, eventually becoming the home of six hectares of Kent Brewery for over a century. After an acquisition, the brewery became the property of CUB and had over 1000 staff until 1980; many lived and socialised in Chippendale. As the area modernised, the industrial brewery slowly became obsolete and closed in 2005 (Central Park Sydney, n.d.). In 2007, the site was developed into an urban village (O'Toole, 2007). The CUB brewery remains structurally intact, and its chimney is still functional. However, the chimney now releases steam, as the building was converted into a tri-generation plant (combining cooling, heat and power from a single generator) and was nominated for a World Architecture award (Brown, 2019). As with the discussion of wine proximity and history (*see Appendix B*), this rich heritage in

beer production provides another solid narrative foundation for this research, which could be seen as a beer by-product revival project conducted only metres from a now modernised brewery town.

Industrial uses

As noted in Rachwał et al.'s (2020) review of the utilisation of brewery wastes in the food industry, the primary uses of spent grain are as animal feed and as an additive that can be used in human consumption. BSG is used as animal feed in dry and wet forms and for livestock, poultry, pigs, goats, and fish. Faccenda et al. argue that sun-dried BSG can be used as a soybean replacement for lactating cows to improve milk production (2017, as cited by Rachwał et al., 2020, p. 5). Arguments support these claims that show improved milk yield and composition without adverse effects on dairy cows (Belibasakis & Tsirgogianni, 1996; Chiou et al., 1998, as cited by Rachwał et al., 2020, p. 5). Additionally, BSG exhibits advantageous protein and fibre contents that are beneficial for introducing food products for human consumption. Öztürk et al. (2002) found that cookies made of a mix of soft wheat flour and a maximum of 15% dried and medium to coarse BSG (212-850 microns) significantly increase the total dietary fibre content of the cookies.

Wet spent grain has been shown to be useful as feed for livestock, as its high moisture content makes it highly digestible. However, this high moisture content is also a limiting factor for the uses of spent grain, as it makes the residue highly susceptible to microbial growth within 7-10 days, particularly in its typical use conditions on farms (El-Shafey et al., 2004). Therefore, finding an ideal process for removing moisture and preservation is key to utilising spent grain.

Mussatto, Dragone and Roberto’s (2004) review of BSG argues that BSG can be utilised as more than animal feed or treated as a waste product. They use statistics from global reports to outline the abundance of BSG produced by the beer industry and identify that this waste product's chemical constituents could be harnessed beyond simple uses such as animal feed. The researchers generated an early list of potential applications for BSG, stating that BSG could be used in other applications such as biofuels and gasses, charcoal production, paper making, and the isolation of chemical constituents such as cellulose. In their review, the researchers outline research where BSG has been explored as a potential biofuel through direct combustion or further fermentation to create biogas. They briefly describe the implementation of BSG in charcoal production and paper manufacture and as an absorbent for removing volatile organic compounds from waste gasses. Lastly, Mussatto et al. outline the use of BSG in biotechnical processes and as a source of value-added products. The main factor influencing these use cases is that BSG is high in polysaccharides, proteins, and minerals,

allowing it to be used as a substrate to cultivate microorganisms and enzymes or processed further to isolate useful constituents.

Preservation

To utilise BSG as a value-added product, BSG must first be processed to remove its high moisture content to avoid microbial activity and subsequent spoilage. Material spoilage can affect further processing techniques and methods. In each piece of literature reviewed, the first process researchers conducted was freeze-drying (Lee et al., 2015; Mishra, Gregor, & Wimmer, 2016) or oven-drying (Hejna et al., 2020; Mussatto et al., 2008; Rachwał et al., 2020; Ravindran et al., 2018; Revert et al., 2017; Santos et al., 2015) their locally supplied BSG in temperature ranges from -5°C to over 45°C.

El-Shafey et al. (2004) investigated and progressed BSG preservation methods in their creation of a novel membrane filter press. The researchers created a 13-step dewatering process, which takes between 115 and 180 minutes to complete. One of the core principles of their process involves cleaning the BSG to reach a neutral pH level. This is followed by membrane pressing, which aids in removing the water from the slurry under pressure. Then, the BSG is washed, squeezed, dried and vacuumed into a 'cake' form. Though this research was mainly based on increasing the storage time for animal feed and reducing weight for the transport of BSG to farms (due to the lower water content), the authors acknowledged that this extended shelf life of up to six months could also be beneficial to using BSG in other instances.

Biocomposites

There have been attempts to utilise BSG in biocomposites. Revert et al. (2017) created an alternate wood-plastic composite (WPC) using BSG as a functional filler in the replacement of wood. Dried and milled BSG was mixed with polypropylene (PP) with up to a total weight percentage of 40% in injection-moulded tests. The PP-BSG mix was compounded in a twin-screw extruder. Through tensile, impact, thermal and water uptake tests, PP-BSG of various weight percentages (10-40%) were compared to virgin PP samples. Revert et al. conclude that PP-BSG mixes have slightly lower mechanical properties and higher water uptake and retention than virgin PP, but they are cheaper, have higher thermal stability and are more environmentally friendly. Ultimately, the researchers state that these WPC alternatives could find exciting use cases in building and automotive industries due to their wood-like appearance if their water retention issues are solved.

More recently, Hejna et al. (2020) successfully performed thermo-mechanical treatment of BSG through a twin-screw extrusion process. This research attempted to solve the main limitations associated with BSG, which are high moisture content and particle size of its cellulose content. The authors explored and confirmed that tailoring extrusion parameters such as the temperature, throughput and screw speed could significantly impact the particle size, colour, chemical structure, antioxidant activity and thermal stability of the resulting material. These results show that BSG could serve as a viable WPC alternative.

Isolation of Chemical Constituent

Researchers are exploring enhancing BSG further than the cases presented above. They aim to isolate and harness the chemical constituents within the BSG and use them to create value-added products. BSG is rich in polysaccharides, mainly cellulose, which, when isolated, can be used in many applications, ranging from medical and pharmaceutical to the construction and textile industries (Aravamudhan et al., 2014; Singh & Singh, 2013).

Ravindran et al.'s study (2018) presented the various attribute changes undergone by BSG when subjected to six different pretreatments. The study aimed to identify which of the six pretreatments isolated the highest cellulose content, increasing the yield of glucose upon enzymatic hydrolysis. The BSG obtained was dried and exposed to the six selected pretreatments. These were then exposed to enzymatic hydrolysis of cellulase and hemicellulase. It was found that microwave-assisted alkali (MAA) pretreatment was the most effective. Before MAA pretreatment, BSG contained 19.12g of cellulose per 100g of biomass. After MAA pretreatment at 400 W for 60 seconds, the cellulose content per 100 g increased to 43.67g with heavily diminished hemicellulose and lignin portions. MAA pretreatment also exhibited the highest crystallinity levels, indicating increased cellulose content (Binod et al. 2012, as cited by Ravindran et al. 2017, p. 278).

Santos et al. (2015) further investigated the modification of cellulose derived from BSG through microwave-assisted carboxymethylation. This study aimed to increase the economic value of BSG by enhancing its cellulosic components. The decision to generate carboxymethyl cellulose (CMC) was due to its usage through many products and industries such as food, drug delivery systems, textiles, paper and oil well drilling (Aravamudhan et al., 2014; Singh & Singh, 2013). Cellulose was initially isolated from dried BSG through an alkaline (NaOH) treatment followed by bleaching. CMC was then prepared through a three-step process of alkalisation followed by etherification in a microwave reactor. Lastly, the resulting slurry was neutralised and filtrated. The solid obtained was CMC, which

was washed in ethanol to remove any undesirable residue. This research's findings state the BSG has excellent potential as a feedstock for obtaining and refining cellulose.

Design Investigations

There have been various implementations of BSG as a novel material in designed products within a design content. An example is the *Mask Stool,* designed by Eva Harlou for Mater Design (Figure 4.3). The stool is constructed with a combination of BSG (known as 'mask' in Danish) from a Carlsberg brewery based in Denmark and from recycled industrial plastic waste (Carlson, 2020; Mater Design, 2020). Harlou, in collaboration with Mater, developed what they call a 'new industrial technology to process waste', where they can produce products from upcycled BSG with other fibre-based waste materials. As this product is being produced commercially (for roughly AUD 650), no reports on the material formulation or production process support the findings discussed in the literature review.



Figure 4.3 The Mask Stool designed by Eva Harlou (Mater Design, 2020).

Two companies implementing BSG in 'biodegradable' packaging materials were found. E6PR (Eco Six Pack Ring), founded in 2017, and Trebodur, founded in 2020 by designers Niko Stoll and Tillmann Schrempf, are using BSG as a material to replace traditional beer can six-pack ring holders. Neither company provides any detailed insight into the preparation of the material or its packaging's full contents. E6PR claim their biodegradable packaging is made from "by-product waste and other

compostable and organic material." Their website has large green tick boxes next to green text stating "Biobased product" and "Biodegradable certified"; however, there are no links to verify these claims (E6PR, 2017). Trebodur has even less information on its website. However, in the text that is provided, they claim, " TREBODUR is bound by the natural amount of proteins in brewers' spent grain. No additional binders are added" and claim their material can be easily composted, "even on garden compost heaps" (Stoll & Schrempf, 2020). Judging by both companies' imagery, one can assume that the BSG is dried, ground and moulded into the required shapes. As discussed in the literature review, designers tend to prefer narrative sharing rather than facts to keep 'trade secrets', often omitting information that could validate their green claims. These two examples neglect to provide information on where their BSG is sourced. What can be taken away from E6PR, Trebodur and Mater Design is that there is a real opportunity and viable use cases to use BSG as a material in composites.

While E6PR and Trebodur omit information on their processes, other design researchers have published recipes exploring the implementation of BSG as a functional material in a novel material. One such example is the recipe published by LABVA, an independent, self-managed community laboratory based in Chile, which posted its recipe on the open-source recipe and data hub Materiom (Besoain & Weiss, 2018). LABVA has a similar philosophy to this research, in which they aim to bring science closer to their community, focusing on creating novel biomaterials. The recipe hosted on Materiom, titled 'Beer spent grain biocomposite', requires readily available tools such as a cooker/stove/hotplate, a scale, stirring spoon, container or bowl, and a cooking pot. The ingredients are 60 grams of BSG, 7.5 grams of agar, 5 ml of glycerol, 250 ml of water, 3.6 grams of calcium propionate and 15 grams of sugar.

The recipe instructions are relatively simple:

1. BSG is dehydrated, mixed with water, sugar, calcium propionate, and boiled.
2. At a boil, water, agar and glycerin are added and brought to a boil again.
3. This is then poured into a mould.

Models produced by LABVA are shown in Figure 4.4; the BSG is unrefined apart from dehydration and is glued together with the other additives.



Figure 4.4 Moulded models designed and created by LABVA using their BSG recipe (Vásquez, n.d).

BSG in Additive Manufacturing

There has been some investigation into the use of BSG in 3D printing. Several companies are offering what they call "beer filament". Again, as these are commercial products, the manufacturers have not released information on creating the 3D printing filament. Online retailer 3D-Fuel, who manufacture their filaments in the USA and Ireland, have the following information available from their 'Buzzed - Beer Filament' store page; "Our composite materials made with Coffee, Beer, Hemp and others are made of over 90% sustainable PLA plastic and a smaller percentage of the recycled product from the material they contain" (3D-Fuel, 2020). There are methods by which we can attempt to calculate the fibre content of composite filaments, such as a chloroform dissolution which can dissolve the PLA matrix, and the remnants can be weighed (Le Duigou et al., 2016). However, at a content of less than 10% BSG, current store-bought filaments are essentially weaker plastic filaments and will not be used in this research (Faludi et al., 2019; Girdis et al., 2016; Kariz et al., 2018; Liu et al., 2019; Montalvo Navarrete et al., 2018; Osman & Atia, 2018).

Other researchers have explored the development of paste-based printing with BSG novel material. Monteiro, Monteiro and da Silva (2020) investigated the upcycling of BSG away from animal feed or landfills through the development of a biomaterial extrudable novel material composite. Their recipe consisted of 35g of water, 2g of carboxymethyl cellulose (CMC) as a binder and 24g of BSG as a filler. Using a 3D Food FoodInni printer, the researchers successfully 3D printed cylindrical forms, which they claimed could have potential use as biodegradable cups.

4.1.5 Sourcing

Due to the abundance of BSG generated during the brewery process, its short shelf life, and its lack of meaningful use cases (El-Shafey et al., 2004), many breweries perceive BSG as a difficult to manage and dispose of waste resource. As a result of this, it has been shown in other research that brewers are happy to freely supply or donate BSG to research-based causes (Andres et al., 2020; Farago et al., 2021; Gomes et al., 2021; Hassan et al., 2020; Nascimento, Calado, & Carvalho, 2017; Ravindran et al., 2018).

As shown in Table 4.3, there are 137 breweries registered with the Australian Independent Brewers Association in New South Wales. A Google Maps search shows tens of breweries located near the university campus, many of which are craft breweries, and some are related to larger breweries such as Asahi Group, who own Carlton & United Breweries (CUB), who own many craft breweries such as 4 Pines Brewing Company. All 4 Pines beers are brewed in Australia, with three breweries located within 20 kilometres of the university campus. Within a hyperlocal context, the closest brewery, The Sporting Globe X 4 Pines, is only 2.2 kilometres away.

A relationship was formed between the Material Ecologies Design Lab (MEDL) and 4 Pines, who donated BSG to the lab for experimentation. Wet BSG was first collected from 4 Pines in Manly, NSW, after meeting with the 4 Pines team on site. Later collections were from 4 Pines Brewery at 'The Sporting Globe' located at King Street Wharf.

4.1.6 Preprocessing and Storage

During the literature review exploring uses for BSG, trends in their formatting began to appear. These trends helped identify and consider the appropriate preparations and procedures to be implemented before sourcing and receiving BSG from a brewery. Most articles focused on an investigation into the use of an organic waste resource (BSG or bagasse, for example) and introduced a section called "materials and methods" or "experimental". In these sections, the first subheading unanimously contains the title 'materials', and follows the structure of:

- Where the focus material (BSG, for example) was sourced from.
- How the focus material was processed (cleaned) and tested (for PH) prior to storage.
- A description of the storage environment, or simply just a storage temperature.
- Further processing information regarding preparing the material for experimentation, such as how the focus material was dried and ground to the appropriate size.
- How the prepared material was stored.
- A description of other materials (such as chemicals used) and their sourcing details (supplier name and location.

Through further analysis of journal articles exploring various uses of BSG, an actionable plan was formed for the preservation and processing of BSG upon receiving it from a brewery. The first two experiments conducted in the research focused on the degradation and preservation of BSG. These were documented through contextual portfolios and made the first two entries for the preservation series, 'PRESERVATION_001_001 BSG expiry' and 'PRESERVATION_001_002 Drying' (Figure 4.5 and Figure 4.6, respectively). These two experiments were conducted simultaneously and were the first attempts to create complied contextual portfolio documents expressing critical information from the experimentation process on a single screen or page.

ANCHOR

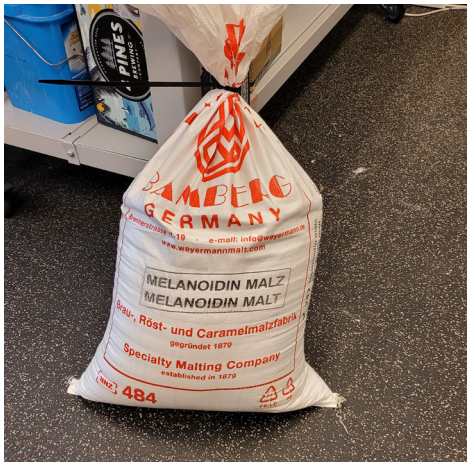
The BSG was dried at 60¡C for 48 h and thereafter ground and sieved using a 350 ?m sieve. It was then stored at room temperature in a dry place for further experiments. - (Ravindran et al., 2018)

Despite the advantages of the additional BSG as animal feed, its use is still limited, which is mainly related to problems with storage of the material. The high moisture content of this residue makes it susceptible to microbial growth in the usual environmental conditions prevailing on farms (Stojceska et al., 2008). Within a few days after production, wet grain can undergo molding and spoilage; therefore, preservation is a key factor in the utilization of this by-product. (Rachwa? et al., 2020)

Deterioration of the wet BSG takes place after an average period of 7 to l0 days from production, and under hot and humid conditions it may not be possible to store the wet BSG for a week.
(El-Shafey et al., 2004)

Three methods for preserving spent grain: freeze-drying, oven drying and freezing were evaluated by Bartolome« et al. (2002). Mussatto et al. (2004)

EXPERIMENTS









25 KgÕs of brewers spent grain (BSG) as provided from 4 Pines brewery. Wet, unaltered BSG before storage. Unaltered BSG one week after collection. Substantial mould patches had formed as well as a strong and unpleasant smell. Frozen BSG one week after collection. Large ice crystals had formed on individual grains in addition to the grain being frozen into large blocks. This is a result of the high moisture content.

Figure 4.5 Contextual Portfolio PRESERVATION_001_001. This experiment explored the degradation speed of BSG left at room temperature and BSG that had been frozen.

OUTCOME

BSG was kindly supplied by 4 Pines Brewery located in Manly NSW. Before collection, BSG was stored in their industrial refrigerator. Upon arrival at the University, the BSG had reached roughly 27-28 C, suggesting that the BSG was undergoing a reaction post-processing at the brewery. As per the preservation methods described by Mussatto et al. (2004), BSG three loads were prepared for preservation tests. Experiment PRESERVATION.001.001 focussed on comparing freezing BSG against ÔunpreservedÕ BSG. Frozen BSG was stored in a glass oven-safe container and left in a consumer freezer at -5C for one week. ÔUnpreservedÕ BSG was stored in an identical container and left and a low light location. After one week, the samples were compared (images c & d).

As seen in image c, unpreserved BSG experienced considerable microbial growth. Large clusters of white mould formed on the surface within the BSG structure. The container had an unpleasant smell and had extensive build-up precipitation on the lid. Frozen BSG (image d) froze into a solid block. BSG was suspended in a large ice cube and had ice crystals covering individual grains.

The purpose of this experiment was to demonstrate the need for immediate intervention when receiving post-production biomass. BSG has a high moisture content and needs to be processed for long term storage if smaller batches are needed for experimentation or immediately processed if bulk production (for design and manufacturing purposes) is intended.

PRESERVATION_001_001

ANCHOR

The BSG was dried at 60C for 48 h and thereafter ground and sieved using a 350 m sieve. It was then stored at room temperature in a dry place for further experiments.
Ravindran et al. (2018)

As soon as obtained, the material was washed with water until neutral pH, dried at 50 5C to 10% moisture content, and then pre-treated by dilute sulfuric acid and subsequently by sodium hydroxide solutions, to remove the protective hemicellulose-lignin wrapper.
Mussatto et al. (2008)

The material was washed with distilled water as soon as it was obtained until a neutral pH was reached, after which it was stored at -5C until further utilisation. The stored material was then dried at 50 5C for 24 h to attain 10% moisture content (untreated material). The dried material was further stored in a hermetic container at -5C to prevent any microbial growth.
Pawan Kumar et al. (2016)

Brewers spent grain (BSG) was provided by Athens Brewery S.A. Before use it was dried at 65C until constant weight and was chopped in a laboratory mill to a particle size smaller than 5 mm. BSG was alkali treated prior to hydrolysis reactions as described previously (Xiros et al., 2008) with 10% w/w NaOH.
Xiros et al. (2011)

Wet brewerÕs spent grain (BSG) was kindly supplied by a local artisan manufacturer, Cervesera Alcoyana S.L. (Alcoy, Spain). Before milling, BSG was died overnight at a temperature of 60C to avoid microorganism proliferation.
Revert et al. (2017)

Figure 4.6 Contextual Portfolio PRESERVATION.001.002. This contextual portfolio used preservation techniques found in reviewed literature to create long-term storage solutions for BSG.

EXPERIMENTS









a. BSG was stored for a week in a domestic freezer. After one week, the BSG had frozen into a solid block. b. Closer view of the ice encapsulating the BSG. The ice moulded into the shape of the bin bag in which the BSG was stored. c. BSG was loaded into domestic baking trays and placed into a Labec Dehydrating Oven. d. The controller settings on the Labec dehydrating oven, set to 60 ¡C with a 100 ¡C safety cut off. e. Dried BSG removed from the oven after 48 hours. f. Close up of the dried BSG, which felt brittle and dry and resembled the feeling of cereal.

OUTCOME

PRESERVATION.001.002 explored the process of generating bulk BSG for isolation tests and other experiments. Image a. shows the first learning experience of this experiment. Ten kilograms of BSG was frozen according to the methods described by Pawan Kumar et al. (2016). Freezing bulk BSG resulted in a large ice block that contained the BSG. It required several hours of manual chiselling to separate enough BSG to fill four large consumer baking trays. This shows that freezing bulk BSG may be an unsuitable preservation method and used only if the quantity of raw material acquired can not be preserved in other methods efficiently.

The four trays of BSG were oven-dried in an industrial oven located in the UTS Design Fabrication Workshop. As per Ravindran et al. (2018), Revert et al. (2017) Xiros et al. (2011), BSG was oven-dried at 60C for 48 hours. The oven was opened regularly to release any moisture build-up and to shuffle the BSG to avoid burning. Image f. shows a close-up image of dried BSG, which was brittle and light compared to its wet and mushy unaltered state when received. This BSG was stored in cereal boxes in order to prevent any contact with moisture and oxygen.

In the experiment Preservation_001_001, four anchors were used to describe the conditions and processes needed for safe BSG storage and provide information regarding the deterioration timeframe expected for wet, unprocessed BSG. The images used and annotations provided document the process of receiving BSG from 4 Pines, close-ups of the wet BSG, and close-ups of the spoiled BSG one week after receiving it without protection from microbial growth. Finally, the Outcomes section features a reflective piece of writing discussing the process and what was learned through this initial preservation process.

'Preservation_001_002 Drying' shows the same process; however, judgements needed to be made before transitioning from finding anchors to the experimentation stage. This was due to a range of reported temperatures and times found for drying BSG, with the aim of the experiment to remove the high water content and allow dry storage of BSG without further energy consumption. Based on the average drying temperatures of the Anchors used, it was decided that BSG would be dried at 60°C for 48 hours in an industrial oven located in the UTS Design Fabrication workshop. However, this was not the finalised drying environment or setting; this research shows that drying could be conducted successfully in various environments, such as household ovens (Preservation_002_002) and dehydrators (Preservation_003_001), enabling users to dry organic waste material effectively in a broad range of environments.

Another trend found in the literature review of BSG-related papers is the formatting in which authors introduced their study's focus material, secondary materials such as binders, and list of methods. These methods vary depending on the study's goals; however, the authors generally describe their initial preparation of BSG for the various methods and experiments described in the following sections. The methods and experimentations are pragmatically described, with the authors reporting the testing purpose, measures and variations employed, machines used and their settings or numerical ranges investigated, and how the results were evaluated.

As mentioned above, the articles reviewed evaluate a range of uses for BSG. More specifically, the authors required BSG or its constituents in different forms. It was found that the most common methods of preparation and processing BSG before experimentation were drying, grinding and sieving BSG to the necessary size (Öztürk et al., 2002; Ravindran et al., 2018; Revert et al., 2017; Santos et al., 2015), and are methods of processing primarily employed in this research. Other studies which focus on obtaining or evaluating the chemical constituents from BSG (particularly concerned with cellulose isolation) first processed BSG in chemical baths (Lee et al., 2015; Mishra, Gregor, & Wimmer, 2016; Rachwał et al., 2020) with a focus on removing unwanted chemicals and

cleaning residue from the BSG. Mussatto et al. (2008) employed these preparation processes (drying, grinding, and bathing), showing that they could be used in unison, an approach employed during the "Isolation" stages of this research, as documented in the contextual portfolio section of the same name.

The primary methods of processing and storage of BSG for this research are: (1) drying or freezing (2) grinding and storing dried material, with a minor investigation into (3) bathing the BSG in chemical treatments to isolate key constituents (cellulose). The processing methods below aim to prepare BSG for different experimentations.

1. Upon receiving BSG, two immediate options are long-term storage, freezing, or drying. Untreated wet BSG from breweries has a high water content, and microbial growth can onset within days if the water content is not reduced or changed (El-Shafey et al., 2004). Freezing or drying the BSG can stop microbial growth. Freezing BSG is suitable as a quick storage solution upon receiving bulk BSG, as storage below 5°C halts microbial growth (Food Standards Australia New Zealand, 2019). In contrast, drying BSG in an oven or dehydrator results in shelf-ready storage and immediately accessible material for further experimentation (Hejna et al., 2020; Ravindran et al., 2018). When possible, BSG was dried immediately after being received, allowing for immediate use in experimentation while avoiding spoilage or taking up large amounts of fridge and/or freezer space.
2. Dried BSG was ground into a fine powder using kitchen appliances such as coffee and spice grinders. This allows for more accessible storage (due to the volume reduction) and easier mixing with other materials; additionally, having a finer grind assisted in having fewer clogs in the extruder during the 3D printing process while improving the surface quality of printed parts.
3. Scientific journal articles reviewed were generally interested in reporting on the isolation of cellulose from the other chemical constituents that make up BSG (Beldman, Hennekam, & Voragen, 1987; Mishra, Gregor, & Wimmer, 2016; Mussatto et al., 2008; Pawan Kumar, Tomas, & Rupert, 2016; Santos et al., 2015; Xiros, Katapodis, & Christakopoulos, 2011). As a minor investigation in this research, this research explored whether I could isolate cellulose from BSG to reintroduce it into the composite mix used for 3D printing (see Contextual Portfolio "ISOLATION"). Of particular interest was whether the methods described in the literature could safely be replicated by a designer with access only to kitchen appliances and store-bought chemicals.

A total of eight ISOLATION experiments were conducted, each experimenting with different techniques of cellulose isolation. Though successful in application, validation of results regarding the

isolation and quality of cellulose was halted due to COVID-19 limiting access to resources in the science faculty, and not revisited.

4.1.7 Recipe design, creation and proof of concept

A seminal book available for free download as a PDF is the *CHEMARTS Cookbook* by Kääriäinen et al. (2020a). This text encompasses a complete guide to creating novel material composites, with detailed and succinctly written sections outlining topics such as: an introduction to scientific material research; the designerly approach to material research; an introduction to wood biomass (cellulose); tools, ingredients, methods and safety rules. It features many recipes for creating novel materials classified into various categories, such as hard, soft, flexible, and transparent.

Several recipes in the *CHEMARTS Cookbook* were pivotal influences in my initial recipe design and material experimentation, such as recipes *1 Cellulose Tubes* (p. 60-61), *7 Shaping Sawdust* (p. 72-73) (see Figure 4.7), *13 Cellulose Meets Natural Rubber* (p. 88-89), and *20 Patterning Cellulose* (pp. 106-107). A crucial trend emerged in the analysis of the ingredients of these recipes, where a pulp or filler material (such as BSG) is mixed with diluted microfibrillar cellulose (MFC) and diluted carboxymethyl cellulose (CMC). The cellulose additives' roles in these recipes indicate that the MFC adds structural support to the composite mix (Lavoine et al., 2012), while CMC acts as a glue and plasticiser for the composite (Ogunjobi et al., 2018). This indicates that recipes tend to be mixes of water, a filler material, a binder, and a strengthening material, a formula consistent with other research reviewed and one embedded in the material design of this research.

HARD



7 SHAPING SAWDUST

CHEMARTS *team 2016*

The forest industry creates various residues and byproducts, for example trimmings, branches, stumps, bark, and sawdust. Utilizing these residues supports system circularity. This recipe shows how wood powder together with another wood-based material, in this case microcrystalline cellulose (MCC), creates a new material mixture that can be moulded into various shapes.

INGREDIENTS

200 g *Microcrystalline cellulose (MCC), DMC 16%*
20 g *Fine wood powder*

EQUIPMENT

Scales
Grinding mill
Bowl and spoon
Mould
(Oven)

METHOD

1. Grind some sawdust into fine wood powder using a Wiley mill or other suitable device.
2. Measure the MCC and fine sawdust into a bowl and mix well.
3. Select a mould with your desired shape, and fill it with the mixture.
4. Dry in an oven at 40–60 °C overnight or at room temperature for several days, depending on the sample thickness.

✱ **SAFETY** Wear a mask when grinding wood with a grinding mill.

♥ **TIP** Try replacing the wood powder with powder of other by-products or residues from forestry or agriculture.
♥ **TIP** You can experiment with other cellulose-based materials instead of MCC, for example, with carboxymethyl cellulose (CMC).
♥ **TIP** If you want to design a shape of your own, it is relatively easy to produce custom shaped moulds from plaster or silicone.

Figure 4.7 Shaping sawdust, CHEMARTS Cookbook, p. 72.

Materiom.org is an information-rich open-source online library of user-submitted novel material composite recipes, which are sortable by ingredients and processes. The website features many recipes with ingredient lists, instructions and clear images uploaded by users (see Figure 4.8). Similar trends appeared in the construction of the recipes in the 3D printable section, echoing the composite formulation methods found in the *CHEMARTS Cookbook*. Though different materials, the composites on Materiom were designed through a mix of similar functional components: water, the filler material, a binder or glue (such as agar or xanthan gum powder) and a plasticiser (glycerin), as shown in Figure 4.9 (Big Circle Studios, 2022a, 2022b; Faludi, Van Sice, & Shi; Hadil, 2022; Otero, 2022; Sauerwein, 2020).



Figure 4.8 Coffee husk/chaff biomaterial (Big Circle Studio/ Materiom).

Collection

Seaweed recipes, Food Waste, Industry Biomass

Process

Molded, Cast, Cooked, Mixed, Air Dried, Boiled, Dehydrator dried,

License

CC BY-SA 4.0

Difficulty

Tools

Cooker/stove/hotplate, Teaspoon, Measuring Cup, Cooking pot, Mould or Form,

Source

Future Matters : Material Library code: BC-21-CH-007

Sawdust | agar Saw01

Composition

Agar agar	15 grams
Water	250 ml
Glycerol	5 ml
Coffee chaff or husks	50 grams

Method

Step one	Mix the 15 grams of agar agar, 250 ml of water and 5 ml of glycerol
Step two	Heat this mixture and stir until the begins to bubble and it becomes a homogeneous thick paste
Step three	Next turn off the heat and add the coffee chaff/husks. Make sure to mix the ingredients well so that all of the husks are connected by the paste
Step four	Prepare your mould to be clean and dry, then spoon or pour the mixture into the mould. The drying time will depend on how well the mould is ventilated and how warm the environment is too (whether drying in an oven or air-drying).

Figure 4.9 Recipe for coffee husk/chaff biomaterial (Big Circle Studios, 2022).

4.1.8 Initial Material Experimentation

Initial material experimentation followed a similar path and took inspiration from the method of Faludi et al. (2019) who tested a range of internally and externally developed novel material recipes for paste extrusion. Their primary research, which centres on "whole-system environmental impacts to standard ABS extrusion, measured by a life cycle assessment" (p. 2), is considered in my work but is not within the scope of this research. However, Faludi et al.'s description of their recipe selection, elimination process, and tests for material strength and printability are crucial influences in my initial investigation.

Faludi et al. initially found and replicated recipes published by other researchers and adapted the recipes as needed (such as when data was omitted from the publication (p. 5)). Again, it was noted that the table structure in Faludi et al.'s work is similar to this research's hypothesis regarding recipe design and the functional role of constituents. First, recipes were mixed into a paste and manually extruded through a syringe. Recipes that performed best in "flow behaviour, self-adhesion and ability to self-support" (p. 7) (shown in Figure 4.10) were advanced to hand casting for strength testing through an ASTM D638-14 Type IV dog bone mould. Again, the best-performing recipes were selected and advanced to 3D printing, using a modified FDM 3D printer utilising pneumatic pressure to extrude pastes.

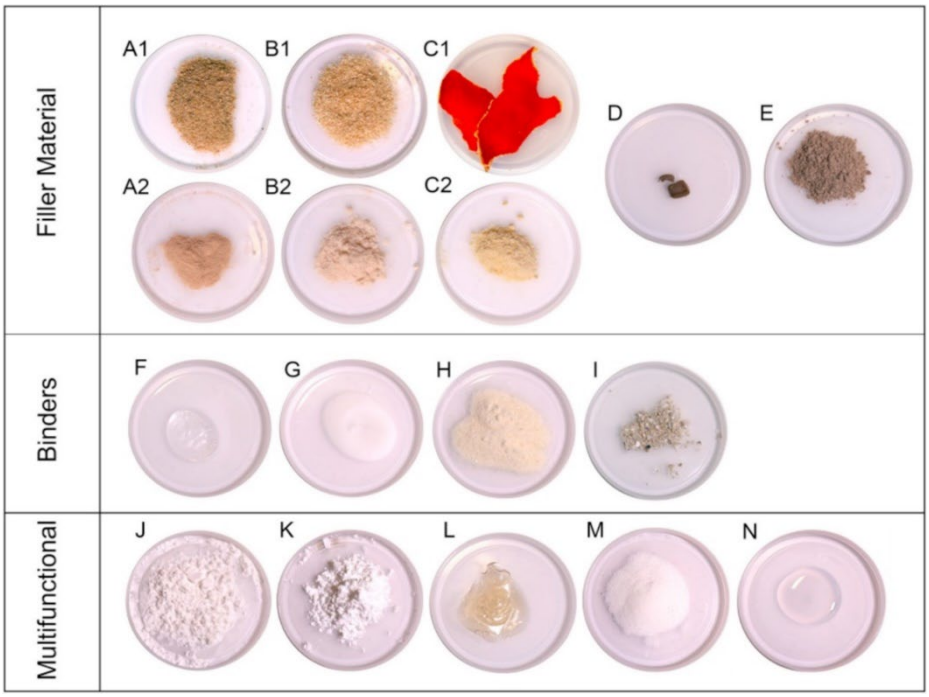


Figure 4.10 Faludi et al. Recipe ingredients table, filler, binder and multifunctional ingredients:
Recipe ingredients. Filler materials: oak sawdust, as purchased and filtered to 0.125 mm grain size (A1, A2); pine sawdust, as purchased and filtered (B1, B2); orange peel, whole and powdered (C1, C2); nanocellulose fibrils, dried (D); pecan shell flour (E). Binders: Sodium silicate liquid (F); polyvinyl alcohol (G); pine rosin powder (H); cyanoacrylate, dried with sediment (I). Multipurpose materials: superfine white rice flour (J); confectioners' sugar (K); gelatin (L); wheat dextrin (M); glycerin (N). (p. 6).

This research follows a similar format, where a series of recipes was developed through an RtD process, each documented and analysed through CPs. The new formations were mixed in small quantities, syringe-printed and moulded, and finally printed with a modified FDM 3D printer utilising pneumatic pressure (see *4.2 Research Question 2)*.

Initial Recipe Creation

The ingredients and quantities chosen for the initial paste mixture were based on several factors. The first paste, documented as PASTE_001_001 (see Figure 4.11), was created in a domestic kitchen during a COVID-19 lockdown in June 2021. Though limited, the utensils available were adequate to mix basic paste mixtures and matched with the recommended tools in the *CHEMARTS Cookbook* and Materiom recipes. As shown in the Anchor column of PASTE_001_001, initial paste testing would be in line with the workflow described by Faludi et al. (2019), in that after a recipe is mixed, it would be manually extruded from a syringe by hand. Unlike Faludi et al., this research aimed to refine the single paste mixture rather than to compare different material recipes to one another (and thermoplastics) and only to move on with testing with the best-performing material.

As referenced in the Anchor column, PASTE_001_001 used ingredients and mixing methods inspired by recipe "20 Patterning Cellulose" from the *CHEMARTS Cookbook*, shown in Figure 4.12 (Kääriäinen et al., 2020a, pp. 106-107). This was due to several reasons. Firstly, the extrusion method described is similar to the testing methods of Faludi et al. in that the paste is extruded from a syringe. "20 Patterning Cellulose" also used cellulose derivatives as binders rather than gums or gelling agents (such as xanthan or sodium alginate), commonly used in recipes featured on Materiom. Combining a cellulose binder with a cellulose-rich filler can create an effective cohesion binding effect, increasing the recipe's strength when dry (Herz et al., 2023). BSG can be a source of cellulose, where up to 25% of its mass can be processed into raw cellulose for further processing into a cellulose derivative such as CMC of MFC (Mishra, Gregor, & Wimmer, 2016). This opens up future avenues for creating a recipe derived wholly from BSG and its constituents (discussed further in 6.5 Recommendations for Future Work*)*.

ANCHOR

Small batch paste mix of:

20g finely Ground Brewers Spent Grain (BSG)

14g of Carboxymethyl cellulose (CMC)

14g of Microfibrillated Cellulose (MFC)

15g of Water.

inspired by Jakovlev, I. (2019).

Recipe 20 Patterning Cellulose

in Kääriäinen et al. (2020), the CHEMARTS Cookbook, p. 106.

In initial tests, materials were mixed into a paste and extruded by hand through a syringe

onto an acrylic surface to test flow behavior, self-adhesion and ability to self-support.

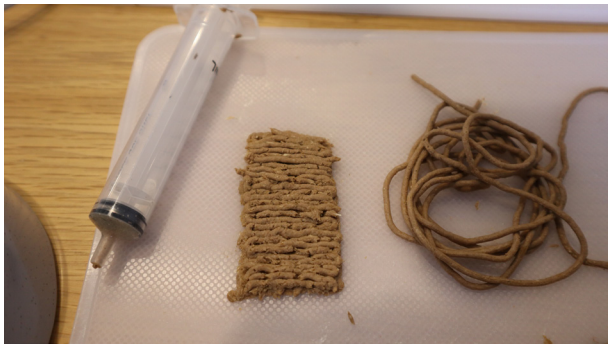
Faludi et al., (2019), p .7

EXPERIMENTS









Material was mixed with a handheld stick mixer and 'nutribullet' blender. Both devices struggled to evenly mix the cellulose with each other and the BSG. Additional water was needed to mix dilute and mix the materials.
The final paste felt like fibrous playdough, with a little less structural rigidity and easier to stick to skin. It was able to hold some hand formed shapes.
The material was packed into a pharmacy bought 5ml syringe and was easy to extrude without significant force on the plunger.
Small cylindrical towers were hand extruded, as well as a flat slab representative of a traditional MEX 3D printing infill pattern. The material was also applied too the exterior of a shot glass to test its moulding capabilties.

OUTCOME

Manual syringe extrusion worked successfully after the 'guess and check' process of paste mixing. Small portions of the ingredients were added until a satisfactory paste was mixed. MFC was difficult to break up and spread evenly into the mix, so I either need to remove this material from the mix or find a more consistent and stronger way to blend the ingredients. Though a good starting point, I feel that the mixing ratios will need to be altered to scale up the mix for larger batches.

Figure 4.11 Contextual Portfolio PASTE_001_001, conducted in a domestic kitchen during a COVID-19 lockdown.

PRINTED MATERIALS



20 PATTERNING CELLULOSE

Iines Jakovlev 2018, CHEMARTS *2019*

With this extrudable material, it is possible to create custom, light, lace-like patterns and structures. The material can be extruded for use in various applications, for example, for creating accessories, or in art installations. You can find inspiration for patterns or applications using biomimicry.

INGREDIENTS

100 ml *Water*
1 g *Pulp*
40 g *Microfibrillar cellulose (MFC), DMC 3%*
10 ml *Carboxymethyl cellulose (CMC), medium viscosity, 1% solution in water*

EQUIPMENT

Scales
Bowl and spoon
Hand blender
Filtration fabric bag
Nylon or polyester filtration fabric
Syringe
Nylon or polyester filtration fabric
Absorbent paper
Light metal sheet

➡ TO PRE-PREPARE 100 ML OF 1% CMC SOLUTION IN WATER

1. Add 1 g of CMC powder to 100 ml of cold water and mix using a hand blender.
2. Let the mixture stand overnight. After complete dissolution, the mixture is a clear, viscous solution.
3. This recipe uses 10 ml of the solution. Store the rest for later use.

METHOD

1. Measure the water into a bowl.
2. Add pulp and mix using a hand blender until the fibres are evenly dispersed.
3. Mix in the MFC.
4. Remove any excess water by placing the mixture in a filtration fabric bag and pressing. The mass should be wet but not dripping.
5. Place the mixture into a bowl and mix in the CMC.
6. Scoop the mixture into a syringe with a spoon and avoid creating air bubbles.
7. Place some nylon fabric on top of an absorbent paper. The fabric prevents attachment and the paper removes moisture from the material.
8. Extrude 2D patterns onto the fabric.
9. Dry at room temperature for one day. The shapes shrink and warp when the material dries. If you want to control warping, place a light metal sheet on top of the pattern when it is half dry.

♥ **TIP** For an alternative way of mixing the fibres into the water is to put them into a closed jar and shake vigorously.

Figure 4.12 Recipe 20 Patterning Cellulose, By Jakovlev (2019), featured in the CHEMARTS Cookbook (Kääriäinen et al., 2020, pp. 106-107)

PASTE_001_001 uses the same ingredients as "20 Patterning Cellulose" but substitutes the 'pulp' for dried and ground BSG and uses equal weights of 6 wt% carboxylmethoyl cellulose (CMC) and 2 wt% microfibrillar cellulose (MFC). The recipe was initially mixed with equal proportions of all four ingredients to understand their contributions and effects on the paste mix going forward. The materials were initially mixed with a stick mixer and Nutribullet blender; however, they struggled to evenly mix the materials until additional water was added to dilute the mixture. Once the ingredients were mixed evenly, the material had a fibrous playdough-like consistency and stuck to the skin easily. This was loaded into the syringe and extruded easily under minimal hand pressure. The material was manually extruded into various shapes, mimicking infill or paths typically taken by a 3D printer. The resulting forms were left on a windowsill to dry. When dry, the final forms showed minimal shrinkage but had become significantly more coarse. Though not overly brittle, the forms were easy to snap and break.

It was acknowledged that though the paste was successfully extruded through a 5ml syringe manually, the paste recipe needed to be mixed into larger quantities to enable 3D printing. This brought further complications regarding the water content and MFC content, which would cause issues with extrusion. The 3D printer and extruder must also be built, modified and calibrated to commence experimentation for research questions 2 and 3, which would also affect and be affected by the paste recipe. Ultimately, there were five revisions to the initial recipe to enable the paste to pass through 30cm air pipes under compressed air power. The first 3D printable paste (CP PASTE_003_001) consisted of 200g BSG, 75g 6% CMC, 400g water and 30g of vegetable glycerin. All MFC was removed from the paste, as it is difficult to obtain commercially, and its functional role (increased structural support) was deemed unnecessary for the small calibration artefacts designed for initial testing. A small amount of vegetable glycerin was added to the mixture due to its characteristics as a preservative and plasticiser, enabling longer shelf life for refrigerated pastes while creating a more malleable and smooth paste, allowing the paste to pass through the piping in the delivery paste delivery system more efficiently.

4.2 Research Question 2

4.2.1 Introduction

What is involved in generating 3D forms for product designers using material extrusion (MEX) 3D printing and novel material composites (NMC)?

Research question 2 explores the further development of a 3D printable paste developed in research question 1, in conjunction with developing a 3D printing system for use in product design prototyping contexts and printing tests. Research question 2 utilises a research-through-design (RtD) approach and is documented, critically reflected, and synthesised through contextual portfolios (CPs) (see *3.5*). The following sections describe several interrelated factors involved in consistently generating forms for product designers who are prototyping using MEX and NMCs, such as: the paste formulation (4*.2.2)*; the 3D printer configuration and extruder design (*4.2.3)*; paste delivery system to the printer and its various components (*4.2.4*); 3D printer firmware configuration and slicer settings controlling printer behaviours and model production (*4.2.5*); 3D model selection (*4.2.6)*; and drying methodology (*4.2.7)*. In this section, these factors will be presented and discussed individually; however, as is apparent in research through design practice, they co-evolved through multiple iterations, often developing based on improvements on interrelated componentry, settings and configurations.

4.2.2 Paste Refinement from Research Question 1

An integral part of all processes involved with generating 3D forms for product designers using MEX is developing and refining the NMC paste. As discussed in *4.1.8 Initial Material Experimentation,* research question 1 transitioned into research question 2, based upon designing a manually extrudable paste. The initial NMC paste recipe, PASTE_001_001, utilising brewer spent grain (BSG), carboxymethyl cellulose (CMC), and water, was mixed using kitchen appliances and manually extrudable through a 5ml syringe with a 2mm nozzle. This result provided the foundation for continued material development towards a 3D printable paste for product design prototyping.

In total, 23 different pastes were developed during the research process, all documented through CPs, and each built upon findings from previous mixtures. The final recipe consisted of BSG, 6% CMC solution, methylated spirits, and glycerin (expanded upon below). Ultimately, paste refinement focused on several factors, such as maximising dry matter content for less shrinkage and cracking in drying and considering CMC content for bed and layer adhesion, but the paste needed to flow to the

extruder body at under 60 PSI (around 4 BAR, for safety purposes) and extrude through a mixture of mainly auger force and minimal assistance by air pressure.

Before mixing, several ingredients need preparation and preprocessing. As discussed in *4.1.6* Preprocessing and Storage, BSG usually arrives wet from breweries and needs to be stored to prevent spoilage. This can be done through drying or freezing (Mussatto, Dragone, & Roberto, 2004). Upon receiving BSG, it was spread onto large dehydrator trays (or baking trays) in thin layers and loaded into a Benchworks 32V-CUD dehydrator at 60-75 degrees Celsius until dry (24-48 hours, depending on the thickness of layers loaded). Dried BSG was then processed into a fine powder through an electric high-speed grain grinder (Figure 4.13) and then sieved through a 40-mesh sieve to achieve consistency in particle size (see PASTE_003_002 pg.x). A 6% CMC solution also needs to be prepared before mixing. This was done by weight percentage, where CMC was gradually added to water and mixed using a 1000w Kenwood TriBlade XL hand blender with a whisk attachment and left in a fridge for 24-48 hours to absorb and settle fully (Figure 4.14)





Left to right
Figure 4.13 KOCONIC 800G multi-functional stainless steel grain grinder (KOKONIC, 2023).
Figure 4.14 Kenwood Triblade XL hand Bblender and accessories (Kenwood, 2023).

While the ingredients and their quantities changed between recipes, the format for mixing the paste remained consistent. All recipes were mixed in a 3-litre Pyrex mixing bowl and wrapped in cling wrap in reusable food storage containers between uses. First, dried and ground BSG was weighed and added to the Pyrex bowl, then the 6% CMC solution, followed by the glycerin and methylated spirits. Once weighed and poured, all materials were mixed manually with spatulas and by hand, then mixed thoroughly with a domestic hand blender (*Figure 4.15*). It was found that mixing the ingredients manually allowed for easier and safer use of domestic hand blenders during their first pass, as the

larger mass of unmixed material was too dense for several hand mixers, which failed several times during mixing. Once mixed, the paste was tested for extrudability (see below), wrapped in cling wrap and stored in airtight containers in the fridge until used. This allowed for complete moisture content absorption into the CMC and BSG, enabling more consistent drying and extrusion when printing.



Figure 4.15 Kenwood Triblade XL puree attachment in use.

Pastes were tested for extrudability twice, once after mixing and 12-24 hours later before printing, comparing the results of compression force readings from a Starr Instruments FGD-1000 digital force gauge mounted to an FGD-MTS Handwheel test stand. Compression force testing was conducted by loading paste into a 5ml syringe with a 2mm nozzle and mounting it into a simple jig, which supported the suspended syringe and captured paste once pressure was applied (Figure 4.16). The FGD-1000 was lowered manually onto the syringe's plunger, extruding the material contents, and force in newton (N) was measured and recorded at its highest value during compression and material extrusion. This process was conducted after mixing and before printing, where a value of N was a strong indicator of the extrudability of the paste (once consistent in the rest of the printing set-up was achieved), allowing for a consistent paste to be mixed, saving time from the guess and check processes of loading pastes that are difficult-to-extrude or control (through pressure). More specifically, this technique was used once the recipe was ready for finetuning and not when the recipe was in development, allowing for more practice-based experimentation during development,

which was then supported by accurate measurement tools. These processes allowed for critical reflection on recipe performance during development, highlighting the transition between the practical and qualitative knowledge built in practice-based experimentation into quantitative modes of measurement that confirm and attach numerical results to recipe performance.



Figure 4.16 Low fidelity syringe-holding jig for paste extrusion testing. Starr Instruments FGD-1000 digital force gauge mounted to FGD-Manual stand (Starr Instruments, 2023).

4.2.3 3D Printer and Extruder Development

Successful MEX 3D printing with pastes depends on several factors; this section will present the investigation and development process of the physical infrastructure needed to 3D print with the BSG-based paste developed in *4.2.2.* In particular, this section will discuss the choice and development of a 3D printer and the design of the extruder system, which is a central part of a paste-extrusion 3D printer.

Two commercial consumer-grade MEX printers were used during this research. Initially, the research utilised an AnyCubic Kossel Delta 3D printer (Figure 4.17), an end-of-life affordable consumer 3D printer. Further, delta-style printers are commonly used in paste-based material extrusion (see *3D WASP*). Later testing, which required more stability from the chassis of the printer and gantry, was performed on a Creality Ender 3 V2 cartesian style 3D printer (Figure 4.18), a consumer-grade MEX printer.





Left to right
Figure 4.17 AnyCubic Kossel Delta 3D printer (3D Printer Universe, 2023).
Figure 4.18 Creality Ender 3 V2 3D printer (Comgrow Store, 2022).

Initial 3D printing, which focussed on the simultaneous development of the extruder design, paste composition, delivery system, and slicer settings, was conducted using the AnyCubic Kossel Delta 3D printer. The AnyCubic Kossel Delta, initial extruder and paste delivery system (*see 4.2.4*) (CP's PRINTER_001_001, EXTRUDER_001_001 and PASTEDELIVERY_001_001) (Figure 4.19, Figure 4.20 and Figure 4.21) were configured following instructions from artist Jonathan Keep's *A Guide to Clay 3D Printing* (2020, pp. 23-35). Some steps were not followed, such as Keep's recommendation to invert

the printer layout, which required moving the electronics from the bottom of the printer to the top and using adapted boilie guns as paste cartridges. These steps were not followed, as the printer was already assembled from previous use and cartridge sets, such as the CERAMBOT Air Clay cartridge set (CERAMBOT, 2023), were purchased. This system was a proof of concept to confirm that the componentry assembly could extrude and 3D print the BSG-NMC. While this was confirmed, the extruder design and paste delivery system proved to be challenging to work with, as they were too heavy for the printer to control and challenging to clean and reassemble, particularly in the case of the extruder design.

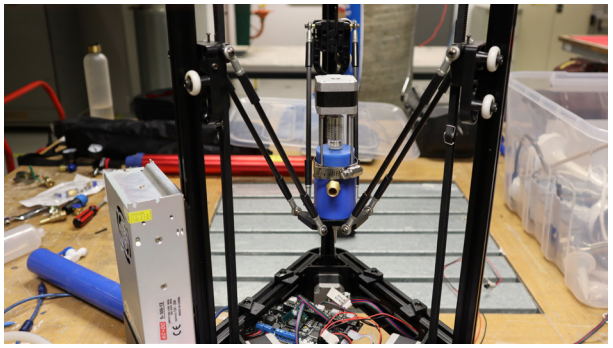
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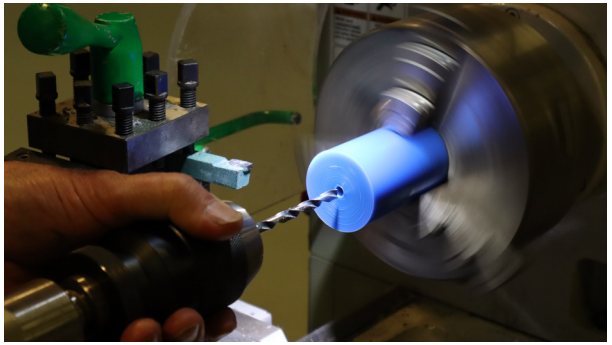
Extruder_001_001 was built based on Jonathan KeepsÕ ÒSelf Build Clay PrintheadÓ (link below). This printhead allows for complete control from the slicer software as it is connected to the motherboard through the same pins as the original plastic extruder. The printhead mounts to the existing gantry of the 3D printer and receives paste through a separate system fed by compressed air. Through commands by gcode generated in the slicer software, the roofing screw connected to the stepper motor acts as an auger that pushes paste through the printhead in a controlled manner. Andrew Purnell from the UTS fabrication workshop aided in constructing the print head.

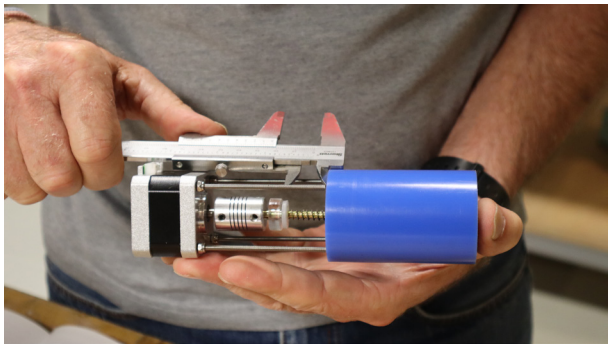
https://wikifactory.com/@jonathankeep/self-build-clay-printhead

EXPERIMENTS









OUTCOME

Though successful in extrusion, extruder_001_001 encountered several issues mainly relating to the nylon body. The body seemed too heavy on the gantry, as it was top-heavy with the stepper motor hose clamped to the top of the nylon body. Additionally, nylon became challenging to clean after printing, as the drilled threaded holes began to strip, creating weaker connections between the various components holding the extruder assembly together. Other options that are easier to (dis)assemble and clean need to be considered. Additionally, the construction of extruder_001_001 required some machinery (lathe) that many aspiring designers may not have access to.

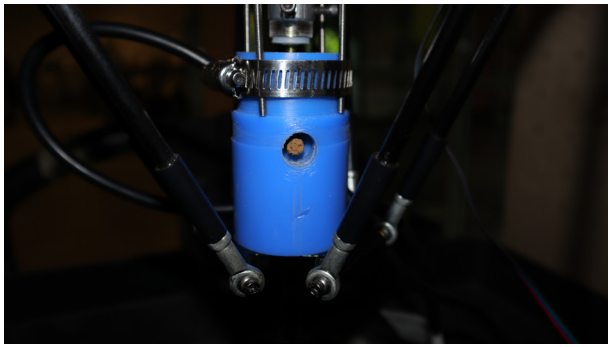
Figure 4.19 EXTRDUER_001_001.

The assembly and testing of the initial paste delivery system. They were designed based on the work of Jonathan Keep (2020) and the open-source StoneFlower3D extruder.









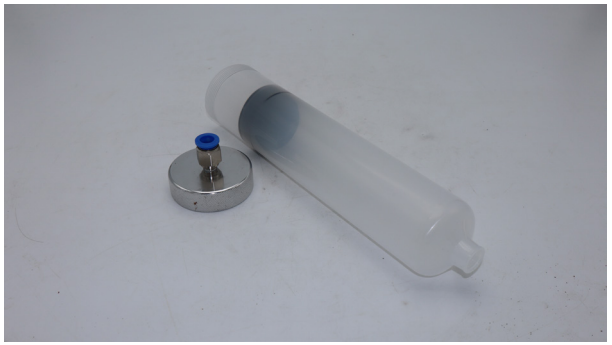
https://youtu.be/Zqo1CbAZup0

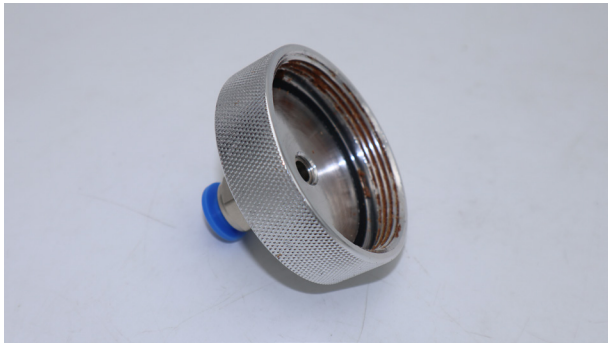
Several issues became apparent after the first phase of testing. Of particular concern was air escaping from various parts of the system, particularly from the syringe backing, which is the connection point between the compressed air system and the paste delivery system. I managed to find an 'official' part on the Cerambot website, which is a metal screw-on base for the syringe body, which will replace my 100% infill 3D printed base.

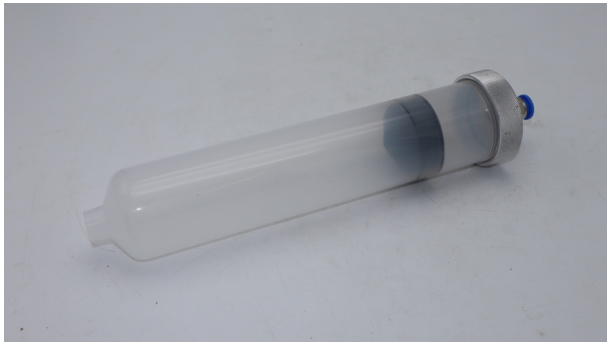
Figure 4.20 PASTEDELIVERY_001_001 proof of concept testing with EXTRUDER_001_001 and PRINTER_001_001.

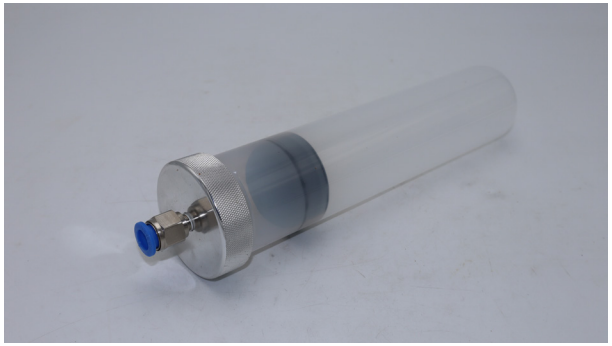
The backplate used to allow air into the cartridge was leaking air. It was 3D printed and seal with epoxy, but was still not air tight enough. The “CERAMBOT Air Clay Cartridge Set” was purchased, which has a metal back cover with a 1/8 inch BSP threaded insert, allowing for press fit fittings to be used.

https://www.cerambot.com/product/cerambot-air-clay-cartridge-set/









This solution worked perfectly. It would be interesting to find a solution that was cheaper and not reliant on someone else making them, but for time purposes this worked well. Other solutions could be the use of https://vormvrij.nl/lutum/shop/#!/Clay-Cartridge-L/p/137376043/category=47484151 or other offerings from LUTUM but these are very expensive. Ideally, one could buy and modify a “automotive fluid extractor” from Amazon and modify this to be airtight and to allow compressed air entry or purchase and modify a pneumatic caulking gun.

Figure 4.21 PASTEDELIVERY_001_002 which uses a 500cc paste cartridge and metal back plate from(CERAMBOT, 2023).

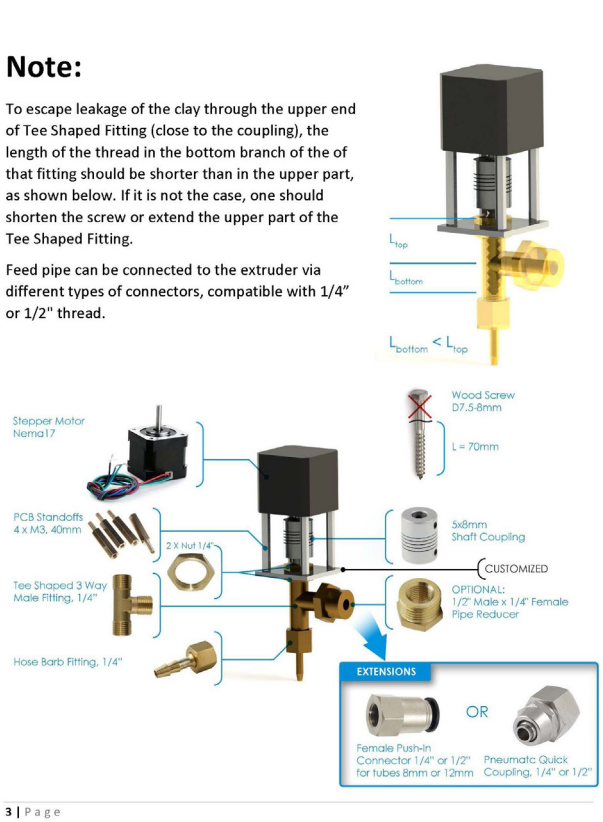
A new extruder was built to replace Keep's design, using the StoneFlower3D (2022) open-source design (Figure 4.22). The design uses similar componentry to Keeps, such as the NEMA17 stepper motor, flexible beam coupling, roofing screw as an auger, and ¼ inch BSP Luerlok nozzle tip adapter; however, rather than using a turned nylon rod as an all-in-one body (which is difficult to clean and reassemble, and requires a lathe to create), the StoneFlower 3D design uses off-the-shelf ¼ inch BSP air tool fittings as the body. EXTRUDER_002_001 differs from the StoneFlower design in that it uses two PLA 3D printed fitting plates instead of the single 3mm aluminium plate StoneFlower lists on their schematic. One 3D printer plate creates a support structure for the stepper motor, matching the use of StoneFlower aluminium plate, and another 3D printed plate gives added structural support and mounting of the extruder assembly to the gantry of the AnyCubic Kossel, which has dedicated holes designed to hold plastic extrusion hot end assemblies. This assembly is significantly more straightforward to disassemble, clean, repair, alter and reassemble than the Keeps design. The design needs further finetuning regarding the tolerances between the auger and the air-fitting body, which help control material flow. This would require the purchasing and testing of additional augers or fittings.

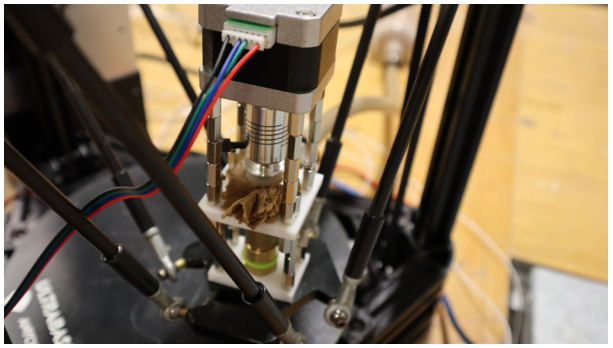
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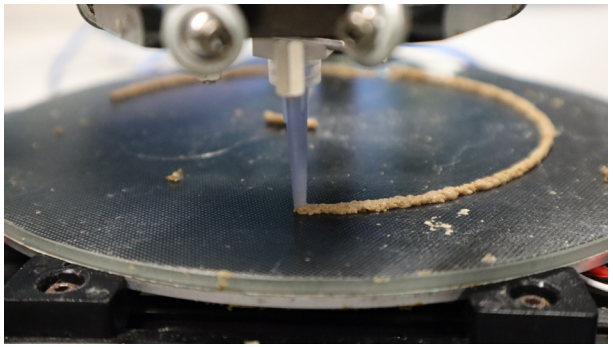
Extruder_002_001 was built according to the open-source design “Clay extruder, prototype V 1.0” hosted by StoneFlower3D (link below). This design can be assembled mostly from readily available components (All components were purchased through eBay, Bunnings and Jaycar) and two simple brackets made from plywood or any sturdy material. One bracket is included in the stoneflower open-source PDF; the other I designed to allow for easier mounting to the gantry and the automatic leving probe designed for the Anycubic Kossel printer to be attached. The brackets were designed in Fusion360 and printed in ABS using a TierTime UP300 3D printer (although they can be printed on the users’ printer prior to modification to a paste system) and are a simple extrude with holes.

https://www.stoneflower3d.com/opensource/

EXPERIMENTS







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Extruder_002_001 was significantly easier to assemble and attach to the AnyCubic Kossell delta printer. The printer does not have a height constraint on the size of the extruder, so the tall stoneflower design does not cause any issues with its height. The assembly and disassembly for clearing processers are much easier than the Jonathan Keep design. The extruder can be easily hand (dis)assembled and can be soaked in hot soapy water to remove any residue leftover in the threaded brass air piping parts.

I found that push-in connectors allowing paste into the tee shaped 3-way fitting can come loose due to pressure built up in the paste delivery system, and I opted for barbed 1/4 inch BSP hose fittings, which allow for significantly stronger holds on the tubing when under pressure. Another modification was an alteration to the customized bracket specified in the stoneflower literature. My bracket was 3D printed, which allowed me to forego the 1/4 inch hex nuts placed on top of the bracket and implement a threaded fitting and cap into the centre of the bracket body. This allows for easier assembly and the creation of a seal above the auger to combat any paste being extruded or pushed out the top of the assembly.

There is still the issue of the assembly tilting to the side where the paste is entering through the tee shape three-way fitting. A rudimentary solution has been employed where the 12 oz syringe holding the paste is being taped on top of a tub of similar height to the extruder.

Figure 4.22 EXTRUDER_002_001

EXTRUDER_002_001, PRINTER_001_001 and PASTREDELIVERY_001_001 were used for a total of 36 3D print experiments (CPs PRINT_001-008 pp. 344-384), which focused on proof-of-concept testing through the extrusion of NMC pastes, and the calibration of the printer system by 3D printing hollow cylindrical forms. Tests conducted calibrated slicer settings and paste formulation for layer height, material flow, auger speed, drying practices, printer movement speed, and achievable height for thin-walled structures. As noted in PRINT_008_SYNTHESIS (p. 378), several factors affected the printer's performance: software issues, such as inaccurate visualisation of models in the slicer software, the complete inability to extrude straight lines using Cura slicer software (see *4.2.5* Slicer Settings), and physical factors, such as the weight and T-shape design of the extruder and paste delivery system pulling the gantry off alignment and the need for tighter tolerances in the extruder body to allow for more control over paste extrusion.

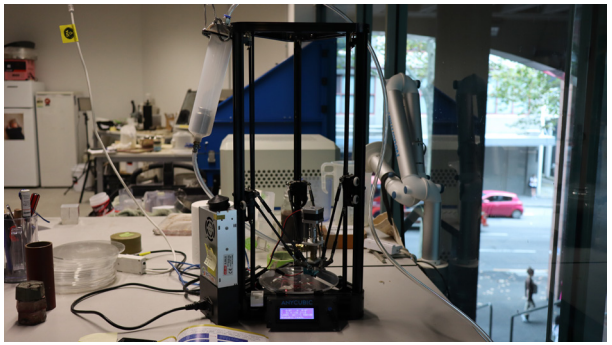
A new paste delivery system was developed to remove lateral weight (pulling) being applied to the gantry from the PASTEDELIVERY_001_001. As documented in PASTEDELIVERY_002_001 (Figure 4.23), a spring balancer mounted above the printer was used to suspend the paste cartridge, acting as a counterbalance and lever system that removed excess weight from the cartridge, affecting the gantry and extruder system. The spring balancer was mounted 1.5 metres directly above the printer from preexisting cable trays; however, a C-stand or camera tripod could serve the same function. Further, a collar with attachment points for carabiners was laser cut using off-cut acrylic and used to suspend the paste cartridge from the spring balancer (Appendix D). The cartridge was lowered from the spring balancer to connect to the extruder assembly sitting at 0.00 z-height. Once connected, the spring balancer was tensioned slightly to allow for continuous cartridge support, as the printer built objects upward. This system immediately allowed smoother paste deposition and smoother extruder movement (Figure 4.24). While these were positive changes, physical and software issues remained, such as the inability to 3D print straight lines (see *4.2.5* Slicer Settings), material escaping from the top of the extruder, and control over extrusion through retraction.

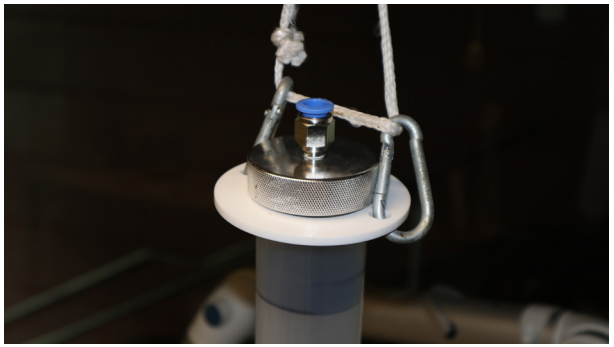
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Whilst watching a video of someone using a DELTA WASP 40100 printer, I noticed that the paste cartridge was supported by some sort of count balance system. After more research i found that this was a spring balancer, and ordered one from Amazon that could support 0.5-1.5kg. Then, I lase cut a collar/ mount, that fit around the paste cartridge using the lip of the metal back plate as a stopper. The collar has two holes for carabiners, and these are hanging from a rope which is tied to to the spring balancer.



EXPERIMENTS







OUTCOME

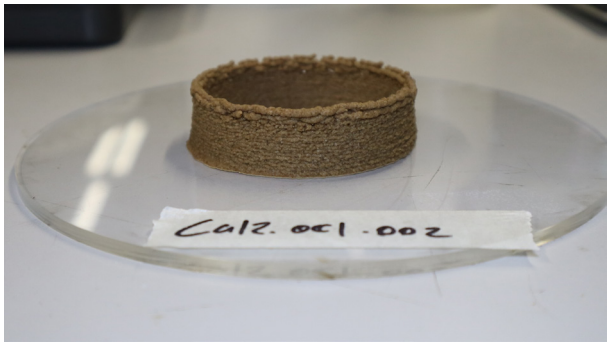
The spring balancer was an immediate success, especially when paired with the Creality Ender 3 V2 printer (PRINTER_002), which has a much more well supported gantry. The system removed most of if not all of the weight off the gantry and extruder assembly, allowing for unencumbered movement and printing of more advanced shapes.

Figure 4.23 PASTEDELIVERY_002_001 which uses a spring balancer to reduce the weight of the paste delivery system on the printer gantry

ANCHOR

CALIBRATION2 is a continuation of the PRINT_002-008 series, in that it focusses on 'dialling' the printing into a workflow and settings which result in a consistent printing experience. The series continued with printing hollow cylinders, but with a focus on moving towards one set of settings that can print a tall structure with unform layer heights and wall consistency.

EXPERIMENTS









OUTCOME

Prints began to have some consistently following settings:

In Cura
Z Offset 21.5 mm
Layer Height 1.5-1.8 mm
Jerk 10
Acceleration 1500_ Relative
Extrusion turned on

2 Bar of pressure, which is too high and causes material to push out of the top of the extruder body where the stepper motor is.

The EXTRUDER_002 was showing its limitations in a few aspects. First the parallel to the ground paste inlet was continently pulling the extruder off axis due to the weight of the piping and syringe with paste. This needs to be fixed in order to allow for smooth movement of the extruder body and gantry. Further, the thickness of the auger is not equal to close to the thickness of the inside of body of the extruder, allowing paste to flow around and and past the auger reducing its control of the extrusion.

Lastly, it seems like the printer cannot print straight lines, in that the stepper motor will not spin when a straight line path is presented to it in the the gcode. This is important to fix however the paste extrusion issues in general need to be addressed first.

Figure 4.24 CALIBRATION2_001_SYNTHESIS

While working towards a consistent workflow for generating and producing 3D printed forms with NMCS, several slicer softwares were used, both free and commercial (see 4.*2.5* Slicer Settings). AnyCubic recommends that Kossel Delta printers operate using Ultimaker Cura (free), which has many AnyCubic models preloaded into the software for easy set-up and use; however, issues arose, prompting testing of other slicers, such as Prusaslicer by Prusa (free) and Simplyfy3D (Commercial software costing USD 199). Ultimately, Simplyfy3D provided the most comprehensive and controllable workflow, and the gcode output solved many of the issues that were appearing in Cura, such as the inability to extrude straight lines (see CALIBRATION2_002_SYNTHESIS p. 400) (see *4.2.5 Slicer Settings)*.

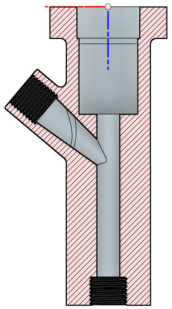
A final extruder assembly system was developed to address issues in previous iterations, such as difficulty in [dis]assembly, cleaning, paste inlet angle and weight and auger tolerances. CP Series EXTRUDER_003 documents the development and functional iterations of a 3D-printed extruder assembly (Appendix D). The extruder (Figure 4.25), which was designed to be 3D printed and functionally useable from a variety of 3D printing technologies, was printed with desktop and commercial MEX printers in PLA, ABS and ASA, Multijet Fusion (MJF) in PA-12 material, and Stereolithography (SLS) with FormLabs Clear Resin. The extruder body is a y-shaped single-body design with ¼ inch BSP threaded in and outlets for paste entry and extrusion. Through the use of parametric design software (Fusion360), hole size and placement, shaft diameter and length for the auger and thread type (or lack thereof) are easily adaptable, allowing the extruder body to be adapted to several prints and with different delivery systems.

ANCHOR

Extruder_003_001 is a progression from the componentry and design used in Extruder_002_001. 003 was designed using Fusion360 and 3D printed in nylon powder using an HP Jet Fusion 3D printed at the UTS Protospace.

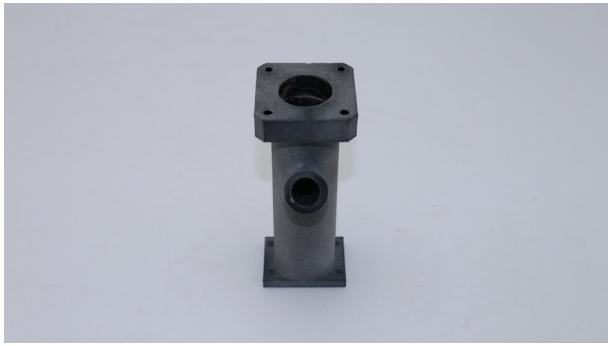
The design turns the many components from previous extruders into a unibody design, allowing for easier assembly, cleaning and reassembly. Additionally, the 3D printed design allowed me to design a 'Y' shaped body with 45 degree angled inlet for the paste. This should allow me to hang the paste syringe above the extruder body and prevent it from being pulled by the weight of the paste delivery system. Lastly, the design allowed me to customise the length and diameter of the auger shaft, allowing me to tailor the design of the shaft to various screw/ auger design, ultimately creating a tighter fit for the auger which should create more control over where paste is deposited via gcode and not through compressed air pressure.

EXPERIMENTS









OUTCOME

The tighter tolerances in the auger section of the extruder made printing under 'screw power' alone very difficult. Paste was not flowing freely, which is was good, but it was still not able to extrude effectively or consistently. Until the events of CALIBRATION3.001.002, it seemed that this extruder was not going to work. Then, after reversing the auger rotation, the extruder worked perfectly, allowing me to print shapes previously impossible. Additionally, the Y angle of the paste inlet and the use of a spring balancer to hold the paste syringe meant that the extruder was not being pulled off axis while printing. Over all this design was a solid time investment. It would be interesting to print this part out of PLA or ABS filaments with a desktop 3D printer, too see if this could be produced at home and printed with.

Figure 4.25 EXTRUDER_003_000

The design used for the CALIBRATION3 series of prints, based on EXTRUDER_003_000, was printed in PA-12 nylon using an HP MJF 4200 printer, which has an 8.15mm central auger hole (allowing slight tolerance for auger fitment and tension from paste inlet force), and uses ¼ BSP threaded in and outlets for secure attachment of 3D printed nozzles and the paste delivery inlet pipe. The design is significantly lighter than previously used extruder assemblies, and the Y-shapes inlet and suspended paste delivery system minimised the angled weight put on the extruder during movement, opening up the print bed to larger and more complex prints.

EXTRUDER_003_000 addressed many issues, particularly the flow and control of paste within the auger shaft. The tighter tolerances in the auger shaft highlighted a pivotal problem in the printer's ability to control paste extrusion using the auger alone. Several new augers in the form of drill bits ranging between 7-8mm in diameter were purchased from a local hardware store and tested with the new extruder design. Augers were selected based on flute depth and helix angle (affecting the number of flutes in the auger shaft), which were viewed as ways to control the paste flow within the auger shaft. It was found that an auger with shallow and few flutes allowed the paste to flow more freely through the auger to the nozzle (Figure 4.26 and Figure 4.27), while an auger with deep, tightly packed flutes slowed the flow of paste and required more pressure to move freely within the auger shaft. While these findings were substantial, the increased resistance in the auger shaft from tighter tolerances around the auger, deeper flutes, and higher helix angle resulted in difficulty extruding paste under increased air pressure and auger speed. Further, the increased pressure needed to extrude paste resulted in increased paste escaping from the top of the auger body, where the beam coupling connects the stepper motor to the auger (Figure 4.28). This indicates that uneven pressure was applied to the paste, where a smaller portion could flow through the auger, and a more significant amount was being forced up and out of the auger shank and through the beam coupling section of the extruder body.



Figure 4.26 Left to right; Sutton Tools 170 x 8mm short auger bit (Sutton Tools, 2023c), Kango 8mm x 150mm masonry drill bit (Kango, 2023b), Kango 8mm HSS drill bit (Kango, 2023a), Sutton Tools 8mm viper jobber drill bit (Sutton Tools, 2023b).



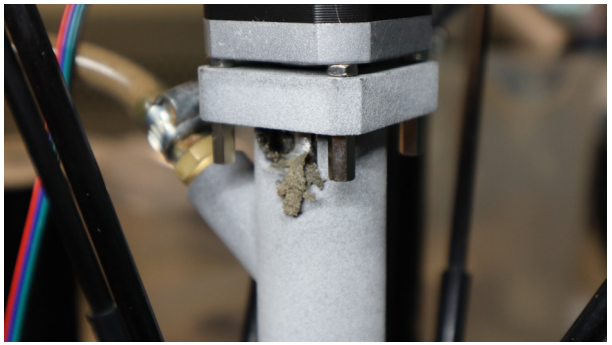
Figure 4.27 The auger used with EXTRUDER_003_000 and onwards. The Sutton Tools 8 x 160mm 2 Cut SDS pus masonry drill bit, (Sutton Tools, 2023a).

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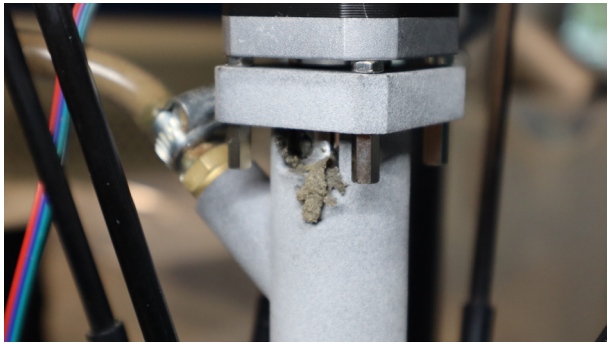
EXPERIMENTS

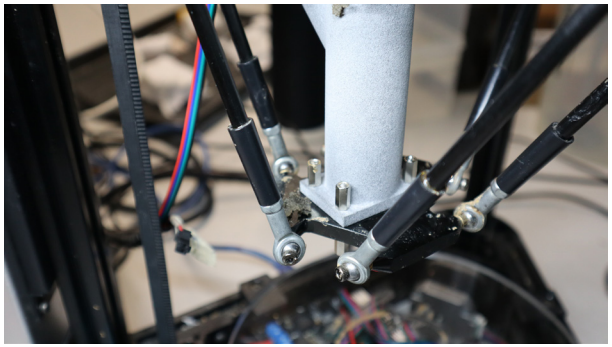
OUTCOME

A persistent problem where liquid paste escapes from the top of the extruder through both the side outlet (which I designed for air to escape and to monitor the spin speed of the auger, and through the top of the beam coupling.









This problem is possibly happening for a few reasons. There is possibly a pressure difference between the amount of paste entering the extruder assembly and the amount of paste being extruded through the nozzle. Liquid and excess paste then finds a way out of the extruder assembly. The paste may be too liquid. What I should explore is trying to find the 'sweet spot' of extrusion and paste delivery speed, and work towards reducing the water content in the paste to avoid liquid moving through the extruder assembly.

Figure 4.28 CALIBRATION3_001_000 shows material escaping up through the auger shank into the beam coupling section of the extrude design and out of the design. This caused several issues, such as material falling on prints and broken stepper motors.

CALIBRATION3_001_000

Deposition through auger control over pneumatic pressure remained critically important, as this would enable exact control over infill properties and retraction movements during 3D printing of complex forms – specifically, 3D printing in product design practice. It became apparent that the properties of the auger, extruder design and tolerances, the paste recipe and delivery system, pressure settings, auger rotations (e-steps) and nozzle diameter have interconnected roles in the efficiency of paste extrusion. While analysing the new augers, it was noted that the helix rotation is designed for 'drilling actions' where matter is pulled through the flutes and towards the drill in a clockwise spin (Figure 4.29). If this action is reversed, the material would be pushed through the flute away from the user. As documented in CALIBRATION3.001.002 (p. 408), this finding prompted the changes to the AnyCubic Kossels firmware, where the 'E' stepper motor rotation was inverted.

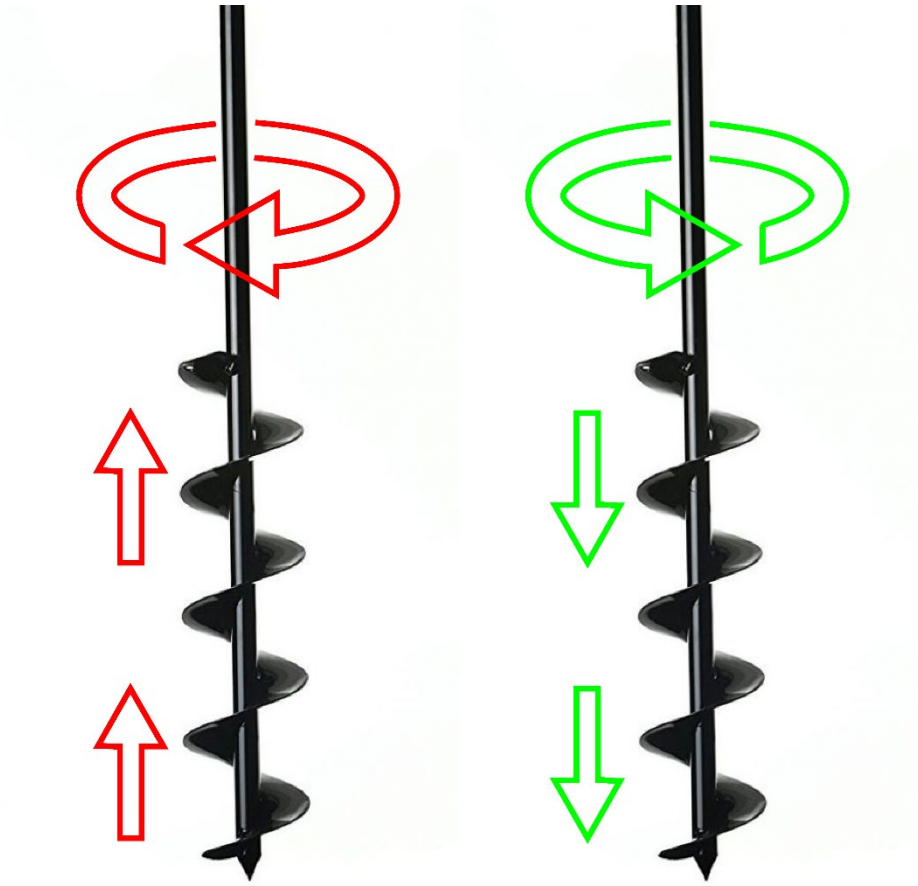


Figure 4.29 Simple diagram of how an auger functions based on direction.

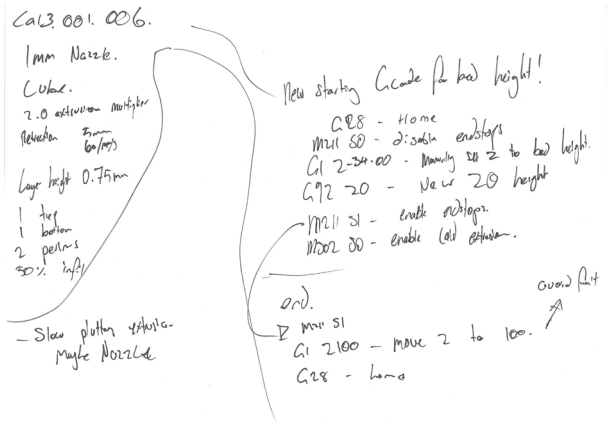
Inverting the default stepper motor rotation immediately impacted material flow, where print CALIBRATION3.001.002 significantly over-extruded due to the more free-flowing paste through the auger's now complimentary rotational movement. This change had several cascading effects, as through settings changes (discussed in *4.2.5* Slicer Settings), the printer now had significantly more control over the deposition of material, material flow, and retraction. As shown through print series CALIRBATION3.001-005 (Figures 4.30-4.34), significant steps were taken in developing the printer, extruder, delivery system, and settings to develop form prototypes for product design practice. Cube-shaped forms with varying styles and density infill were achieved; however, it became apparent that the AnyCubic Kossel was the bottleneck for larger and more intricate 3D prints. This was mainly due to the limited stability and strength of the gantry system, which uses a dated linear pulley system with wheels to move (newer Delta 3D printers use a linear rail system; see WASP (2023b).

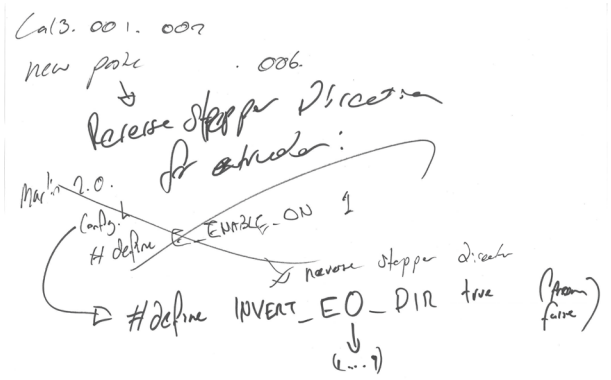
ANCHOR

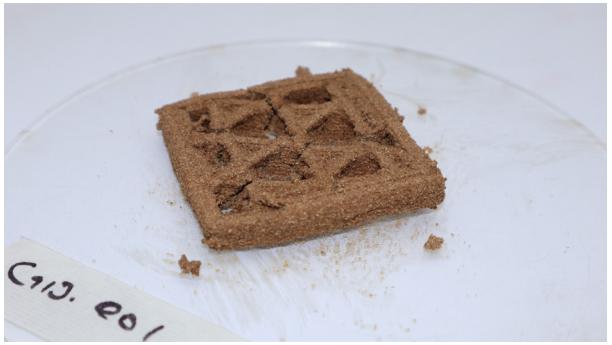
CALIBRATION3 continues on the findings from CALIBRATION2, developing a set of best settings to use in Simplyfy3D. This series also feature the first use of a custom designed and 3D printed extruder for the printer and paste, EXTRUDER_003_001.

The series of CALIBRATION3 explores many forms and settings, from hollow cubes and cylinders, to cubes with various infill settings. This is all made possible by the move from Cura to Simplyfy3D, which inexplicably enabled the printer to extruder straight lines.

EXPERIMENTS









OUTCOME

There was a learning curve when using Simplyfy3D and EXRTUDER_003. First, new Z offset heights needed to be measured; however, this proved difficult as the nozzle was now further away from the gantry, beyond the software enable limitations enabled by the printer to avoid collision with the bed. This meant I had to upgrade and change settings in the printers Marlin firmware. I also generated new starting gcode, stored in the slicer software, which defines the Z Offset without crashing the printer, as shown in CALIBRATION3_001_006.

While changing settings in Marlin 2.0, the new firmware, I disabled features relating to the software end-stops, which limited how close the gantry body can get to the bed, I also changed settings related to the unused heating elements which occasionally created error messages halting or stopping prints.

The most significant, and project altering change was noted in CALIBRATION3_001_002, in which I reversed the stepper motor direction. While watching the printer struggle to print, I was playing with a screw that I considered using as an auger. I spun the screw in between my fingers and noticed that the screw moved away from me if I spun it clockwise, the opposite direction it was currently spinning on the stepper motor. This meant that the current counter clockwise spin was pulling material towards the stepper motor, rather than pushing it away. I tested this in the Simplyfy3D printer controller GUI, and a string of smooth extracted material was released when spinning the auger clockwise. I changed the auger spin direction in the firmware by inverting all 'E' motor directions. This enabled smooth and controller extrusion and enabled the ability to create infill and do retraction between deposits.

Figure 4.30 CALIBRATION3_001_SYNTHESIS.

CALIBRATION3_001_SYNTHESIS

ANCHOR

CALIBRATION3.002 applied the findings from CALIBRATION3.001 to more complex forms, all printed with infill, extra wall counts, and top and bottom layers.

EXPERIMENTS









OUTCOME

CALIBRATION3.002 showed that more complex forms, print paths and manoeuvres were now achievable for the printer and paste. This series features dense cubes and with high infill, inward leaning structures with support layers such as a pyramid, and a failed but information rich attempt at printing a 3DBenchy at 150% scale.

Best practice and settings were now taking shape that showed the way forward for the project for attempt at more complex shapes and tool paths.

Settings:

Nozzle 2mm
Extrusion Multiplier 4
Retraction 5mm at 60mm/s with 0.5mm lift
Layer Height 1mm
Top layers 2
Bottom Layers 2
Perimeters 2
Infill 50%
Infill Pattern ‘traingle’
Infill width 100%
Infill Overlap 25%
Speed 20 mm/s

No speed alterations between layers.

Figure 4.31 CALIBRATION3_002_SYNTHESIS.

ANCHOR

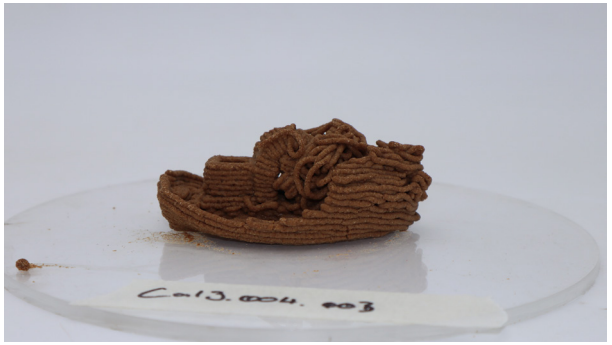
EXPERIMENTS

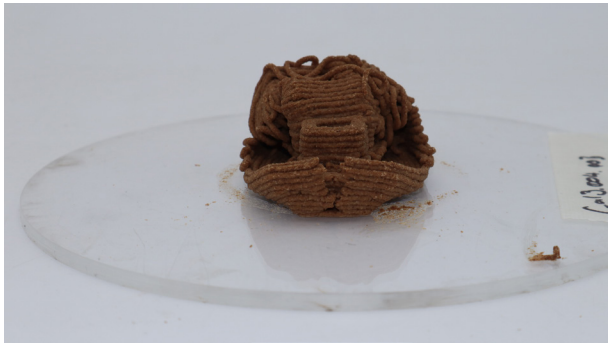
OUTCOME

This series experimented with the settings from CALIBRATION3_002_004, which provided great results. These settings were applied to another 3DBenchy and a cylinder.









The cylinder produced during this series was a fantastic benchmark for how far the capabilities of the printer has come. The 3DBenchy is an indicator that the project should move towards refining the paste mixture to create something stronger.

Figure 4.32 CALIBRATION3_003_SYNTHESIS.

ANCHOR

There was a quick change from Series .003 to CALIBRATION3.004, due to a change in the paste mixture. The paste was remixed to try combat some of the deficiencies seen in the drying from the high water content. Prints continued to investigate the effects of infill and wall settings on the outcomes of parts. Different nozzles were also used to test how a finer extrusion would effect the finished artefacts.

EXPERIMENTS









OUTCOME

While pleased with the wet printed results, the dried artefacts were ruined in the dehydrator. The same heat and time settings were used as with previous prints, however the dehydrator turned off and left the prints too cool, resulting in uneven and cracked parts.

Additionally, the smaller nozzle prints were unsatisfactory, being very stringy and struggling with layer adhesion. This may be changed with a less viscous paste however, in the meantime thin extrusions will be avoided. New nozzles at 1.5mm and 1.75mm were 3D printed for future testing.

Figure 4.33 CALIBRATION3_004_SYNTHESIS.

ANCHOR

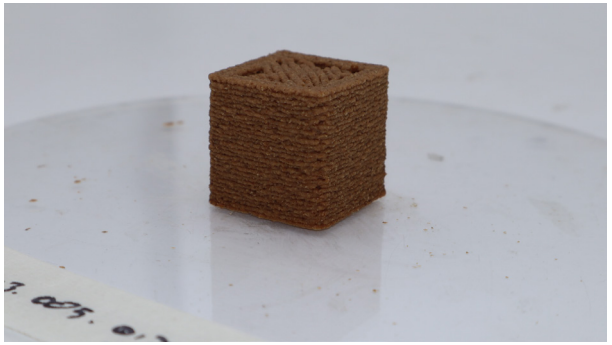
EXPERIMENTS

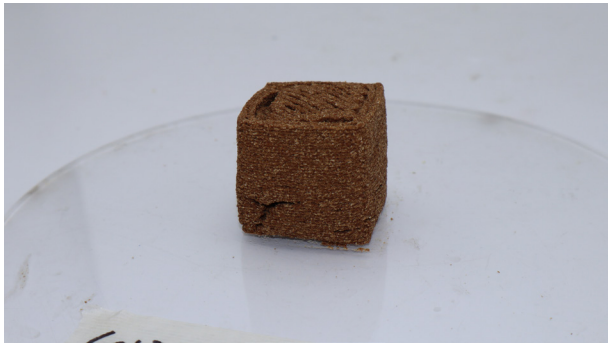
OUTCOME

This series explored further development of slicer settings and the extruder set up.
Cubes with infill were primary investigated as a target shape to evaluate printer performance through ‘neatness’ and uniformity between prints.









This series showed strong progression towards consistent and reliable printing results.
Neat cubes with infill were successfully printed, however drying behaviours still need to be understood and adjusted towards.
Interaction between internal and external walls (infill and perimeters) needs to be better understood to avoid delamination in drying.

Figure 4.34 CALIBRATION3_005_SYNTHESIS.

It was decided to transition to printing with a newer and more stable system; a Creality Ender 3 V2 Cartesian printer was purchased, as well as a dual Z-axis upgrade kit (for improved support of the gantry and extruder) and an Ender 3 direct drive kit (Figure 4.36). The transition to the Ender 3 V2 utilised the knowledge gained in developing the AnyCubic Kossel and extruders to streamline the process, which took only six days. A new adapter plate was designed and printed (Figure 4.35 and Appendix D), which was attached to the e-plate from the direct drive kit, enabling fast changes between the paste extruder assembly and the plastic melting hot end and stepper motor.

An updated extruder was designed and printed, EXTRUDER_003_002 (p. 337 and Appendix D), which rotated the paste inlet towards the front of the printer to minimise force from the delivery system moving against the e-plate pully system. Further, EXTRUDER_003_002 changed the paste inlet to a 19mm hole, suitable for 19mm ID hoses to be directly mounted to the extruder body (discussed in *4.2.4* Paste Delivery System). Finally, a new firmware developed by Risco-Castillo (2023) was loaded into the printer, which has advanced features such as visualised bed mesh, advanced bed levelling and more options for changing printer settings using the printer control screen itself that are usually firmware-based, such as: inverting stepper directions, setting min/max e-step speeds which control the auger speeds, live adjustments to the z-offset while printing.

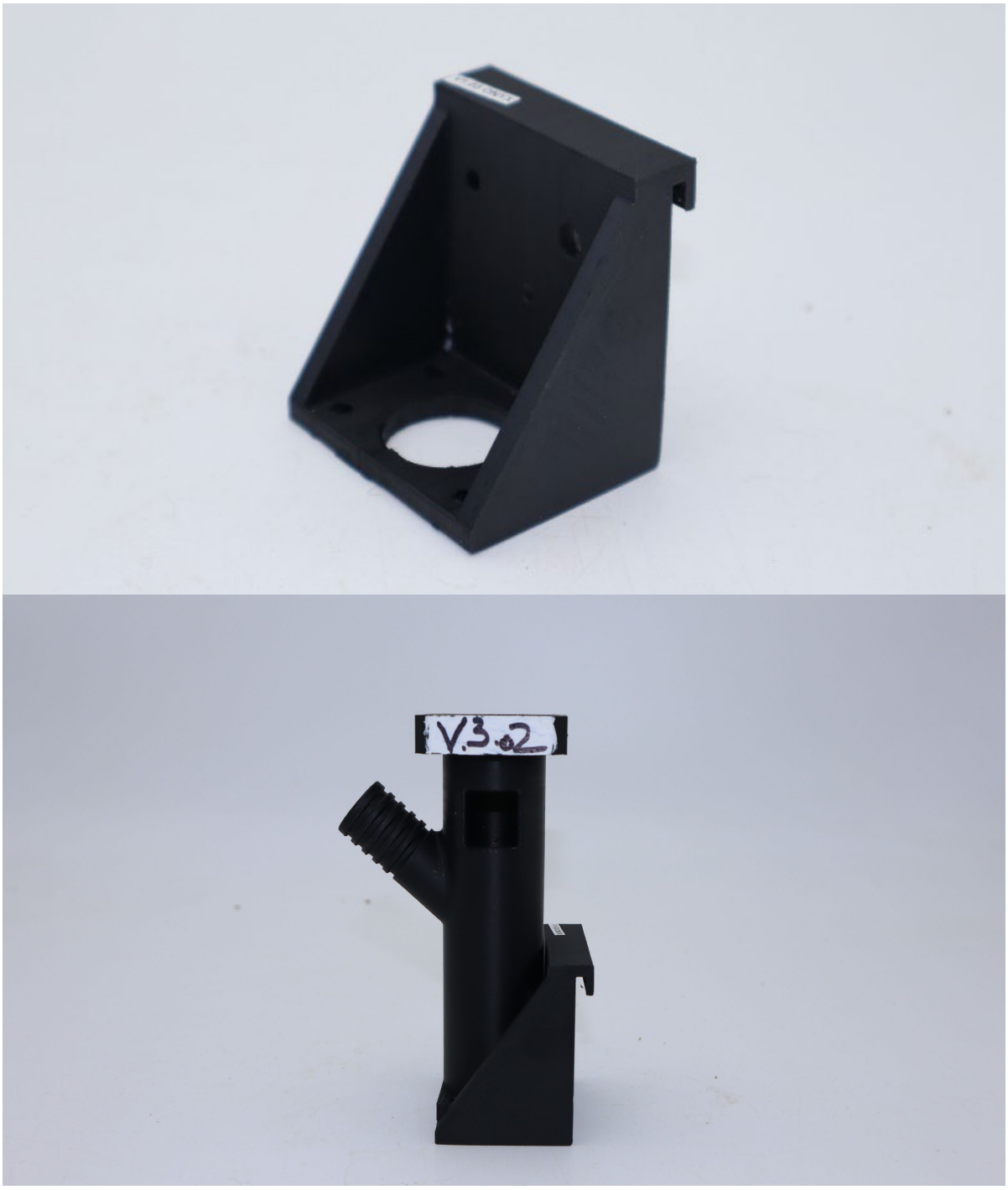


Figure 4.35 EXTRUDER_003_ENDERMOUNT1, designed to slot directly onto the e-plate of the Ender 3 V2 and fit the existing design of EXTRUDER_003.

ANCHOR

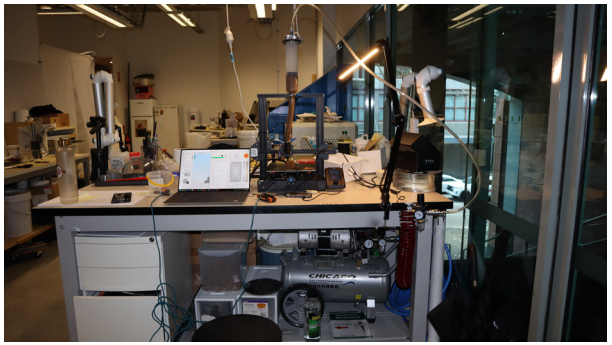
The Creality Ender 3 V2 is a cheap (around 300-350 AUD from Amazon in 2023) consumer 3D printer with a 220 x 220 x 250mm build platform. Part of the low price is that the printer requires some assembly (not wiring) which takes roughly 1-2 hours. The Ender series from Creality is immensely popular with hobbyist, with free printable modifications downloadable from Thingiverse or printables.com, and many purchasable directly from Creality such as direct drive kits, auto levelling tools (Cr-Touch), dual-z upgrade kits and more. The Ender 3 v2 was purchased from Amazon initially as a prototyping tool to produce extruders and nozzles for PRINTER_001, however, it became apparent that it would be better used as a dual purpose machine, printing thermoplastics parts for itself to use as a paste-extrusion printer. To improve the printing experience:

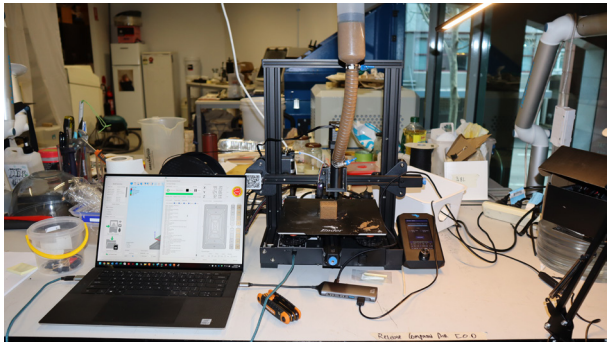
A CR-touch was purchased for bed-mesh and leveling,

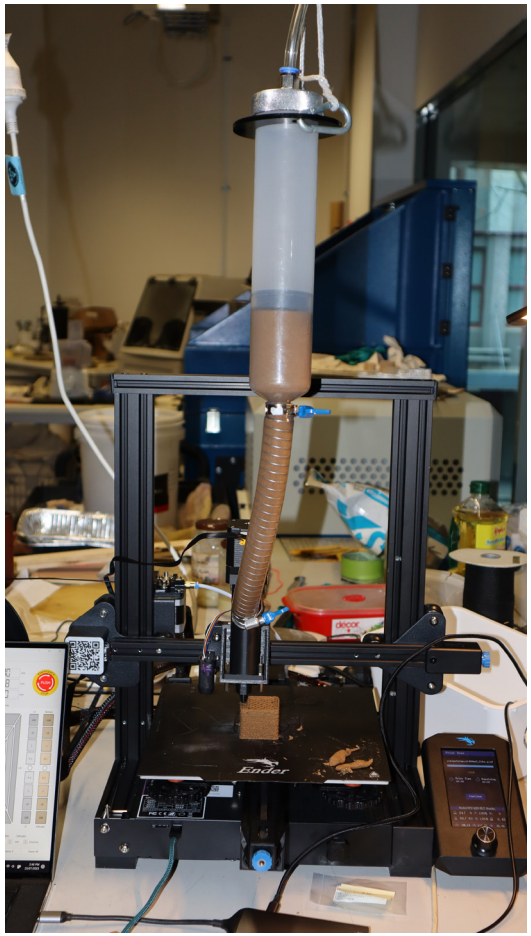
a Creality direct-drive kit, which comes with a larger e-plate (which holds the extruder assembly). This would be used to mount the paste-extruder and to remove the existing e-motor from the z-axis when not in use (and replace it with the direct drive motor)

A dual z-axis kit was purchased for added strength to the z-axis to support the direct-drive and paste-extrusion extruder assembly.

EXPERIMENTS







OUTCOME

The ender 3 v2, paired with EXTRUDER_003_002 and PASTEDELIVERY_002_002 worked extremely well for paste printing, and was used in research question 3 to produce great printed results. The printer was eventually flashed with Professional Firmware" from Miguel Risco-Castillo (username mriscoc) from https://github.com/mriscoc/Ender3V2S1/releases/tag/20230522. This added ease of use in aspect such as bed level visualisation, bed level visualisation and changing the stepper motor rotation between thermoplastic printing and paste-extrusion. Further refinement to the system would be developing a quick change system for extruder assemblies between paste and thermoplastic, a heated chamber design for increasing the range of thermoplastics printable and to explore alternate drying modes for NMC pastes, and a system to mount the spring balancer and filament spool directly above to the system rather than relying on external structures.

Figure 4.36 PRINTER_002_001 using PASTEDELIVERY_002_002, and EXTRUDER_003_002.

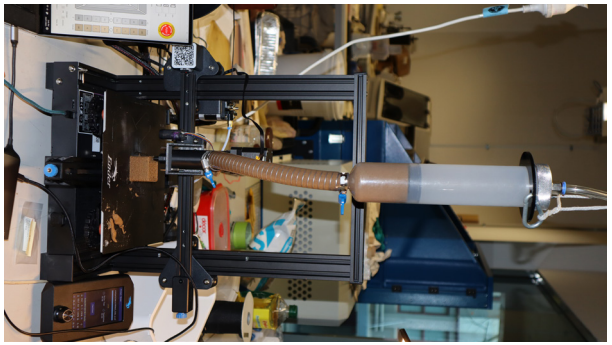
ANCHOR

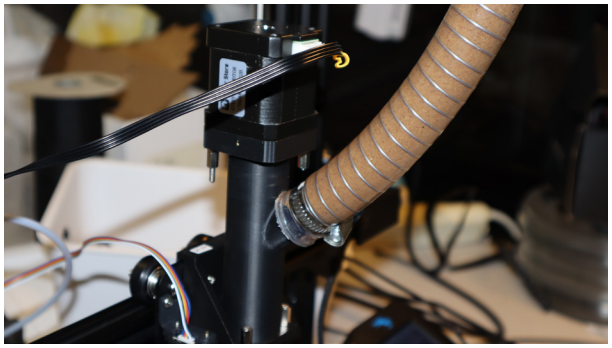
Extruder_003_002 was designed to be used with the Ender 3 V2 printer.

Modifications include a rotation of the base mounting plate by 90 degrees, which was initially designed for mounting to the stock gantry plate on the Anycubic Kossel printer.

The most significant change was the redesign of the paste entry point, which was extended and designed to accommodate hose clamps instead of the previously used internal BSP thread. This design allows for a 19mm internal diameter reinforced hose to be hose clamped over the paste entry point on the extruder, which results in lower pressure needs to delivery paste through the tubing to the printer. This modification is enabled by the added support and strength of the cartesian design of the Ender 3 V2 printer.

EXPERIMENTS









OUTCOME

The new mount and and front paste entry worked extremely well. The gantry and nozzle were unaffected by any movement or the weight of the paste delivery system. The hose clamps need to be closed very tightly, as the pressure pulled the hose lose running prints and emptying the cartridge onto the built plate. A collar was 3d printed which fit tightly around the auger shank and filled the area between the bottom of the coupling and the auger shaft, this stopped excessive paste moving up through the shaft into the coupling section of the assembly.

This extruder was used for the final prints in series PRODUCT_001-003.

Figure 4.37 EXTRUDER_003_002, which was designed with a larger paste inlet that acts as a hosebarb for 19mm ID hoses.

As documented in CP series CALIBRATION4.001 (Figure 4.38), PRINTER_002_001 had immediate benefits over PRINTER_001_001. The cartesian design of the Ender 3 V2, along with the upgraded dual z-axis kit, provided significantly more support to the gantry and extruder assembly during print processes. This was further reinforced by the printer being able to support the weight of the fully assembled and paste-filled extruder design after prints had finished, which was not possible on the AnyCubic Kossel, where the gantry would slowly slide back down towards the bed, ultimately crashing into the bed or finished prints if not removed. Prints were now more controllable and predictable, with minor settings changes needed to dial in the set.

ANCHOR

This is the first print using the newly modified Creality Ender 3 V2 printer, with a custom mount allowing for relatively quick changes between my extruder design (extruder series 3) and the plastic extruder standard to the Ender 3 V2. This print uses a newer version of extruder 3, which uses a hose clamp connection to the paste delivery pipe rather than the screw in hose barb I had been previously been using. This new system allows for large diameter pipes to be used on the printer (through extruder design and printer stability), which allows for denser pastes to be extruded under lower pressure requirement.

Using PASTE.004.007 which had been in the fridge, cling wrapped for 2 weeks. 1 BAR using 19mm ID hose.

1.75 mm Nozzle

1mm Layer Height

4mm Retraction @ 40mm/s (printer default through Simplyfy3D profile)

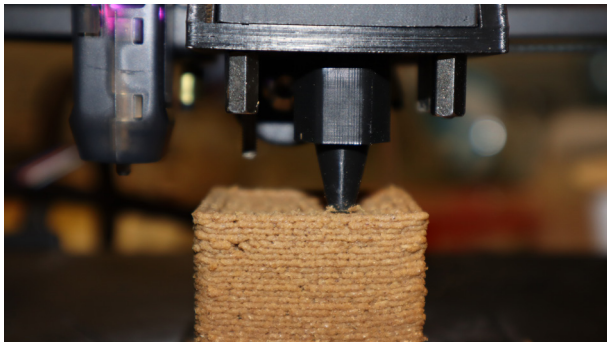
50% Rectilinear infill with 50% overlap on perimeter layers

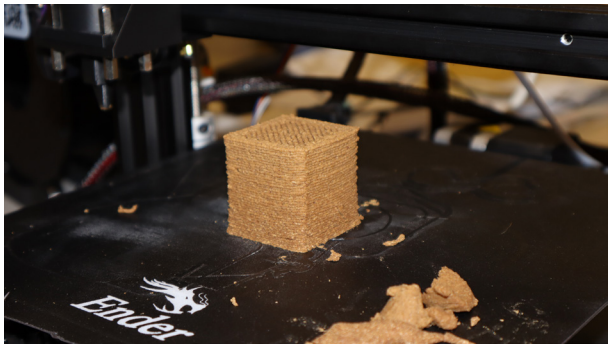
50 degrees C heated bed

40mm/s Speed (using default profiles of 50% out wall speed, 80% inner wall speed, 80% solid infill speed).

It was noticed that there is a slight Z offset difference between the plastic extruder and the paste extruders (+0.42 for the paste nozzle and -1.64 for the plastic nozzle).

EXPERIMENTS









OUTCOME

The benefits of the ENDER 3 v2 compared to the ANYCUBIC Kossel were immediately apparent. Whilst further calibration was needed, the ENDER 3 v2 moves much more smoothly and confidently under load. There is no worry of the print head plummeting into finished parts after printing, or the cartridges responsible for movement coming loose under load.

Figure 4.38 CALIBRATION4_001_001.

CALIBRATION4_001_001

4.2.4 Paste Delivery System

In a traditional MEX 3d printer, such as the Creality Ender 3 v2 and AnyCubic Kossel used in this research, thermoplastic filaments are slowly unwound from a spool of material and fed through to the 3D printer hot end, which melts and deposits the material onto the print surface. The movement of the extruder assembly controls this action: a series of gears push and pull the filament towards and away from the hot end, mounted to a stepper motor that receives machine commands from the printer motherboard (Figure 4.39).

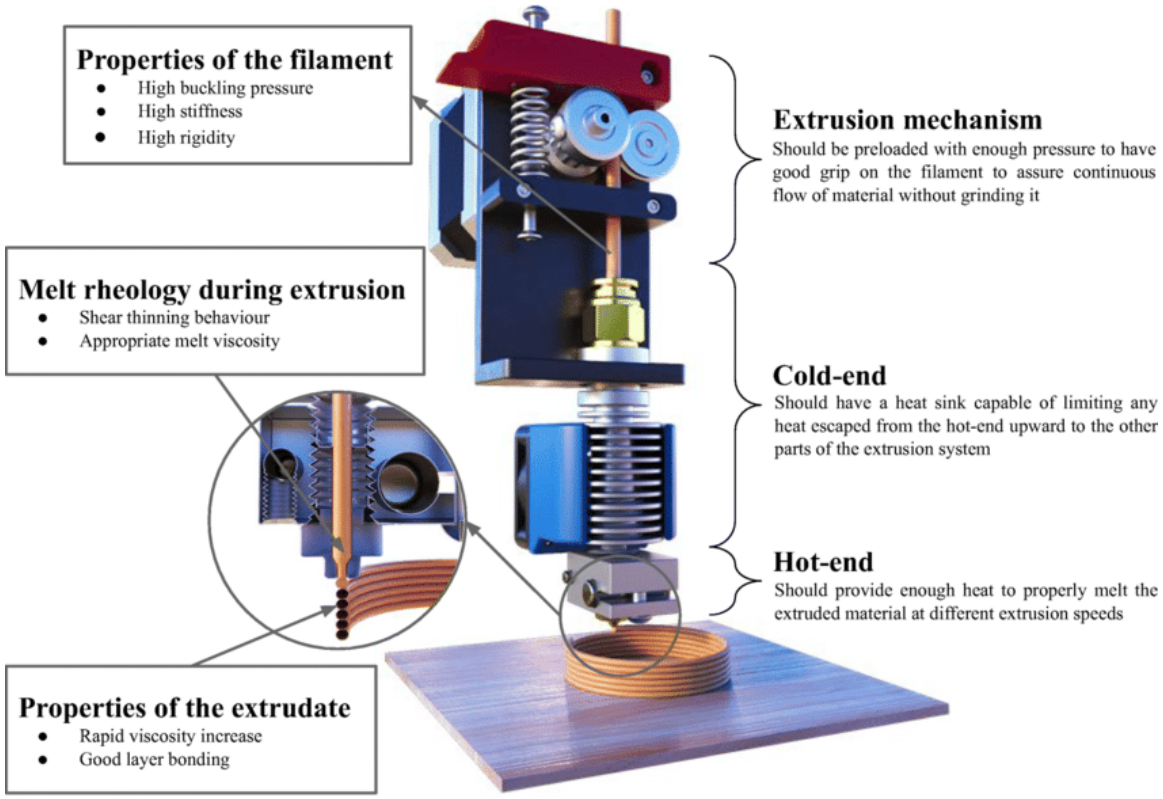


Figure 4.39 Thermoplastic extruder assembly by (Shaqour et al., 2021)

While 3d printing with pastes and thermoplastics falls under the International Organization for Standardization (2021) standard ISO/ASTM 52900:2021 (material extrusion [MEX]), in which material is forced through a nozzle onto a build surface, paste delivery systems need further tailoring and equipment to work. While thermoplastic machines use the motion from the extruder assembly to pull material from a spool and push that material through a nozzle, paste extrusion typically requires an external force to supply paste to an auger and nozzle. This process usually relies on a ramrod system (Figure 4.40) or a pneumatic pressure system (Figure 4.41). This research utilised a pneumatic air system, as this does not require added electronics and can be tailored to various paste

cartridge sizes, avoiding the typically size-limited designs of ram designs, which are mounted to the extruder body, adding weight to the gantry.



Figure 4.40 3D PotterBot 10 Micro by (3D Pottter, 2023). The Ramrod style system retails at 3499 USD.

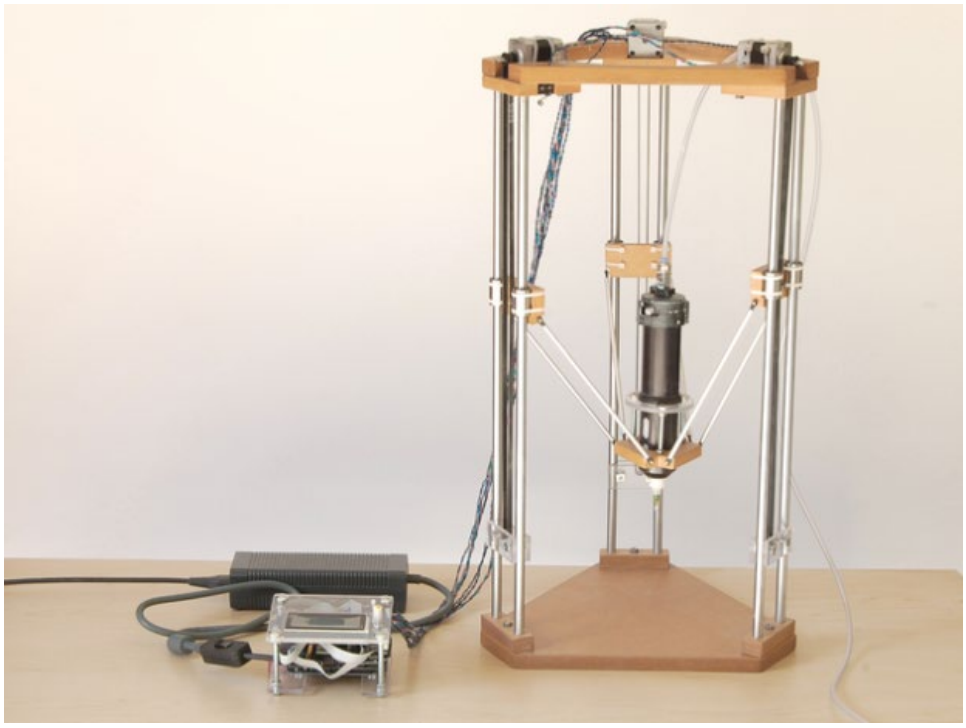


Figure 4.41 Pneumatic Air system developed and built by (Keep).

The paste delivery system was designed in line with commercially available systems from retailers such as WASP (2023a), Eazao (2022b), and CERAMBOT (2023) and used similar methods to Keep (2020). As seen previously in Figure 4.36, compressed air (from a Chicago Ar Hush 30), at around 2 BAR, is moved through air tubing to a regulator and then through to a 500ml clear PVC cartridge holding the paste. The cartridge, purchased from Cerambot (also available from Eazao), has an airtight screw on the back cover with a push-fit inlet and a rubber stopper. The front of the cartridge has an ¼ inch BSP female threaded tip, and threaded inserts varying between male push fit and hose barbs were used during printing. Pressure and the plunger push paste out of the cartridge and down clear tubing to the extruder body. Various systems were developed to accommodate thicker, lower water-content pastes, minimising the delivery system's impact on the extruder body's stability, and ease of cleaning and assembly.

Where this research differs from others is the goal of symbiosis between paste entry via air compression force and paste deposition from the extruder body using the e-stepper motor and auger in unison. The research goal is to 3D print complex forms more typically in line with what product designers would print, such as explorative form prototypes for handheld devices, and less in line with traditional paste 3D printing of continuous vase forms that extrude mainly under pneumatic or ram pressure.

PASTEDELIVERY_001_001 was designed based on the work of Keep (Figure 4.20 as seen on page 112), utilising an air compressor, the secondary regulator for faster access to pressure, a purchased cartridge and a 3D printed and epoxy-sealed back plate for the cartridge. While this system worked in that paste could be moved through the tubing to a printer and extruded, many issues needed addressing. Firstly, a substantial amount of air was escaping from the cartridge back plate, causing the air compressor to continually fill its tank and reducing the air pressure supplied to the cartridge tubing. Second, the paste cartridge and tubing were on the tabletop while printing, and they outweighed the strength of the AnyCubic Kossel gantry, which pulled the gantry off its movement path and moved the nozzle out of alignment. Third, the 10mm outer diameter (OD) vinyl piping used was limited in its pressure rating, and the small internal diameter made thicker pastes difficult to extrude, due to the need for increased pressure for paste delivery.

Air escaping the cartridge was remedied by purchasing a kit from CERAMBOT (2023) (Figure 4.42). The kit comes with the same 500ml cartridge initially being used but includes a screw-on metal back plate and an internal o-ring for increased airtight contact with the cartridge (also available from Eazao). The backplate has a 1/8 inch BSP female thread, which can be used for push-fit attachments for air inlet piping. This system provided an airtight network for air and paste flow through the tubing, providing greater control for the auger system to extrude paste.

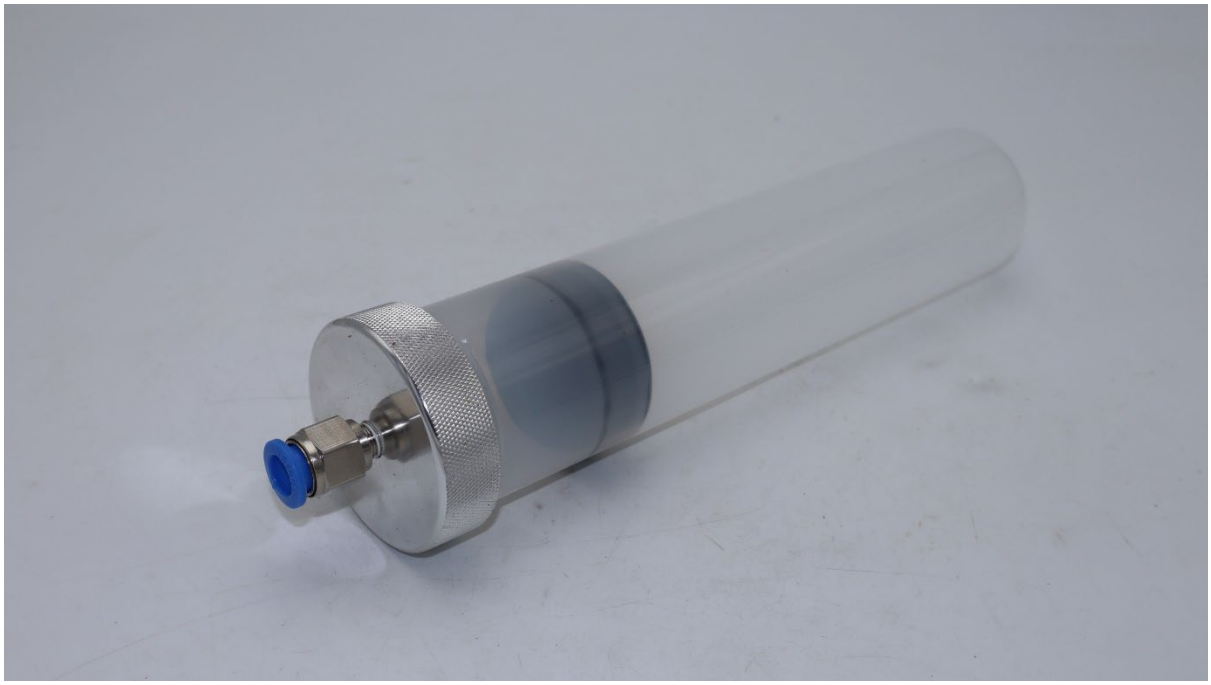


Figure 4.42 PASTEDELIVERY_001_002 using the CeramBot metal back plate.

A significant factor affecting what objects could be printed was the paste-filled cartridge's positioning and weight and the tubing length used to deliver paste from the cartridge to the extruder. If an object moves the gantry far away from the cartridge, the tension in the tubing connecting the extruder assembly to the cartridge would pull the extruder off the axis and cause missed layers and failed prints. Attempts were made to mitigate this tension; this was done by attempting to evenly disperse the weight and tension from the cartridge and tubing by propping the cartridge above the usually printed height and by shortening the tubing and positioning the system in such a way that any movement away from the centre point of the bed of the printer would have equal pressure from the cartridge (whether pushing or pulling). This bandaid solution worked in the initial stages of printing but was unreliable and required constant readjustment while experiments were being printed.

While watching a video tutorial of industrialised pneumatic air delta style clay printers, it was noticed that their large cartridges were suspended inside the body of the print (Figure 4.43). Upon further inspection, it was noted that inbuilt spring balancers were holding these cartridges within the machine. This prompted the redesign of the paste delivery system, as seen in CP PASTEDELIVERY_002_001 (Figure 4.44), in which a spring balancer was purchased online, and an attachment collar was laser cut for the cartridge (Appendix D). The spring balancer was mounted to the ceiling rails of the Material Ecologies Design Lab, and carabiners were used to hook the spring balancer to the attachment collar around the cartridge. In conjunction with the Y inlet design of EXTRUDER_003_000 (see page 516), this design allowed for significantly more control over the extruder and gantry movement, mitigating the tension and weight being applied to the extrude with the tabletop set-up.

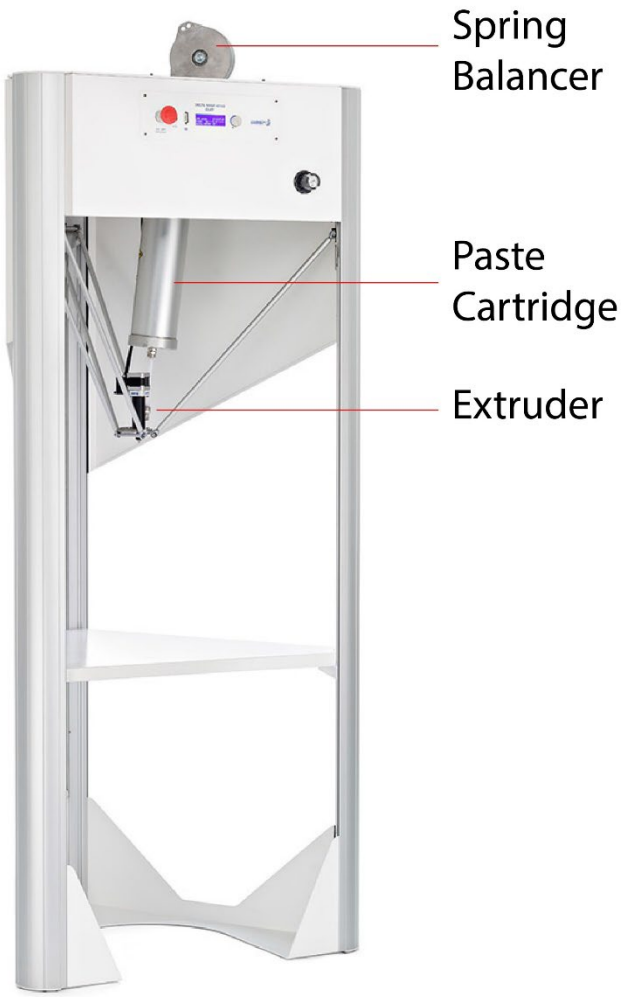


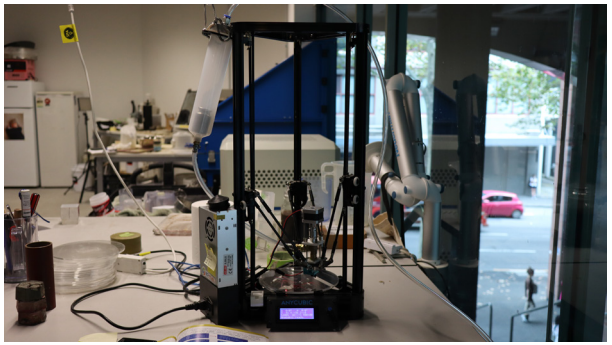
Figure 4.43 WASP 40100 with spring balancer (WASP, 2023b).

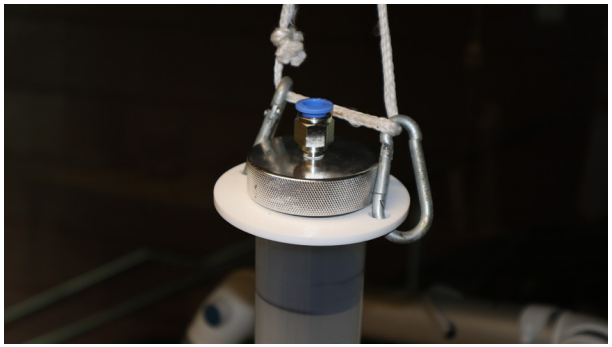
ANCHOR

Whilst watching a video of someone using a DELTA WASP 40100 printer, I noticed that the paste cartridge was supported by some sort of count balance system. After more research i found that this was a spring balancer, and ordered one from Amazon that could support 0.5-1.5kg. Then, I lase cut a collar/ mount, that fit around the paste cartridge using the lip of the metal back plate as a stopper. The collar has two holes for carabiners, and these are hanging from a rope which is tied to to the spring balancer.



EXPERIMENTS







OUTCOME

The spring balancer was an immediate success, especially when paired with the Creality Ender 3 V2 printer (PRINTER_002), which has a much more well supported gantry. The system removed most of if not all of the weight off the gantry and extruder assembly, allowing for unencumbered movement and printing of more advanced shapes.

Figure 4.44 PASTEDELIVERY_002_001 using a spring balancer to support the paste cartridge

PASTEDELIVERY_002_001 worked successfully for the production of several prints. The system was used for both PRINTER_001 and PRINTER_002 and was a significant factor in the progression of the printer and paste development process. The system went through one last iteration, PASTEDELIVERY_002_002 (Figure 4.45), in which the diameter of the paste delivery tubing was increased. Initially, the system used 10mm OD tubing for air and paste delivery. However, it was noticed that the diameter of the tubing was a bottleneck in the refinement of the paste for reduced water content, as a paste with reduced water content needs higher pressure to move through the tubing. It was hypothesised that larger diameter tubing would require less pressure to move the paste, as there would be less friction in total on the body of the paste moving. In conjunction with the redesign of EXTRUDER_003_002 (Figure 4.46), 19mm helical reinforced PVC tubing was purchased, rated with a maximum working pressure of 4 BAR. A 19mm ID to ¼ inch BSP hose barb was also purchased, which would connect the cartridge to the new tubing. Once mounted to the 19mm inlet on the extruder and the 19mm hose barb, the 19mm ID hose was hose-clamped in place.

ANCHOR

The spring balancer system was further modified by increasing the dimeter or the cartridge outlet, tubing and inlet of the extruder assembly to 19mm. It was found that smaller diameter piping had increased friction (Nur et al. 2019) .

Tubing was sourced online with careful attention being paid to the pressure rating of piping. 19ID helical reinforced PVC tubing was sourced online. 19ID was found to provide the best mix of flexibility and safe working range (around 4 BAR or 60 PSI). Smaller ID piping was more rigid but had higher pressure rating, and larger ID was very flexibly but had very low pressure rating.

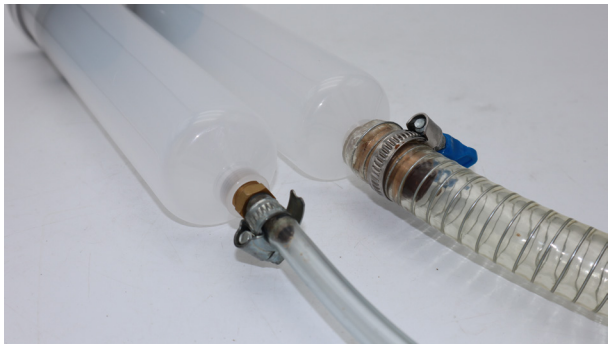
Further, a 1/4 inch BSP to 19mm ID hose barb was sourced cheaply from eBay for use on the cartridge, and hose clamps purchased from local hardware stores

This system was paired with EXTRUDER_003_002

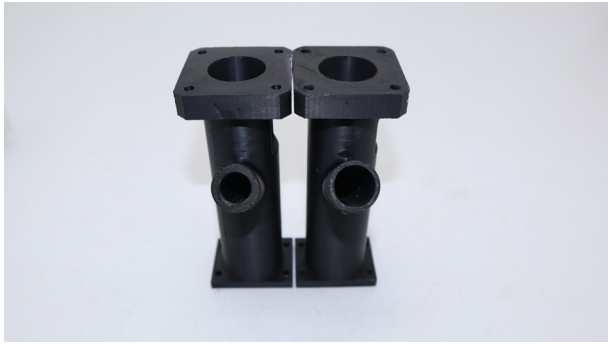
See: DOI 10.1088/1757-899X/602/1/012058 Effect of pipe diameter changes on the properties of fluid in closed channels using Osborne Reynold Apparatus by Nur, Afrianita1 and Ramli

EXPERIMENTS









OUTCOME

This system worked well, with a few minor hiccups. Hose clamp[s] needed to be extremely tight, or the hose could come loose. This resulted in the helical wire breaking through the PVC pipe after many uses and did need monitoring.

The system allowed for refilling or replacing cartridges mid print, as the cartridges could be unscrewed from the metal back plate mounted to the spring balancer and unscrewed from the 19mm ID hose barb which was secured to the hose by clamps.

Ultimately this system was used in the majority of experimentation in research question 3 and worked extremely well. It would be used in experimentation going forward with minimal changes if any.

Figure 4.45 PASTEDELIVERY_002_002 using 19mm ID tubing.

ANCHOR

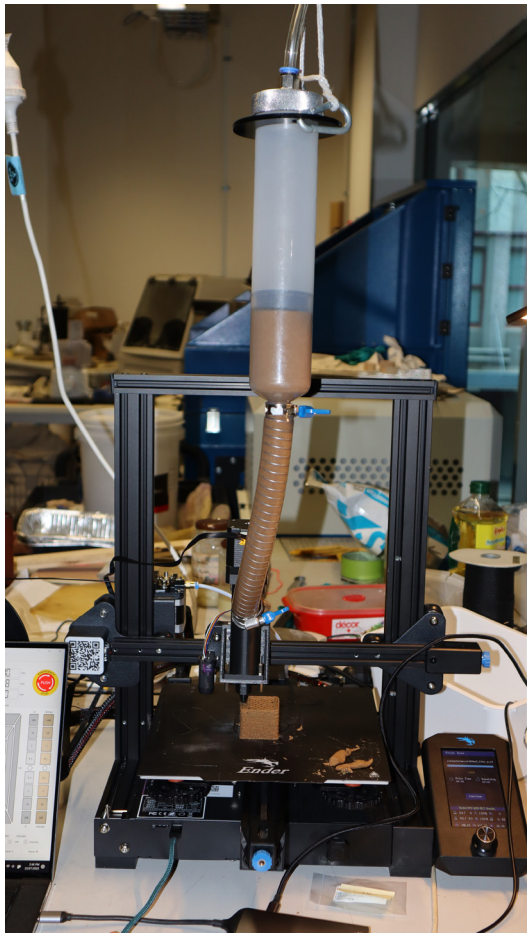
EXPERIMENTS

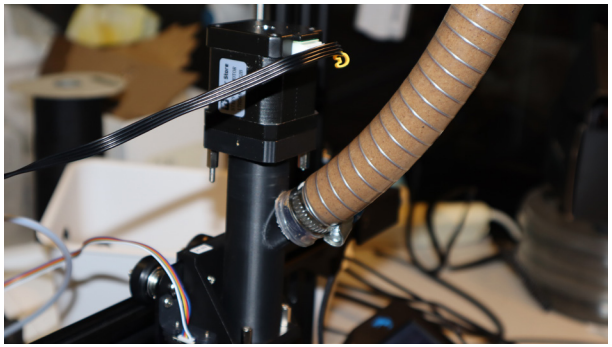
OUTCOME

Extruder_003_002 was designed to be used with the Ender 3 V2 printer.

Modifications include a rotation of the base mounting plate by 90 degrees, which was initially designed for mounting to the stock gantry plate on the Anycubic Kossel printer.

The most significant change was the redesign of the paste entry point, which was extended and designed to accommodate hose clamps instead of the previously used internal BSP thread. This design allows for a 19mm internal diameter reinforced hose to be hose clamped over the paste entry point on the extruder, which results in lower pressure needs to delivery paste through the tubing to the printer. This modification is enabled by the added support and strength of the cartesian design of the Ender 3 V2 printer.







The new mount and and front paste entry worked extremely well. The gantry and nozzle were unaffected by any movement or the weight of the paste delivery system. The hose clamps need to be closed very tightly, as the pressure pulled the hose lose running prints and emptying the cartridge onto the built plate. A collar was 3d printed which fit tightly around the auger shank and filled the area between the bottom of the coupling and the auger shaft, this stopped excessive paste moving up through the shaft into the coupling section of the assembly.

This extruder was used for the final prints in series PRODUCT_001-003.

Figure 4.46 EXTRUDER_003_002 was designed with a larger paste inlet that acts as a hose barb for 19mm ID hoses.

4.2.5 Slicer Setting Development

While the printer, printer firmware, extruder assembly, and paste delivery system were being developed, so were the slicer settings for successful, predictable and reliable prints. While slicer settings, the instructions for the 3D printer on how to build a given object, can be used as a standard for a purchased printer, which often has default profiles created by manufacturers available in the software, modifying (or building) a MEX printer to print with a paste requires tailoring the slicer settings to the specific needs of the paste, printer and extruder assembly design. There are many slicer software to choose from; however, in this research, three were considered: Free software Ultimaker Cura and PrusaSlicer, and Simplyfy3D, which needs to be purchased.

It should be noted that slicer settings are heavily dependent on the cohesion of the physical factors of the printing system, such as the consistency of the paste, the paste delivery system and the speed at it is delivering paste to the extruder assembly, the extruder assembly design regarding tolerances of the auger, the auger design regarding flute depths and helix angle, and firmware settings such as the maximum speed the auger can spin (e-steps), auger rotation direction, and enabling of cold extrusion.

Initially, Ultimaker Cura was used to control the AnyCubic Kossel as recommended by AnyCubic. Machine profiles are immediately available in the software, tailored to thermoplastic 3D printing. Modifications to the slicer settings were based on Keep's instructions in 'Guide to Clay 3D Printing', which are for printing hollow ceramic vessels:

- Nozzle size (adjusted to match the 2mm nozzle used on the extruder)
- Layer heights (changed to half the width of the nozzle (standard practice in 3D printing)
- Bottom and top layers (set to 0 to enable the printing of hollow vessels)
- Flow rate set to 100% (this would change depending on material flow guided by the auger)
- Print speed set to 25mm/s, (this is the speed the printer moves while depositing material)
- Spiralise outer contour enabled (converts the layer-by-layer building process of MEX printers into a smoother single-rimmed exterior constructed of one long extrusion. This setting is often used by those building vases and other hollow objects)
- Infill and support were turned off (for hollow vessel printing)
- Lastly, adding the line of 'M302 S0' to the starting g-code in the printer settings enables 'cold extrusion'. If this is not enabled, printers will halt or show error messages, as, without further firmware modification, the printer will detect a cold hot end (there is no hot end connected to a paste printer) and will not allow printing.

Keep's settings are a good starting point and demonstrate the modifications needed for the printer and the slicer software to start 3D printing with pastes. It was apparent that these settings would require further modification and tailoring to achieve the forms desired for form prototyping in product design. As documented in print tests PRINT_001-008 pp. 344-384), key settings such as layer height, movement speed, flow rate, and paste delivery pressure were calibrated individually, working towards predictable and controllable print outcomes.

Through PRINT_001-008, a hierarchy of settings was beginning to appear, where changes to key settings such as flow rate (the rate at which the auger would spin) had significantly more impact on the printed outcome than changing a more superficial setting such as wall thicknesses (which ultimately are dependent on the flow rate and travel speed). While the outcomes of the initial PRINT series were satisfactory, insofar as the system of PRINTER_001, EXTRUDER_002, PASTEDELIVERY_001 and PASTE_003_001 and Ultimaker Cura (version 4.13.1) could extrude, deposit and build rudimentary forms from BSG based NMC pastes, several factors needed improvement. These were: the printer could not print straight lines when trying to print slots (series PRINT_005, see p. 371), the printer movement was limited (stuttering, and slow-moving), material flow (both firmware and physical issues), and retraction were not possible, indicating a lack of control over the auger and subsequently, the flow rate.

Key Cura settings at this point are:

- Flow rate @ 225%
- Movement Speed @ 10-12.5 mm/s (this was still developing)
- Slow layers @ 0 (the first layer would be deposited at full speed)
- Layer Height @ 1mm (half of the 2mm nozzle)
- Line Width @ 2mm (this has no impact on the print as it was affected by flow and movement speed)
- Spiralise outer contours on (vase mode)
- PASTE_003_001 (BSG 200, 75g 6% CMC, 400g Water, 30g glycerin).

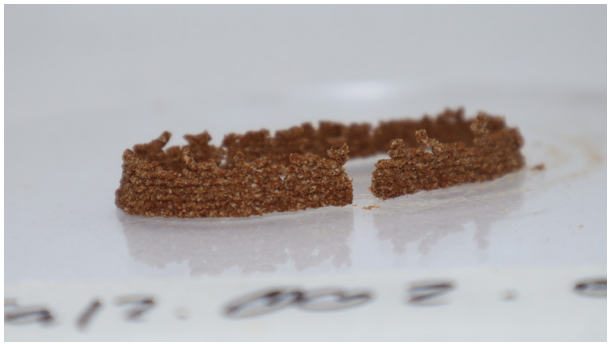
Other slicers were tested to address the printer's inability to print straight lines (the auger would not spin on 'straight' travel paths). PrusaSlicer, which, like Cura, is free, had difficulty interpreting the thicker tool paths and layer heights and would not allow printing with spiralised outer contours (vase mode). Ultimately, Simplyfy3D, a paid slicer, was used and had immediate success, as seen in CALIBRATION2_002 (Figure 4.47), where slots with controlled wall thicknesses were printed. Settings from Cura needed to be translated into Simplyfy3D and resembled the following:

- Extrusion multiplier @ 10 (this is the 'flow rate' and would be key in the future)
- Extrusion width @ auto (this is controlled by flow rate, paste consistency and pressure)
- First layer speed @ 100% (translation from 'slow layers in Cura)
- Perimeter shells @ 1 (a single outer shell pass with no interior printing)
- Corkscrew mode ON (this is 'vase' mode)
- Speed @ 30mm/s (this setting is not working at this point)
- Nozzle @ 2mm
- Layer Height @ 1.5 (lowered to 1mm in later prints)
- PASTE.003.002 (BSG served through a 40-mesh screen) printer @ 2 BAR.

ANCHOR

CALIBRATION2.002 documents the transition of slicer software from Cura to Simplyfy3D. When comparing the Gcode between the two slicers, Simplyfy3D's output showed promising signs that it produce straight lines on the 3D printer, a problem found was encountered multiple times in Cura (see PRINT_005_001 & CALIBRATION2_001_014).

EXPERIMENTS









OUTCOME

For unknown reasons, models with straight lines loaded into Simplify3D were able to be printed on the printer. This series of prints documents the various settings tested and the changes in settings values from Cura to Simplify3D. Settings differences were:

Nozzle 2mm

Extrusion Multiplier 10 with auto width (this would be similar to flow rate from Cura)

Layer Height 1.5mm

Perimeter Shells 1

Corkscrew ON (vase mode)

First Layer Settings all at 100%

Extruder temp 0

Cooling 0

Z offset 6mm (firmware differences from Cura)

Speed 30mm/s

Figure 4.47 CALIBRATION2_002_SYNTEHSIS shows print progression using Simplify3D.

While the settings above were satisfactory in producing similar forms, such as hollow slots and cylinders, there was still a lack of control over material flow, such as the ability to deposit material predictably and to create retraction movements (momentarily stop the material flow). This prompted changes, such as purchasing new augers with tighter helix rotations and deeper flutes for use with EXTRUDER_003_000, and inverting the auger rotation via firmware alterations, which ultimately gave control of material flow (see CALIBRATION3.001.002 on p. 408). These alterations, along with the spring balancer suspended paste cartilage (PASTEDELIVERY_002_001), enabled PRINTER_001_001 (AnyCubic Kossel Delta) to print with significantly more control over material flow (deposition and retraction) as well as stability. As documented in CP series CALIBRATION3_001 to CALIBRATION3.005 (pp. 407- 445, and shown in Figure 4.48), these changes enabled the printing of more complex shapes, such as multilayered cubes (between 20 and 50mm^3), with infill (using retraction), and top and bottom layers, which functionally mimics the traditionally expected behaviours of printing with thermoplastic filaments. Slicer settings used in these experiments are as follows:

PRINTER_001_001, PASTEDELIVERY_002_001, EXTRUDER_003_000, PASTE_004 (series)

- Extrusion multiplier @ 4-6.5 (flow rate, changed depending on paste consistency)
- Retraction @ 5mm at 60 mm/s (speed and distance at which material is pulled back into the extruder during non-extrusion movements)
- Perimeter walls @ 2 (No longer printing in vase mode)
- Top and Bottom Layers @ 2 (to create enclosed vessels)
- Infill @ 30-60% (triangular and rectilinear showed the most promise)
- Nozzle @ 1.75mm (3D printed in PLA)
- Layer Height @ 0.875 (half of nozzle diameter)
- Speed @ 30 mm/s (this still did not seem correct regarding translation to real-time movement.

ANCHOR

CALIBRATION3.002 applied the findings from CALIBRATION3.001 to more complex forms, all printed with infill, extra wall counts, and top and bottom layers.

EXPERIMENTS









Figure 4.48 CALIBRATION3_002_SYNTHESIS shows some of the more complex shapes achieved through setting, printer and material configuration.

OUTCOME

CALIBRATION3.002 showed that more complex forms, print paths and manoeuvres were now achievable for the printer and paste. This series features dense cubes and with high infill, inward leaning structures with support layers such as a pyramid, and a failed but information rich attempt at printing a 3DBenchy at 150% scale.

Best practice and settings were now taking shape that showed the way forward for the project for attempt at more complex shapes and tool paths.

Settings:

Nozzle 2mm

Extrusion Multiplier 4

Retraction 5mm at 60mm/s with 0.5mm lift

Layer Height 1mm

Top layers 2

Bottom Layers 2

Perimeters 2

Infill 50%

Infill Pattern ‘traingle’

Infill width 100%

Infill Overlap 25%

Speed 20 mm/s

No speed alterations between layers.

CALIBRATION3_002_SYNTHESIS

As discussed in 4*.2.3* 3D Printer and Extruder Design, ultimately, it was decided that the printing system should transition away from the AnyCubic Kossel Delta due to stability issues with the gantry. All systems were adapted to use PRINTER_002, a Creality Ender 3 V2. Creality recommends using Cura. However, it was decided that Simplyfy3D would continue to be used, particularly due to its robust machine control panel system during printing (allowing gcode to be easily sent live to the print and easy printer movement controls), multi-process control panel (different prints can have different settings on the same bed), and variable layer heights.

The new system, using PRINTER_002 (using improved firmware by (Risco-Castillo, 2023)), PASTEDELIVERY_002_002 (larger hose), EXTRUDER_003_002 (larger inlet), and PASTE_004_012, was able to generate consistent, accurate and complex 3D forms resembling those used by product designers in rapid form prototyping. Models such as computer mice, video game controllers, and 3D scans of native seed pods were able to be printed using the following settings.

- 2 BAR (adapted per material)
- Inverted E motor through the ‘Professional Firmware’ screen option
- E-Steps maximum @ 150 mm/s (through firmware, control of auger spin speed)
- Extrusion multiplier @ 10 (will change with material consistency)
- Retraction @ 4mm at 40mm/s with 2.5mm lift between movements (stops dragging between layers)
- Nozzle @ 1.75 mm
- Layer height @ 0.875 mm
- Top layers @ 2 (2 or more can cover gaps of material layers on top)
- Bottom layers @ 2 (needed to prevent bowing and flexing in drying)
- Outside perimeters @ 1 (more perimeters can delaminate during drying; using one and having an overlap with infill stops this)
- Infill @ 40% triangular with 100% width and 50% overlap with outline layers
- First layer speed, height, width @ 100% (trying to keep extrusion consistent requires adaptation of pressure, e-step speed; if the first layer is different, this can cause too much or too little pressure and require changing of pressure while printing, which can affect line thickness and perimeter uniformity)
- Heated bed sequence @ layers 1-10 @ 35c, layers 11-25 @ 45c,layers after 25 @ 35c
- Extruder set to 0c with cold extrusion enabled (default extruder is still connected to mainboard for use if needed)
- Default speed @ 55 mm/s (all speeds set to 80%, outer perimeters set to 70%)
- Support enabled @ 80% infill triangular pattern, with 3mm inflation distance (this makes support material coverage wider and easier to remove)

These final settings represent a malleable baseline for further experimentation and are not definitive. They demonstrate the interconnected nature of the physical and digital systems in past printing. Some settings, such as flow rate, line width, and speed, are distinctly tied to the consistency of the paste and the pressure behind the paste being delivered to the extruder.

ANCHOR

Model used is of a scanned Logitech computer mouse from thingiverse: thing #4398925

Ender 3 v2 with Dual Z Axis Modification

Using extruder_003_002 (extruder v3.02) which uses a hose clamp to attach a 19mm ID spiral reinforced PVC tube

1.75 Nozzle

0.875 Layer Height

12.0 Extrusion Multiplier

3mm Lift on Retraction movements to avoid nozzle dragging in material on longer passes

3 Top Layers

2 Bottom Layers

1 Perimeter

40% Rectilinear Infill @ 100% width with 50% overlap

40mm/s ALL Speeds

EXPERIMENTS









OUTCOME

Initially it took hours of troubleshooting to get consistent layer adhesion and paste flow. There was also a scratching noise coming from the extruder body, and an occasionally high pitch squeak coming from Z axis lead screws which move the gantry up and down.

I think the squeak is due to the new weight from the extruder, paste, paste delivery system, and stepper motor. I will be removing the stepper motor for the plastic extruder and replacing it with different style of extruder called a 'direct drive', which situated the extruder and hot end in close proximity ,allowing me to remove all weight and plastic printing components quickly before replacing them with paste extrusion components.

For this print, which initially failed due to the hose clamp for the paste delivery coming loose, I increased the 'lift' of the nozzle on retraction movements, which should avoid future situations where the nozzle drags through material when moving between paths.

I am also looking to increase the print speed, and found through reddit posts that I can increase to up to 60-70mm/s from the current 40mm/s.

Figure 4.49 CALIBRATION4_001_010, a 3D printed explorative prototype based on a Scan of a Logitech G1 gaming mouse.

CALIBRATION4_001_010

4.2.6 Form Testing

In answering research question 2, various forms were produced. These forms were indicative not only of the experimentation processes' investigation into achievable forms, but also documented the development of form complexity achievable by the paste printing system developed and the paste itself. The final forms achieved, a computer mouse and various 3DBenchys, show the system's ability to meet the needs of product designers who are producing explorative prototypes in industry, education, and environments. This is where the transition from research question 2, which explains what is involved with generating 3D forms for product design use, to research question 3, which asks what is required for these forms to be used in practice, takes place.

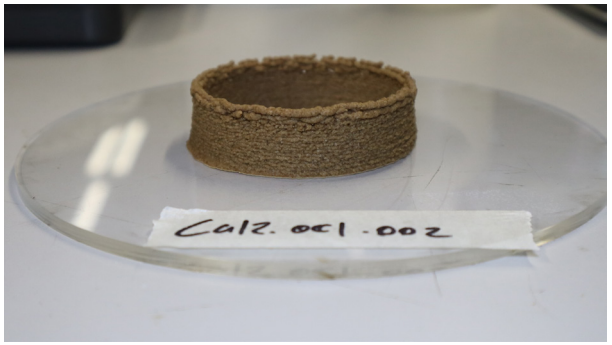
Forms produced during the experimentation were indicative of the printers' and pastes' capabilities, and the forms developed remained consistent throughout the research, to document improvement or decline through setting and machine system changes. Initial forms represented simple shapes, such as hollow cylinders, and evolved slowly through the testing of new machine settings and features, such as the addition of more perimeter walls, infill use and top and bottom layers. Once a baseline was established in the slicer, extruder assembly, and paste, more complex shapes that represented possible applications of the system, such as handheld products like computer mice, were introduced. A running test that appeared later in the research was the printing of 3DBenchy boats, a commonly used benchmarking tool used by hobbyists and professionals who are setting up MEX printers to use with thermoplastic filaments (Creative Tools, 2020a). The 3DBenchy acted as a strong barometer of the capabilities of the printer's system as a whole.

As documented in series PRINT_001-8 and CALIBRATION2_001, the first form 3D printed was single-walled spiralised cylinders ranging between 50mm and 100 mm diameter and a maximum of 50mm tall. These prints, printed on PRINTER_001_001, explored the initial development of the paste, printer, extruder and paste delivery system. The repeatability of desired results, such as uniform extrusion width and adhesion of the walls, determined the print quality. Initially, forms had inconsistent wall thickness, printed slowly, and lacked layer uniformity. Neater, taller single-walled cylinders were achievable through the development of the printer's other system and print settings (Figure 4.50) Once satisfactory results were achieved and slicing issues around straight lines were removed, the prints transitioned from this form. A series of slots was printed, and much like the cylinders, they were used to develop slicer settings and the other interconnected systems further (Figure 4.51).

ANCHOR

CALIBRATION2 is a continuation of the PRINT_002-008 series, in that it focusses on 'dialling' the printing into a workflow and settings which result in a consistent printing experience. The series continued with printing hollow cylinders, but with a focus on moving towards one set of settings that can print a tall structure with unform layer heights and wall consistency.

EXPERIMENTS









OUTCOME

Prints began to have some consistently following settings:

In Cura
Z Offset 21.5 mm
Layer Height 1.5-1.8 mm
Jerk 10
Acceleration 1500_ Relative Extrusion turned on

2 Bar of pressure, which is too high and causes material to push out of the top of the extruder body where the stepper motor is.

The EXTRUDER_002 was showing its limitations in a few aspects. First the parallel to the ground paste inlet was continently pulling the extruder off axis due to the weight of the piping and syringe with paste. This needs to be fixed in order to allow for smooth movement of the extruder body and gantry. Further, the thickness of the auger is not equal to close to the thickness of the inside of body of the extruder, allowing paste to flow around and and past the auger reducing its control of the extrusion.

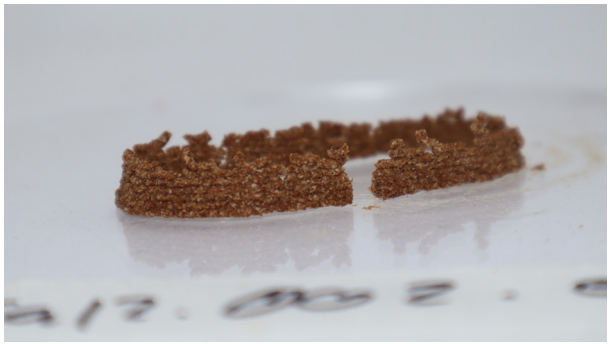
Lastly, it seems like the printer cannot print straight lines, in that the stepper motor will not spin when a straight line path is presented to it in the the gcode. This is important to fix however the paste extrusion issues in general need to be addressed first.

Figure 4.50 CALIBRATION2_001_SYNTHESIS

ANCHOR

CALIBRATION2.002 documents the transition of slicer software from Cura to Simplyfy3D. When comparing the Gcode between the two slicers, Simplyfy3D's output showed promising signs that it produce straight lines on the 3D printer, a problem found was encountered multiple times in Cura (see PRINT_005_001 & CALIBRATION2_001_014).

EXPERIMENTS









OUTCOME

For unknown reasons, models with straight lines loaded into Simplify3D were able to be printed on the printer. This series of prints documents the various settings tested and the changes in settings values from Cura to Simplify3D. Settings differences were:

Nozzle 2mm

Extrusion Multiplier 10 with auto width (this would be similar to flow rate from Cura)

Layer Height 1.5mm

Perimeter Shells 1

Corkscrew ON (vase mode)

First Layer Settings all at 100%

Extruder temp 0

Cooling 0

Z offset 6mm (firmware differences from Cura)

Speed 30mm/s

Figure 4.51 CALIBRATION2_002_SYNTHESIS

When results from the single-walled slots and cylinders were achieved, a proof-of-concept hollow cube was printed to evaluate the system's ability to navigate and extrude while moving through tight corners. While this print was unsuccessful structurally (see CALIBRATION3_001_004 on p. 410), the printer showed it could successfully manage right-angled corners and print straight lines. This marked a major transition in the experimentation process, in that corkscrew, also known as vase mode, was disabled, and infill was enabled. This meant that prints would more closely mimic the layer-by-layer construction typically followed when 3d printing with thermoplastics rather than the spiralised single-wall construction used in clay and cement-based printers.

CALIBRATION3_001_005 (p. 411) to CALIBRATION4_001_009 (p. 455) documents the development of settings to print consistent solids cubes, cylinders and pyramids with infill (Figure 4.52), as well as investigations exploring the shrinkage rate of the paste from wet to dry. Printing with infill required enabling and calibrating new settings such as infill percentage, width, speed, pattern, retraction, and layer heights, while balancing previously developed settings like flow rate (extrusion multiplier), print speed, paste consistency and pressure to supply paste to the extruder (as discussed above in *4.2.5*). This series of prints also highlighted the need for structural stability of the extruder assembly on the assembly, which prompted the change from the Anycubic Kossel Delta printer to the Creality Ender 3 V2 (PRINTER_001 to PRINTER_002).

ANCHOR

EXPERIMENTS

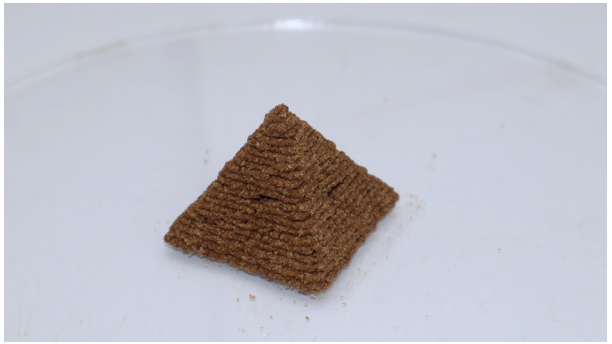
OUTCOME

Same settings as CALIBRATION3.002.004

Pyramid with 40mm base and 35mm height.









https://youtu.be/a9v-_3vZB0g

A complete print!

Figure 4.52 CALIBRATION3_002_005.

During the series of prints discussed above, at milestone moments of consistency, a 3DBenchy would be printed, marking a point of comparison throughout the development process. The 3DBenchy, developed by Creative Tools (2020b), is a well-known calibration test enthusiasts and professionals use to configure their thermoplastic MEX printers. It is designed to be built without support at 1:1 scale and printed in under 2 hours on most MEX printers. The 3DBenchy features smooth curved surfaces, overhangs, square and circular shapes, sloping surfaces, and horizontal holes, to name a few. 3DBenchys were printed at various stages as a bookmarking exercise to document the system's progression (as seen in Figure 4.53 and CP's CALIBRATION3_002_006, CALIBRATION3_002-002, CALIRBATION3_004_003, CALIBRATION4_001_004, CALIBRATION4_001_007 & PRODUCT_004).

The conclusion to series CALIBRATION4_001 was print _010 (Figure 4.54), which utilised a 3D scan of a Logitech G1 Mouse sourced from Thingiverse (thing:4398925 by Kim (2020)). This print, which resembled a traditionally thermoplastic 3D printed form study of a computer mouse, was the culmination and proof-of-concept of paste development (PASTE_004_009), 3D printer, extruder, paste delivery alterations and slicer setting configuration. While other considerations and areas of development needed to be refined (see Drying), the system could now print forms that were useful to product designers in the rapid development of explorative prototyping exercises.



Figure 4.53 3D Benchy development from CALIBRATION3.002.006 to PRODUCT_004_003

ANCHOR

Model used is of a scanned Logitech computer mouse from thingiverse: thing #4398925

Ender 3 v2 with Dual Z Axis Modification

Using extruder_003_002 (extruder v3.02) which uses a hose clamp to attach a 19mm ID spiral reinforced PVC tube

1.75 Nozzle

0.875 Layer Height

12.0 Extrusion Multiplier

3mm Lift on Retraction movements to avoid nozzle dragging in material on longer passes

3 Top Layers

2 Bottom Layers

1 Perimeter

40% Rectilinear Infill @ 100% width with 50% overlap

40mm/s ALL Speeds

EXPERIMENTS









OUTCOME

Initially it took hours of troubleshooting to get consistent layer adhesion and paste flow. There was also a scratching noise coming from the extruder body, and an occasionally high pitch squeak coming from Z axis lead screws which move the gantry up and down.

I think the squeak is due to the new weight from the extruder, paste, paste delivery system, and stepper motor. I will be removing the stepper motor for the plastic extruder and replacing it with different style of extruder called a 'direct drive', which situated the extruder and hot end in close proximity ,allowing me to remove all weight and plastic printing components quickly before replacing them with paste extrusion components.

For this print, which initially failed due to the hose clamp for the paste delivery coming loose, I increased the 'lift' of the nozzle on retraction movements, which should avoid future situations where the nozzle drags through material when moving between paths.

I am also looking to increase the print speed, and found through reddit posts that I can increase to up to 60-70mm/s from the current 40mm/s.

Figure 4.54 CALIBRATION4_001_010

CALIBRATION4_001_010

4.2.7 DRYING TESTS

Much like other 3D printing technologies, paste printing requires postprocessing to prepare parts for further use. Once prints have been completed, they need to be removed from their build plate, dried, and have support structures removed (if needed). Depending on the needs of the prototype, they can be sanded and finished with part lines and other features. Drying is a critical factor of this process and interplays with other factors of the production, such as the paste consistency and liquid content, as well as slicer settings like infill type and percentage. For the most part, the drying of components mimicked the temperatures and environments used to dry BSG before grinding and storage (as discussed in *4.2.2*), where prints were placed in a BENCHFOODS 23V-CUD dehydrator at 60 degrees Celsius. Drying with the more developed PASTE_004 series took 24-48 hours and was heavily dependent on infill percentage, part size, and airflow through the part (perimeter walls).

Ultimately, processes were integrated into the entire printing process to aid in printing. Water content within the pastes was reduced and, where possible, replaced with methylated spirits for faster drying (paste); bed heating was enabled to 45 degrees while printing to create dry and stable bottom layers of parts that were easier to remove from the print bed. Further, 2 40mm 5v fans were added to the extruder gantry to try drying infill while printing (p. 340 and Appendix D). Prints were also blown with a hot air gun before removal from build plates to give the external form a crisp and stronger layer. The hot air gun was set to medium heat with high airflow, moving slowly from front side to side to avoid burning or delaminating the outer layer. Prints were removed from the build plates by running fishing wire under the part and placed on mesh beds before being placed in the dehydrator.

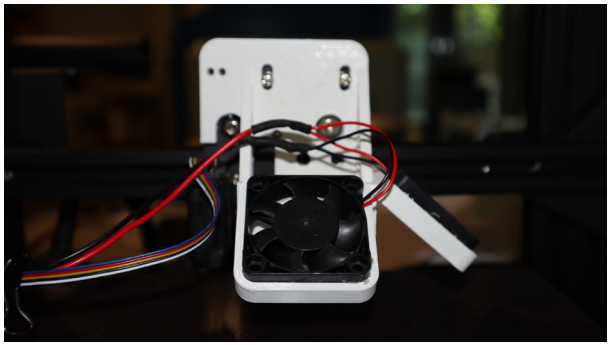
Other drying techniques were tested, particularly focusing on drying speed, but none matched the uniformity of dehydration. A domestic microwave (Anko P11034AL-B6) and toaster oven (Breville B0V845BSSUSC) were used in the experiment to examine the feasibility of drying prints faster than dehydration. Microwaving (prints and products) was used on low settings for up to half an hour. Prints would deform and have a poor surface finish (see PRODUCT_001_009 and _014 on pages 466 and 471). The Breville toaster oven was used in later testing; however, the increased temperatures from both the toaster and oven settings caused the other wall layers to delaminate from infill layers, ruining prints.

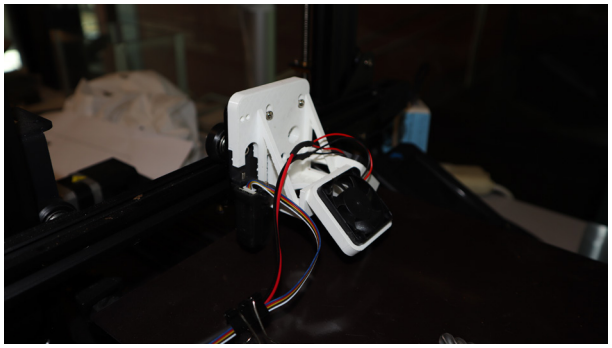
ANCHOR

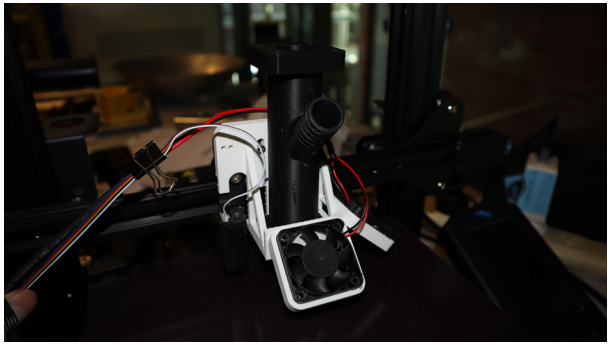
EXPERIMENTS

OUTCOME

This mount progresses from the first design for the Ender 3 V2, and adds two 40x10x10 fans which run on the same circuit as the cooling fan used on the auger stepper motor. The idea was to apply some level of drying to parts while printing, mainly aiming to begin drying the infill before being sealed by the top layers.









The mount and fans worked well. Whilst the fans do not dry the parts significantly, they do give the exterior a layer of 'crust' which makes parts slightly more stable to handle before being removed from the build plate. Further development would look at:

Using heat sources behind or in front of the fans for added drying effect

Adding a third fan or moving the side fan slightly as the mount reduces the build volume slightly by hitting the post

removing the mount entirely and creating an extruder body that slots and mounts to the existing e-plate.

Figure 4.55 EXTRUDER_003_ENDERMOUNT2, which was designed to hold two 40x10x10 12v fans to try dry parts while printing.

4.2.8 Material Management (Storage and Disposal)

As with other print technologies, feedstocks must be carefully stored before printing. Where printing with NMC differentiates is the need for careful storage and consideration of ingredients, paste ingredients, paste, storage of prints, reprocessing or disposal of prints. While the material designed for this research is intended to have a limited life insofar as it is used for form prototyping in product design practice, care must be taken when storing any natural ingredients and, by extension, printed parts.

The material developed for this research aimed to find a functional use case for a locally derived organic industrial waste product by developing an NMC for use within product design practice. Within this process is also the consideration of using environmentally friendly ingredients in the paste development process. Before sourcing material, careful consideration should be made regarding material storage and disposal and in the safe processing and mixing. Incorrectly stored organic materials can spoil and mould; processing these, such as heating and grinding them, can release small inhalable particles into the air.

As discussed, brewers' spent grain (BSG) was sourced locally and collected immediately after use in production, dried and stored in airtight containers.

- Carboxylmethyl cellulose was also stored in airtight containers. Once a 6% solution was made, it was refrigerated in airtight containers
- Glycerin was kept in its bottle in a pantry (cool, dry place)
- Methylated spirits were kept in a cool, dry place.

As discussed in *4.2.2*, prints were dehydrated at 40-60 degrees until dry. After printing, they were treated as one would with cookies, and kept in airtight containers with silica packs in cool, dry places. After being displayed and taken out of their box for extended periods, they would be dried in the dehydrator and placed back in their container. Failed prints or unused material from paste batches were dehydrated to avoid spoilage. The pastes are developed with food-safe materials, meaning they can be disposed of with food waste, and were proven to compost through domestic vermicomposting (Figure 4.56).

Finally, dried paste (from prints and leftover paste batches) can be reused in printing. This process was tested in the CP series [re]Animation (Figure 4.57), and the concept of adding water back into a dried paste was explored. Failed prints and dried material from paste batches were ground through a 40-mesh sieve and thoroughly blended with water. This paste was extrudable under low pressure

(0.1 BAR) and could be printed into previously printed forms, such as mouse mice (as discussed in *4.2.6*) and kurrajong seedpods (as seen in *4.3.5*). The dried results cracked substantially, indicating the need for more CMC and possible BSG; however, proof-of-concept shows that the material can be reused in printing.

ANCHOR

EXPERIMENTS

OUTCOME

Vermicomposting was tested in domestic worm farms. Two prints, PRODUCT_001_002 and 001_003 were placed in the domestic worm farms which remained in use for regular food scrap composting. Prints were placed in the worm farms on 18/10/23 and were consumed by 07/11/23 (20 days).



The confirmation that the material is compostable is a tremendous result. All ingredients are bioderived, and printed and dried models are still absorb moisture where are also positive. Along with the results of the REANIMATION tests, the material shows significant environmental benefits in terms of reuse and disposal (in comparison to thermoplastics and poly foams). Further development on both reanimation/reuse and composting options of NMC materials would be interesting areas of future research.

Figure 5.2 PASTE_004_COMPOST vermicomposting experimentation, prints were composted in 20 days

ANCHOR

ReAnimation

Reusing dried paste from previous prints, tests, paste batches.

Assuming that all dry matter has a mix of BSG, CMC & Glycerine.

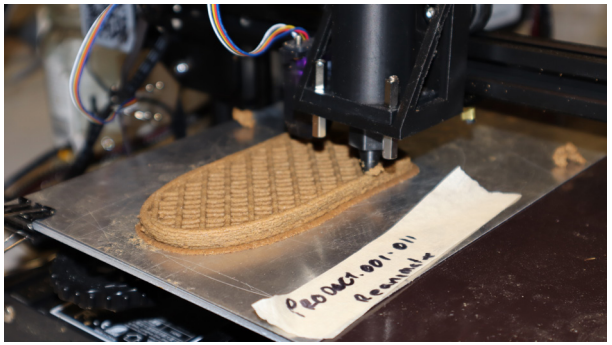
Dry Paste 200g through 40-mesh

Water 270g

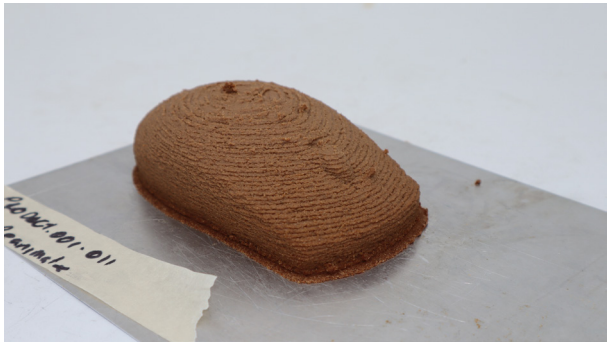
Methylated Spirits 15g after 24 hours

20-24N on force meter.

EXPERIMENTS









OUTCOME

Almost immediately after the water made contact with the ground material, it was back to a thick paste. Whilst the consistency was more liquid than pastes such as those developed in the PASTE_004 series, it was deemed printable through manual extrusion with a 5ml syringe. Whilst this remained true, the prints extruded at 0.1 BAR, indicating that they needed less water. WHilst the prints completed and were comparable to PASTE_004 series prints when wet, they cracked significantly when dried. This again my be tied to the high water content. Future experimentation would explore using less water in mixing, adding more BSG to the mixture, and leaving the mixture overnight to set as per PASTE_004_012.

Figure 4.57 PASTE_005_002 [re]Animation testing using recycling prints

4.3 Research Question 3

4.3.1 Introduction

To what extent can MEX printing of NMCs support the physical prototyping requirements of product designers?

The experimentation process conducted in research question 3 explores a potential use case for the BSG-NMC paste developed in research question 1 and the processes and systems developed for 3D printing with the BSG-NMC paste in research question 2. Specifically, research question 3 explores the extent to which MEX printing with NMC pastes can support product designers' explorative prototyping needs, particularly in form prototypes. As discussed in Chapter 1, explorative prototyping is a commonly used explorative technique in product design practice where a designer converts two-dimensional sketches into three-dimensional forms to examine further overall form, aesthetics, ergonomics, and user feedback (Camburn et al., 2017; Hallgrimsson, 2012; Milton & Rogers, 2017). Traditionally, explorative prototypes were made through subtractive practices with materials such as polyurethane and polyurethane foams. However, it is increasingly becoming common practice to generate form prototypes with additive manufacturing technologies, which significantly benefits in their approachability, accuracy, and speed, as they are based on 3D modelling. The most commonly used 3D printers use thermoplastic materials, which can considerably impact the environment (*see 2.3,* Additive Manufacturing), especially when the model is used briefly for reflection and user feedback purposes in an iterative design process. This research aims to find a space within these practices where prototyping can still be conducted rapidly with 3D printers but where the materials are designed more closely or purposefully in terms of how long they are used and how long they can either be recycled, decomposed, composted or re-used.

This section will first introduce the finalised Paste Recipe (*4.3.2*), 3D Printer Configuration and Paste Delivery (*4.3.3*), Slicer Settings for Explorative Prototyping (*4.3.4*), Prototyping Processes (*4.3.5*), and Explorative Prototyping Development (*4.3.6*) in this investigation. Then, the forms used as exemplars in explorative prototyping will be presented: computer mice, kurrajong seedpods and Xbox controllers, including discussions around their development and refinement for improved printing, drying and postprocessing performance.

4.3.2 Paste Recipe

As discussed in *4.1.4 Identification (Research Question 1)*, Brewers spent grain (BSG) was identified as a suitable locally sourced organic waste product from the industry that could be implemented as a functional filler in a cellulose-based NMC. BSG was sourced from 4 Pines Brewery and preprocessed for use in paste mixtures in line with processes found through a literature review (see PRESERVATION pp. 292-299). Through preliminary testing (*4.1.8,* Initial Material Experimentation*)*, a paste of dried and ground BSG, CMC, MFC and water was found to be manually extrudable through syringes and was deemed suitable for further development for 3D printing (Figure 4.58, also shown in page 301).

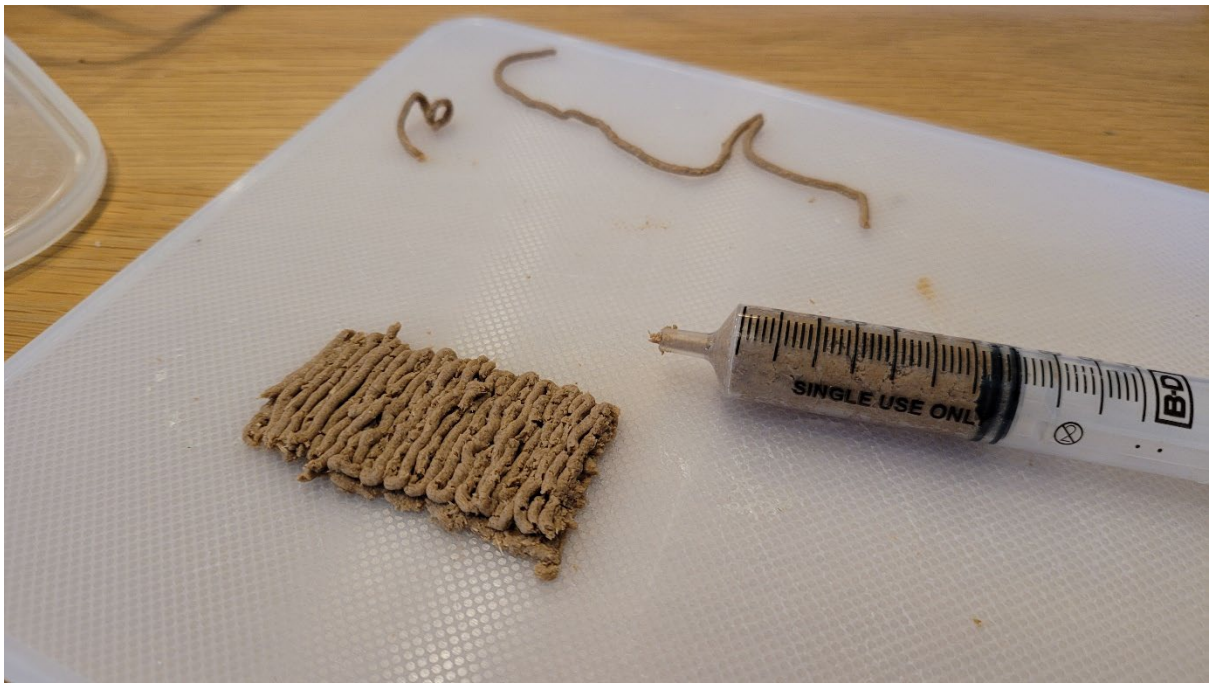


Figure 4.58 PASTE_001_001 manual extrusion test using a 5ml syringe.

Through 23 iterations, the BSG-NMC was developed alongside the 3D printing system and paste delivery systems. The BSG-NMC was developed for reliable delivery to the auger under air pressure, extrusion from the auger, bed and layer adhesion, and drying, being consistent between setting changes to the 3D printer. Moreover, the BSG-NMC was developed to be a reliable factor within the printing process and could be controlled through changes to other settings and systems with predictable results.

The initial recipe PASTE_001_001 was based on Jakovlev (2019):

BSG @ 32% (20grams)

CMC @ 1.3% (14 grams at 6% = 0.8g)

MFC @ 1.3% (14 grams at 6% = 0.8g)

Water @ 65% (41g)

This evolved into the final recipe PASTE_004_012 (Figure 4.59):

BSG @ 37% (200g)

CMC @ 2% (12g as content of 6% solution)

Glycerin @ 11% (60g)

Water @ 39% (210g as content of 6% solution)

Methyl @ 11% (60g)

Several factors affect paste extrusion, and recipe development focuses on creating a balance between them. Considerations in the recipe affected factors such as the ease of movement for the BSG-NMC paste through the delivery system (this needed to be below 4 BAR for safety purposes), extrudability under auger power through the 1.75mm nozzle, layer adhesion, and water content (for drying speed). Ultimately, each ingredient filled its functional role within the recipe for successful and repeatable printing (*see 5.1.3*). BSG acts as a functional filler material where it makes bonds to the CMC to create solid structures when dry (Civancik-Uslu et al., 2018; Faludi et al., 2019; Hejna, 2020; Revert et al., 2017); CMC is used as a binder material whose content affects the 'smoothness' of the material. Glycerin is used as a lubricant for smoother travel through the delivery system and as a barrier to microbial growth between uses of paste. Methylated spirits are added last to reduce water content, which enables faster drying.

ANCHOR

BSG 200g

CMC 6% 220

Glycerine 60g

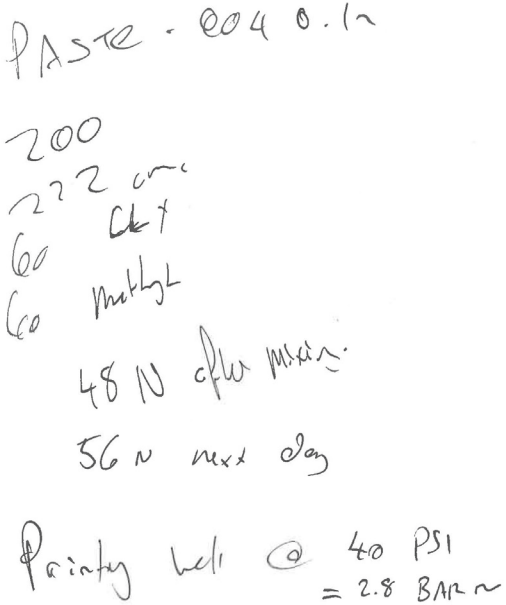
Methylated Spirits 60g

48N after mixing

56N next day

Prinitng at 2.8 BAR (40 PSI)

EXPERIMENTS



OUTCOME

The process of allowing paste to sit overnight after mixing, and this mixture provided the best results thus far, and will be used going forward for consistency in the final sets of experimentation. the material extrudes well at around 2.5-3 BAR, allowing for ample adjustments of the pressure to control line thickness while printing. Further experimentation would look at changing other factors (such as the auger, extruder design, stepper strength), and not the paste alone.

Figure 4.59 PASTE_004_012

4.3.3 3D Printer Configuration and Paste Delivery

As described in *4.2.3,* 3D Printer and Extruder Development and *4.3.4,* Paste Delivery System*,* extensive development was conducted to achieve the desired reliability, repeatability, and print quality across all systems. The systems developed in *4.2,* Process (research question 2) carried over into the investigation conducted here in research question 3 and described below.

The 3D printer used for this experimentation was the Creality Ender 3 V2, fitted with official Creality dual Z-axis and direct drive kits and the CR Touch bed levelling system (seeFigure 4.60). The dual Z-axis kit provides added structural support and strength to the gantry, which is under extra load due to the paste extruder placement and design. The direct drive kit is used for its larger e-plate, which mounts to the x-axis, providing more flexibility in mounting points for the extruder assembly mount. Further, the direct drive kit allows for fast changes (10 minutes) between the paste extrusion configuration and regular thermoplastic printing. The Ender 3 V2 is flashed with 'Professional Firmware' by Risco-Castillo (2023), which adds advanced features to the printer's control screen. These include visualisation of bed levelling, changes to min/max values of printer speeds and movements, and controls for extrusion, such as the direction of auger rotation (which is crucial between paste and filament-based printing).

ANCHOR

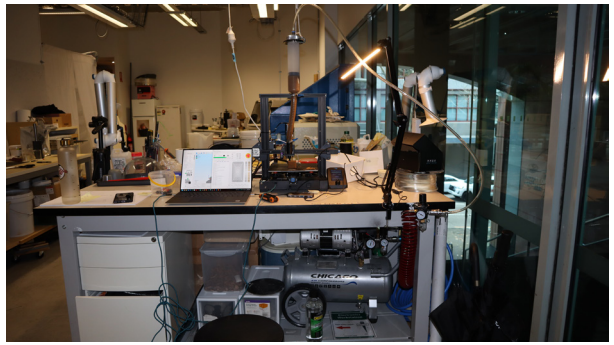
The Creality Ender 3 V2 is a cheap (around 300-350 AUD from Amazon in 2023) consumer 3D printer with a 220 x 220 x 250mm build platform. Part of the low price is that the printer requires some assembly (not wiring) which takes roughly 1-2 hours. The Ender series from Creality is immensely popular with hobbyist, with free printable modifications downloadable from Thingiverse or printables.com, and many purchasable directly from Creality such as direct drive kits, auto levelling tools (Cr-Touch), dual-z upgrade kits and more. The Ender 3 v2 was purchased from Amazon initially as a prototyping tool to produce extruders and nozzles for PRINTER_001, however, it became apparent that it would be better used as a dual purpose machine, printing thermoplastics parts for itself to use as a paste-extrusion printer. To improve the printing experience:

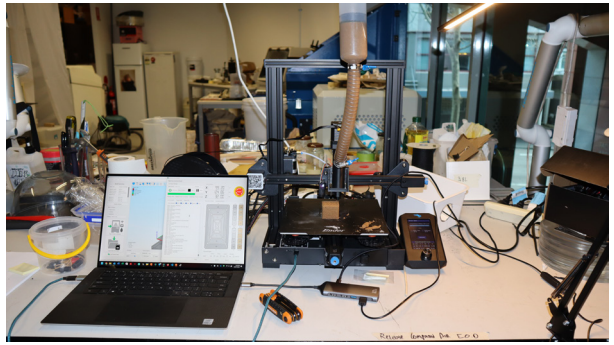
A CR-touch was purchased for bed-mesh and leveling,

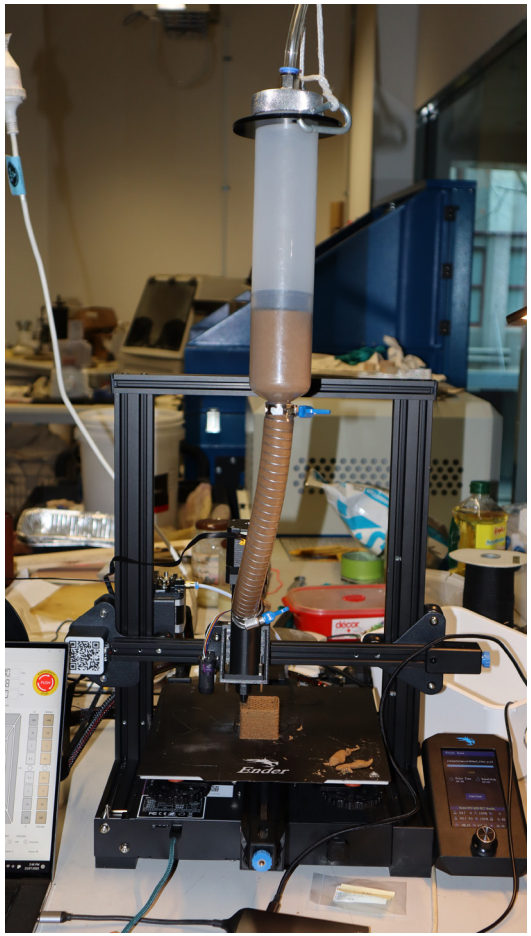
a Creality direct-drive kit, which comes with a larger e-plate (which holds the extruder assembly). This would be used to mount the paste-extruder and to remove the existing e-motor from the z-axis when not in use (and replace it with the direct drive motor)

A dual z-axis kit was purchased for added strength to the z-axis to support the direct-drive and paste-extrusion extruder assembly.

EXPERIMENTS







OUTCOME

The ender 3 v2, paired with EXTRUDER_003_002 and PASTEDELIVERY_002_002 worked extremely well for paste printing, and was used in research question 3 to produce great printed results. The printer was eventually flashed with Professional Firmware" from Miguel Risco-Castillo (username mriscoc) from https://github.com/mriscoc/Ender3V2S1/releases/tag/20230522. This added ease of use in aspect such as bed level visualisation, bed level visualisation and changing the stepper motor rotation between thermoplastic printing and paste-extrusion. Further refinement to the system would be developing a quick change system for extruder assemblies between paste and thermoplastic, a heated chamber design for increasing the range of thermoplastics printable and to explore alternate drying modes for NMC pastes, and a system to mount the spring balancer and filament spool directly above to the system rather than relying on external structures.

Figure 4.60 PRINTER_002_001

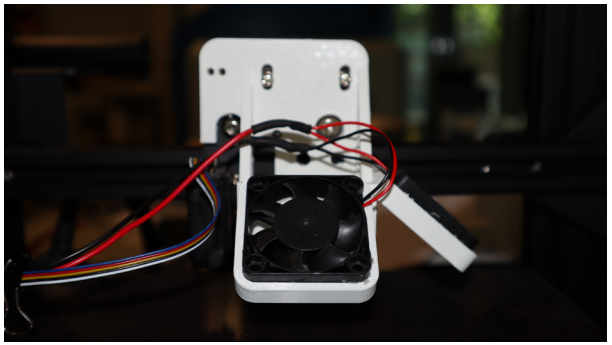
EXTRUDER_002_EXTRUDERMOUNT (Figure 4.61 and Appendix D) was designed to mount to the direct drive e-plate using pre-existing grooves and screw holes used for thermoplastic extruders and hot ends. The design has two 40x40x10 mm 12v DC fans facing towards the print bed, slowly drying and crusting the exterior of prints and enabling easier handling between the print bed and dehydrator. The final extruder developed and used in research question 3, EXTRUDER_003_002 (Figure 4.62, and Appendix D) was developed for use with the Creality Ender 3 V2, and PASTEDELIVERY_002_002, designed with a y-shaped inlet that doubles as a hose connector (with hose clamps) and a four-screw mounting system to both the e-plate mounting system and to the stepper motor. Mounted to the top of the extruder body and powering the auger is 560mN.m NEMA17 stepper motor (which has a 40x40x10 mm fan fitted for cooling). MakerStore (2023) uses the same 4-pin Dupont connector as the direct drive stepper motor. A 6.35 to 5 mm flexible beam coupling connects the stepper motor to a Suttons Tools 8 x 160mm 2 cut SDS plus masonry drill bit, which is used as the auger. The extruder system uses 3D printed nozzles (printed using the Creality Ender 3 V2), which feature a ¼ inch BSP thread (the standard for air tool parts) and an adjustable size 1.75mm tip (Appendix D).

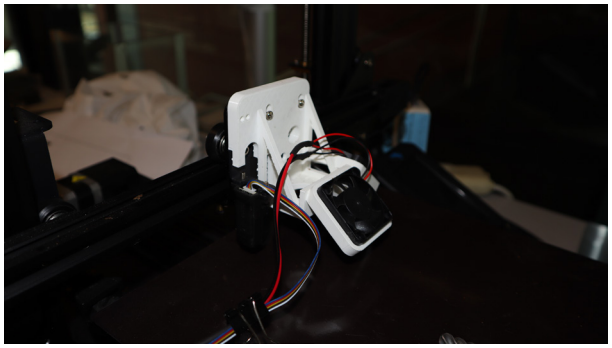
ANCHOR

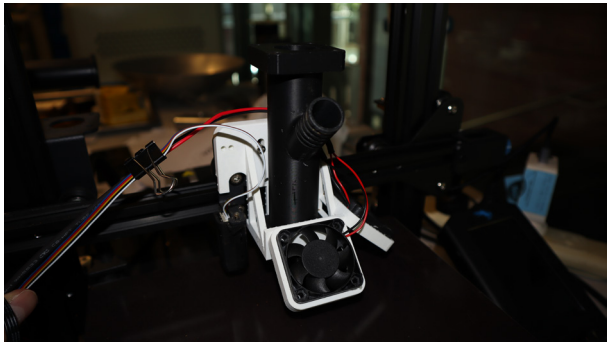
EXPERIMENTS

OUTCOME

This mount progresses from the first design for the Ender 3 V2, and adds two 40x10x10 fans which run on the same circuit as the cooling fan used on the auger stepper motor. The idea was to apply some level of drying to parts while printing, mainly aiming to begin drying the infill before being sealed by the top layers.









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Using heat sources behind or in front of the fans for added drying effect

Adding a third fan or moving the side fan slightly as the mount reduces the build volume slightly by hitting the post

removing the mount entirely and creating an extruder body that slots and mounts to the existing e-plate.

Figure 4.61 EXTRUDER_003_ENDERMOUNT2 with 40x10x10 12v fans

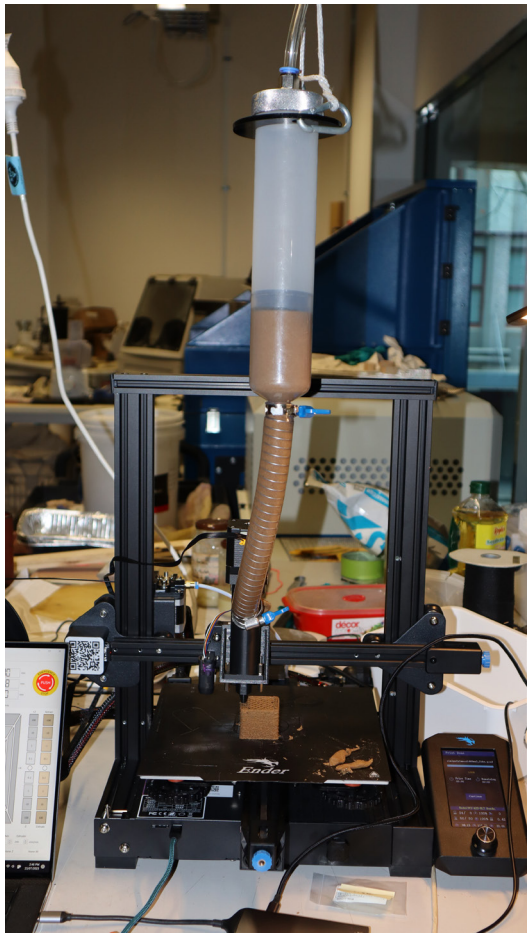
ANCHOR

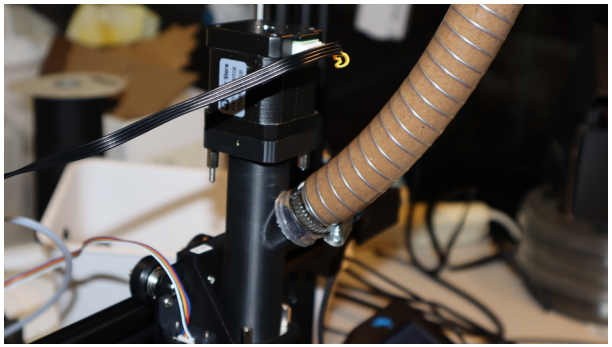
Extruder_003_002 was designed to be used with the Ender 3 V2 printer.

Modifications include a rotation of the base mounting plate by 90 degrees, which was initially designed for mounting to the stock gantry plate on the Anycubic Kossel printer.

The most significant change was the redesign of the paste entry point, which was extended and designed to accommodate hose clamps instead of the previously used internal BSP thread. This design allows for a 19mm internal diameter reinforced hose to be hose clamped over the paste entry point on the extruder, which results in lower pressure needs to delivery paste through the tubing to the printer. This modification is enabled by the added support and strength of the cartesian design of the Ender 3 V2 printer.

EXPERIMENTS







OUTCOME

The new mount and and front paste entry worked extremely well. The gantry and nozzle were unaffected by any movement or the weight of the paste delivery system. The hose clamps need to be closed very tightly, as the pressure pulled the hose lose running prints and emptying the cartridge onto the built plate. A collar was 3d printed which fit tightly around the auger shank and filled the area between the bottom of the coupling and the auger shaft, this stopped excessive paste moving up through the shaft into the coupling section of the assembly.

This extruder was used for the final prints in series PRODUCT_001-003.

Figure 4.62 EXTRUDER.003.002

A Chicago Hush 30L air compressor powers the paste delivery system, and air pressure is controlled through a secondary regulator mounted to the workbench (Figure 4.63). Clear PVC tubing runs from the second regulator to the paste cartridge (500ml clear PVC cartridge from CERAMBOT (2023) and Eazao (2022a)), connected via press fit on the screw on a back plate from Cerambot. Paste exits the cartridge through a 19mm ID hose barb connected to a 19mm ID clear PVC helical reinforced tubing and moves through to EXTRUDER_003_002.

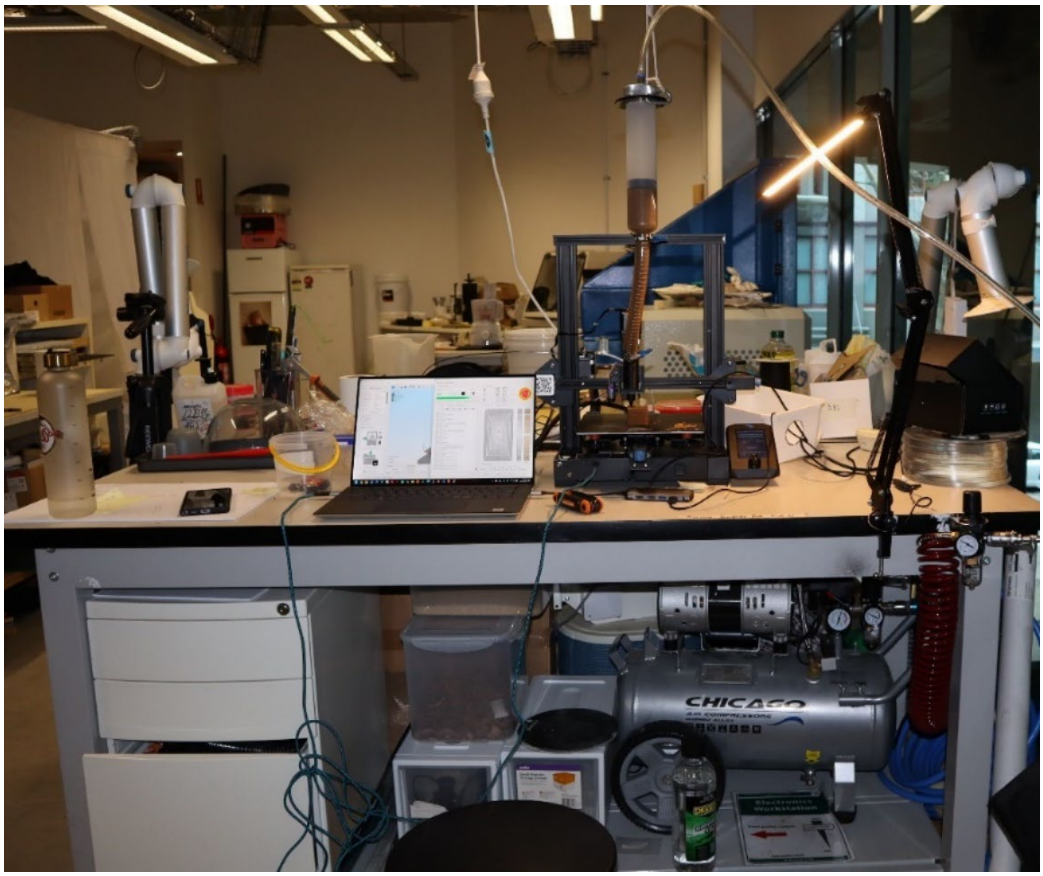


Figure 4.63 The assembled system shows the Chicago Hush 30 air compressor pushing paste to the Creality Ender 3 V2.

As discussed in *4.2.5,* Slicer Settings, 3D models were prepared and exported to gcode using Simplyfy3D ver 5.0 and were printed via a USB connection from a laptop or saved to a micro SD card and printed directly from the printer. Printing from a laptop was best for calibrating settings and pausing the printer between layers to clean nozzles, load more paste, and add reinforcement to parts (such as PRODUCT_003_004 seen on page 224). Printing directly from the printer allowed for live settings changes (such as first layer height calibration and heated bed temperature), faster loading of preconfigured print files, and faster stopping of prints. The best practice was to set up and calibrate the printer using the onboard print controller and screen, adjust the Z-offset and pressure, and then move to print using slicing software on a computer on a separate workbench.

Prints were printed onto 0.5 mm sheet metal held on the printer bed by bulldog clips (Figure 4.64). This thickness closely matches the thickness of the magnetic bed used for thermoplastic printing, allowing for mesh building and bed levelling to translate between print configurations and further allowing heat to pass from the bed heating elements to the print effectively. Once prints were complete, the sheet metal plate was removed from the bed and placed on the workbench. A hot air gun was then used on high speed and medium heat to crust the outer surface of the prints. This gives prints a stronger exterior, which is less likely to deform in handling before being placed in the dehydrator (Figure 4.65). Inspired by potters using wire tools to remove vessels from a throwing wheel, fishing wire is pulled slowly under prints to separate them from the build plate. Prints are placed on steel mesh and in a dehydrator at 60 degrees C until dry. After drying, application or specific project-specific postprocessing can be performed by clipping support material, sanding, plugging and puttying holes, drilling holes, and coating (Figure 4.66). Prints should be stored in air-tight and dry boxes until use, and recycled silica gel packets can be used as further protection against moisture. If displayed in open air, dried prints can first be coated using a 6% CMC gel (the same as used in the BSG-NMC recipe), which can act as a moisture barrier protecting the prints from becoming soft and weak (Ma et al., 2017; Tavares et al., 2020). Nonetheless, displayed prints that are kept for display should be dehydrated often to remove moisture buildup.

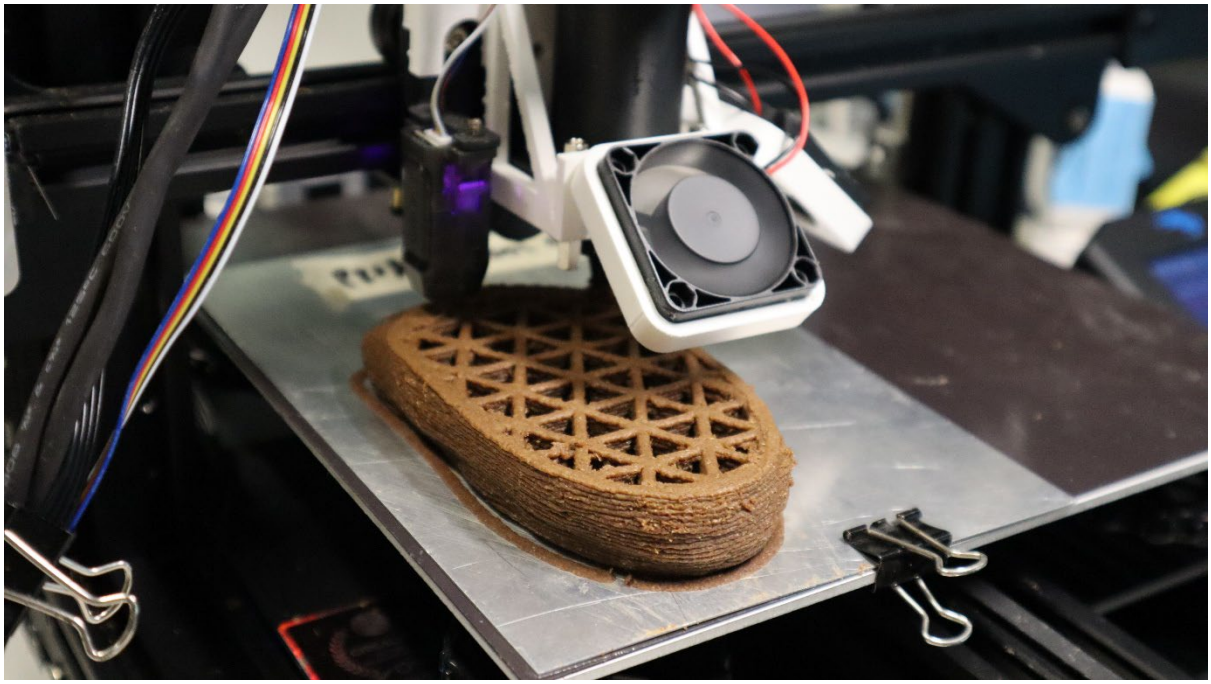


Figure 4.64 PRODUCT_001_020 mid print. The 0.5mm sheet metal bed is held to the printers headed bed by small bulldog clips.



Figure 4.65 PRODUCT_001_020 being crusted with a heat fun. This allows for better handling of parts when being transferred into the dehydrator.

ANCHOR

EXPERIMENTS

OUTCOME

Final post processing followed the following steps: dried and assembled seedpods (from 002_009), were sanded again using the Dremel with 120 and 240 grit sanding bands. Careful attention was paid to the tail and joining point making sure to keep these areas smooth. Then, the interior cavity of the seedpod was cleaned and sanded using the Dremel with cone shaped tungsten carbide burs. Last, body was coated with a 6% CMC solution, the inside using a thin brush to reach all tight corners, and the outside by hand. Seedpods were then placed in the dehydrator to dry the CMC layer.









This process has created a strong proof of concept for future post processing to make assemblies and increase prototype fidelity with NMC pastes. The material has responded well to intensive post processes with power tools (drills, rotatory tools), and it would be interesting to explore making more consumer product prototype assemblies with this workflow.

Figure 4.66 Assembly and postprocessing of kurrajong seedpod models, as documented in PRODUCT_002_008.

4.3.4 Slicer settings for explorative prototyping

As discussed in *4.2.5,* Slicer Settings, reliable slicer settings were established through the investigation conducted in research question 2. It is important to note that these settings were configured for use with the systems developed for this research and may need reconfiguration for other pastes and system designs. The slicer settings below were used for experimentation in research question 3, and key settings that affected parts outcomes in regard to usability for form prototyping practice will be highlighted.

The final system implemented in research question 3 used PRINTER_002, PASTEDELIVERY_002_002, EXTRUDER_003_002, PASTE_004_012. The nozzle diameter is 1.75mm, and it was 3D printed in PLA using the Creality Ender 3 V2. Paste was delivered at 2 BAR. The stepper motor direction (e-motor) was inverted through professional firmware, and its maximum rotational speed was set at 150mm/s (through professional firmware).

- Extrusion multiplier @ 10.0 (effects extrusion speed and line width)
- Nozzle size @1.75 mm
- Layer height @ 0.875mm
- Retraction @ 4mm at 40mm/s with 2.5mm lift between movement
- Top layers @ 2
- Bottom layers @ 2
- Outside perimeter @ 1
- Infill @ 40% triangular with 100% width and 50% overlap with outside layers
- Layer speeds @ 100%
- Heated bed sequence @ layers 1-10 @ 35c, layers 11-25 @ 45c, layers after 25 @ 35c)
- Default speed @ 55mm/s (outer perimeters at 70% and all others at 80%)
- Support enabled (manually added) @ 60% infill triangular, with 3mm inflation.

As with traditional MEX printing using thermoplastics, slicer settings can affect the speed of printing and the quality of a part. The settings configured from this series of experiments focused on form prototyping through rapid printing processes, which were then able to be post-processed and handled. Through the development process of the printing system for the production of parts suitable for form prototyping in product design, various settings, which had the greatest effect on part visual quality, drying, and postprocessing abilities were focussed on:

1 Deposit quality, consistency and thickness are determined by the flow rate (extrusion multiplier), paste and pressure required for paste delivery. These settings can be altered live during printing; however, once the variables are calibrated, settings can remain the same. During paste development, these settings were calibrated by running a 'priming and first layer print' (Figure 4.67), which was used to prime the auger and extruder while simultaneously allowing for adjustments to the pressure and z-offset to alter line quality.

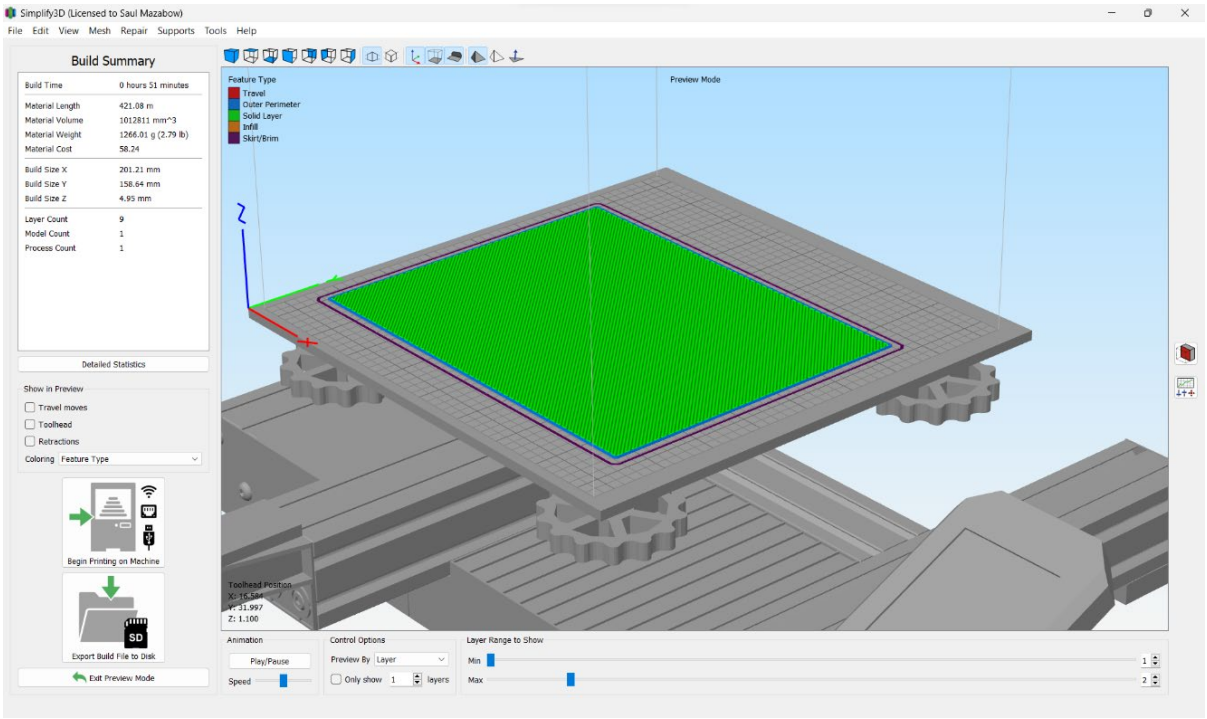


Figure 4.67 The priming print is used to prime the auger and nozzle and to calibrate the first layer height and line thickness. Shown in Simplyfy3D.

2 The number of top, bottom, and perimeter layers affects the surface quality of parts, how they dry, and the degree of postprocessing. Overall, it was found that more layers meant parts took longer to print and to dry but were more robust and had more material for detailed subtractive postprocessing, such as sanding, due to thicker finalised walls. Most prints would have one bottom and perimeters and two top layers. It was found that increasing layer numbers could remedy defects in printing; this was particularly evident in top layers, which need to bridge larger gaps in infill to create closed layers, occasionally leaving small holes in prints (Figure 4.68). While these can be patched before or after drying with wet paste, adding another top layer would seal these holes on the second pass. It was found that perimeter holes were less likely due to the 'overlap' settings enabled in infill and the smoother path that the printer travels when creating the outline of a print.



Figure 4.68 Gaps in the top layer of PRODUCT_003_004. The triangular infill at 40% used was difficult for the printer to bridge at the wider sections of the triangles. These could be avoided by having a third top layer, more dense infill, or in post-processing.

3 Infill influences a printed part's time to finish and physical strength and strongly impacts drying behaviours regarding drying time, shrinkage and vertical slumping. Various infill patterns at different percentages were tested for their effects on strength and drying (Figure 4.69). Triangular infill (at 40-50%), which overlaps the perimeter walls (50%), was found to be the best setting for printing speed, wet strength, and drying behaviours. The triangular infill was particularly effective in managing the slumping behaviours of prints, which was crucial for achieving dimensional accuracy (see PRODUCT_001_023 and PRODUCT_001_027 pages 480 and 484).

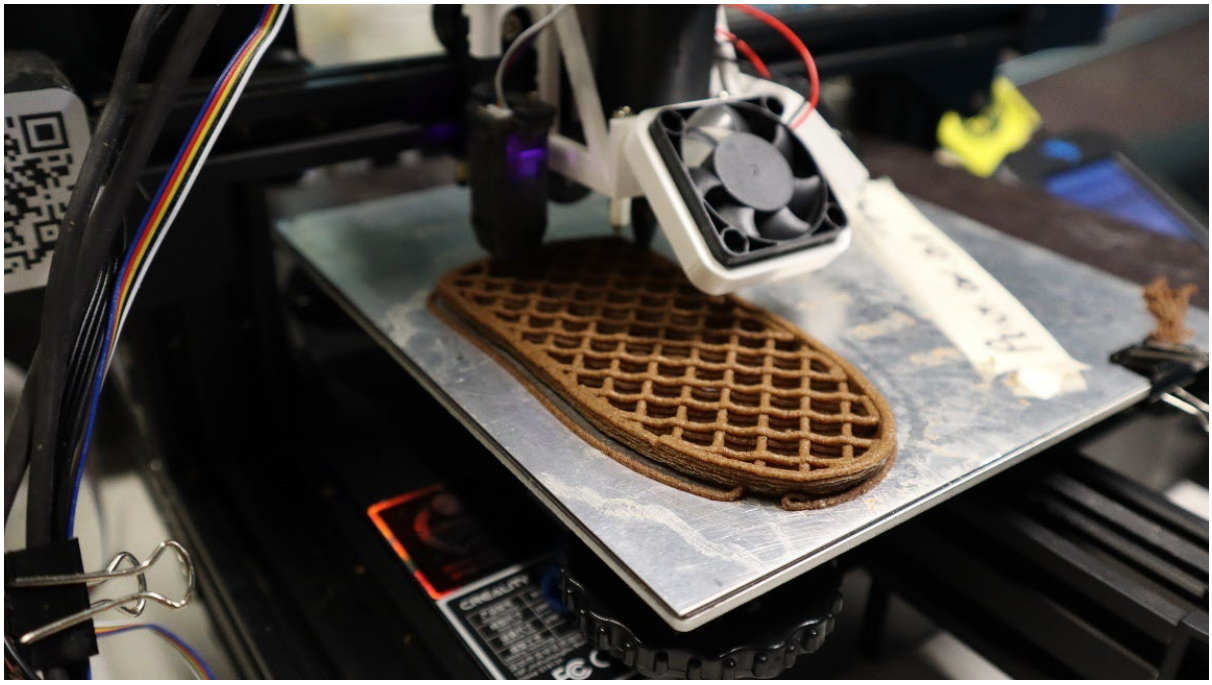


Figure 4.69 25% Rectilinear infill from PRODUCT_001_018.

4 Support material settings were also developed. The support material was found to be effective for parts with overhanging edges exceeding 45 degrees (Figure 4.70); however, calibration was needed. The support material was added automatically and manually using the Simplyfy3D interface. As wet material provides minimal structural support, densely packed triangular support material would be used, which provides more structural stability for edges with angles over 45 degrees. Inflation, which expands the boundary of support structures, was used to increase the overall coverage of individual columns of support for further support and strength (Figure 4.71). Rather than building single beams, multiple connected support sets were generated to provide a larger coverage area. Support was removed after drying, and imperfections left on the part body were either sanded or puttied if needed (Figure 4.72).



Figure 4.70 Close-up of wet support material on PRODUCT_003_004.

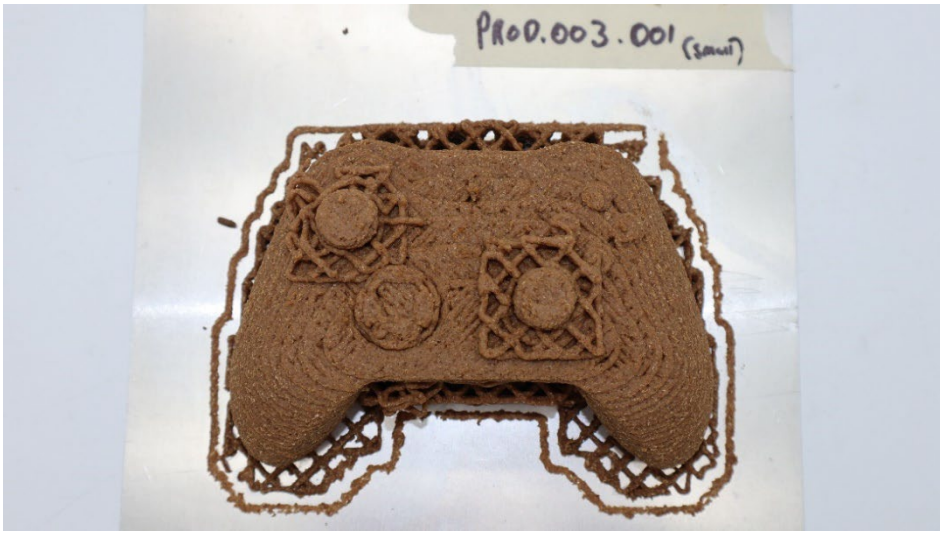


Figure 4.71 Wet print of PRODUCT_003_001. This print had 10mm inflation distance on support material, which can be seen in the wide-reaching support on the top layer.

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EXPERIMENTS

OUTCOME

100% scaled controlled based on overall measurements found online.

Width 152.90mm

Depth 103.17mm

Height 61.00mm

Support overhang angle @ 20.00 degrees with 4mm pillar size

Support inflation reduced to 5.00mm









During this print I wanted to try pause and replace the empty cartridge with a full one. However, after pressing 'pause' using the printers display and loading in a new cartridge, the printer got stuck in an endless loop of reheating, which is something coded into the onboard pause function. This meant that the print could not resume and i could not print the detailed top layers of the controller. This did give insights into other options of loading material, such as testing using the simplyfy3d control panel for controlling pause and resume functions. Further ,the part was puttied extensively using wet BSGNMC paste and was give a crusted outer layer using a head gun for quickly handling of the model once puttied.

Figure 4.72 PRODUCT_003_002 had extensive puttying performed to seal the completely open top layers.

4.3.5 Explorative Prototyping Development

Research question 3 investigated the viability of the developed system and NMC paste as a tool for batch form prototyping commonly conducted in product design practice. Three forms were selected, each exploring separate aspects of producing form prototypes and the capabilities of the printing system and paste.

Computer mice (PRODUCT_001) were selected as an organic-shaped product, typically 3D printed in explorative prototyping practices. Several mice could be printed simultaneously and evaluated in regard to their representation of digital files and used for explorations into postprocessing methods.

Kurrajong seedpods (PRODUCT_002) were produced to explore the process of rapidly developing multiple, organic and difficult-to-print bodies, including extensive postprocessing. Seedpods were modified individually in both digital preparation and postprocessing. The final series of seedpods were prepared for display in First Nations artist Lucy Simpson's *Holding Ground* exhibition at the Museum of Contemporary Art (MCA).

Xbox Controllers (PRODUCT_003) were printed to explore the system's capabilities to produce more complex and technically challenging components. In particular, the series explored printing extensive support structures both under and on the prototype body to support overhanging structures, which required additional postprocessing in removal.

PRODUCT_001 Computer Mouse

Through print series PRODUCT_001 (pp. 457-484), two computer mice were printed, which investigated a potential use case of the printing system as a means for explorative prototyping. Initially, a scan of the Logitech G1 gaming mouse (Figure 4.73) (Kim, 2020) was used to develop further the printer settings for more organic and detailed models and explore the workflow needed for batch prototyping of explorative prototypes typically seen in product design practices. Further, this series explored initial postprocessing techniques, such as sanding, puttying, drying, and drilling. The second mouse, a Logitech Master MX 3 (Figure 4.7) (Duncan, 2023), examined the printer's capabilities to print more complex forms with overhangs and smaller details while also exploring print accuracy and shrinkage compensation (PRODUCT_001_024 to PRODUCT_001_027).



Figure 4.73 Logitech G1 optical gaming mouse (CDRinfo, 2006).



Figure 4.74 Logitech MX Master 3 (Norman, 2023).

Throughout the explorative prototyping experimentation in prints, PRODUCT_001_[001-023], drying was a focal point of each experiment. While the accuracy of wet prints was closely representative of 3D files (Figure 4.75), slumping in drying and drying speed remained challenges (Figure 4.76). Drying speed was experimented with through the use of domestic appliances, such as toaster ovens (PRODUCT_001_015), microwaves (PRODUCT_001_009), hot air guns (PRODUCT_001_014), DIY dry boxes, and dehydrators with varying temperatures. As shown in PRODUCT_001_014, PRODUCT_001_015, and PRODUCT_001_016 (pp. 471-473), more intensive drying, such as the toaster oven, microwave and hot air gun, resulted in poor drying uniformity in both surface quality and overall form (including delamination and collapsing walls). Furthermore, it was found that, through printing batches of prototypes, drying time is mitigated by the speed of prints, as shown in Figure 4.77, where beds of 4 mice from studies are printed together. In the time it takes to print one PLA mouse on the Creality Ender 3 V2 at 10% infill (4 hours 45 minutes), seven can be printed in BSG-NMC paste. Therefore, in an explorative prototyping workflow based on the capabilities of the BSG-NMC paste print system, significantly more form prototypes around the same design could be designed and dried (three times) in the same period of time.



Figure 4.75 PRODUCT_001_013 'ENLARGED' explored scaling the dimensions of the print to try mitigate shrinkage below the intended size.



Figure 4.76 PRODUCT_001_013 dried, showing significant shrinking.

	BSG-NMC Print	PLA
1 mouse	40 minutes	4 hours
full build plate (4)	160 minutes	22 hours
1 business day (8hrs)	12 mice	4 mice

Monday	12	4
Tuesday	12	4
Wednesday	12	4
Thursday	12	4
Friday	12	4
Weekend	Drying Time	
Total weeks ouput	60	20

Figure 4.77 Calculations comparing printing large batches of explorative prototypes between the paste extrusion system developed in this research and thermoplastic printing with consumer 3D printers.

In research question 2, slumping was found to be a significant factor affecting the post-drying accuracy of components (as discussed in *4.2.7*). Drying environments, paste recipes, and slicer settings changes were experimented with to address slumping. Slumping behaviour was found to create around a 30% reduction in part height (Figure 4.78). Initially, aspects related to drying were investigated to attempt to mitigate slumping. These included reducing water content in the paste recipe and faster drying attempts (as discussed above), but they proved ineffective. Further, prints were filled with dried BSG after printing in an attempt to provide structural rigidity and mitigate the space prints had to slump (Figure 4.79). Success was found in alterations of print settings around the infill pattern and the density and scale of components. Infill pattern and density were found to have a strong effect on slumping behaviours, and triangular infill was found to be more supportive and stronger in drying than others. Further, increased infill resulted in decreased slumping and increased print time and material usage. It was also found that scaling components based on previous shrinkage results using the slicer interface effectively mitigated slumping (Figure 4.80). Further, it was found that increasing (stretching) the height (z-axis) of components to combat slumping resulted in less shrinkage in the other axis. While further investigation is needed to accurately scale components in the slicer software for shrinkage, rather than more accurately altering these in CAD software, this method proved suitable for the application of batch prototyping of forms, where slight deviation in the physical body may be more accessible than in the production of end-use components.

ANCHOR

Using the same settings as previous prints, the overall dimension of the 3D model were increased in Simplyfy3D, to match the shrinkage rates recorded in previous prints.

1:1 scale Logitech G1 Scan

L 116.94mm

W 61.70mm

H 37.31

Dried prints

L 103.50mm (11.5% shrink)

W 57.23mm (7.2% shrink)

H 25.93mm (30.5% shrink)

This print used the shrinkage rates to increase dimensions to:

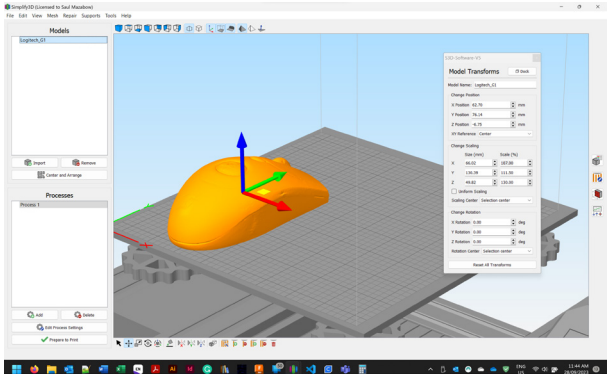
L 130.4mm

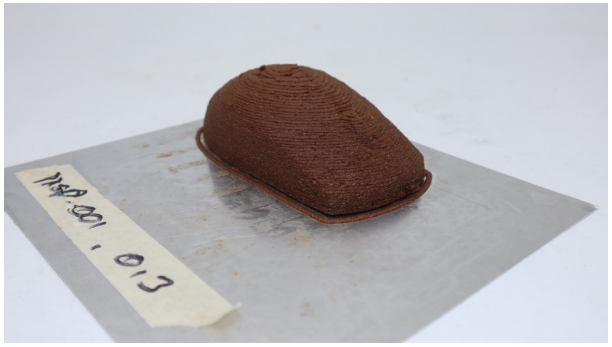
W 66.16mm

H 48.709mm.

Prints were dried at 40 degrees C in the dehydrator until dry.

EXPERIMENTS









OUTCOME

Dried dimensions:

L 117.78mm (-1% off 1:1)

W 58.05mm (6% off 1:1)

H 28.24mm (24% off 1:1)

These shrinkage rates show that vertical slumping is the key factor to solve in shrinkage, as it effects the others. This will need further investigation into factors such as material water content and drying environment which effect the drying time, as well all wall thickness, infill type and percentage. Perhaps slumping can be mitigated by better structural stability from the infill during the drying/shrinking processes.

Figure 4.78 PRODUT_001_013 explored mitigating slumping in drying. The prints height shrunk over 30% in drying.

PRODUCT_001_013_ENLARGED

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EXPERIMENTS

OUTCOME

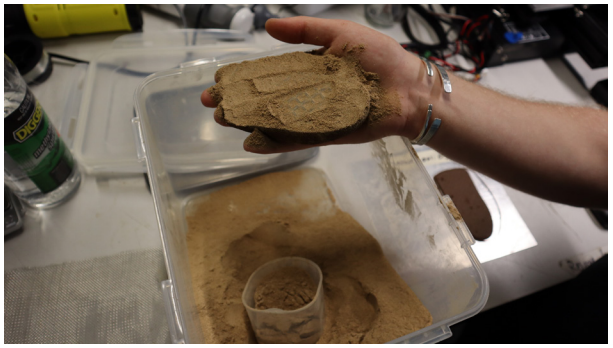
Drying and Slump Testing

Exploring the concept of filling parts with dry matter to prevent slumping.

Using the same settings as PRODUCT_001_013, two bodies were printed; a three layer tall base, and a body missing the bottom 3 layers.

Once removed from the build plate, the main body was filled with dried BSG. Prints were the placed in the dehydrator. Once dried, they were joined using 6% CMC as a glue and seal to prevent BSG from falling out.









The dried print warped and slumped significantly, with the front of the model lifting significantly. This could be a result of high dehydrator temperature (60 degrees C), and the missing structural rigidity of a full external ‘skin’ provided by the outer layers of the models. Further, the parts shrunk at different rates, were the separately printed bottom was smaller than the bottom surface area of the model.

The model has more weight to it and feels dense, which adds a nice presence to it while handling.

It was only realised afterwards that the print was using a the 1:1 scale model and not the enlarged print, showing that slumping was improved through the use of packed infill. Shrinkage was around 23%.

Figure 4.79 PRODUCT_001_020, printed with no base, was then filled with dried BSG before being placed in a dehydrator. This was also experimented with in PRODUCT_001_022 and could be effective in reducing slumpage with further development.

PRODUCT_001_020 _DRY INFILL

ANCHOR

EXPERIMENTS

OUTCOME

Printing the Logitech Master MX 3 based on shrinkage rates from PRODUCT_001_026.

Infill Triangular 40%

3D Model Dimension:

L 124.61mm

W 84.33mm

H 50.31mm

Enlarged imensions

L 133.00mm

W 96.44mm

H 70.00mm

Print Time 1 Hour 51 Minutes (111 minutes)









Dried Dimensions:

L 87.07m (9.3% shrink and -3.25% of goal)

W 120.37 (9.5% shrink and 3.4% of goal)

H 46.52 (33.54% shrink and 7.5% from goal)

Whilst still not achieving 100% dimensional accuracy, the print was a success. Confirmed through 3D scanning the dried print and compared to the digital files, the shrinking can be assessed, planned and further developed for future experimentation. Overall, the model is roughly within 10% range of the desired size, showing significant progression in controlling of shrinkage behaviour.

Figure 4.80 PRODUCT_001_027 explored reducing slumping via increasing internal support and scaling the print. Final results were within 10% of the desired size.

Postprocessing methods were also explored during the development of the PRODUCT_001 series. This was inspired by the postprocessing that can typically be seen utilised by designers in improving the quality of explorative form prototypes generated with subtractive and additive manufacturing technologies. Initially, prints were sanded using 80- and 120-grit sanding paper. As seen in Figure 4.81, prints responded well, similar to soft timbers, and were used for further postprocessing investigation. Further testing was conducted, indicative of postprocessing in product design practice, where prints had holes drilled and cut on a bandsaw (Figure 4.82) and were sanded and carved with a Dremel rotary tool. Further, CMC was used as a light coating to protect parts against moisture absorption, altering the prints' surface quality and finish (Figure 4.83). Lastly, wet paste was used as filler material for gaps and holes and glue to combine or repair broken prototypes.



Figure 4.81 PRODUCT_001_005 documented post-processing experimentation. Dried prints were sanded by hand using 120, 150 and 240 grit sanding paper.

Holes in prints were drilled with electric drills. Prints were then cut in half with a band saw.









Prints responded well to heavier post processing such as drilling and cutting. This may come into use for building multi part assemblies or parts that require additional post processing.

Figure 4.82 PRODUCT_001_010 dried prints have holes drilled in them and are cut using a bandsaw.

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EXPERIMENTS

OUTCOME

Using the same settings as PRODUCT_001_007

When dried, the print was coated with 6% CMC, smeared on by hand.









This print was done to mimic the processes undertaken in PRODUCT_001_008 whilst removing many of the additives in Nahum's starch and cellulose mixture. once dried, there was no obvious physical difference between dried prints with or without CMC coating, however, visually the model looked improved due to the glossy finish. I imagine this will look good on well sanded and hand finished models.

Figure 4.83 PRODUCT_001_012 once dried, the print has 6% CMC solution coated onto it before being dehydrated again. This gives prints an added moisture barrier.

PRODUCT_001_012_CMC

The experimentation in PRODUCT_001 transitioned from the Logitech G1 to the Logitech Master MX 3 upon determining that the printing system and paste were capable of producing larger, more complicated forms with increased levels of intricacy. PRODUCT_001_[024-027] documents printing the Logitech MASTER MX 3, exploring the printer's capabilities to print overhangs, fine details such as the thumb scroll wheel, the texture of the sloping design, and shrinkage. PRODUCT_001_024 (Figure 4.84) was printed at a 1:1 scale and focused on the printer's ability to produce the organic form of the mouse. PRODUCT_001_027 (Figure 4.85) focussed on producing an upscaled version of the mouse, exploring the accuracy of printed forms post-drying, with a particular focus on z-height slumping behaviour affecting the overall accuracy of the form and affecting shrinkage of the x and y-axis.



Figure 4.84 PRODCUT_001_024, a 1:1 print using a scan of a Logitech Master MX 3 mouse next to a Logitech Master MX 3. The print is wet and has not been dehydrated.



Figure 4.85 A still image comparing dried PRODUCT_001_027 with the Logitech Master MX 3 Mouse. Through setting changes and scaling, this print dried within 10% of the true dimensions.

PRODUCT_002 Kurrajong Seedpod Series

PRODUCT_002 documented the development of a series of Kurrajong Seedpod 3D prints, based on a 3D scan provided by First Nations artist Lucy Simpson. The series of twenty-one seedpods were displayed at the Museum of Contemporary Art (MCA) and used in an interactive display in the Belle Room (Figure 4.86). The series applied the knowledge and workflow developed in the PRODUCT_001 series in the rapid construction of multiple bodies in the form of printing, drying, and extensively postprocessing 3D printed seedpods for exhibition. Twenty-one seedpods were produced (Figure 4.87), each with purposefully crafted differences in their size (slicer controlled) and postprocessing methods to align with natural processes. The significance of this series to the development of the printing system and paste was in the organic shape of the seedpod form and the extensive postprocessing techniques applied to the prints. The seedpod body contains overhangs, organic details (creases) and thin regions, which required careful planning for calibration of the paste and system and further reinforced the system's ability to print complex objects (Figure 4.88).



Figure 4.86 Seedpods printed in PRODUCT_002 series on display in Lucy Simpson's Jackson Belle Room commission at the Museum of Contemporary Art.



Figure 4.87 Seedpods were photographed in a light booth before collection.473



Figure 4.88 Close-up of the front of a seedpod

The series of PRODUCT_002 (pp. 485-494) provided significant insights into the abilities of the material to align with the postprocessing activities typically undertaken by product designers, such as constructing multi-component assemblies, refining surface-finished and imperfect printed components for presentation, and using form prototypes as skeletons for appearance models. As seen in PRODUCT_002_002 (Figure 4.89), it was found that while achievable, printing a complete seed pod required extensive support structures, which increased print time and more delicate postprocessing to remove. This was solved by printing the seedpod in two parts: the front (the larger section) and the back (tail) (Figure 4.90). This allowed for the development of a joining system that reinforced the tails and connection point with a 3mm bamboo skewer. As shown in PRODUCT_002_006 (Figure 4.91), tails were printed as a batch. Prints would be paused after three layers, where a skewer would be hand-pressed into the tail body. Prints would then resume and seal the skewer in the print body. Once both front and back were dried, a 3mm hole was drilled into the bottom of the front part, where the skewer would be inserted (Figure 4.92). This connection would then be sealed with more BSG-NMC paste and dried again to create a strong seal (Figure 4.93).



Figure 4.89 PRODUCT_002_002 explored the use of infill and support material to 3D print a complete seedpod. It was found that through drying and attempts to remove the support material, the tail would be too fragile to create the series through all-in-one prints.

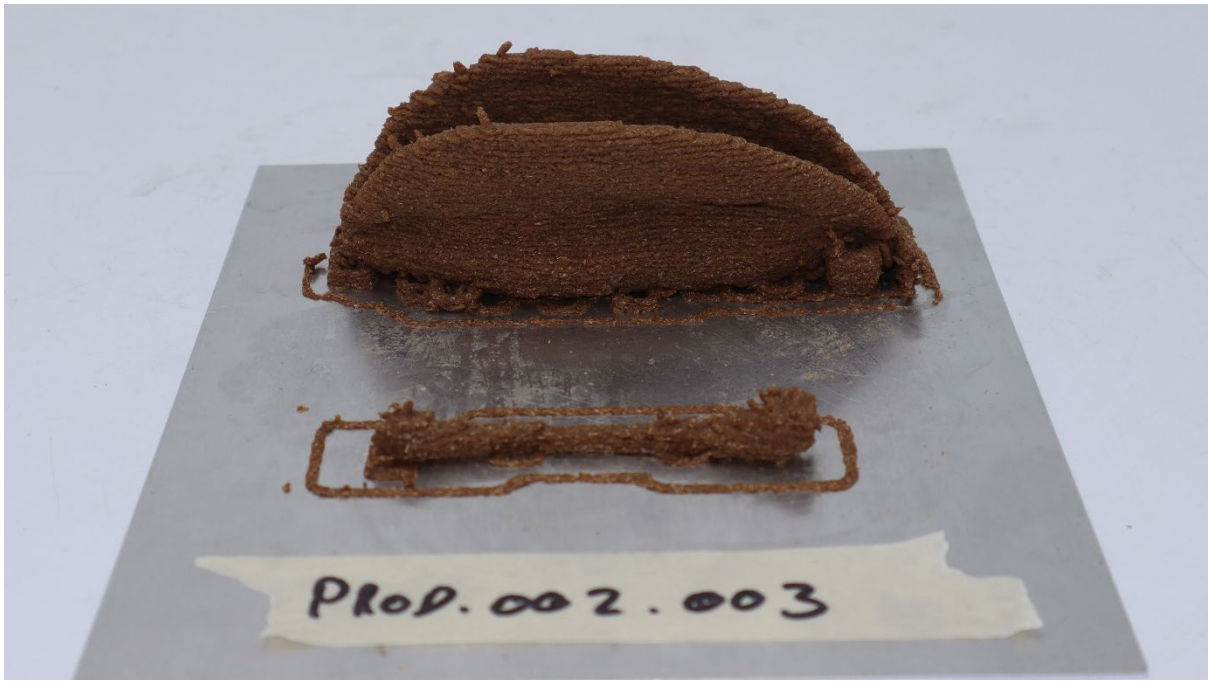


Figure 4.90 PRODUCT_002_003, the seedpod was successfully printed in two parts.

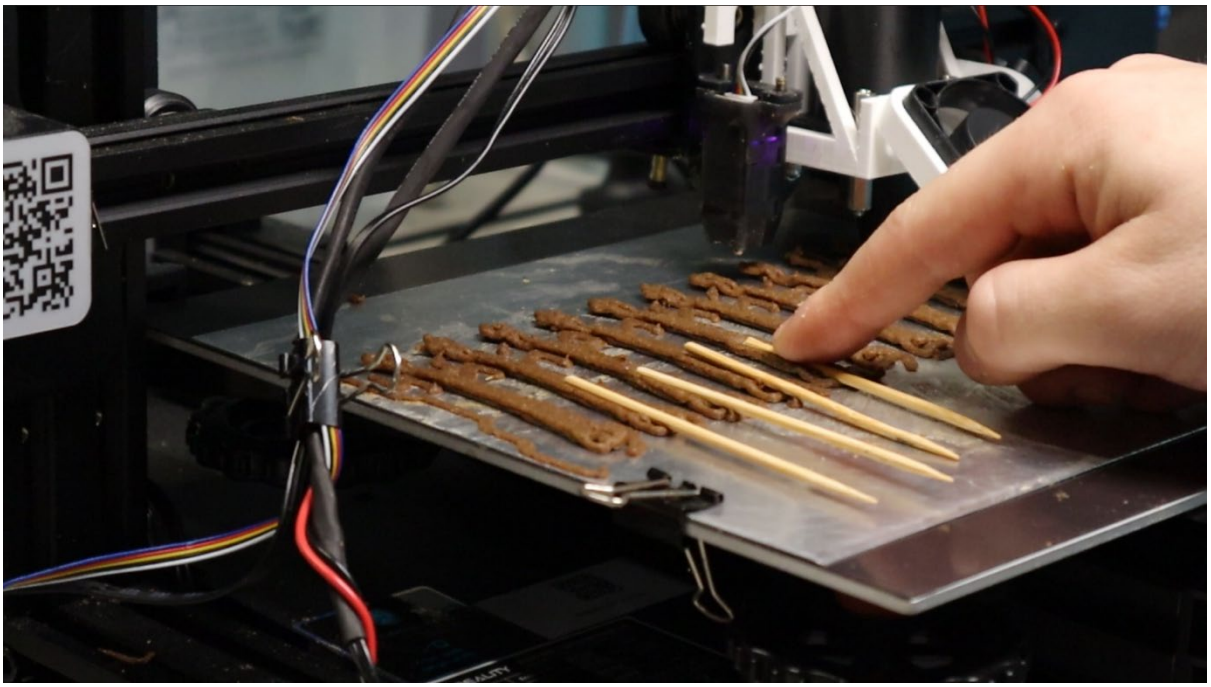


Figure 4.91 While paused, 3mm bamboo skewers were pressed into the bodies of a batch of seedpod tails mid-print PRODUCT_002_005



Figure 4.92 seedpod having a 3mm hole drilled



Figure 4.93 After joining the tails to the fronts with BSG-NMC paste, seedpods were dehydrated until dry before the final phases of postprocessing. PRODUCT_002_007

Most significantly, PRODUCT_002 documents the experimentation, development and use of extensive postprocessing methods to assemble, repair, alter and improve the surface finish of parts. After seedpods were assembled and dried (as discussed above in PRODUCT_002_006), they were prepared for further postprocessing. As discussed in PRODUCT_001_005, 006, and 010, dried parts responded well to manual postprocessing, such as sanding and drilling. PRODUCT_002 explored the rapid development of multiple components and subsequently explored more aggressive postprocessing, such as the use of power tools. Each seedpod was sanded and carved using a Dremel 3000 rotary tool. First, the exterior of the fully assembled seedpods was sanded using the Dremel drum mandrel accessories, first with 80-grit sanding bands, then 120-grit (Figure 4.94). The internal faces of the seedpod were then sanded and carved with tungsten carbide burs, which could easily fit inside the seedpod opening (Figure 4.95). The BSG-NMC paste was then used as a sealing putty and applied to the exterior of seedpods by hand, focussing on closing any holes or gaps that had opened from sanding or imperfections in printing. Seedpods were then dried in the dehydrator and, once dry, sanded with the Dremmel using 240 grit sanding bands for a smoother finish (Figure 4.96). Lastly, the seedpods were coated with 6% CMC by hand, creating a seal and softer surface finish, and placed in the dehydrator (Figure 4.97). Complete seedpods were displayed at the MCA and were used as part of an installation (Figure 4.98).



Figure 4.94 PRODUCT_002_006, a batch of seedpod fronts are sanded with a Dremel rotary tool.



Figure 4.95 PRODUCT_002_008, a seedpod has its internal cavity carved and smoothed with tungsten carbide burs.



Figure 4.96 PRODUCT_002_008, seedpods are finished by sanding with 240 grit paper. Careful attention is paid to blend the tail joint to the main body.

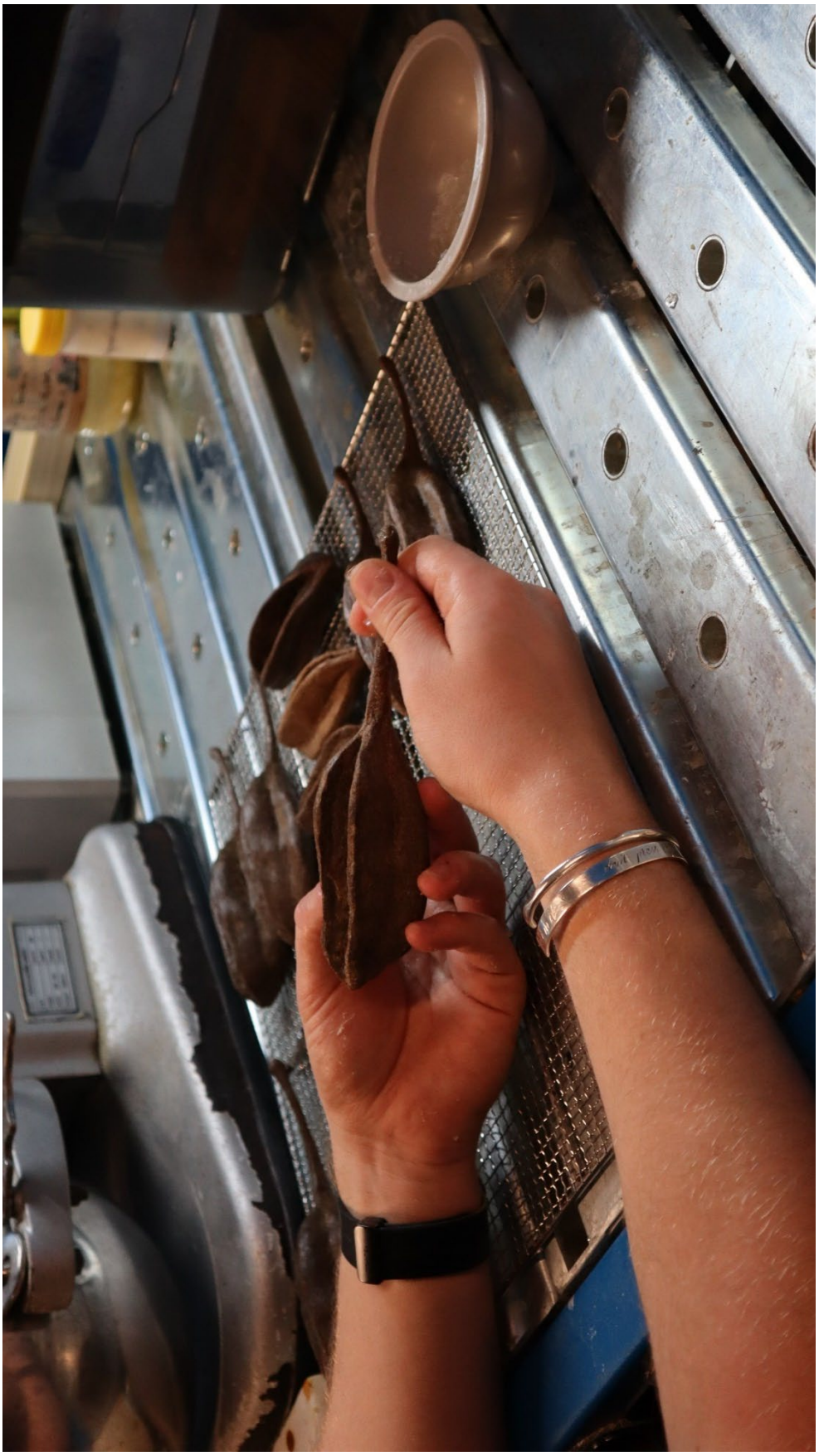


Figure 4.97 PRODUCT_008_008, seedpods are coated by hand with 6% CMC as an added moisture barrier. They are then dehydrated overnight to cure.



Figure 4.98 PRODUCT_002_009, a finished seedpod before collection.

PRODUCT_003 Xbox Controller

PRODUCT_003 explored 3D printing of more complex and technically challenging components. Xbox One controllers (Figure 4.99) were selected to be the subject of the experimentation, which would explore printing with extensive support materials, removal of supports, technical resolution on smaller model details, and postprocessing and shrinkage. This series applied the culmination of the recipes, systems, and settings developed from previous experiments to the printing of explorative prototypes that could be representative of form and ergonomic testing done in professional practice.



Figure 4.99 Xbox One Controller, (Amazon, 2023)

First, 3D scans of Xbox controllers were sourced freely from repositories such as Thingiverse and Printables (Sears, 2021). The first print, PRODUCT_003_001, gauged if the printing system could produce the organic form with significant overhangs and small features (Figure 4.100). As this was a proof of concept, the dimensional accuracy of sourced files was not checked, resulting in a digital file roughly 11% smaller than a true-to-size model. The print used overhang settings similar to those used in PRODUCT_002_002, where a support 'inflation' setting of 10mm was used to create a wider net of support material that expanded beyond the overhanging surface. This was particularly effective in creating a more supported contact area on the thumbsticks on the top of the controller, which have overhangs. PRODUCT_003_001 was a successful proof of concept insofar as the printer system and paste could rapidly produce the organic structure in 90 minutes, which is estimated to be eight times faster than printing in thermoplastics on the same printer. Furthermore, the support structures effectively provided structural support in building and drying, and once dry, were easily removed using the side-cutting nipper tool in the 3D printer box.

ANCHOR

XBOX Controller - THING: 41837344 by GIULIA1999 Thingiverse

Nozzle 1.75mm

Layer Height 0.875mm

Extrusion Multiplier 10.00

Retraction 4mm with 2.5mm lift @ 40mm/s

Tops 3

Bottoms 3

Perimeter Walls 1

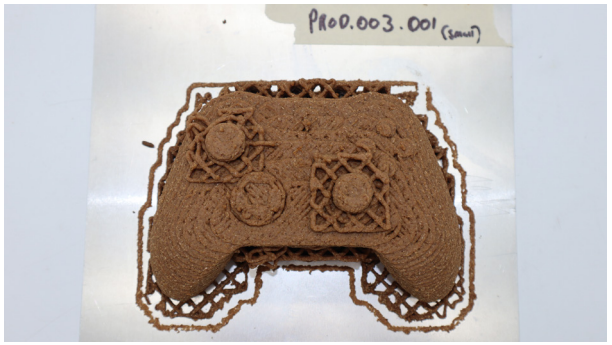
Infill 25% with 50% Overlap of Perimeter

SUPPORT 30% rectilinear with 10mm inflation

Speed 55mm/s (default) with 60% outer, 80% inner, 60% solid infill, 80% spares infill, 70% dense infill

Total time 91 minutes

EXPERIMENTS









OUTCOME

This print explored the printer and pastes capabilities to produce complex shapes and the performance of support material. Whilst it was noted that the print was scaled a bit smaller then 1:1, it was a success and printed to completion including complex shapes such as the significant overhang under the body of the controller, and the overhangs of the thumb sticks on the top. Support inflation was a useful settings which increases the area covered by individual support structures, which is particularly useful here as the slicer does not interpret the size of the material being deposited and does not scale supports correctly.

Further, support was relatively easy to remove using snipper tools, but does cause superficial damage to the body of the print. This requires further sanding and it was found that the BSGNMC paste can be reapplied as a putty on the the model to plug or rebuild holes made during post processing.

Figure 4.100 PRODUCT_003_001, proof of concept gauging the systems ability to produce organic forms that require support structure to print.

PRODUCT_003_002 (Figure 4.101) and PRODUCT_003_003 (Figure 4.102) used the findings of 003_001 to print true-to-size models. Model dimensions were input based on those listed by Microsoft and controlled via the Simplyfy3D manual scaling function. Settings alterations explored the reduction of inflation distance from 10mm to 5mm, as 10mm was deemed excessive. Both prints used the same settings and were stopped before completion due to material running out. PRODUCT_003_002 was particularly affected as the paste cartridges were refilled mid-print (Figure 4.101), but it was found that pausing prints utilising the onboard control would halt the printer in an infinite reheating cycle, where nozzle heat is set to 0 for the print, but needs to reach a certain temperature to resume from the pause function. PRODUCT_003_003 was more successful and printed an enclosed top and bottom, excluding the thumbsticks (Figure 4.102). This print took 135 minutes and showed promise for explorative prototyping in terms of the quality of surface finish, details of the buttons, weight, and scale.



Figure 4.101 Top view of PRODUCT_003_002 while wet. The print was unable to finish after a firmware error occurred while pausing the print to refill the paste cartridge.

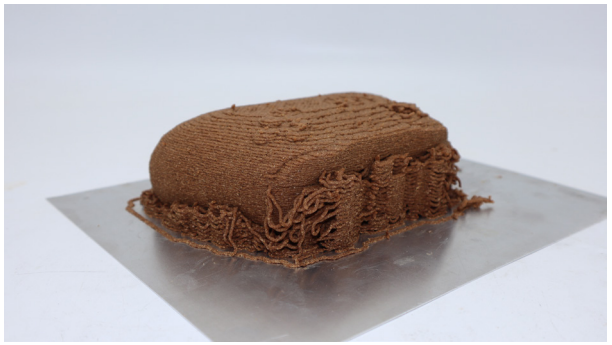
ANCHOR

EXPERIMENTS

OUTCOME

Using the same settings as PRODUCT_003_002 but with a full cartridge to start.

Printed for 135 minutes (2 hours 15 minutes) before running out of material.









This print had to be stopped earlier as the cartridge ran out of material and the print was run using the onboard controller. The print was very close to finishing, and just had the thumb sticks left. I was very happy with the surface quality and details of what was produced, with the gradient of layers looking quite interesting ,and the buttons on the top of the controlled showing well. Further the support material was simply to remove the holes were patched with BSGNMC paste.

This model was displayed at Sydney Design Week and was interacted with by the general public. People like interacting and handing the model showing use as a explorative ergonomic model.

Further experimentation should explore printing a full controller with a pause function for paste reloading, and methods for dealing with shrinkage and slumping for dimensional accuracy.

Figure 4.102 PRODUCT_003_003

Further postprocessing experimentation was conducted on PRODUCT_003_002 and 003 to explore improving the surface finish of components after support removal. Postprocessing techniques were continued from the kurrajong seedpod exploration, where parts were hand-sanded after support removal, with particular attention paid to leftover support lines embedded into the body; holes and imperfections were puttied using the paste in wet form. Through these processes, it was shown that the sanding and puttying process could be used to improve significant imperfections of components, such as in the case of PRODUCT_003_002, which had no top layers (Figure 4.103 and Figure 4.104). Furthermore, the paste can be used to repair loose or broken parts sections, such as in the case of PRODUCT_003_003, which had a broken right trigger that cracked during support removal Figure 4.105 and Figure 4.106). It was noted that there was shrinkage in line with that of the mouse printing experimentation (PRODUCT_001), where particular slumping and shrinking occurred vertically. Further digital scaling to mitigate shrinkage would be necessary.



Figure 4.103 PRODUCT_003_002 dried with support material removed



Figure 4.104 PRODUCT_003_002 dried after puttying with the BSG-NMC paste



Figure 4.105 PRODUCT_003_003 with a broken right trigger.



Figure 4.106 PRODUCT_003_003 after puttying. The right trigger was reattached and sealed.

PRODUCT_003_004 (Figure 4.107), like PRODUCT_001_027, applied the culmination of systems and processes developed through experimentation. Utilising a new and dimensionally accurate model of an Xbox One controller (Sears, 2021), the print explored dimensional accuracy in shrinkage, printing organic structures with support materials. Further, the experiment explored printing larger structures with the system by loading more material while printing. First, the model was scaled based on the shrinkage rates of previous prints and insights from the mouse printing series. Further, the infill and support material patterns were changed to 'triangular', with infill at 40% for a mixture of speed and strength and support material at 60% density for added strength during drying.

The upscaled print of PRODCUT_003_004 took 220 minutes to complete (compared to 889 minutes with thermoplastic at 1:1), including the thumbsticks. The wet print weighed 450g and dried to 200g. The paste was successfully reloaded into the cartridge mid-print using the pause function from the Simplyfy3D control panel (instead of the printer's onboard control screen). The print was paused while placing the infill to avoid any possible artefacts on the perimeter walls, and the depleted cartridge was removed from the paste delivery system and replaced with a full one. The print was recommenced without any issues, and it was indicated that this method makes larger prints possible. Further, the finer details of the design, such as the thumbsticks, buttons and directional pad, were clearly defined. The surface quality of the part was suitable for explorative prototyping and needed minimal sanding and puttying for the potential use case of exploring form and ergonomics (Figure 4.108, Figure 4.109, Figure 4.110, Figure 4.111 and Figure 4.112).

Ultimately, the paste, paste delivery system and 3D printer proved to be suitable for explorative prototyping in product design. The system proved capable of producing organic consumer electronics forms through experimentation, which could be further improved visually through manual postprocessing methods traditionally used in product design practice. While drying time and vertical shrinkage and slumping need further investigation, the system has proved effective in rapidly outputting organic forms for prototyping practice that can be easily recycled back into reusable material or composted.

ANCHOR

Exploring getting dimensional actuary through enlarging the part in the slicer to match shrinkage rate_based on shrinkage of PRODUCT_001 and of other PRODUCT_003 prints:

L 170.00mm (9% increase from 155.28 1:1)

W 117.81 (9% increase from 155.28 1:1)

H 72.27 (22.51% increase from 56.00 1:1)

Nozzle 1.75m

Layer Height 0.875mm

Retraction 4mm @ 40mm/s with 2.5mm lift

Top and Bottoms 2

Perimeters 1

Infill 40% triangular with 50% overlap of perimeter

Support 60% triangular with 3.0mm inflation

Speed 55mm/s with 70% outer perimeter speed, all others 80%

Printed via Simplyfy3D from computer to control pause function for loading of extra material

Print Time 220 minutes (3 hours 40 minutes)

EXPERIMENTS









OUTCOME

The final model completed and showed interesting details into the capabilities of the system. Shrinkage of the length and with reached under 1% of the intended 1:1 models dimension, whereas the vertical shrink was 16%. Further exploration of infill and external support to control slumping is needed for full dimensional accuracy. Pausing the print using the simlpyfy3d controller allowed for refilling the paste cartridge mid print, exploring ways of doing this with the onboard controller would also be useful to minimise wires and possible lose connection failures. The surface quality of the part was very good, and would be useable in scenarios where users needed to handle the prototype. Further exploration of infill and support material is needed, first to control slumping, and second in relation to bridging movements where the top layers of the print struggling to cover the distance needed in closing the top layers. Overall this print shows good progression of the settings, system and material for producing explorative prototypes with improvement needed mainly to shrinkage calculations.

Figure 4.107 PRODUCT_003_004.



Figure 4.108 PRODUCT_003_004 wet post-print.



Figure 4.109 detail, PRODUCT_003_004 wet post-print.



Figure 4.110 PRODUCT_003_004 dried with support material removed.



Figure 4.111 front detail, PRODUCT_003_004 dried with support material removed.



Figure 4.112 comparison between Xbox One Controller and PRODUCT_003_004

5 Discussion

During the research through design approach applied to this research, various threads have emerged that have guided or been considered in developing a 3D printable novel material composite (NMC) paste for use in product design form prototyping processes. This chapter aims to provide interpretive insights into the findings of experimentation and explore theoretical and empirical threads that appeared throughout the research process. The research was guided by three research questions, which were investigated sequentially and thus had narrative, theoretical, and empirical threads intertwined between them.

5.1 Identification

5.1.1 Locally Sourced Organic Industry Waste

The climate crisis is well documented, and its widespread implications are continually being investigated alongside intergovernmental proposals for action and intervention (Intergovernmental Panel on Climate Change [IPCC], 2022a, 2022b). A key contributor to climate change is overconsumption, fuelled by the continued development of materials and products manufactured using petrochemical-derived materials with lifespans well beyond their intended use case (Heinrich-Böll-Stiftung & Break Free From Plastic, 2020; WWF, 2021). Researchers from a broad range of disciplines have been investigating and developing alternative sustainable materials for petrochemical feedstocks for use in diverse applications (Faludi et al., 2019; Kääriäinen et al., 2020b; Rognoli et al., 2015; Sauerwein, 2020). While there have been positive developments in the field, it has been identified that aspects of novel material development have been influenced by greenwashing tactics while providing limited benefits regarding sustainability or in terms of their functional use (Goel et al., 2021; Schmuck, Matthes, & Naderer, 2018). This research argues that while there are many reasons a researcher may develop a novel material composite (NMC), their use should be tailored to the found qualities in the material developed rather than comparing them to thermoplastics and petrochemical plastics, materials that have been continuously developed for over a century and are now capable of working in a plethora of use cases.

Developing a novel material composite usually starts with selecting a natural material to be the subject of investigation. While the selection process and criteria are scarcely described in academic literature, it was identified that materials used as the substrate of NMC development are often locally sourced as waste outputs from growers and producers (see *Context 4.1.2*). There are many avenues to identifying and selecting local organic waste, such as country and region-specific waste reports, agricultural reviews, and production and export reports, which can be consulted to find

information on the types of waste products produced by local industry, the size of industries and their outputs, and how local producers are using their waste (such as for biofuel and animal feed).

Sourcing organic waste as feedstocks for NMCs creates unique opportunities for designers regarding projects that may be specifically related to their local culture and environment, using regional agriculture as a source for their feedstock. Locally sourcing materials creates unique opportunities for circular relationships and business models with local businesses, assisting in managing waste outputs that may have previously been difficult for the producers to store and process effectively.

Another consideration during the selection process is the research or design process's intended use case or output. A material scientist may be researching the efficiency of a material based on a local waste resource; a designer may have an intended purpose for a material they are developing. In this process, the selection of the waste resource joins the consideration of the other 'ingredients' in the mixture, focusing on how they will mix, bond and cure (see 5.1.3 Roles of Ingredients). Further research considering waste resources' current use cases in academic research and commercial applications, and chemical constituents and their potential qualities as a functional filler may be needed to understand how best to utilise waste as part of a mixture. Furthermore, the lifecycle of an NMC should be considered, particularly around the types of binder materials the research may be using.

Within this research, the material selection process described above followed the steps shown in Table 5.1.

Table 5.1 Material selection process through the lenses of macro, meso and micro.

National (macro)	Waste Report	The Australian Nation Waste report was reviewed but did not give specific examples of 'organic' waste outputs from industry,
	Agricultural Production	The Australian agricultural industry was reviewed, documenting the largest organic producers and exporters of organic materials.
State (meso)	Agriculture Reivew	Industries specific to New South Wales were reviewed regarding their outputs to industry, waste output, and current cases. Specifically wheat, barley, grape, and sugarcane production.
	Production Review	Breweries (barley) and vineyards (grapes) were identified as potential local sources of waste material, as they had the closest proximity to the university campus.
Local (micro)	Material Selection & Review	Brewers spent grain (BSG), beer making most significant solid waste output, was identified as a possible feedstock for use in NMC development. First, breweries can be accessed within 15 minutes from the university campus. Second, BSG was identified as an under-utilised organic waste; BSG accounts for up to 80% of all solid waste from breweries and has a short life span of 5 days before spoilage without proper storage (drying or freezing). It is mostly used as animal feed and as biofuel (Mussatto et al., 2004).
	Literature Review	A review of academic literature and current uses of BSG in design was conducted, highlighting its potential use as structural reinforcement through its underutilised cellulose content. Further, potential processes for sourcing and processing BSG were identified through the academic literature, which outlined the grain's high moisture content as the main point of contention for use and the need to mitigate this through freezing or drying immediately.
Hyperlocal (micro)	Sourcing	Potential sources of BSG were identified through.

5.1.2 Material

Scale of Making

Of central consideration throughout the research process was the accessibility of information and ease in replication of processes and experiences by other designers. This led to the adaptation of Sadokierski's (2019) contextual portfolio format, which serves a dual purpose as a vehicle for conducting and documenting design-led action research and an interface for sharing the experimentation process with users (see *3.6*). However, another central consideration within the scope of the research was users' access to similar or adequate machinery, additives for mixing, knowledge bases, and other tools used to conduct parallel or comparable projects.

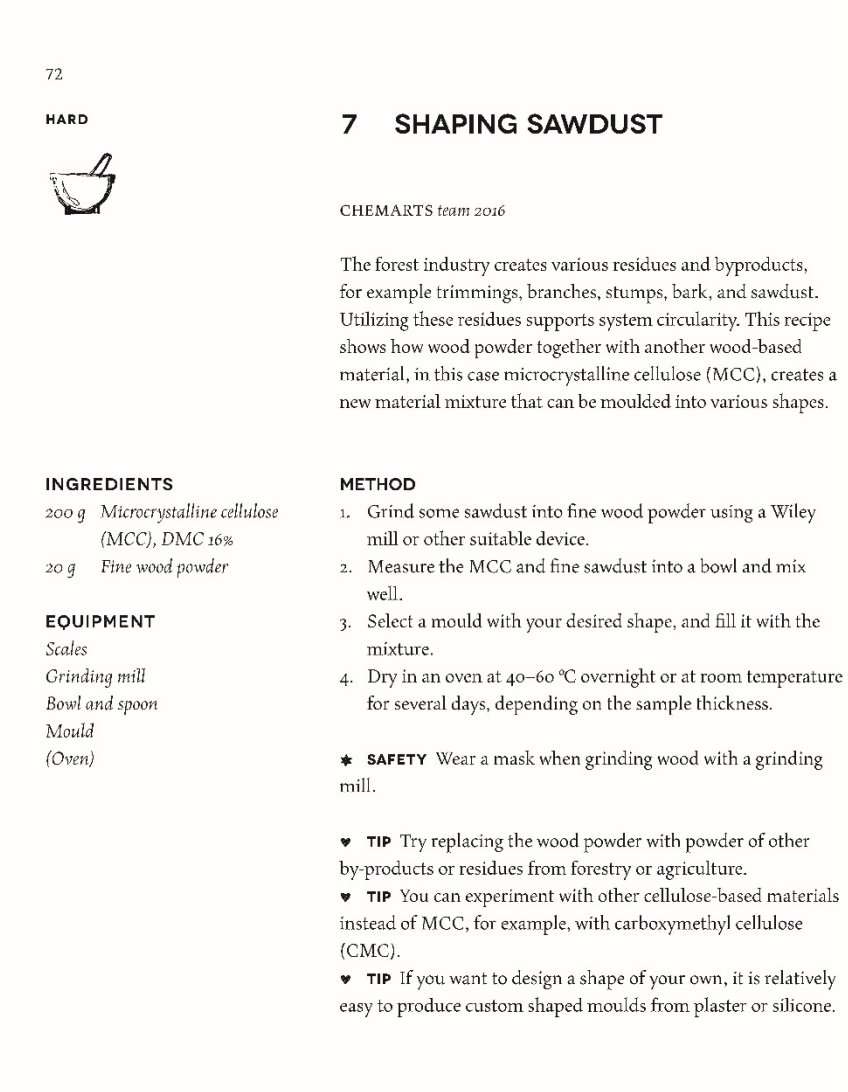
The 'scale and measurement' theme appeared during the literature review and initial experimentation utilising BSG, particularly during experiment planning and design. The most information-rich sources of inspiration and guidance regarding material preservation, processing, and composite formulation were from scientific journal articles, in which the majority used the same field-specific language and writing flow. The field-specific language implied a level of prerequisite knowledge needed to understand the reported information. This notion also applies to reporting measurements and scales regarding test subjects, methods and equipment.

A comparison between a designer's studio and a scientist's laboratory highlights these practical disciplinary differences. The material scientist may work in milligrams and smaller (depending on the experiment), using specialised equipment that outputs graphs, numerical readings, or detailed images of microscopic detail. In contrast, the material-focused designer works upward in scale from the same values, measuring their results not only with numerical values but in tacit knowledge and from peer and audience feedback on samples. The material-focused designer uses a range of adapted technologies to suit their needs.

The comparison of scale between disciplines brought forward a discussion regarding the scale at which the material-focused product designer works. Traditionally, designers have worked at the 'kitchen scale', a space that is an approachable entry point to make and test proof of concepts simply. The kitchen scale implies easily approachable experimentation that could take place in a domestic kitchen environment, using kitchen appliances and utensils and having a satisfactory outcome during their experimentation and prototyping process. This is reflected in the resources available to designers: knowledge-based resources like the *CHEMARTS Cookbook* (Kääriäinen et al., 2020a) and websites like Materiom.org list their composites as recipes, featuring ingredient lists (in

grams), lists of the equipment needed (such as bowls, spoons, syringes and grinders), and the writing and presentation of the methods sections (Figure 5.1).

Distinguishing the scale of experimentation is essential to this research, as a key output is the sharing and translating of the data from the experimentation and prototyping processes to designers new to the field of novel material design. Understanding the scale at which a designer traditionally works allows translation of the data from non-design-specific resources to language (both visual and written) that is approachable and understandable to a designer aspiring to undertake material experimentation from their home or studio.



72

HARD

7 SHAPING SAWDUST

CHEMARTS *team 2016*

The forest industry creates various residues and byproducts, for example trimmings, branches, stumps, bark, and sawdust. Utilizing these residues supports system circularity. This recipe shows how wood powder together with another wood-based material, in this case microcrystalline cellulose (MCC), creates a new material mixture that can be moulded into various shapes.

INGREDIENTS

200 g *Microcrystalline cellulose (MCC), DMC 16%*
20 g *Fine wood powder*

EQUIPMENT

Scales
Grinding mill
Bowl and spoon
Mould
(Oven)

METHOD

1. Grind some sawdust into fine wood powder using a Wiley mill or other suitable device.
2. Measure the MCC and fine sawdust into a bowl and mix well.
3. Select a mould with your desired shape, and fill it with the mixture.
4. Dry in an oven at 40–60 °C overnight or at room temperature for several days, depending on the sample thickness.

✱ **SAFETY** Wear a mask when grinding wood with a grinding mill.

♥ **TIP** Try replacing the wood powder with powder of other by-products or residues from forestry or agriculture.
♥ **TIP** You can experiment with other cellulose-based materials instead of MCC, for example, with carboxymethyl cellulose (CMC).
♥ **TIP** If you want to design a shape of your own, it is relatively easy to produce custom shaped moulds from plaster or silicone.

Figure 5.1 Recipe 7 'Shaping Sawdust' from the CHEMARTS Cookbook. The recipe shows ingredients, equipment, a description, method, tips and safety advice (Kääriäinen et al., 2020b)

Preparing

Before sourcing a material, best practices for handling, preprocessing, and storage should be established. Some materials have preexisting material safety data sheets, such as sugarcane bagasse, which is used extensively in mass manufacturing (for example, Risk Management Technologies, 2022); however, many others may not. Safe handling, storage and processing behaviours should be paramount in NMC development to protect the researcher and others. As discussed in Processing and Storage *4.1.11,* the best practices for handling, preprocessing and storing material can be found through a literature review and translated to the scale or machinery available. Material scientists, in particular, describe their processing from sourcing through to processing and development in depth, and these workflows can be adapted to a designer's needs.

Plans should be made for safe and efficient preprocessing before sourcing; questions should be asked regarding:

- The chemical composition of the material; useful, safe mixing
- Considerations for safe handling regarding the skin, eyes and ingestion
- First aid procedures for skin, eye and ingestion
- Fire risk and the type of fire extinguisher needed
- Consideration for spills
- Handling needs of raw and processed materials
- Storage needs of raw and processed materials
- Transport safety considerations
- Disposal methods.

Formal safety datasheets can be created by following Safe Work Australia (2023).

Within the context of this research, materials were sourced, stored, and preprocessed, following safety guidelines developed according to the criteria above. Answers to material safety questions were found in academic literature, which guided the process. Key considerations were identified, such as the need for BSG's immediate processing to be stored to avoid spoilage, as it is highly reactive after brewing. Further, precautions were made while grinding and sieving dried BSG, such as wearing a mask and using a downdraft table or in a well-ventilated space. For disposal, it was identified that BSG could be composted, as discussed by Bianco et al. (2022) and Assandri et al. (2020); this is further confirmed in PASTE_004_COMPOST, where BSG-NMC prints were

vermicomposted in two separate worm farms (Figure 5.2). As shown, the prints were vermicomposted in two weeks.

ANCHOR

EXPERIMENTS

OUTCOME

Vermicomposting was tested in domestic worm farms. Two prints, PRODUCT_001_002 and 001_003 were placed in the domestic worm farms which remained in use for regular food scrap composting. Prints were placed in the worm farms on 18/10/23 and were consumed by 07/11/23 (20 days).



The confirmation that the material is compostable is a tremendous result. All ingredients are bioderived, and printed and dried models are still absorb moisture where are also positive. Along with the results of the REANIMATION tests, the material shows significant environmental benefits in terms of reuse and disposal (in comparison to thermoplastics and poly foams). Further development on both reanimation/reuse and composting options of NMC materials would be interesting areas of future research.

Figure 5.2 PASTE_004_COMPOST vermicomposting experimentation, prints were composted in 20 days

5.1.3 Roles of ingredients in a paste mix

In developing a paste-based NMC, ingredients and processes must be identified and tested to find a possible use case. Rather than developing a thermoplastic replacement, the material developed should be designed towards achievable and suitable scenarios that become apparent within the initial development processes. While finding and processing an organic waste resource can be supported by scientific literature, the initial assessment of NMCs and the development of a material through an RtD approach requires more freeform experimentation that is more in line with the work of product design prototyping practices. While there are growing repositories providing information for these processes (such as Faludi et al., 2019; Garmulewicz & Corbin, 2018; Sauerwein, 2020), individual designers engaging with NMC design have limited options for educating themselves on the processes that need to be understood to develop an NMC.

Each ingredient within an NMC has a functional role, and understanding these roles is crucial to developing and tuning the NMC for the desired case. Further, understanding the possible reactions between ingredients is important for safety and for developing material qualities. This research focussed on using cellulose-derived and cellulose-rich materials to create high affinity, further strengthening bonds between ingredients during processing (Kim et al., 2021; Tenhunen et al., 2018). Within the scope of this research, ingredients fell under three roles: functional fillers, binders and multifunctional additives (Faludi et al., 2019; Varvara, Szabo, & Vodnar, 2021).

Functional Fillers

Within the context of a localised NMC being produced in Australia utilising cellulose-rich organic industrial waste, potential functional fillers could be dried organic waste sourced from the agricultural industry. Examples include but are not limited to:

- Brewers spent grain (BSG) - 13-21% cellulose (Mishra, Gregor, & Wimmer, 2016)
- Sugarcane Bagasse - 40-50% cellulose (Mahmud & Anannya, 2021)
- Corn waste (Zea mays) - 35-50% cellulose (Corbin et al., 2015)
- Grape marc - 20-48% cellulose (Corbin et al., 2015)
- Olive pomance - 13-30% cellulose (Freitas et al., 2022)
- Spent coffee grounds (SCG)- 12-25% (Oliveira et al., 2021; Tapangnoi et al., 2022).

Filler materials are commonly used in industries like plastics and concrete mixing and are used to tailor the qualities of the material in aspects such as performance, appearance, cost and environmental impact (Civancik-Uslu et al., 2018; Falcone Jr., 2000); Senthil Muthu Kumar et al.,

2020). Within cellulose-based NMCs, filler materials have several functions; as they are fibrous, they create strong links with cellulose-derived binders, they dictate the colour of the composite, they affect the strength of components through their fibre length and bonds, and they affect the ease of processing of NMC pastes through their size (Al-Oqla, Hayajneh, & Aldhirat, 2021; Senthil Muthu Kumar et al., 2020; Tri-Dung, 2020)

Binders

In NMCs, binder materials can be viewed as the glue that holds the filler materials together. Binders work through either adhesion or cohesion (von Fraunhofer, 2012), creating bonds through attraction between dissimilar modules binding their surfaces (adhesion) or binding through similar chemical molecular structures (cohesion). It is, therefore, important to consider the chemical constituents of a functional filler in relation to possible binder materials. This process may not be explicitly known to a practitioner, and testing various binders with functional fillers is a fundamental research step when developing an NMC.

Examples of natural binders with potential use in NMC paste creation are:

- Carboxylmethly cellulose (CMC)
- Gums (agar, guar, xanthan)
- Sodium silicate
- Sodium alginate
- Sugar
- Cornstarch is a natural polymer, but with further activation and mixture, it can be used as a binder.

When developing an NMC, binders have several roles. In a wet form during mixing and making, binders hold functional fillers (and other materials) together and dictate material behaviours such as viscosity, strength, and drying time. During and after drying, binders hold objects/forms together through either adhesion or cohesion. What makes organic binders unique, particularly cellulose, is their ability to be reused after hydration. Applications for NMCs should embrace the qualities of their ingredients (Gardner et al., 2008; Rahman et al., 2021; Tayeb et al., 2018).

Multifunctional Additives

Multifunctional additives exist within NMC mixtures that serve various roles in the NMC's creation and lifecycle. Multifunctional ingredients can be project-specific, aiming to alter a range of or

singular material qualities. These goals centre around the specific needs of a material, seeking to improve the qualities achieved when first mixing a binder and filler material. Multifunctional ingredients can improve material longevity in storage, create easier material mixing processes, improve material flow, and alter NMC visual appearance, drying times, handling, and storage needs. Examples of multifunctional additives are:

- Vegetable glycerin can be used as a lubricant, plasticiser, and preservative (Morrison, 2000; Williams & Hillmyer, 2008)
- Gelatin can be used as an emulsifier, thicknesser, and gelling agent (Gelatin, 2020)
- Methylated spirits (alcohol) can be used as a replacement for water and allow for faster drying
- Starch as a thicknesser and strengthening agent (Kääriäinen et al., 2020a; Wang et al., 2022).

Final BSG-NMC Paste Recipe Explained (PASTE.004.012)

- BSG was used as a functional filler. BSG was first dried and ground through a 40-mesh sieve to enable better dispersion through the paste mixture and for easier extrusion through the extruder
- A 6% CMC solution was used as the binder. 6% CMC was prepared by weight percentage, where CMC was gradually added to water while mixing. CMC was used, as it would bond through cohesion with the cellulose in the BSG to create a strong bond when dried. 6% CMC is a clear, sticky, thick gel that requires shear force from a blender or stick mixer to break apart
- Vegetable glycerin was used as a multifunctional additive due to its lubricant and plasticising qualities, which assisted the NMC paste in flowing through the tubing. Further, vegetable glycerin provides preservative qualities that enable longer storage of materials
- Methylated spirits were used during mixing as a replacement for water. Methylated spirits evaporate at lower temperatures than water, allowing for faster drying.

5.2 Processes

5.2.1 Affordability and approachability in development

Paste extrusion for MEX has been used since 1997, first developed by Cesarano (El Mesbahi, Buj-Corral, & El Mesbahi, 2021). At present, paste extrusion is typically used in niche settings such as biomedical experimentation (Bozkurt & Karayel, 2021), creative uses such as ceramics (Keep, N.D.-b), material science in the development of NMCs (Faludi et al., 2019), material development (Junai, 2023b), food-based printing (Wang et al., 2022), and construction (Wu, Wang, & Wang, 2016). Paste extrusion utilising MEX platforms is currently an expensive endeavour in that commercial offerings for extruders, printers, and full systems are significantly more expensive than a comparatively sized thermoplastic machine (see Table 5.2).

BOM	PRINTER_002_002	Junai Extruder Kit (no printer)	LDM WASP Extruder 3.0	LDM WASP Extruder XL 3.0	Eazao Matrix M500	Eazao Zero	Delta WASP 2040 Clay	3D PotterBot 10 Micro	Junai Ender 3 v2 Biomaterials
Package Cost		330	475	1620	2246	1347	5370	5238	1060
Creality Ender 3 V2	300	300	300	300	These columns feature complete systems including a printer, extruder assembly and delivery system				
Direct drive kit	65								
X-axis upgrade	55	55	55	55					
CR Touch	60	60	60	60					
NEMA17	20								
Auger	10								
Pipes	40		40	40					
Cartidge	20		20	20					
Cartidge backing	20		20	20					
BSP fitting	20		20	20					
Hose clamps	10		10	10					
Spring balancer	30		30	30					
Air Compressor*	400		400	400					
without air	650	745	1030	2175	2246	1347	5370	5238	1060
with air compressor	1050	Ramrod	1430	2575	2646	1747	5770	Ramrod	1460
*Chicago Hush 30 Air Compressor									

Table 5.2 Bill of material (BOM) comparison between the printer developed in this research and other commercially available options

Researchers, makers and DIY enthusiasts have developed systems for affordable paste 3D printing, creating extruder assemblies and workflows that mount onto existing budget/affordable 3D printer hardware (Amza, Zapciu, & Popescu, 2017; Junai, 2023a; Keep, n.d.-a; StoneFlower3D, 2022; Sun & To, 2023). These systems excel in their affordability, user customisation (where open-source), and use of minimal added componentry. Furthermore, DIY systems typically do not require extensive software or firmware changes and will function using free and open-source slicers used for thermoplastic printing. While these systems may be designed for the initial phases of testing and development of NMCs, they can be cumbersome with limited paste reservoirs, as their ramrod

designs require the extruder assembly, stepper motor, and material cartridge to be mounted on the same point (Figure 5.3).



Figure 5.3 Junai extruder kit mounted to a Creality Ender 3 V2 (Junai, 2023b)

High-end commercial systems, such as the Delta WASP 2040 Clay (WASP, 2023a), replace the heavier ramrod assembly by using compressed air to push material from the paste cartridge to the extruder assembly and stepper motor assembly (Figure 5.4). This system requires extra hardware and action to control, such as an air compressor, regulators and air fittings, pressure-rated tubing, and a spring balancer to support the paste cartridge overhead. While raising the cost of the total paste extrusion system (suitable air compressors start around $120 AUD), these extras enable fast and accurate printing by removing excess weight and instability from the gantry. Further, they enable the printing of larger models through the use of larger cartridges while allowing more control over material flow and extrusion.



Figure 5.4 Delta WASP 2040 Clay printer, with LDM WASP extruder and mounted 3L material tank (WASP, 2023a)

This research aimed to create an easily replicable and cheap system that could be used in product design prototyping practice. The system uses high-end hardware as inspiration for the development of an affordable pneumatic paste delivery system and extruder assembly while following DIY processes such as using a budget class MEX printer (Creality Ender 3 v2) and designing a 3D printable extruder assembly and printer mounting system that can be printed using the printer (Figure 5.5 and

Figure 5.6). Overall, the system used in this research costs around 1000 AUD, but it could be closer to 800 AUD if a cheaper air compressor is purchased.

The significance of the system developed in this research and by others developing open-source designs is in the technologies tied to enabling researchers and makers in NMC development. Affordable printer technologies enable the testing and rapid development of NMC, which could provide efficacy to a potential use case for organic waste resources. Makers, designers, and researchers who have access to affordable and adaptable advanced manufacturing technologies enable potential remote investigations of localised waste.

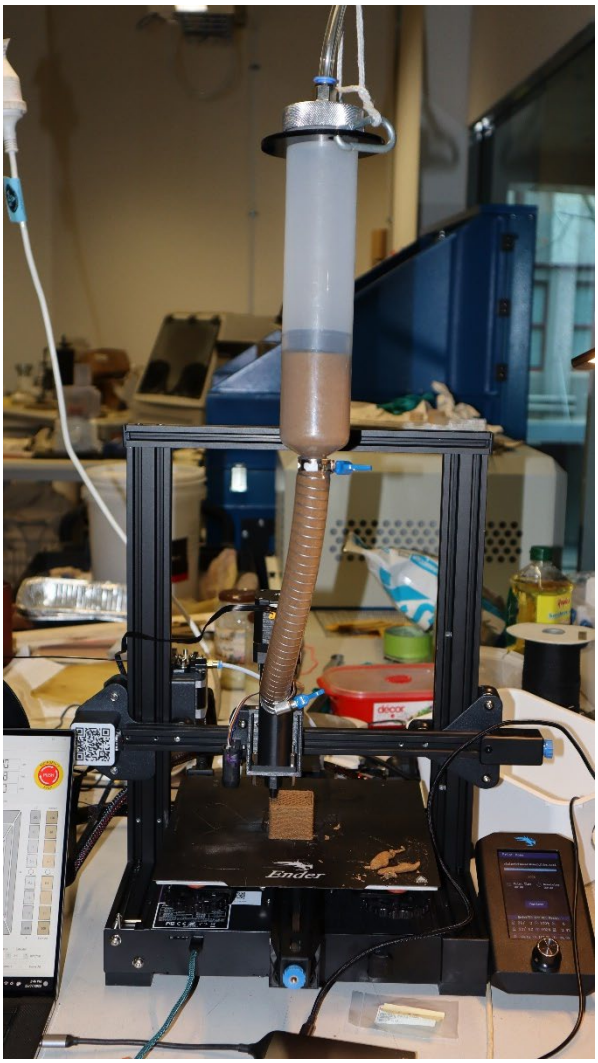


Figure 5.5 PRINTER_002_001 while printing a test cube

ANCHOR

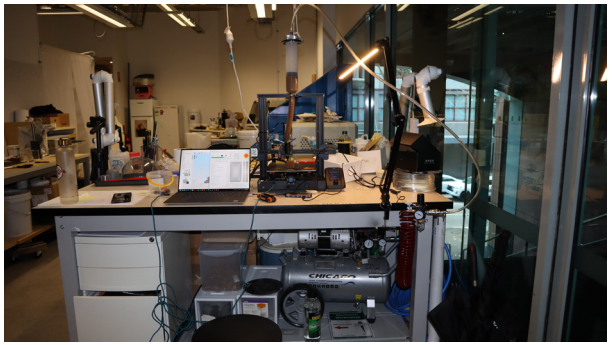
The Creality Ender 3 V2 is a cheap (around 300-350 AUD from Amazon in 2023) consumer 3D printer with a 220 x 220 x 250mm build platform. Part of the low price is that the printer requires some assembly (not wiring) which takes roughly 1-2 hours. The Ender series from Creality is immensely popular with hobbyist, with free printable modifications downloadable from Thingiverse or printables.com, and many purchasable directly from Creality such as direct drive kits, auto levelling tools (Cr-Touch), dual-z upgrade kits and more. The Ender 3 v2 was purchased from Amazon initially as a prototyping tool to produce extruders and nozzles for PRINTER_001, however, it became apparent that it would be better used as a dual purpose machine, printing thermoplastics parts for itself to use as a paste-extrusion printer. To improve the printing experience:

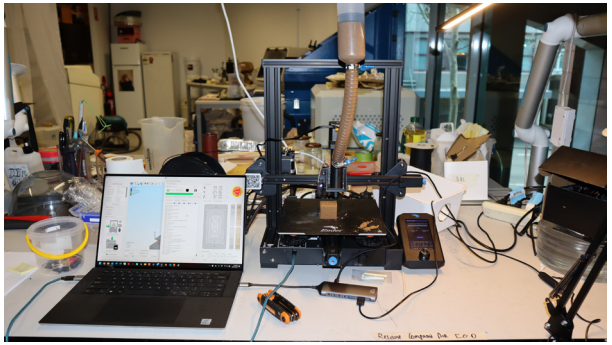
A CR-touch was purchased for bed-mesh and leveling,

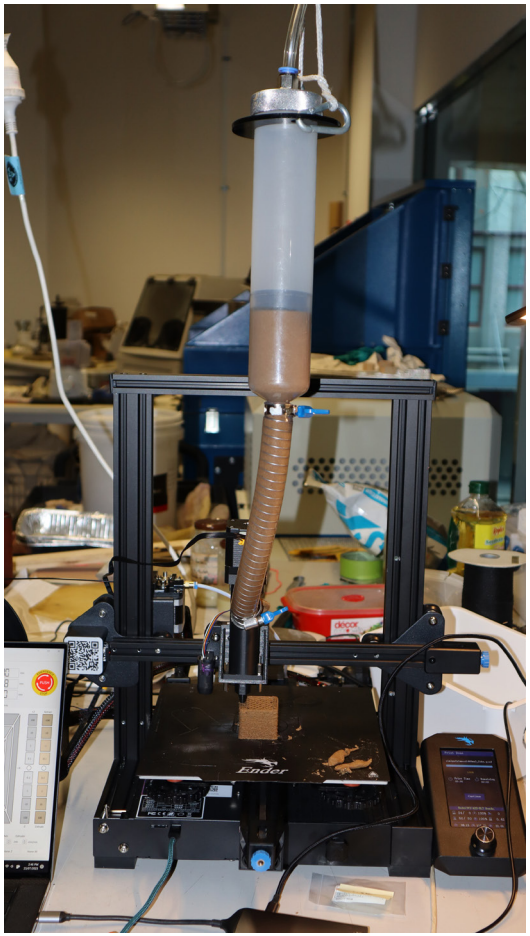
a Creality direct-drive kit, which comes with a larger e-plate (which holds the extruder assembly). This would be used to mount the paste-extruder and to remove the existing e-motor from the z-axis when not in use (and replace it with the direct drive motor)

A dual z-axis kit was purchased for added strength to the z-axis to support the direct-drive and paste-extrusion extruder assembly.

EXPERIMENTS







OUTCOME

The ender 3 v2, paired with EXTRUDER_003_002 and PASTEDELIVERY_002_002 worked extremely well for paste printing, and was used in research question 3 to produce great printed results. The printer was eventually flashed with Professional Firmware" from Miguel Risco-Castillo (username mriscoc) from https://github.com/mriscoc/Ender3V2S1/releases/tag/20230522. This added ease of use in aspect such as bed level visualisation, bed level visualisation and changing the stepper motor rotation between thermoplastic printing and paste-extrusion. Further refinement to the system would be developing a quick change system for extruder assemblies between paste and thermoplastic, a heated chamber design for increasing the range of thermoplastics printable and to explore alternate drying modes for NMC pastes, and a system to mount the spring balancer and filament spool directly above to the system rather than relying on external structures.

Figure 5.6 PRINTER_002_001

5.2.2 Configuring Flow

All forms of MEX 3D printing require calibration of the material flow. Material flow is the amount of material leaving the nozzle during printer movements and is affected by a range of slicer settings such as the flow rate, material temperature, and the e-steps setting (3DPrintBeginner, 2020). Over time, material flow has become significantly more manageable, especially in the affordable 3D printer market. Free slicer software now comes preloaded with material profiles for generic and manufacturer-specific materials, allows for downloading community profiles for materials, and enables simple manual user entry of desired settings for new materials (see Ultimaker Cura). While these preconfigured settings are available to users, further calibration of material flow can be manually controlled by users. Material flow can be tailored through multiple calibration processes, such as simple visual feedback methods from Sackett (2021), or more advanced calibration following procedures such as those from 3DPrintBeginner (2020) and Santana, Lino Alves and da Costa Sabino Netto (2017).

Repeatable and consistent 3D printing with NMC pastes using consumer printing hardware requires consideration of the same settings as thermoplastics while also developing the paste mixture and physical systems involved in delivering paste to the extruder. Specifically, successful paste extrusion requires cohesion between the paste mixture, the pressure required to deliver paste to the extruder assembly, the tolerances in the extruder assembly, the slicer settings of flow rate, speed, layer height, and physical nozzle size.

Paste Mixture and Configuration

The paste mixture is the first factor to assess and tailor for application, due to its cascading effect on the rest of the systems and settings. A thick viscous paste mixture will require higher air pressure to move through to the extruder assembly, which will need to be designed to accommodate thicker pastes through higher pressure-rated tubing, auger selection and strength and speeds of the stepper motor, while considering the size of the nozzle. Thicker pastes may not extrude through smaller nozzle sizes and can result in inconsistent extrusions, which tear and break while leaving the nozzle, even with higher flow rates enabled through the slicer and air pressure.

A watery, loose paste can move through the delivery system and pass through the auger thread under minimal pressure, removing elements of control over the paste extrusion that the extruder assembly and auger should dictate. Watery paste can reach the auger and nozzle under minimal pressure; this removes additional factors that control material flow and ultimately, line thickness,

where the pneumatic pressure and the slicer flow rate will dictate how quickly material flows from the nozzle. If this process is happening too fast at minimal pressure, flow control is lost, and line width will be affected. This ultimately affects part aesthetics, dimensional accuracy, drying, material usage, and the pressure of top layers on the ones below.

Within this research, materials were designed to extrude at around 2 BAR (30 PSI), allowing for the live-finetuning of flow rate and ultimately, line width through smaller adjustments to pressure. Furthermore, this did not affect material flow in retraction movements, which were controlled by the auger. Repeatability in mixing and extrusions was achieved by documenting recipe proportions and performance (see 4.2.2 and PASTE series pages 300-328) and introducing further quality control measures, such as measuring paste performance with a digital force gauge. Measurements from the force gauge were used to indicate whether the material would be controllable through the paste delivery system and extrude in a controlled manner under auger power.

Paste Delivery System

The paste delivery system should provide a consistent supply of paste to the extruder assembly. The paste delivery system affects material flow specifically through its configuration and, more importantly, its constraints over material movement through friction in its tubing. As discussed in *4.2* and above in *5.2.1*, the paste delivery system can affect the speed and accuracy of prints, possibly altering the nozzle positioning through excess weight or tension on the extruder assembly and gantry. More specific to material flow, the paste delivery system also affects the rate and flow of material to the extruder assembly and can be a limiting factor in the speed of prints through the componentry selected. It can affect factors such as the size of prints achievable (through the size of the paste cartridge), and the amount of pressure needed to move paste through to the extruder assembly.

Considerations regarding the tubing used in a pneumatic paste delivery system are critical to material flow. Ultimately, the internal diameter (ID) of the tubing delivering paste from the cartridge to the extruder dictates the required pressure; smaller pipes create more friction, resulting in the need for increased pressure, whereas pipes with larger diameter have less friction (Nur, Afrianita, & Ramli, 2019). However, it was also found that smaller diameters had maximum higher-pressure ratings from manufacturers than larger ID tubing, which became a limiting factor in the material design and pressure range used. Piping flexibility also became a consideration. Flexible piping tended to have lower pressure ratings but applied less force onto the gantry during printing, while reinforced piping had significantly higher pressure ratings but was more rigid and could move the

extruder assembly off-axis. Transferring weight from the gantry to other parts of the system, such as the spring balancer and tubing, will translate into a more controllable and faster printing experience.

The paste delivery system tested several tubing thicknesses and styles in this research. Ultimately, 19mm ID clear helical reinforced tubing was found to be the most effective for paste delivery. Clear tubing was used for easier monitoring of paste movement through to the system and cleaning. While smaller internal diameter tubing had a higher pressure rating, the maximum load of 7.5 BAR of the 19mm ID material was suitable for this application, where maximums of 4 BAR were reached occasionally. Further, the larger size of the tubing was more flexible than the smaller options, creating less tension on the extruder assembly and gantry while mounted. The larger diameter allowed for easier movement of thicker pastes with less water content and more controlled movement of the final paste recipe, which extruded well at 2 BAR.

Extruder Assembly and Auger Choice

The extruder assembly in thermoplastic and paste-based MEX printing can significantly affect material flow and, consequently, the consistency of material deposition. As discussed above (*5.2.2*), the extruder assembly in thermoplastic printing is responsible for delivering material (usually in filament form) to the hot end to melt and to be the force behind material extrusion (Figure 5.7). In this process, the extruder (e-motor) can be mounted directly to the e-plate with the hot end (direct drive) or be mounted elsewhere and pass the material through tubing to the hot end (bowden tube). The speed and consistency of material flow are controlled by the speed of the extruder (e-steps) and the temperature of the hot end, both controllable settings in the slicer software.

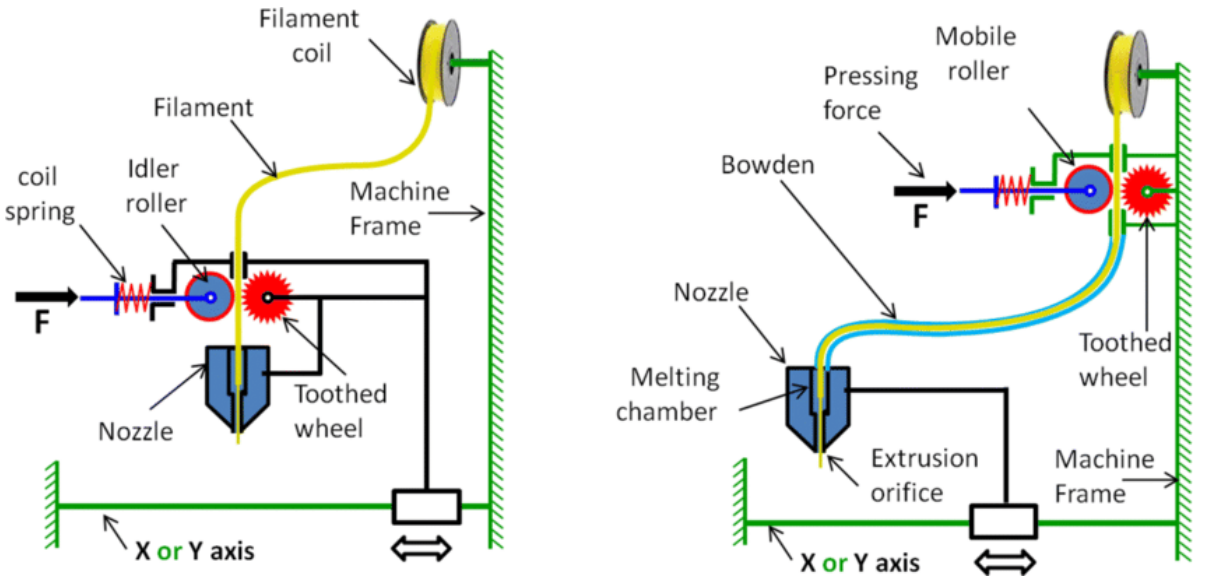


Figure 5.7 How a thermoplastic extruder works in bowden and direct drive configurations (Boulaala et al., 2020)

While 3D printing with NMC pastes use consumer 3D printers and software functions similar to thermoplastic printing, in that material is fed through to a nozzle; the speed of extrusion (e-step, typically controlled through the 'flow rate' or 'extrusion multiplier' settings in slicers) is a factor which must align with other variables to achieve a consistent and reliable printing process. Where most thermoplastic extruders and hot-ends are designed to be interchangeable and be used with similar filaments and printers, paste printing requires and allows for further tailoring. Some paste extrusion systems are similar to thermoplastic printers in that the extruder assembly is designed to simply deposit paste through the force from the paste delivery system (Figure 5.8). These systems mount an extruder design to the gantry that does not require electronics but instead is a mounting point for the paste delivery tubing to deposit material through a syringe. These simpler systems do not have retraction functions and are typically used to create hollow vase-type vessels.

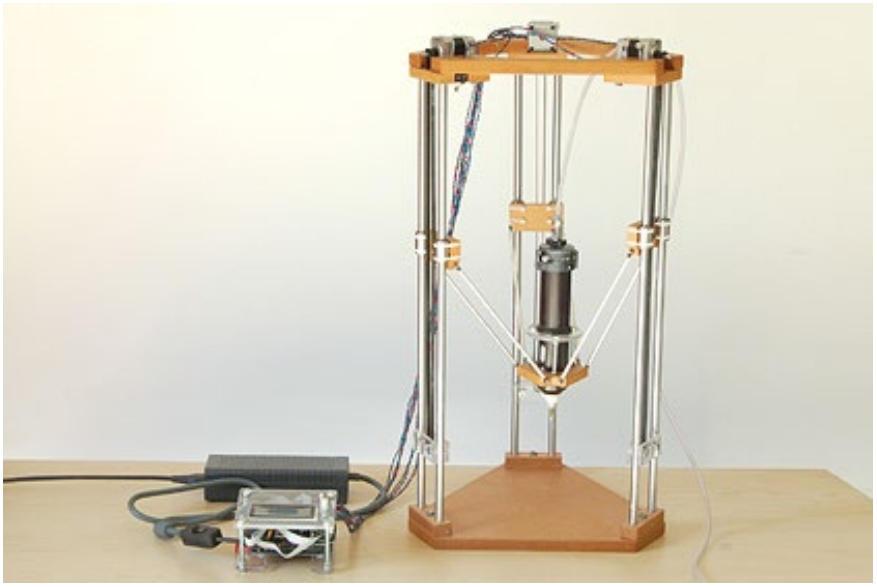


Figure 5.8 Jonathan Keep's DIY Delta 3D printer for clay printing. The printer does not use an extruder to control the flow of paste but rather the pressure and flow of paste from an air compressor. (Keep)



Figure 5.9 3D printer clay vase for sale by Alterfact Studio (2023)

Some systems use stepper motors to interpret the e-step speeds typically used for thermoplastic extrusion into rotational force for augers (Figure 5.10). Auger-based extruders can be purchased commercially and can be costly; however, open-source designs exist (Figure 5.11). While thermoplastic systems have a singular value for material extrusion, in which the extruder pulls material from the spool and pushes it to the printer, this process is split into two functions for auger-controlled paste extrusion. Pneumatic paste extrusion functions like a Bowen tube 3D printing system but with two 'e-step' (extrusion) settings controlled individually; one 'e-step' can be considered the pressure value for the paste delivery system, and the other is the actual extruder (e-step) controlling the auger spin. These variables work off each other to control material flow and paste deposition, and various factors affect them.



Figure 5.10 LDM WASP Extruder XL 3.0 which retails at 990 euro (WASP, 2023c)



Figure 5.11 Open-source designed StoneFlower extruder schematic. Most of the parts can be purchased from hardware store (StoneFlower3D, 2022)

Like the paste delivery system, auger-controlled paste extrusion has several components that can affect material flow. The extruder assembly, which is mounted on the printer gantry where the hot-end would traditionally be found, consists of the main extruder assembly body, which has a paste inlet, paste outlet (nozzle), auger hole, and mounts for the stepper motor connected to an auger with a flexible beam coupling. As discussed above, these can be purchased commercially, built through open-source designs, or designed for project-specific purposes. When designing an extruder assembly, tolerances in the auger shaft and auger selection (regarding flutes and helix angle) are critical for controlled and consistent material flow. Further, the choice of nozzle diameter affects this flow and is also affected by the particle size and thickness of the paste.

In the paste extrusion system used in this research, a custom 3D-printed extruder assembly was designed after inconsistent results from open-source designs (Figure 5.12, Figure 5.13 and Figure 5.14). Using parametric modelling and 3D printing allowed for the rapid development of new iterations. The all-in-one body was designed to minimise weight and allow for simple mounting of the e-stepper motor, paste delivery system, and mounting to the printer gantry. Designing and printing the extruder body allowed for the finetuning of the auger shaft tolerances around the selected auger, enabling significant control over material extrusion. The design allowed for minimal to no material leak from the nozzle between prints and retraction functions, enabling large non-extrusion movements without leaking.

Further, minor changes to line width could be controlled live through the delivery system or through the slicer software settings between prints for consistency. The experimentation process in this research showed that the development of consistent printing with an NMC and 3D printing system can happen in unison. While various milestones could happen sequentially, such as paste development, delivery system, and printing system, iterations to the previously developed and designed aspects can be improved.

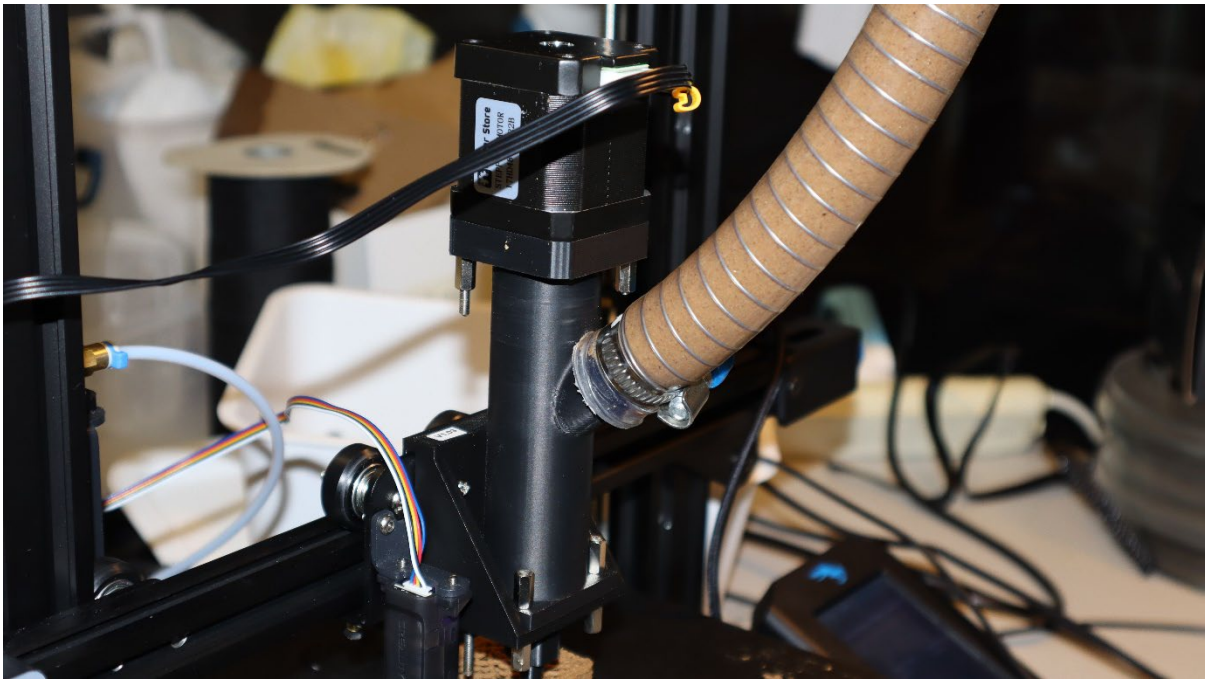


Figure 5.12 EXRTUDER_003_002 in use.



Figure 5.13 EXTRUDER_003_002 photographed in a light booth. The angled inlet was designed to act as a hose barb.

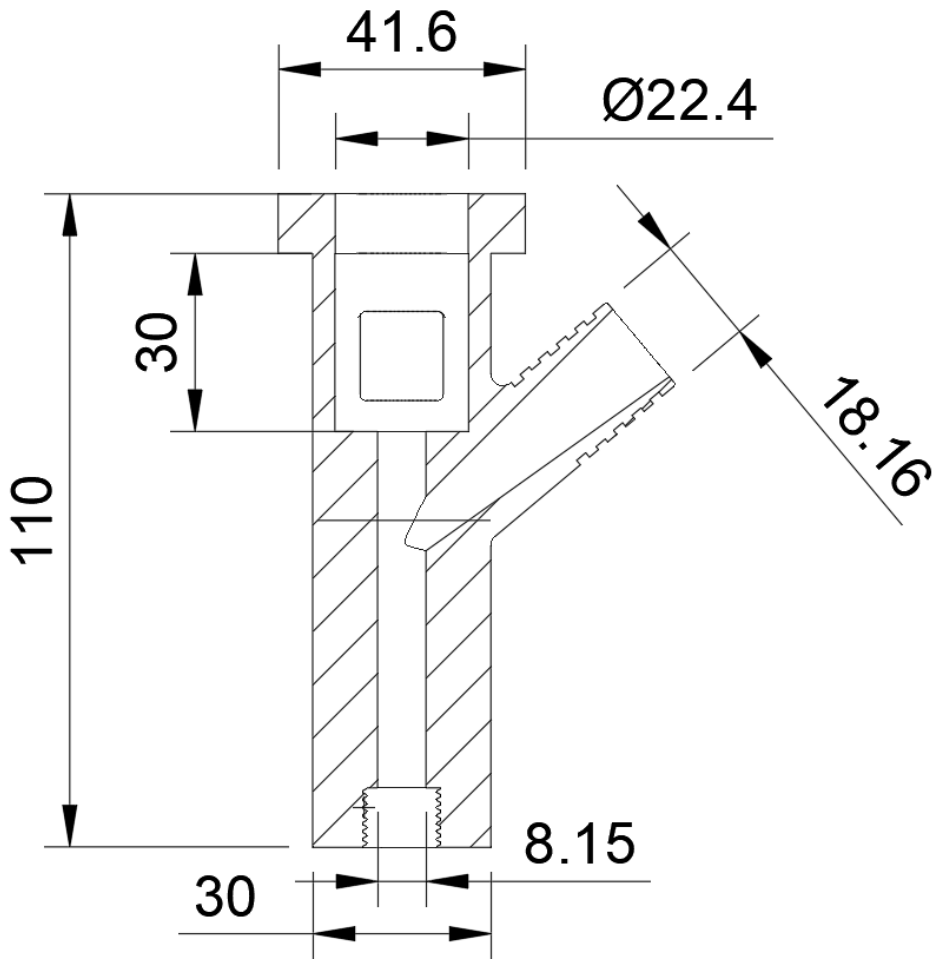


Figure 5.14 Section View of EXTRUDER_003_002.

5.3 Application

As discussed in the Literature Review *(2.1),* prototyping and product design processes are central to knowledge generation and product development in academic and industrial practice (Walden et al., 2018). McElroy (2016a) states that prototypes are the physical embodiment of the development of ideas, whose purpose is to be tested, analysed, reflected upon and refined based on self-analysis and user feedback. Wensveen and Matthews (2014) analyse the various roles that prototypes can embody during different modes of design practice. They argue that prototypes can serve as an experimental component in formalised research processes and a means of inquiry for data collection within a design project; a prototype can also be a research archetype that physically embodies the culmination of a design research process. These roles can overlap, where a prototype generated within an academic design project can serve as an experimental component of practice and a physical embodiment of the culmination of a design research process (Dunn, 2017; Stappers, Sleeswijk Visser, & Keller, 2015).

Within prototyping practice, the fidelity of a prototype often depends on the means of enquiry for which the prototype is intended (Hallgrimsson, 2019; Trudeau, 1995). Product fidelity has been defined differently by researchers and practitioners. Both Hallgrimsson (2019) and McElroy (2016b) categorise prototyping as high-fidelity and low-fidelity prototypes. Low-fidelity prototypes have also been referred to as mock-ups (Augustin, Augustin, & Coleman, 2011; Milton & Rogers, 2017; Säde, 2001; Thomas et al., 2011), but are considered 'explorative prototypes' in this research; they are generally rough and are generated quickly, made from cheaper and easy to manipulate material like form core, foams, paper, cardboard (Hallgrimsson, 2019) (Figure 5.15). Explorative prototypes encompass prototyping investigations such as sketch, form, and other low-fidelity prototyping. Explorative prototypes are used for faster iterative prototyping cycles, such as rapid form development, for initial ergonomic testing and user feedback.

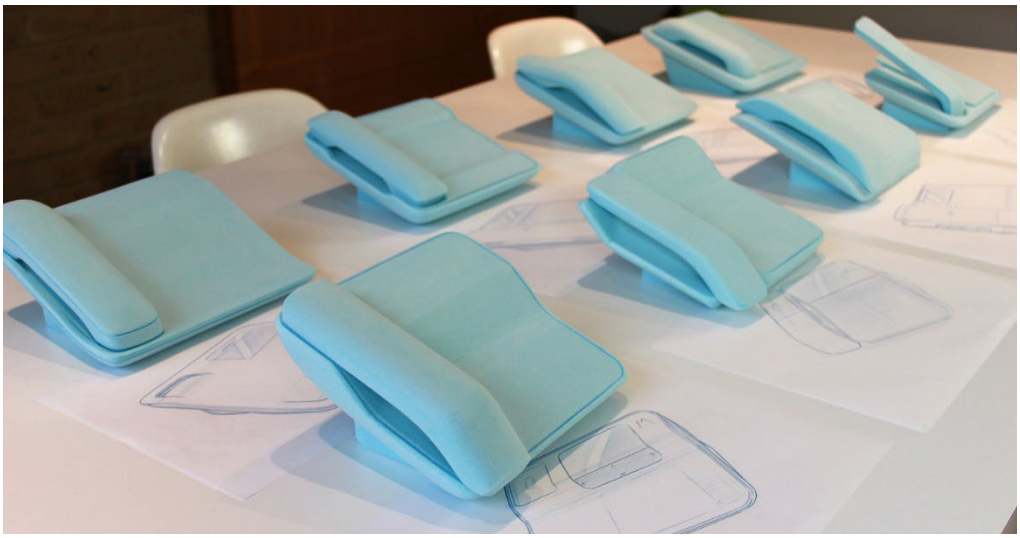


Figure 5.15 Explorative foam prototypes created by (Curventa, 2023)

High-fidelity prototypes are models used to accurately determine a design's final appearance and functionality (Hallgrimsson, 2019). Usually, high-fidelity models such as appearance models are produced using higher quality and end-use materials such as timbers, composite materials, and alloys, and may be produced using advanced machinery like CNC machines and commercial 3D printers (Milton & Rogers, 2017). High-fidelity prototypes will often have careful attention paid to their minute details and will be a highly accurate 1:1 scale representation of a finished product, but may not be functional (Figure 5.16). These types of prototypes can often be found at trade fairs, on display at corporate offices or shop windows, and used in demonstrations with prospective customers.



Figure 5.16 Appearance prototypes (Kanoski, 2018)

As discussed, this research focused on explorative prototyping, which can be viewed as an embryonic stage of product development in that ideas and concepts are translated from 2D sketches to 3D objects. The explorative prototyping process is usually fast-paced; a designer will quickly construct a prototype from cheap materials such as paper, cardboard, and foam, representing initial ideas and concepts. These models are produced rapidly and tend to be used quickly to evaluate form, ergonomics and user feedback. As discussed in *2.2* Additive Manufacturing, rapid prototyping in 3D printing has become more accessible and approachable. It has become implemented as a tool for explorative prototyping in product design practice at all levels, such as industrial firms, academic research, educational settings and hobbyist activities.

Prototypes developed through both handmade and 3D printing explorative studies have tremendous benefits to design development and research. However, the models tend to have short lifecycles, using materials that can have lasting impacts on the environment. Of particular interest was identifying functional use cases in academic, educational and industrial settings, where the BSG NMC and systems developed could provide meaningful change to product design practice. The NMC and printing system were developed envisioning more sustainable explorative prototyping practice through localised sourcing of organic waste material and in-house material development, focussing on potential use cases of the material and system rather than replacement, and the exploration of functional use in academic, educational and industrial product design practice.

Through the research through design practice in this thesis, the BSG-based NMC developed was identified as a capable and suitable material for use as a sustainable material in the 3D printing of explorative prototyping, particularly in rapid generation for form, scale and ergonomics investigations. Two consumer electronic devices, Logitech mice and Xbox controllers, and a series of kurrajong seedpods were used to explore the 3D printing systems and NMC pastes' capabilities for explorative prototyping (Figure 5.17, Figure 5.18, Figure 5.19, and Figure 5.20). The gaming mice and controller were selected to represent the types of objects product designers in industry, academic, educational, and hobbyist settings would be developing in terms of form, complexity, size, and volume. Further, the series of kurrajong seedpods were created to explore explorative production for end-use and user interaction via extensive postprocessing, improving prototype fidelity and physical qualities. The development of NMC paste, 3D printer and related systems and the making and processing of artefacts through research through design practice provided insights into potential material applications.

Through the process of developing the NMC, printer, and related system (described in 4.2 and 4.3), a potential use case for the material and system as a tool to rapidly produce explorative prototypes became apparent. While aspects of the research focused on finetuning recipes and developing system and slicer settings, the artefacts produced showed potential for use in the rapid production of explorative prototypes, where many iterations can be produced quickly, exploring scale, form, and ergonomics. Explorative prototyping of handheld consumer electronics such as mice and controllers can be printed in roughly a quarter (or less) of the time taken by thermoplastics on the same printer. While drying time and shrinkage remain a consideration, large batches can be printed and dried simultaneously for further experimentation, testing, user feedback and evaluation.

These capabilities are suitable for industry, academic, educational and hobbyist settings, where the paste development process, 3D printer and associated system can serve as a tool for more sustainable rapid production of explorative prototypes. More specifically, for prototype creation, the system is suitable for educational settings where many students may need to produce explorative studies to evaluate scale and overall form. The system could be used in professional settings by companies such as Logitech and Razer during the design and development of computer mice and similarly sized electronics, where many CAD designs with slight alterations need to be produced physically for presentation to users and clients of ergonomic and form experimentation.

Further, as identified in the development of Kurrajong Seedpods for display at the MCA in Lucy Simpsons' *Holding Ground* exhibition and through refinement to 3D printed mice, dried 3D printed components can have extensive postprocessing, increasing its use cases beyond explorative prototyping towards more high-fidelity model making. Through experimentation, the 3D printed models showed that they could withstand extensive sanding by hand and power tools and drilling, and that further postprocessing could be conducted, such as puttying holes, glueing parts together, creating assemblies, and coating. These processes could be implemented in professional, educational, academic and hobbyist practices, where explorative prototypes could be advanced through postprocessing into high-fidelity models, such as appearance prototypes, with smooth exteriors and finished exterior details. Prototyping exploration can continue with wet paste being sculpted onto solid and wet bodies to create new features and seal imperfections. Parts can be smoothed through sanding, and assemblies constructed from separately printed or sculpted parts. Multimaterial assemblies could be constructed, where a prototype's larger or main body is printed in NMC paste, and smaller details could be applied to reusable prefabricated components.

The NMC paste and 3D printing system developed in this research have shown the potential to impact prototyping practice in product design significantly. More specifically, the system can potentially create more sustainable explorative prototyping practices through localised organic waste material sourcing, processing and development for use with affordable consumer 3D printing technologies. The processes, materials, and systems developed are viewed as points of maturation in product design practice, identifying the need for systems for sustainable material development utilising material attributes rather than developing materials for broad replacement of thermoplastics.

ANCHOR

Using the same settings as previous prints, the overall dimension of the 3D model were increased in Simplyfy3D, to match the shrinkage rates recorded in previous prints.

1:1 scale Logitech G1 Scan

L 116.94mm

W 61.70mm

H 37.31

Dried prints

L 103.50mm (11.5% shrink)

W 57.23mm (7.2% shrink)

H 25.93mm (30.5% shrink)

This print used the shrinkage rates to increase dimensions to:

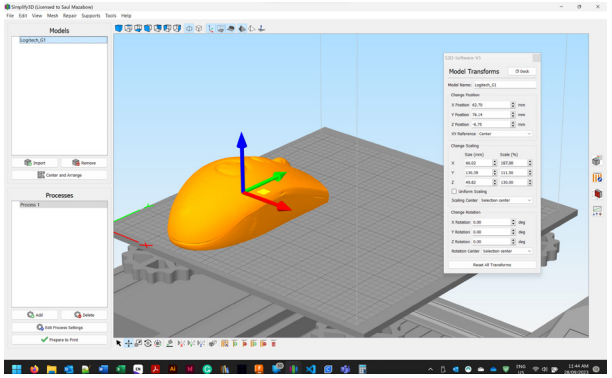
L 130.4mm

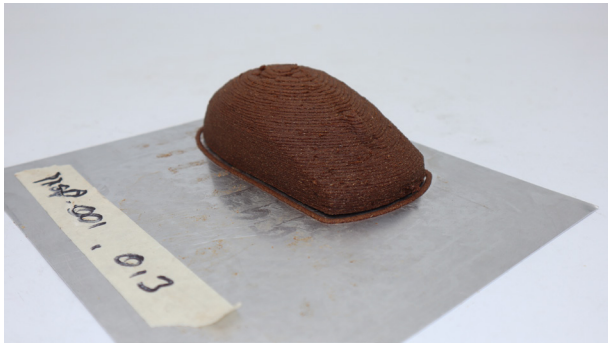
W 66.16mm

H 48.709mm.

Prints were dried at 40 degrees C in the dehydrator until dry.

EXPERIMENTS









OUTCOME

Dried dimensions:

L 117.78mm (-1% off 1:1)

W 58.05mm (6% off 1:1)

H 28.24mm (24% off 1:1)

These shrinkage rates show that vertical slumping is the key factor to solve in shrinkage, as it effects the others. This will need further investigation into factors such as material water content and drying environment which effect the drying time, as well all wall thickness, infill type and percentage. Perhaps slumping can be mitigated by better structural stability from the infill during the drying/shrinking processes.

Figure 5.17 PRODUCT_001_013

PRODUCT_001_013_ENLARGED

ANCHOR

Printing the Logitech Master MX 3 based on shrinkage rates from PRODUCT_001_026.

Infill Triangular 40%

3D Model Dimension:

L 124.61mm

W 84.33mm

H 50.31mm

Enlarged imensions

L 133.00mm

W 96.44mm

H 70.00mm

Print Time 1 Hour 51 Minutes (111 minutes)

EXPERIMENTS









OUTCOME

Dried Dimensions:

L 87.07m (9.3% shrink and -3.25% of goal)

W 120.37 (9.5% shrink and 3.4% of goal)

H 46.52 (33.54% shrink and 7.5% from goal)

Whilst still not achieving 100% dimensional accuracy, the print was a success. Confirmed through 3D scanning the dried print and compared to the digital files, the shrinking can be assessed, planned and further developed for future experimentation. Overall, the model is roughly within 10% range of the desired size, showing significant progression in controlling of shrinkage behaviour.

Figure 5.18 PRODUCT_001_027



Seedpods were displayed at Lucy Simpon's Belle Room commission at the MCA in Sydney.

Figure 5.19 PRODUCT_002_009

ANCHOR

Exploring getting dimensional actuary through enlarging the part in the slicer to match shrinkage rate_based on shrinkage of PRODUCT_001 and of other PRODUCT_003 prints:

L 170.00mm (9% increase from 155.28 1:1)

W 117.81 (9% increase from 155.28 1:1)

H 72.27 (22.51% increase from 56.00 1:1)

Nozzle 1.75m

Layer Height 0.875mm

Retraction 4mm @ 40mm/s with 2.5mm lift

Top and Bottoms 2

Perimeters 1

Infill 40% triangular with 50% overlap of perimeter

Support 60% triangular with 3.0mm inflation

Speed 55mm/s with 70% outer perimeter speed, all others 80%

Printed via Simplyfy3D from computer to control pause function for loading of extra material

Print Time 220 minutes (3 hours 40 minutes)

EXPERIMENTS









OUTCOME

The final model completed and showed interesting details into the capabilities of the system. Shrinkage of the length and with reached under 1% of the intended 1:1 models dimension, whereas the vertical shrink was 16%. Further exploration of infill and external support to control slumping is needed for full dimensional accuracy. Pausing the print using the simlpyfy3d controller allowed for refilling the paste cartridge mid print, exploring ways of doing this with the onboard controller would also be useful to minimise wires and possible lose connection failures. The surface quality of the part was very good, and would be useable in scenarios where users needed to handle the prototype. Further exploration of infill and support material is needed, first to control slumping, and second in relation to bridging movements where the top layers of the print struggling to cover the distance needed in closing the top layers. Overall this print shows good progression of the settings, system and material for producing explorative prototypes with improvement needed mainly to shrinkage calculations.

Figure 5.20 PRODUCT_003_004

6 Conclusion

The design of sustainable novel materials is a broader industry-based answer to the challenges posed by petrochemical thermoplastics. This research presents a design-for-purpose approach to novel material development aimed at creating a space where NMCs could be designed through product design practice for use in product design practice. The research highlights that through the process of NMC development, suitable scenarios for use have become apparent. This contrasts with current trends, where NMC utility is determined by comparing it with production-ready thermoplastic materials. This design-for-purpose approach enables product designers to tailor the material's use case and lifecycle situationally, enabling the design of suitably recyclable, compostable, biodegradable, and reusable within their intended application.

The research presents a complete material development process explored through product design practice. The research outlines processes for product designers that assist in identifying local organic industrial waste and guidance in developing NMCs for specific purposes. These processes can be adapted to the practice of product designers in educational, academic, professional and hobbyist settings. This includes defining processes for designers to identify locally available waste resources for use in NMCs (see *4.1*) and material development and refinement processes for product designers (see *4.2*). Further, the research reports and shares the development of a combination pneumatic and auger-controlled paste extrusion 3D printer, which uses consumer-grade hardware (see *4.2*). The material, processes, and 3D printing systems developed were then applied to product design practice, where the BSG-NMC paste and printing systems were evaluated and confirmed for suitability in product design explorative prototyping processes (see *4.3*).

Methodological approach

This research is situated within the context of product design practice and novel material development. The practice-based aspects of the research utilise research-through-design (RtD), an iterative solution-focused process where designers probe their way through unknowns towards a desired outcome. The RtD process is documented using aspects of action research, such as critical diary-inspired documentation, incorporated within a contextual portfolio (CP) practice (Sadokierski, 2019). RtD and CP practices are complementary; CPs help designers capture, analyse and share research-through-design practice, creating a framework for extracting and sharing the embedded knowledge in artefacts generated in practice.

Taking inspiration from processes found in action research (Kemmis, 2009; Swann, 2002) and annotated portfolios (Gaver & Bowers, 2012), the marriage of RtD and CPs allows practitioners to plan, document, reflect, synthesise and share their process with a wider audience (Sadokierski, 2019). The workflow developed in this research utilised CPs as vehicles for the planning, documentation, critical reflection, synthesis and sharing of RtD practice, which can be implemented in a wide range of product design and practice-based settings.

CPs provide designers at all levels of practice with a flexible vehicle for sharing their process, giving viewers deep insights into the possible hidden actions and intentions in the development of artefacts. CPs are flexible documents that can be adapted to context, such as a contextual display next to an artefact, used in magazines or advertisements, used as project share panels and used as a supporting document encapsulating an entire design journey.

Research Questions

Based on findings in the literature review, three research questions were created as guides for this research. The questions were primarily investigated through RtD, with research question 1 using a hybrid literature review to build a knowledge base that underpinned the subsequent practice-based investigations. The research questions were designed to be answered sequentially, where the findings from each question become the foundational knowledge required and the point of entry to begin investigating the next. The sequential nature of the research questions allowed for more meaningful transitionary periods between research questions; new findings entered into a cyclical evaluation process through their utilisation and refinement in the experimentation of the next question.

1. What is involved in identifying, sourcing, managing and preprocessing a sustainable waste material suitable for development into a novel material composite (NMC) for material extrusion (MEX) printing?
2. What is involved in generating 3D forms for product designers using MEX 3D printing and NMC?
3. To what extent can MEX printing of NMC support the physical prototyping requirements of product designers?

Thematically, the questions ask for investigation into specific aspects of novel material development. Research question 1 asks about *material* development processes, research question 2 asks about the *processes* involved when developing a 3D printing system for NMC development and use, and

research question 3 asks about the development of material and processes towards a specific *application*. This conclusion presents key research findings under these three categorical themes, *material, process,* and *applications*, as a way to group, collate, and extrapolate outcomes from across the thesis and link the research output with the recommendations of future works (see *6.5*).

6.1 Material

Through the literature review, it was found that researchers from a broad range of disciplines, such as the sciences, engineering, and design, have been developing sustainable NMCs for MEX as possible sustainable substitutions for thermoplastic polymers (Faludi et al., 2019; Rael & San Fratello, 2018; Sauerwein, 2020). Further, a trend in material sourcing was found, where researchers investigated the implementation of underutilised organic waste from local industries as functional filler materials in their NMC feedstocks. Researchers identified, sourced and tested potentially underutilised local waste streams, such as BSG, grape marc, bagasse, orange peels, and coffee grounds as functional fillers in NMC pastes and filaments for MEX 3D printing, exploring potential use cases for their materials or comparing them to more established materials such as PLA and ABS.

The literature review highlighted the advantages in developing NMCs from localised organic waste resources and identified potential and meaningful cases for these materials beyond comparison with established and refined thermoplastics. It was identified that through a systematic and thorough enquiry and with transparent sharing of results, NMCs could be developed more broadly with functional use cases (Sauerwein et al., 2019). Through these findings, this research aimed to create transparent, accessible and repeatable processes for developing and assessing functional use cases of NMCs utilising local organic waste.

The findings from the literature review became the foundational research for research question 1, which documented the research process for identifying, sourcing, managing and preprocessing a locally sourced waste product into a preliminary NMC. Potential underutilised organic waste sources were identified through a review process that prioritised the locality of potential waste, evaluation of the waste's current use cases and limitations, and narrative connections that could be made between the producer, the locality of the production, and product design.

Ultimately, Brewers spent grain (BSG), the most substantial solid waste output from beer brewing processes, was selected to be the subject of the study. A substantial amount of BSG is produced locally in NSW, with breweries as close as 2.2 kilometres from the university campus. Due to its fast degradation, BSG, a wet and reactive mix of used barley husks, has limited meaningful use cases beyond its use as animal feed; this limitation can only be mitigated by substantial investment from brewers. It was found that designers, scientists, and engineers have been experimenting with BSG as a functional filler in NMC feedstocks; however, a worthwhile use case that could require upcycling of BSG output has yet to be identified, and processes for identifying such a process were not readily available.

A preliminary bioderived and cellulose-based BSG-NMC was developed, utilising carboxymethylcellulose (CMC) as a non-toxic biodegradable binder, dried and ground BSG as a functional filler, and water for dilution and mixing. This proof-of-concept NMC confirmed BSG as a functional filler in a manually extrudable material for MEX 3D printing. All processes, from sourcing and storage to mixing and manual extrusion testing, were documented through the CP practice, incorporating seminal research as inspiration to create easily interpretable, transparent, accessible, and repeatable processes conducted using kitchen appliances. These preliminary material development processes created foundational knowledge for the progressions into the *process* development stage of the research

6.2 Process

Research question 2 documented developing and refining *processes* related to consistent and predictable MEX printing with an NMC. This research built upon the *material's* findings, refining the proof-of-concept BSG-NMC to a designed-for-purpose 3D printable material for use in product design prototyping practice. Additionally, this phase of the research documented the development of an economical 3D printing system with easily accessible components. It also presented the development of a pneumatic paste delivery system and slicer-controlled auger-based extruder that is easily manufactured (through 3D printing), adapted to new componentry, controlled, and mounted to consumer-range desktop thermoplastic 3D printers. While reported separately, the actions undertaken in research question 2 demonstrate that the *processes* involved in material development and mixing, auger design, paste delivery and printer configuration are interconnected in regard to the effectiveness of an NMC for functional use.

Material development continued from development goals of proof of concept to functional development. Material development goals balanced the constraints of functional goals, sustainable efficacy, availability for consumer purchase, and extrudability. Ultimately, the material BSG-NMC evolved alongside the development of the paste delivery system and extruder design-balanced constraints, such as functional goals, drying speed, smoothness, self-adhesion, and self-supporting strength.

This research developed an economical and easily replicable paste MEX printing system. Developed using two consumer 3D printers (AnyCubic Kossel Delta and Creality Ender 3 V2), the system configured utilised the benefits of larger material capacity pneumatic paste delivery systems with accurate and consumer slicer-controlled paste deposition through an e-stepper motor-controlled auger system housed in a customisable 3D printed body.

Realising the material and systems potential as a tool for product design explorative prototyping became achievable through shifting experimentation processes and system development towards use cases in product design practice (*process to application)*, which took form in the transition from abstract shape printing to printing shapes that may be produced in product design explorative prototyping practices.

The significance of the MEX and pneumatic paste delivery systems developed in this research is in the technologies that enable researchers and makers in NMC development. Consumer printer technologies enable the testing and rapid development of NMCs, which could provide efficacy to

potential use cases for organic waste resources. Makers, designers, and researchers who have access to affordable and adaptable 3D printers enable potential remote investigations of localised waste. The material and printing system was developed through product design practice to be accessible and replicable in multiple settings. The ingredients and components for printing can be sourced and purchased easily by consumers, and the system's adaptability to new materials and workflow processes enables it to be used as a testing rig for NMC development or a practical tool for product design prototyping practices.

6.3 Application

Through the development process of research question 2, the combination of the BSG-NMC and interconnected paste extrusion and printing systems was identified as suitable for product design explorative prototyping practice. This was due to the speed of printing, the resolution of printed components, their ability to accommodate post-processing, and a sustainable alternative for the *materials* lifecycle (from local underutilised waste to compostable), answering the initial questions raised about unsustainable material used in product design practice.

The final BSG-NMC recipe (PASTE_004_012) considered the functional roles of the ingredients (see *5.1.3*) to develop a material that could predictably and reliably pass through the paste delivery system and extrude with preset slicer settings. PASTE_004_012 uses dried and ground BSG sourced locally from 4 Pines Brewers as a functional filler material, a 6% solution of CMC as a binder, the multifunctional additives of vegetable glycerin as a lubricant, plasticiser and preservative, and methylated spirits for faster drying. PASTE_004_012 can be printed in much the same format as other consumer thermoplastic MEX printers (layer by layer with infill and support material) into forms traditionally 3D printed in explorative prototyping practice, such as computer mice and game controllers. Once dried, these forms could undergo extensive post-processing (see *4.3.5*), increasing their fidelity and solidifying the system's usability in product design practice.

Within the workflow of product design explorative prototyping, printing handheld devices such as computer mice and gaming controllers, the developed system can print models in roughly a quarter of the time it would usually take to print with a standard thermoplastic configuration on the same printer. While nozzle size, drying time, and shrinkage rates remain a consideration, large batches can be produced more quickly for form evaluation, physical testing, and user feedback. These capabilities suit industry, academic, education, and hobbyist settings, where localised *material* development, low-cost paste MEX printing systems and related *processes* can be implemented in sustainable rapid explorative prototyping.

While the *material* and *processes* developed in this research focused on developing an NMC utilising locally sourced BSG and consumer-grade paste MEX printing system for explorative prototyping, the processes can be applied to the development of other *materials* with alternate *applications.* Examples could include the development of sustainable novel alternatives to materials used in subtractive prototyping practice, such as polystyrene and polyurethane foams, foam-core and MDF board, and the development of bioderived adhesives and clay alternatives. In developing a suite of

NMCs utilising locally sourced organic waste, designers could develop more sustainable prototypes at a wider range of fidelities suitable for all stages of product development.

6.4 Chapter Summaries

In this conclusion, I now summarise my answers to the three guiding research questions and demonstrate the implications of these answers by identifying their significance and contribution to product design practice and the development of NMCs. This conclusion presents the main findings of my research as presented in each chapter; then, it outlines the original theoretical, methodological, and empirical contributions made. Finally, it raises possible areas for future research that have emerged from the findings of this research.

Chapter 1, Introduction, positioned the research by describing the problem context concerning creating more sustainable product design practices. Further, the research questions were introduced, and the methodological approach for addressing them was outlined. Next, the rationale and significance of the research were provided, outlining the need for more targeted development of NMCs for specific applications rather than as replacements for well-established and highly developed human-made polymers such as ABS and PLA.

Chapter 2, Literature Review, constructs an in-depth review and analysis of the problem space, outlining the relationship and interconnected behaviour between the climate crisis, product design prototyping practices, AM and novel material development. The chapter first introduces product design prototyping practices and describes their importance and the central role prototyping plays in product design practice in academic and industrial contexts. Further, traditional and current prototyping practices and techniques, particularly around material use, are reviewed regarding their sustainability and environmental effects. Next, the climate crisis is addressed, particularly focusing on the negative impacts of human-made polymers. Additive manufacturing (AM) is then reviewed concerning its growth and now established use cases in prototyping, through its affordability, scalability, on-demand nature, and increased approachability. Further discussions explore the negative environmental impact of current materials used with consumer AM technology. Last, current efforts by scientists, engineers and designers developing NMCs by utilising organic waste resources as feedstock for AM are reviewed and assessed. The results, which described the need for more transparent and situationally targeted materials rather than overall human-made polymer replacements, formed the foundational knowledge and direction for the practical investigations undertaken in later chapters.

Chapter 3, Methodology, introduced the methodological approach utilised to answer the research questions. This practice-based research utilised a research-through-design approach, which was documented, reflected, synthesised, and shared through CPs. Using CPs to capture RtD practice

provides a framework for synthesising and sharing the often difficult-to-interpret and hidden information designers unconsciously embed in prototypes.

Chapter 4, Experimentation, is split into three sections, each focusing on answering a single research question. The research questions were investigated and answered sequentially, where the findings and outcome of the first question became the foundational knowledge required to commence experimentation into the next. The three sections can be summarised as follows:

4.1 Research Question One describes the systematic process of identifying, sourcing, managing and processing local organic waste resources into novel material composites. Using Chapter 2's literature review as foundational knowledge, the research identified trends in NMC research, such as the use of locally sourced organic waste resources from industry. A selection criterion was developed, focusing on the selection of high cellulose content, low use, locally sourced organic waste from significant Australian industries. The wheat, barley, grapes and sugarcane industries were reviewed, and ultimately, brewers' spent grain (BSG), the most significant solid waste output from breweries, was identified as suitable for developing an NMC.

Before sourcing, academic publications utilising BSG were reviewed to create a baseline of best practices for the safe storage, management, and processing of BSG. Ultimately, BSG was sourced locally from 4 Pines Brewery and was stored and processed according to findings in the literature. Finally, an initial cellulose-based NMC paste recipe was created and mixed, utilising BSG as a filler material, and upon successful extrusion, the experimentation transitioned to research question two.

4.2 Research Question Two continued with the findings from research question one and explored the development of the NMC, a paste delivery system and configuration of a 3D printer for use in explorative prototyping in product design practice. Ultimately, an extrudable cellulose-based NMC paste was developed, utilising BSG as a functional filler and CMC as a binder, which was consistently extrudable, repeatable, and could be used to build organic shapes. Further, an economical and replicable paste delivery system utilising compressed air, a 3D printed extruder design and a consumer-grade 3D printer utilising accessible components were developed to reliably, accurately, and rapidly 3D print organic forms.

4.3 Research Question Three explored the extent to which the NMC paste and 3D printing system could support the needs of product designers conducting explorative prototyping. A series of Logitech mice, Xbox controllers and Kurrajong seedpods were printed, exploring the system's ability to fulfil the functional prototyping needs of product designers. It was shown that the paste and 3D

printing system could fulfil the needs for explorative prototyping in product design, such as rapid printing of organic shapes with infill and support materials using consumer hardware and software. Further testing explored the dimensional accuracy of printed components and post-processing needs and capabilities of models for further refinement of prototype fidelity.

Chapter 5, Discussion extrapolates findings from the experimentation reported in Chapter 4 regarding the accessible implementation of the processes developed into product design practice. This process is reported sequentially following the progression of the research questions and reviews processes relating to research question one, such as localised material identification, the adaptation of scientific explorations into designerly activities, and analysis of the roles of ingredients in NMC recipes.

Relating to research question two, the accessibility of paste-extrusion 3D printing is reviewed with particular interest in developing economical systems for rural and remote development of NMCs using localised waste resources. Next, the considerations required in successfully configuring interconnecting systems regarding material flow for consistent 3D printing are presented. Key considerations focussed on the interconnected relationships between paste recipe, choice and design in paste delivery systems, extruder design and auger choice on material flow.

Last, concerning research question three, prototyping in product design practice is analysed, and the application and capabilities of the paste and 3D printing system regarding successful implementation in product design explorative prototyping practice are discussed. The results from experimentation are used to align the paste and 3D printing system with the needs of product designers at hobbyist, educational, academic and industrial levels of practice. It was shown that the paste development process and 3D printing system have the potential to impact product design practice by facilitating more sustainable explorative prototyping practices utilising local organic waste.

6.5 Recommendations for Further Research

Based on the outcomes of the research conducted in this research, several avenues for further investigation can be recommended. These recommendations can be categorised through *material, process and application* themes, each tied to the actions and findings of the three research questions.

Material

As identified in research question one, entry into the world of novel material design can be challenging for product designers. Design-orientated studies reveal scarce details on material selection and development, and while the opposite is true for material scientists, the field-specific language used to report on processes and findings can be a limiting factor for designers engaging with novel material design. While material repositories are available (such as the *CHEMARTS Cookbook* (Kääriäinen et al., 2020a), Martiom (Garmulewicz & Corbin, 2018) and Material Design Map (2024)), the process of material identification, selection, processing and supporting information for the creation of NMCs is limited. This research recommends the development of digital repositories and communities that transparently share processes and translate field-specific scientific language into easier-to-follow protocols, processes, and direct actions that are understandable by designers and those interested in material development. These repositories could assist designers in understanding possible material choices in their location and aid users through safe potential actions in developing an NMC utilising available materials. Furthermore, users could share their recipes, actions (through CPS) and outcomes back into the platform to assist others in conducting similar processes.

Additionally, it was identified that researchers have been exploring extracting constituents from organic waste as a means to upscale their potential use cases. This was noted particularly in the case of BSG, an underutilised and abundant organic waste, where researchers were exploring extracting cellulose for further refinement. Further research would be recommended to explore the potential sustainability ramifications of developing an NMC utilising a single organic waste, refining portions into binder materials and functional filler. Research into the performance and life cycle analysis comparing the environmental impact of a single source NMC and an NMC using sourced ingredients could provide valuable insights into the sustainability ramifications of NMC design.

Process

During this research, an extensive investigation was undertaken to develop an NMC and paste extrusion 3D printer utilising off-the-shelf componentry. Within this development process, various avenues were chosen due to scope and time limitations; this section will recommend potential avenues for further research relating to material and printer development.

First is the consideration of the roles of the ingredients within an NMC. While this research explored cellulose-derived materials, utilising locally sourced BSG as a functional filler and CMC as a binder, other options for locally sourced organic waste and binders remain. Research exploring combinations of binders and fillers regarding their functional capabilities in paste extrusion 3D printing could provide designers with a baseline understanding of the possible use cases of available materials. Further, this could be developed into an environmentally friendly repository (discussed above) where users could submit their testing and application of use to assist future users in material development journeys. Furthermore, recipes and combinations of ingredients may be suitable for alternative applications beyond material extrusion 3D printing. Examples could be to vary the quantities of CMC and BSG to create dense foams and bricks that are useful for subtractive and low-fidelity prototyping methods.

Further development and refinement of the paste delivery system for more seamless use is suggested. Currently, available systems and the system developed in this research require material premixing and loading into cartridges and further material flow management during printing to the extruder assembly. Moreover, pastes require safe storage once mixed and have a reduced shelf life compared to their dry states. Further research could explore the development of a printer-mounted twin or single-screw mixer system that mixes ingredients during the printing and extrusion processes. This system could significantly reduce the preparation time needed to begin printing with NMCs while minimising unused material spoilage and storage needs. Further, the system could enable the printing of larger bodies through continuous material feeding and remove the need for premixed and preloaded cartridges. A mounted screw-based mixer and extruder system could further allow the implementation of paste extrusion systems in more settings, such as print farms or larger-scale manufacturing processes, by reducing overall preparation and hands-on time needed to manage paste extrusion systems.

Lastly, continued research exploring the development of open-source and economic paste delivery systems and extruder assembly designs could be key to the wider adoption of paste extrusion. Current commercial offerings are significant investments, and open-source designs can be cumbersome and lack refinement in their tolerances (see WASP, 2023a). The designs developed in

this research represent a positive contribution to this field. Further development in auger selection and tolerances, improved management of air pockets, stepper motor size, overall size and weight reduction, and quick-release mounting systems could increase the overall usability and adoption of paste extrusion printing.

Application

While the investigation in this research explored the development of an NMC paste and MEX 3D printing system developed for use in explorative prototyping practice in product design, higher levels of fidelity in prototyping through post-processing and drying methods should be explored. These investigations could be central in the widespread adoption of paste extrusion systems in product design practices. Variations in the level of prototype fidelity output by NMC paste print should be explored, such as high-fidelity appearance models and semi-functional models such as interaction design models. Developing and implementing NMC pastes in a broader range of prototyping activities could be a maturation process for locally refined NMCs, enabling more widespread adoption to their use in industry settings.

Further research is needed to investigate rapid drying processes of explorative 3D-printed paste prototypes. Drying is currently a limiting factor for NMC paste extrusion, where prototypes can be printed significantly faster than thermoplastic printing but can require extended periods to dry. Exploring rapid drying methods and other factors affecting drying behaviours, such as slumping, could be significant milestones in the possible implementation of the NMC paste extrusion system in educational, academic, and professional settings. NMC paste extrusion opens avenues for significantly more sustainable prototyping practices and provides users with opportunities for material knowledge development. Improving aspects of current systems, such as faster drying, less hands-on mixing, and methods of post-processing to a broader range of prototype fidelity, will give users in academic, educational and professional practice more incentive to implement similar systems in their workflows.

The end.

Appendix

Appendix A

Researcher and material location

Authors	*Field*	*Research Location*	*Material a (main)*	*Sourcing Location*	*Material b*	*Sourcing Location*	*Printing Type*
Carlo Ratti Associati	Design	Italy	Orange Peels	Not Listed	PLA	Not Listed	MEX [Filament]
Rael and San Fratello	Design	USA	[1]Salt [2]Sugar [3]Coffee [4]Chardonnay Waste	[1] Newark, California [2, 3] Not Listed [4] Soma Country	[1]"Glue from natural Materials" [3] "Water-based binder"	Not Listed	Binder Jetting
Nataša Perković [Hitti, 2020]	Design	Japan	Oil Palm Waste	"South East Asia"	PLA	Not Listed	MEX [Filament]
Markos Georgiou, Materiom	Design	UK	Oyster Shell	"from local restaurants"	Sodium Alginate Honey	Not Listed	MEX [Paste]
Ana Otero, Materiom	Design	Not Listed	Eggshell Waste	Not Listed	Xanthan	Not Listed	MEX [Paste]
Project Pomace (Sedar Asut)	Design	Netherlands and Turkey	Olive Pomace	Not Listed	Sodium Alginate	Not Listed	MEX [Paste]
Krill Design	Design	Italy	Orange Peels	Not Listed	100% vegetable material	Not Listed	MEX [Filament]
Forust	Design	USA	Saw Dust	Not Listed	"Plant based binder"	Not Listed	Binder Jetting
Mitterberger and Derme, 2020	Design	Austria	"Soil"	Not Listed	"Hydrogel"	Not Listed	Robotic Binder Jetting
MANUFACTURA (Shaikhnag, 2023)	Design	Mexico	Eggshell Waste	Mexico City	"bio-binder"	Not Listed	Robot Arm [Paste]
Model No.	Design	USA	"Plant-Based Polymers"	Not listed	PLA	Not Listed	MEX [Filament]
Milosevic et al., 2017	Engineering	New Zealand	[1] Harakeke (flax) [2] Hemp	[1] Templeton Flax Mill, NZ, [2] Hemp Farm NZ Ltd	Pre Consumer Polyproptlene	Astron Plastics, NZ	MEX [Filament]
Girdis et al., 2017	Engineering	Australia	Macadamia Nut Shell Waste	"Local"	ABS Maleic	Not Listed	MEX [Filament]

					Anhydride Binder		
Ali Osman & Atia., 2018	Engineering	Egypt	Rice Straw	"Local farmlands"	ABS	Taita Chemical Company Ltd, Taiwan	MEX [Filament]
Tran et al. 2017	Engineering	Italy	Cocoa Shell Waste (CSW)	Ferrero SpA. Italy	Polycaprolactone (PCL)	*Polysciences,Inc.* USA	MEX [Filament]
Mogas-Soldevila et al. 2014	Engineering	USA	[1] Chitosan (85% deacetylation), [2] Sodium alginate, [3] Chitin powder	[1] Alfa Aesar, USA, [2] Molecule-R, Canada, [3] NutriCargo LLC, USA	[1] Acetic acid, [1] Sodium hydroxide pellets	[1] Alfa Aesar, USA	MEX [Paste]
Lu et al. 2019	Engineering	Singapore	[1] Magnesium Oxide [2] Ground granulated blast-funaced slag	[1,2] Singapore	Fly Ash Cenosphere	China	Spray-Based
Stoof et al. 2017	Engineering	New Zealand	[1] Hemp[2] Harakeke (flax)	[1] & [2] New Zealand	PLA	NatureWork, USA	MEX [Filament]
Depuydt et al. 2019	Engineering	Belgium	[1] Bamboo [2] Flax	[1] Buco Import BVBA (Belgium) & Bambooder Biobased Fibers B.V (Netherlands) [2] "Flaxtape", Lineo, NV (Blegium)	PLA (cPLA1 & cPLA2)	Proviron Industries NV, Belgium	MEX [Filament]
Koushki et al. 2020	Engineering	Canada	Hemp Fibers	Ontario Hemp Materials Company (Canada)	GE 100% Silicone	Not Listed	MEX [Paste]
Sauerwein and Doubrovski 2018	Engineering/ Design	Netherlands	Mussell Shells	Netherlands	Sugar Water	Not Listed	MEX [Paste]
Saurewein et al. 2020	Engineering/ Design	Netherlands	Mussell Shells	Netherlands	Sodium Alginate	Netherlands	MEX [Paste]
Chinga-Carrasco et al. 2018	Engineering/ Science	Argentina	Sugarcane Bagasse	San Javier Sugar Mill, Misiones, Argentina			MEX [Paste]

Grigsby et al. 2020	Science	New Zealand	Kertain (wool derived)	Not Listed	[1] Lignin [2] Glycerol [3] Acetic Acid [4] Guar Gum [5] PEG400 [6] Kappa-Carageenan)	[1] USA [2,3] BDH [4,5,6] Sigma	MEX [Paste]
Liu et al., 2019	Science	China	Milk Protein Concentrate (MPC485)	Fonterra Co-operative Group (New Zealand)	Sdoium Caseinate (NaCN)	Fonterra Co-operative Group (New Zealand)	MEX [Paste]
Severini et al. 2018	Science	Italy	Carrots, Pears, Kiwi, Broccoli raab leaves, and Avacado	"Purcahsed Locally"	Fish Collagen	Paneangeli, Cameo s.p.a, Italy	MEX [Paste]
Kariz et al. 2018	Sciences	Slovenia	Beech Wood	Not Listed	PLA	NatureWork, USA	MEX [Filament]
Zhao et al., 2016	Sciences	China	Bamboo	Jiangxi Province, China	PLA	*NatureWork*, USA	MEX [Filament]
Liu et al., 2018	Sciences	China	Sugarcane Bagasse	Guangzhou Sugarcane Industry Research Institute, China	[1] PLA, [2] Sodium Hydroxide (>96%), [3] sodium Chlorite (80%), [4] Glacial acetic Acid (>99.5%)	[1] NatureWork, USA [2] Guanzhou Chemical Reagents Factory, [3] Shanghai Macklin Biochemical Co. Ld, [4] Damao Chemical Reagent Factory	MEX [Filament]

Appendix B

Wine

Australia Global

- **Fifth largest exporter** behind China (37%), USA (15%), U.K. (14%) and Canada (7%) (Australian Bureau of Agricultural and Resource Economics, 2020).
- Australia is the **sixth-largest wine producer** globally, producing 12 million hectolitres (mhl, 1 Hectolitre is 100 litres) in 2019. The largest producers are Italy (47.5), France, Spain, USA (24.3) Argentina (13) (International Organisation of Vine and WIne [OIV], 2020b).
- Australia is also the **tenth largest consumer of wine** at 5.9 mhl, which makes up 2% of global consumption. The top 5 consumers are USA 33, France 26.5, Italy 22.6, Germany 20.4, and China 17.8, making up 48% of all global consumption (International Organisation of Vine and WIne [OIV], 2020a).

Australia Domestic

- **Fourth biggest agricultural export** (in terms of dollars produced) in 2018, behind beef and veal, wheat (inc flour) and wool. Export value of 2.8 billion (Austrade, 2019).
- **1,653 thousand metric tonnes of wine grapes were crushed** for production in 2019. South Australia 859, Murray Darling- Swan Hill 386, New South Wales 359, Western Australia 36, Tasmania 13 (Wine Australia, 2020)
- Red production 57%, white 43% (excluding Murray Darling-Swan Hill).
- The **tenth-largest area for production,** 133 thousand hectares in the financial year of 2019-20, behind Wheat (10,159 thousand hectares), barley, canola, oats, lupins, grain sorghum, sugar can, cotton, chickpeas and field peas (The Australian Bureau of Agricultural and Resource Economics and Sciences, 2019).

Waste products

Muhlack, Potumarthi and Jeffery (2018) conducted a literature review of the utilisation of grape marc. From a scientific standpoint, the review investigates the instances where marc is being used, such as animal feed, biofuel, or soil. During the winemaking process, solid waste is known as grape marc or grape pomace (Figure). It is generated after the juice is extracted to ferment white wine and after the red wine's fermentation and pressing. It mainly consists of skins, stalks, seeds, moisture, organic acids, and polyphenols. Unfermented white marc contains residual sugars, whereas red marc has residual sugars and some ethanol quantities. These vary significantly according to the source of wine and processing practices (a point that is stated and essential when

using any naturally grown material). Figure B is from Muhlack et al. and shows grape marc's physical and chemical properties.



Figure A Raw grape marc as presented in an article by the Bargato Research Institute in their proposition for processing it into hand sanitiser during the COVID-19 pandemic (Bragato Research Institute, 2020)

An average Winegrape production of around 12 tons per hectare (t/ha) in Australia could generate over 2 t/ha marc, equivalent to approximately 20% of the fresh weight as solid waste (International Organisation of Vine and WIne [OIV], 2020b). In 2015, Australia crushed around 1.7 million tonnes of various grapes, resulting in several hundred thousand tonnes of marc. Various environment protection authorities in Australia mandate that wineries record the quantity of marc generated and its method of safe disposal (for example, Environment protection authority South Australia, 2004).

Parameter	Value	Reference
pH	3.6 ± 0.2	Lafka et al. (2007) (red grape marc)
Moisture	73.6 ± 2.6% w/w	
Reducing sugars	1.5 ± 0.3% w/w	
Ash	4.6 ± 0.5% w/w	
Cellulose	20.8% w/w	Mendes et al. (2013) (grape skins only)
Hemicelluloses	12.5% w/w	
Tannins	13.8% w/w	
Proteins	18.8% w/w	
Ash	7.8% w/w	

Figure B Physical and chemical properties of grape marc. Created by Muhlack et al., 2018.

"Grape marc is a form of biomass which, together with other organic residues from wine production such as vineyard prunings and grape stalks, would typically be considered a waste product. In some cases, these residues might be recycled for compost or stock-feed supplements (Arvanitoyannis et al.,

2006a) or further processed for ethanol, pigment and tartrate recovery (Braga et al., 2002). Thermal conversion of this biomass resource into high-value products such as energy (in the form of heat and electricity), charcoal (biochar), or chemical feedstock and transport fuels (liquids) are alternative process treatment options that can yield environmental and economic benefits (Digman and Kim, 2008)."

Current Waste Uses

Wine production plays a significant role in the Australian agricultural industry, and its waste products' use has become the subject of investigation. Grape marc has been explored as a waste product with the potential to be upcycled in various industries. Many studies have explored Grape marc to create biofuel (Celma, Rojas, & López-Rodríguez, 2007; Kendall R Corbin et al., 2015). Other avenues of exploration have been the creation of alternative alcoholic beverages with grape marc. Grape marc has large quantities of sugars that can still be used for ethanol fermentation. Alcoholic beverages such as 'Pomace Brandy' have been made using grape marc (Buglass, 2011). There have also been explorations into the use of grape marc in agricultural spaces, such as animal feed, bio-fertilisers and compost (Muhlack, Potumarthi, & Jeffery, 2018)

Wheat

Globally, wheat was the second most-produced grain in 2018-19, at 734.74 million metric tons. Corn was most produced at 1099.61 million metric tons (FAO & US Department of Agriculture, 2019).

Australia Global

- Australia was the **seventh leading exporter of wheat**, flour and wheat products from 2014-20 (US Department of Agriculture, 2020b).
- Australia was the **twelfth leading wheat producer** globally in 2019-20, producing 16,100 thousand metric tons. This number has decreased since 2016-17, in which Australia produced 30,363 thousand metric tons (US Department of Agriculture, 2020a).

Australia Domestic

- Wheat had the **largest area for crop production** in Australia for the financial year of 2019-20. Though this is slightly down from 2018-19 (10,159 thousand hectares), 2019-20 used 10,119 thousand hectares for wheat production. This is almost three times more than the second-largest crop production, barely at 3,930 hectares used in 2019-2020 (The Australian Bureau of Agricultural and Resource Economics and Sciences, 2019).
- Australia's **second-largest agricultural commodity** in terms of gross value was produced in 2019 at 6.4 billion AUD. Cattle and calves are the largest at 11.1 billion AUD in the same period (Austrade, 2019).
- The **second-highest export value of agricultural commodities** was produced in 2019, at 3.6 billion AUD. Again, this is only trailing beef and veal, which generated 9.1 billion AUD in the same period (Austrade, 2019).

Waste products

The main by-product of wheat cultivation is wheat straw *Triticum aestivum L.* (Figure C). Wheat straw has been identified as one of the agro-residues with one of the highest cellulose contents (Panthapulakkal & Sain, 2014). According to Panthapulakkal and Sain, wheat-to-straw production is 1:1, and only a small portion of the wheat straw is used in applications such as animal feed, while the rest is left on the field to decompose (general practice being to either bury or burn it). Decomposition leads to large amounts of carbon monoxide leaking into the atmosphere; however, legislation has been introduced to reduce these harmful practices. Other authors have reported a different harvest ratio, stating that wheat to straw-production is 850 grams per kilogram (Bakker et al., 2013, as cited by Millati et al., 2019, p 5). Millati et al. state that the total global wheat production in 2017-18 was 758 million tons, and their ratio equates to 640 million tons of wheat

straw. Interestingly, in their literature review, Panthapulakkal and Sain outline that some authors were able to obtain wheat straw at reported prices of between $0.04-0.33/kg, which is significantly less than the price of jute fibres, $1.45/kg or wood fibres (which vary) between $0.31-0.55/kg.



Figure C Online store selling wheat straw header tailings (AgSales Australia, n.d.).

Current Waste uses

Only a small portion of the wheat straw is used in applications such as animal feed and bedding, construction of mud houses and energy production.

With regards to current experimentation investigating the use of wheat straw as biocomposite reinforcement has shown promising results. Panthapulakkal and Sain (2014) compared the mechanical properties of wheat straw-PP composites with wood flour-PP composites. The results compared the tensile strength, tensile modulus, flexural strength, flexural modulus and notched impact strength and showed highly comparable figures suggesting that wheat flour could be used as an alternative to wood fibres in composites.

Sugarcane

Sugarcane bagasse is a "Fibrous waste remaining when sugarcane stalks are crushed to extract juice" (Figure D) (Pickin et al., 2018). Sugarcane production **has consistently increased globally** from 1965 to 2020. 531.3 metric tons were produced in 1965, and in 2020 1,907.02 metric tonnes were produced (FAO, 2020b).



Figure D Sugarcane Bagasse (Wilson, 2018)

Australia Global

- Australia was the **tenth largest sugar producer globally** in 2019-20, generating 4.29 million metric tons of sugar. In contrast, as the largest producer, Brazil produced 29.93 million metric tonnes (US Department of Agriculture, 2020c).
- Australia was the **fourth-largest exporter of sugar** in 2019-2020, exporting 3.32 million metric tons. Brazil was the global leader, exporting 19.3 million metric tons. (Agriculture, 2020). China imported the most sugar in this period, importing 4.1 million metric tonnes, followed closely by Indonesia at 4.04 and the USA at 3.38.
- Australia produced 33.51 million metric tonnes of sugar cane in 2018, making us the **ninth-largest producer** of sugar cane globally (FAO, 2020a). Brazil leads this category again with 746.83 million metric tons in the same timeframe.

Australia Domestic

- **Australia's second-highest generated organic waste is** 6,033 thousand metric tons or 20% of total organic waste. First is manure at 9,849 thousand metric tonnes, or 33% of total waste (Pickin et al., 2018).
- 95% of all sugar production in Australia is grown in Queensland. The other 5% comes from New South Wales. More than 80% of sugar produced is exported as bulk raw sugar (Department of Agriculture Water and the Environment, 2020).

Current uses

Often sugarcane bagasse is used as an onsite biofuel. It is collected after the milling process to be fed into a boiler for electricity generation at the milling site (Millati et al., 2019). Liu et al., 2018 explored using sugarcane bagasse fibre as composite reinforcement in PLA. The authors compared the effects of Raw Sugarcane Bagasse (RSCB) and refined Sugarcane Bagasse Fibre (SCBF) as additives to "clean" PLA filament for use with MEX printing. They use a chemical treatment (sodium hydroxide solution) to remove hemicellulose and lignin from raw sugarcane bagasse, and then the sample is treated in sodium-chlorite solution.

Appendix C – Contextual Portfolios

ANCHOR

The preservation series is tied to research question 1, in that it explores the nature of pre-processing a locally sourced organic by product.

Preservation processes were collected through a literature review which examined the landscape of experimental upcycling of BSG for its chemical constituents or in design processes.

Processing practices were identified and implemented through the preservation series until a suitable storage and processing workflow as found.

EXPERIMENTS









OUTCOME

Through the experimentation process, BSGs short shelf life was examined, and methods for safe and effective long term storage were assessed.

Ultimately, it was found that bulk drying BSG was significantly more efficient than bulk freezing. While effective for immediate storage of BSG, BSG should be parcelled into more manageable portions before being frozen to avoid the formation of difficult to manage ice blocks. BSG has an incredibly high water content of up to 80%, and removing this reduces the overall footprint BSG in storage. Furthermore dried BSG is immediately usable for experimentation, whereas frozen BSG needs to be dried before experimentation or use in pastes.

BSG was dried between 50-60 degrees C in a dehydrator, and stored in airtight containers. Some of this was also finely ground and stored separately allowing for immediate use in paste mixtures.

ANCHOR

The BSG was dried at 60°C for 48 h and thereafter ground and sieved using a 350 ?m sieve. It was then stored at room temperature in a dry place for further experiments. (Ravindran et al., 2018)

Despite the advantages of the additional BSG as animal feed, its use is still limited, which is mainly related to problems with storage of the material. The high moisture content of this residue makes it susceptible to microbial growth in the usual environmental conditions prevailing on farms (Stojceska et al., 2008). Within a few days after production, wet grain can undergo molding and spoilage; therefore, preservation is a key factor in the utilization of this by-product. (Rachwal et al., 2020)

Deterioration of the wet BSG takes place after an average period of 7 to l0 days from production, and under hot and humid conditions it may not be possible to store the wet BSG for a week. (El-Shafey et al., 2004)

Three methods for preserving spent grain: freeze-drying, oven drying and freezing were evaluated by Bartolome´ et al. (2002). Mussatto et al. (2004)

EXPERIMENTS









25 Kg's of brewers spent grain (BSG) as provided from 4 Pines brewery. Wet, unaltered BSG before storage. Unaltered BSG one week after collection. Substantial mould patches had formed as well as a strong and unpleasant smell. Frozen BSG one week after collection. Large ice crystals had formed on individual grains in addition to the grain being frozen into large blocks. This is a result of the high moisture content.

OUTCOME

BSG was kindly supplied by 4 Pines Brewery located in Manly NSW. Before collection, BSG was stored in their industrial refrigerator. Upon arrival at the University, the BSG had reached roughly 27-28 C, suggesting that the BSG was undergoing a reaction post-processing at the brewery. As per the preservation methods described by Mussatto et al. (2004), BSG three loads were prepared for preservation tests. Experiment PRESERVATION.001.001 focussed on comparing freezing BSG against 'unpreserved' BSG. Frozen BSG was stored in a glass oven-safe container and left in a consumer freezer at -5C for one week. 'Unpreserved' BSG was stored in an identical container and left and a low light location. After one week, the samples were compared (images c & d).

As seen in image c, unpreserved BSG experienced considerable microbial growth. Large clusters of white mould formed on the surface within the BSG structure. The container had an unpleasant smell and had extensive build-up precipitation on the lid. Frozen BSG (image d) froze into a solid block. BSG was suspended in a large ice cube and had ice crystals covering individual grains.

The purpose of this experiment was to demonstrate the need for immediate intervention when receiving post-production biomass. BSG has a high moisture content and needs to be processed for long term storage if smaller batches are needed for experimentation or immediately processed if bulk production (for design and manufacturing purposes) is intended.

PRESERVATION_001_001

ANCHOR

The BSG was dried at 60C for 48 h and thereafter ground and sieved using a 350 m sieve. It was then stored at room temperature in a dry place for further experiments.
Ravindran et al. (2018)

As soon as obtained, the material was washed with water until neutral pH, dried at 50 5C to 10% moisture content, and then pre-treated by dilute sulfuric acid and subsequently by sodium hydroxide solutions, to remove the protective hemicellulose-lignin wrapper.
Mussatto et al. (2008)

The material was washed with distilled water as soon as it was obtained until a neutral pH was reached, after which it was stored at -5C until further utilisation. The stored material was then dried at 50 5C for 24 h to attain 10% moisture content (untreated material). The dried material was further stored in a hermetic container at -5C to prevent any microbial growth.
Pawan Kumar et al. (2016)

Brewers spent grain (BSG) was provided by Athens Brewery S.A. Before use it was dried at 65C until constant weight and was chopped in a laboratory mill to a particle size smaller than 5 mm. BSG was alkali treated prior to hydrolysis reactions as described previously (Xiros et al., 2008) with 10% w/w NaOH.
Xiros et al. (2011)

Wet brewer's spent grain (BSG) was kindly supplied by a local artisan manufacturer, Cervesera Alcoyana S.L. (Alcoy, Spain). Before milling, BSG was died overnight at a temperature of 60C to avoid microorganism proliferation.
Revert et al. (2017)

EXPERIMENTS









a. BSG was stored for a week in a domestic freezer. After one week, the BSG had frozen into a solid block. b. Closer view of the ice encapsulating the BSG. The ice moulded into the shape of the bin bag in which the BSG was stored. c. BSG was loaded into domestic baking trays and placed into a Labec Dehydrating Oven. d. The controller settings on the Labec dehydrating oven, set to 60 °C with a 100 °C safety cut off. e. Dried BSG removed from the oven after 48 hours. f. Close up of the dried BSG, which felt brittle and dry and resembled the feeling of cereal.

OUTCOME

PRESERVATION_001_002 explored the process of generating bulk BSG for isolation tests and other experiments. Image a. shows the first learning experience of this experiment. Ten kilograms of BSG was frozen according to the methods described by Pawan Kumar et al. (2016). Freezing bulk BSG resulted in a large ice block that contained the BSG. It required several hours of manual chiselling to separate enough BSG to fill four large consumer baking trays. This shows that freezing bulk BSG may be an unsuitable preservation method and used only if the quantity of raw material acquired can not be preserved in other methods efficiently.

The four trays of BSG were oven-dried in an industrial oven located in the UTS Design Fabrication Workshop. As per Ravindran et al. (2018), Revert et al. (2017) Xiros et al. (2011), BSG was oven-dried at 60C for 48 hours. The oven was opened regularly to release any moisture build-up and to shuffle the BSG to avoid burning. Image f. shows a close-up image of dried BSG, which was brittle and light compared to its wet and mushy unaltered state when received. This BSG was stored in cereal boxes in order to prevent any contact with moisture and oxygen.

PRESERVATION_001_002

ANCHOR

"The BSG was dried at 60°C for 48 h and thereafter ground and sieved using a 350 ?m sieve. It was then stored at room temperature in a dry place for further experiments."(Ravindran et al., 2018)

"Before milling, BSG was dried overnight at a temperature of 60°C to avoid microorganism proliferation."
(Revert et al., 2017)

Brewers spent grain (BSG) was provided by Athens Brewery S.A. Before use it was dried at 65 C until constant weight and was chopped in a laboratory mill to a particle size smaller than 5 mm. BSG was alkali treated prior to hydrolysis reactions as described previously (Xiros et al., 2008) with 10% w/w NaOH.

Brewer's spent grains (BSG) were supplied by Ambev, S.A.(Anápolis, Goiás, Brazil). As soon as obtained, the material (approx.80% moisture content) was dried at 105?C to 94% dry matter. Then the dried BSG was milled using a knife mill fitted with a 1 mm-sized grating and used in all experiments.(Santos et al., 2015)

EXPERIMENTS









a. Dried BSG oven-dried for 48 hours. b. Image of the workflow (right to left); Dried BSG was blended in a kitchen coffee grinder and then sieved through a 50 mesh sieve. The process was repeated until all BSG was processed. c. 50g of processed BSG. d. Close up of ground BSG. Each particle fit through a 50 mesh sieve meaning each particle was roughly 1mm in size.

OUTCOME

Following the processes explored by Xiros et al. (2011), Ravindran et al. (2018), and Santos et al. (2015), dried BSG was ground and sieved through a mesh in order to achieve a particle smaller than 5mm. BSG was ground using a Breville 'Coffee 'n' Spice Grinder' and was processed through a small kitchen 50 mesh sieve purchased from a nearby Woolworths.

This process was labour intensive and slow due to the grinding process. Various other domestic coffee grinders were used to speed up the grinding process; however, achieving particle sizes that would fall through the sieve took several hours. Physically shaking the Breville grinder whilst holding the start button sped up the process but was labour intensive. Image d. shows a close up of the ground and sieved BSG.

Through further research and discussions with scientists at UTS, it was recommended to use a ball mill to process the grain faster and achieve more uniform particle sizes. It was also found that using a flour mill or knife mill would combine both grinding and sieving into a single process. Furthermore, a polymer chemist at UTS suggested that BSG does not need to be ground before chemical isolation processes and that grinding and sieving can be conducted post isolation.

PRESERVATION_001_003

ANCHOR

It was found that careful selection of milling-ball size is important to produce fibers instead of powders. If the balls are too small, they do not have sufficient impact energy to de-fibrillate nanofibers. If the ball size is too large, they have too high impact energy to damage the fibers to form particles. Milling time and ball-to-pulp mass ratio were also found important to control the number of collision events between balls and fibers and in turn the production efficiency. If the total number of collision events is too small, the defibrillation will be slow. Too many collision events lead to the damage of nanofibers in a short milling time. Zhang et al. (2015)

Nanocellulose (NC) was successfully isolated from eucalyptus sawdust using a combination of ball mill and high-intensity ultrasonication methods; all the proposed milling times (1, 2, 3, and 4 h) resulted in cellulosic particles in the nanometric scale. Ferreira et al. (2020)

Physical pretreatment methods are considered to be relatively less effective in enhancing the hydrolysis rate when compared to chemical pretreatments (Gharpurary et al. 1983). Moreover, physical treatment such as high-energy radiation and ball milling are reported to be energy-intensive and therefore expensive (Varga et al. 2002).

EXPERIMENTS



a. Verticle ball milling vessel filled dried BSG and two balls. b. Vessells being secured in the ball mill. c. Vessel after ball milling with milled BSG inside. d. Storage of the milled BSG.

https://youtu.be/r4z3UxTh-qw

OUTCOME

Ball milling was recommended as a faster option for grinding material to controlled particle size. It is acknowledged that not all designers will have access to laboratory-grade equipment; however, I was fortunate enough to have access to the Fritsch Planetary Micro Mill Pulverisette 7 ball mill located in the UTS science building. The ball mill has various limitations due to its age (manufactured in 2012); it cannot be run for more than 5 minutes without tripping, and there is only one choice of ball size. Zhang et al. (2015) described that the careful selection of ball size and milling time are crutial factors for conducting successful ball milling.

Regardless of the machine limitations, I was able to process significantly more material in the same period of time as PRESERVATION.001.003. A factor I found I could control, which had a noticable impact on the consistency of the BSG, was the amount of BSG place in each vessel. Filling the vessel more than half resulted in an inconsistent end product with fibres ranging in size from a flour-like powder to longer unaltered fibre strands shaped like broken toothpicks. I found that filling the vessel to half (and no more) and using two balls resulted in a consistent particle size.

PRESERVATION_001_004

ANCHOR

The BSG was dried at 60C for 48 h and thereafter ground and sieved using a 350 m sieve. It was then stored at room temperature in a dry place for further experiments.
Ravindran et al. (2018)

As soon as obtained, the material was washed with water until neutral pH, dried at 50 5C to 10% moisture content, and then pre-treated by dilute sulfuric acid and subsequently by sodium hydroxide solutions, to remove the protective hemicellulose-lignin wrapper.
Mussatto et al. (2008)

The material was washed with distilled water as soon as it was obtained until a neutral pH was reached, after which it was stored at -5C until further utilisation. The stored material was then dried at 50 5C for 24 h to attain 10% moisture content (untreated material). The dried material was further stored in a hermetic container at -5C to prevent any microbial growth.
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Revert et al. (2017)

EXPERIMENTS



BSG was dried with the same settings and precautions as '001_002 Drying.
However, this time BSG was dried in a household consumer oven. The oven has better ventilation and airflow than the industrial ovens initially used.

OUTCOME

Using a household oven was vastly more effective in bulk drying BSG in comparison to the industrial ovens in the UTS workshop. Household ovens have better ventilation and airflow control due to their various programs and features. The only disadvantages are that while in use, the oven is occupied for 12-24 hours at a time and that the user's house will smell like dry grain.

ANCHOR

It was found that careful selection of milling-ball size is important to produce fibers instead of powders. If the balls are too small, they do not have sufficient impact energy to de-fibrillate nanofibers. If the ball size is too large, they have too high impact energy to damage the fibers to form particles. Milling time and ball-to-pulp mass ratio were also found important to control the number of collision events between balls and fibers and in turn the production efficiency. If the total number of collision events is too small, the defibrillation will be slow. Too many collision events lead to the damage of nanofibers in a short milling time.
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Nanocellulose (NC) was successfully isolated from eucalyptus sawdust using a combination of ball mill and high-intensity ultrasonication methods; all the proposed milling times (1, 2, 3, and 4 h) resulted in cellulosic particles in the nanometric scale.
Ferreira et al. (2020)

Physical pretreatment methods are considered to be relatively less effective in enhancing the hydrolysis rate when compared to chemical pretreatments (Gharpurary et al. 1983). Moreover, physical treatment such as high-energy radiation and ball milling are reported to be energy-intensive and therefore expensive (Varga et al. 2002).

EXPERIMENTS





The DIY creation process of the grain tumbler - the idea being to combine ball milling, air flow and heat to dry and grind BSG at the same time.

OUTCOME

Though the grain tumbler experiment fell short, it is a worthwhile project for future investigation. The idea was to combine ball milling processes (crushing and grinding)w with the drying process - on a large scale. This experiment was conducted during a COVID19 lockdown, so it was difficult to access tools and assistance.

The thought was to convert the store-bought bin into a container for tumbling the grain with heat, airflow and rotational force. The bin had hundreds of holes drilled into it, which were then covered with a fly screen. The bin would be mounted onto a thick and long threaded rod through its base, with some supporting beams inside to try to tension off the rod's body. Finally, the modified bin would be placed on a rolling platform (an upside-down dolly) and rotated using the threaded rod, which was secured into a drill. As the bin rotated with grain (and possibly rubber balls as a grinding medium), a heated fan would blow hot hair down the body of the bin to aid in moisture wicking and the drying of BSG.

ANCHOR

The BSG was dried at 60C for 48 h and thereafter ground and sieved using a 350 m sieve. It was then stored at room temperature in a dry place for further experiments.
Ravindran et al. (2018)

As soon as obtained, the material was washed with water until neutral pH, dried at 50 5C to 10% moisture content, and then pre-treated by dilute sulfuric acid and subsequently by sodium hydroxide solutions, to remove the protective hemicellulose-lignin wrapper.
Mussatto et al. (2008)

The material was washed with distilled water as soon as it was obtained until a neutral pH was reached, after which it was stored at -5C until further utilisation. The stored material was then dried at 50 5C for 24 h to attain 10% moisture content (untreated material). The dried material was further stored in a hermetic container at -5C to prevent any microbial growth.
Pawan Kumar et al. (2016)

Brewers spent grain (BSG) was provided by Athens Brewery S.A. Before use it was dried at 65C until constant weight and was chopped in a laboratory mill to a particle size smaller than 5 mm. BSG was alkali treated prior to hydrolysis reactions as described previously (Xiros et al., 2008) with 10% w/w NaOH.
Xiros et al. (2011)

Wet brewer's spent grain (BSG) was kindly supplied by a local artisan manufacturer, Cervesera Alcoyana S.L. (Alcoy, Spain). Before milling, BSG was died overnight at a temperature of 60C to avoid microorganism proliferation.
Revert et al. (2017)

EXPERIMENTS









The Material Ecology Design Lab purchased a large dehydrator. BSG was removed from the freezer and microwaved for two minutes to help thaw the frozen blocks. Roughly 1 KG of frozen/wet BSG was placed on each tray and then placed in the dehydrator for 24 hours at 75 degrees C. It was calculated that roughly 75% of BSG's wet weight is water content.

OUTCOME

PRESERVATION_003_001 shows the most efficient and successful BSG drying method tested to date (16/08/2022).

The dehydrator can efficiently dry bulk BSG faster than all other methods tested, this is due to its ability to heat the BSG whilst wicking moisture from the air. Additionally, the machine's size allowed for the drying of up to 5 kilograms of wet BSG and enabled faster processing.

Since PRESERVATION_003_001, the Material Ecology Design LAB has upgraded to a larger dehydrator,the BENCHFOODS 32V-CUD, which can process more than double the previous model.

ANCHOR

The PASTE_001 series finalised research question one and guided the research into research question two. The initial pastes mixed were based on findings from a literature review which explored how other researchers have implemented organic waste materials within novel material composites. Recipes and potential workflows were examined and adapted from researchers such as Faludi et al., and the CHERMARTS cookbook, and the examination showed the roles of various material elements within a novel material composite paste. Past expiry and longevity was also explored.

EXPERIMENTS









OUTCOME

Pastes generated during this phase of the research were not used for 3D printing and instead were used as proof of concepts. They were manually extrudable through syringes which was in line with the initial testing procedures found in literature. Visually, the pastes seemed to be too thick for 3D printing requirements, as they would need to be pushed through piping by compressed and and then extruded using an auger set up. Further refinement to the ingredients would be needed to create a more viscous paste. It was also found that once water was reintroduced to BSG, its fast expiry process began again. Pastes were found with extensive mould growing on them only after a few days of being mixes, even when stored in the refrigerator. There are additives such as glycerine which could help with this.

ANCHOR

Small batch paste mix of:

20g finely Ground Brewers Spent Grain (BSG)

14g of Carboxymethyl cellulose (CMC)

14g of Microfibrillated Cellulose (MFC)

15g of Water.

inspired by Jakovlev, I. (2019).

'Recipe 20 Patterning Cellulose'

in Kääriäinen et al. (2020), the CHEMARTS Cookbook, p. 106.

In initial tests, materials were mixed into a paste and extruded by hand through a syringe

onto an acrylic surface to test flow behavior, self-adhesion and ability to self-support.

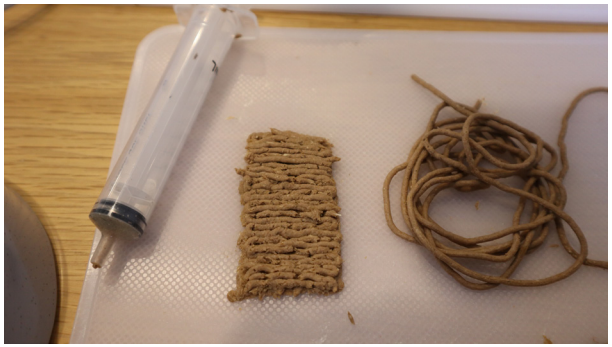
Faludi et al., (2019), p .7

EXPERIMENTS









Material was mixed with a handheld stick mixer and 'nutribullet' blender . Both devices struggled to evenly mix the cellulose with each other and the BSG. Additional water was needed to mix dilute and mix the materials.
The final paste felt like fibrous playdough, with a little less structural rigidity and easier to stick to skin. It was able to hold some hand formed shapes.
The material was packed into a pharmacy bought 5ml syringe and was easy to extrude without significant force on the plunger.
Small cylindrical towers were hand extruded, as well as a flat slab representative of a traditional MEX 3D printing infill pattern. The material was also applied too the exterior of a shot glass to test its moulding capabilties.

OUTCOME

Manual syringe extrusion worked successfully after the 'guess and check' process of paste mixing. Small portions of the ingredients were added until a satisfactory paste was mixed. MFC was difficult to break up and spread evenly into the mix, so I either need to remove this material from the mix or find a more consistent and stronger way to blend the ingredients. Though a good starting point, I feel that the mixing ratios will need to be altered to scale up the mix for larger batches.

PASTE_001_001

ANCHOR

Ingredients
100g Base cellulose glue
65g CMC 6%
26g MFC 10%
9g Water
200g CMC 6% solution
180g dried BSG
50g Cationic starch 4% solution
160g Water

Process
Mix all ingredients together with a stick mixer
Once well combined, form mixture into a ball and flatten to desired thickness on baking paper
Bake at 60 degrees

Notes
Cationic starch solution was added to increase bonding strength, this could be substituted for tapioca starch or a similar kind of starch (I would choose one with higher levels of amylose pecin) or you could even omit this entirely and use water. Note that the starches have to been 'cooked' or gelatinised before using.

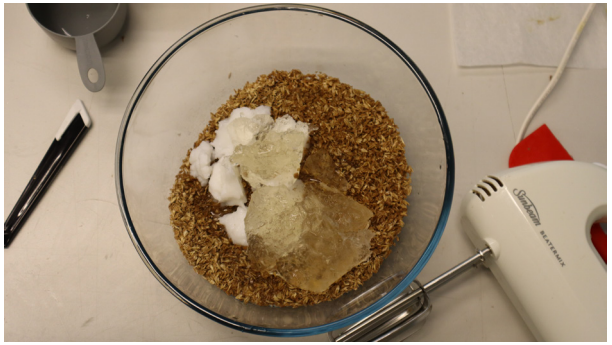
In the process of using a stick mixer to combine the BSG does get a bit finer which should increase bond strength.

Total weight = 690g
DMC = 200.5g
Email from Nahum McLean

EXPERIMENTS









Dried and unground BSG being weighed and prepared for mixing.

The mix of BSG, CMC, MFC, water and cationic starch before blending and mixing.

A stick mixer was the most effective kitchen appliance for mixing the ingredients into a paste.

OUTCOME

The paste was too thick for extrusion. It seems the ratios used when mixing in smaller quantities don't translate to larger quantities. This paste would be better for use in making bricks or moulds.

PASTE_001_002

ANCHOR

Despite the advantages of the additional BSG as animal feed, its use is still limited, which is mainly related to problems with storage of the material. The high moisture content of this residue makes it susceptible to microbial growth in the usual environmental conditions prevailing on farms (Stojceska et al., 2008). Within a few days after production, wet grain can undergo molding and spoilage

therefore, preservation is a key factor in the utilization of this by-product.

(Rachwa? et al., 2020)

Deterioration of the wet BSG takes place after an average period of 7 to l0 days from production, and under hot and humid conditions it may not be possible to store the wet BSG for a week.

(El-Shafey et al., 2004)

EXPERIMENTS









Photographs of mould appearing on PasteCreation_001_001 which was stored in a fridge.

The mould appeared after 5 days and spread rapidly.

OUTCOME

Mould appeared and spread rapidly on pastes. This is most likely to the reintroduction of moisture to the dried BSG. Moulds were unusable after 5 days of sitting in the fridge. This meant that I needed to find a solution to the storage of paste mixes. One option would be to freeze the paste

however, this would create issues when I want to print, as i would need to thaw the frozen paste. Another option would be to try to mix ONLY the amount I needed for the day's print. Lastly, finding another additive to help with mould prevention would be a great middle ground. It was suggested that I use vegetable glycerin due to its preservation properties.

ANCHOR

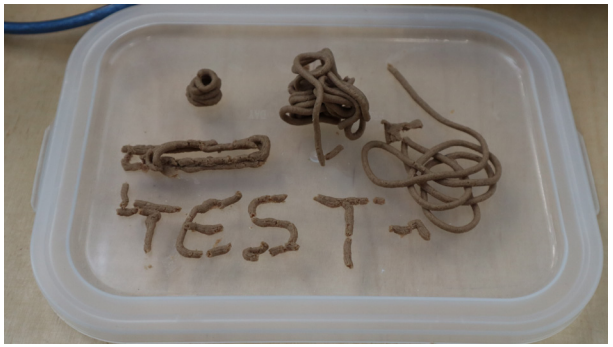
PasteCreation_002_001 develops on PC_001_001 through simple guesses and tests work. Pastes were mixed and then assessed visually and physically (touch and syringe tests) by colleagues and myself.

EXPERIMENTS









Written notes, photographs and video of the paste being mixed and extruded using kitchen appliances.

OUTCOME

This experiment process was useful as the collaboration process with colleagues allowed me to reflect WITH them. This gave me an insight into the tactic knowledge they have developed during their practices. The paste developed will be stored and then used for initial 3D printing tests.

ANCHOR

PASTE_003 documents development and progression of the first 3D printable pastes. These pastes were developed alongside machine and settings changes to the 3D printer in effort to achieve consistent extrusion when printing. The recipe evolved from previous paste series, completely removing the use of MFC (microfibrillated cellulose) which would provide structural support, instead opting to use for CMC (carboxymethyl cellulose) which is better suited to the creation of pastes and gels.

EXPERIMENTS









OUTCOME

The pastes developed in PASTE_003 developed into relatively effective materials for MEX printing. They were able to support simple 3D shapes such as cube and cylinders to heights of up to 50mm.

The recipes used finely ground and sieved BSG, 6% CMC solutions, water and glycerine (to help it with preservation).

Though the recipes have a high water content, the pastes passed through the delivery system well, extruded consistently (once the extruder configuration issues were solved), and dried with minimal shrinkage and kept uniformity.

Future paste development will focus on reducing the water content, to try eliminate shrinkage and cracking while drying.

ANCHOR

EXPERIMENTS

OUTCOME

Print mix 2

200 g BSG

75 g 6% Carboxymethyl cellulose (CMC)

400 g water

30 g Glycerine

Glycerine has useful qualities such as its ability ot act as a humectant, lubricant and food preservation.

(American Chemistry Council, 2022)









This mix took longer to get mouldy in comparison to mixes without glycerine- by two extra days at least.

The paste moved through the tubing easily at 3 BAR giving me confidence in the ‘printability’ of the paste.

Now time to start configuring printing settings.

The ingredients were mixed using a blender and stick mixer until ‘smooth’ visually and physical consistency. Prior to printing, the paste was placed into three moulds

a dog bone, a tensile test and a 50 x 50 x 5mm square mould to test for shrinkage.

ANCHOR

Based on Paste_003_001 but BSG was sieved through a 40 mesh sieve

EXPERIMENTS







OUTCOME

First time making a paste for new extruder and paste delivery assembly.

Final mix of

240g BSG
90g CMC
400g Water
40g Glycerine

After mixing a batch of paste.003.001, but with sieved material, it was found that the water content was too high. It seemed like less water is needed for finer material, possible because of less surface area for the water to absorb into. More BSG, CMC and glycerine were added until the paste felt more porous and required additional pressure to extrude from a hand held syringe. The high water content was also apparent in printing processes as if the paste and machine were left dormant with the pressure on, water droplets would fall from the extruder body and tip. To me, this indicated that there was excess water within the mix, and that a new batch should focus on a 'ground up' approach to mixing, where water should be sparingly added last.

ANCHOR

EXPERIMENTS

OUTCOME

BSG 200g

6% CMC 75

H20 250g

GLYCERIN 30g









The morning after mixing, the paste was noticeably drier after being taken out of the fridge. This could mean the water content is too low, or that I would need to change the pressure settings on the compressor.

PASTE_003_003

ANCHOR

EXPERIMENTS

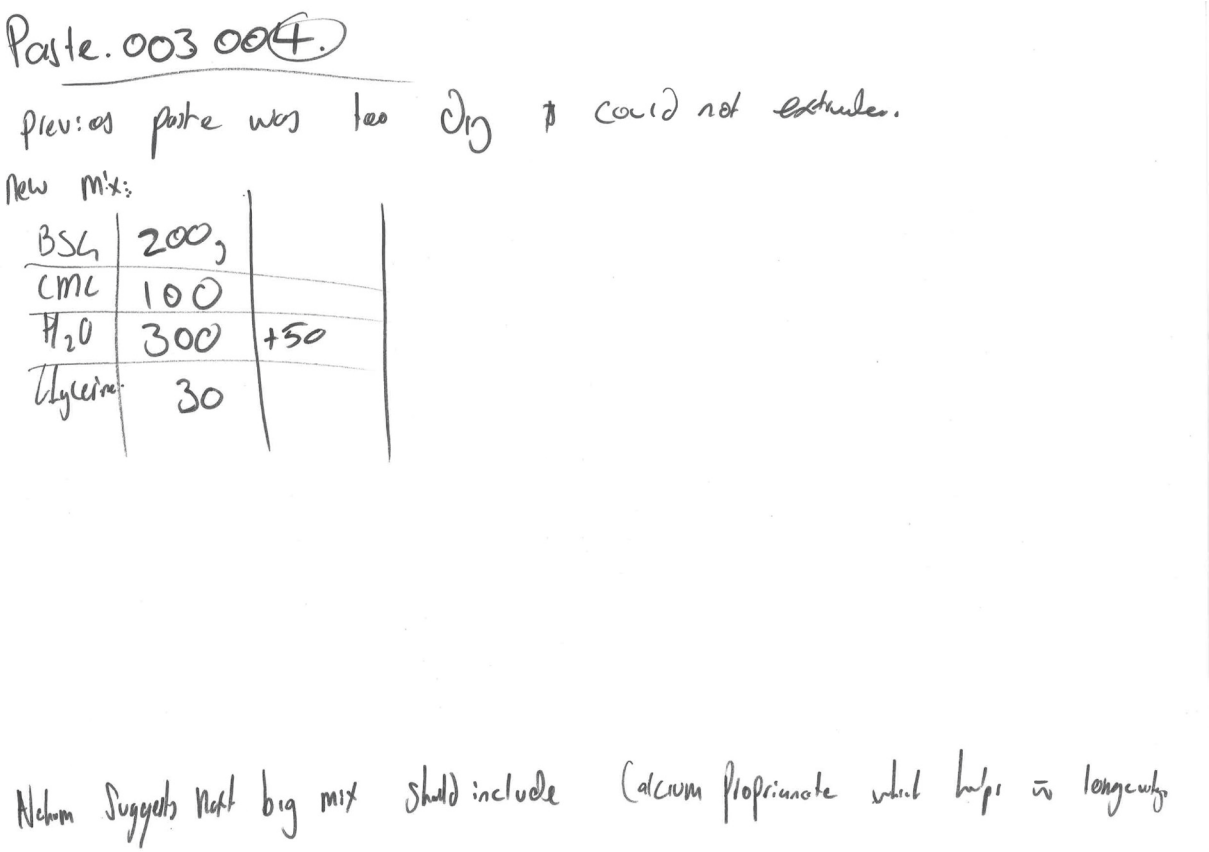
OUTCOME

PASTE_003_003 was too dry and could not extrude. BSG 200g

CMC 100g

H20 300g

GLYCERIN 30g.



Nahum suggested that the next paste mix should include calcium propionate which will help with keeping paste fresh between use.

PASTE_003_004

ANCHOR

Trying to mix less paste to avoid waste

BSG 200g

CMC 100g

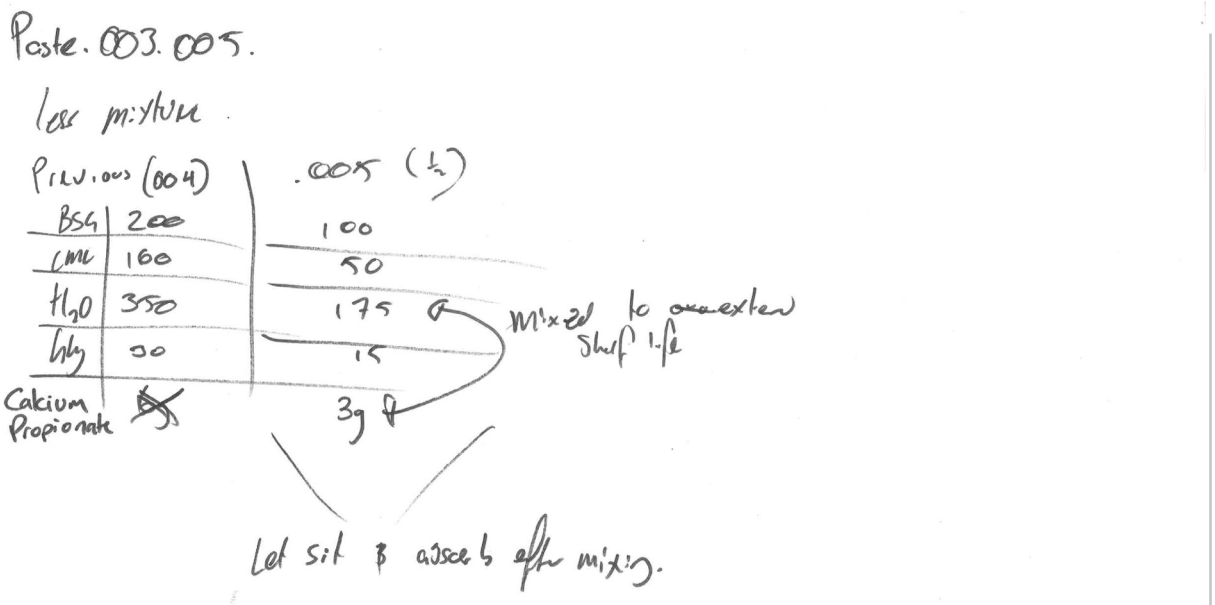
H2O 175g

GLYCERIN 15g

Calcium Propionate

Paste was left to sit for a time after mixing in an attempt to allow water to be fully absorbed.

EXPERIMENTS



no images

OUTCOME

Longer time for water absorption seems to have a positive effect on extrusion and drying. The BSG and CMC seem to compete over the water and need time to set.

PASTE_003_005

ANCHOR

First paste with new extruder design, EXTRUDER_003_001.

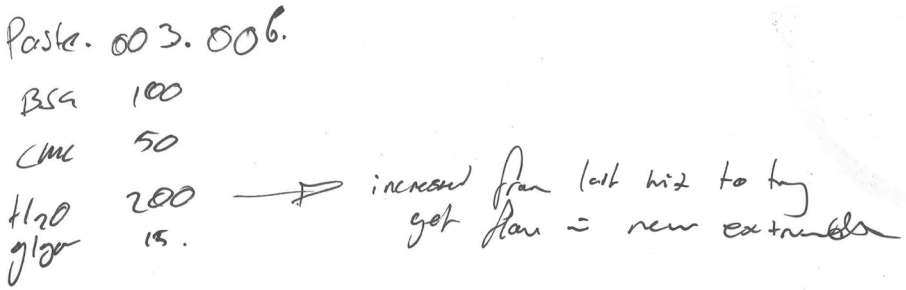
BSG 100g

CMC 50g

H2O

GLYCERIN 15g.

EXPERIMENTS



no images

OUTCOME

In reflection, it seems that the paste is less of an issue that the extruder tolerances, flow rate and auger movement.

PASTE_003_006

ANCHOR

Adding more glycerine to try smoothen the flow of paste through piping and to avoid breaks and tears on extrusion.

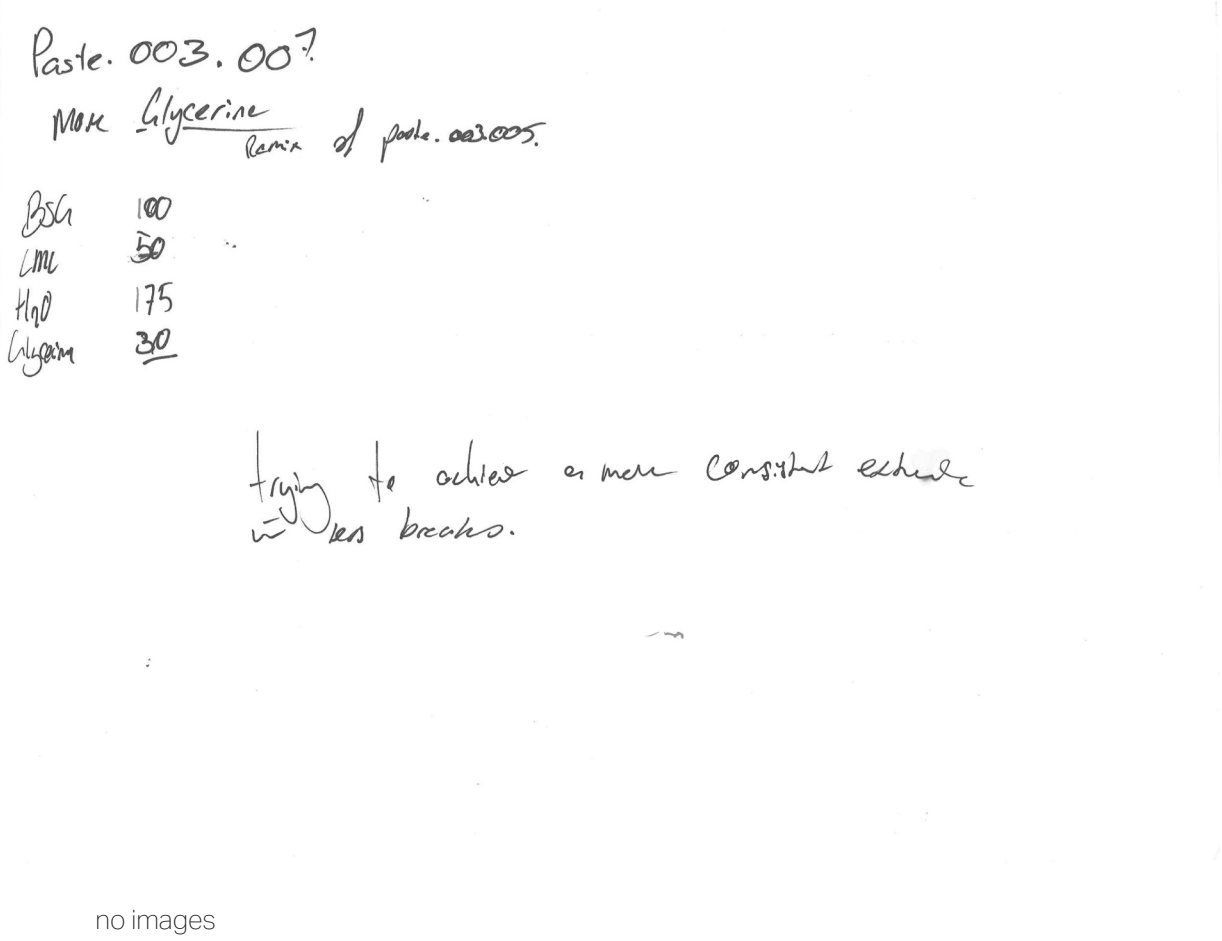
BSG 100g

CMC 50g

H2O 175g

GLYCERINE 30g (double previous content)

EXPERIMENTS



no images

OUTCOME

AS with PASTE_003_006, the difficulty of extrusion comes from the better tolerances of the new extruder design, and now the paste itself. The paste was previously extrudable.

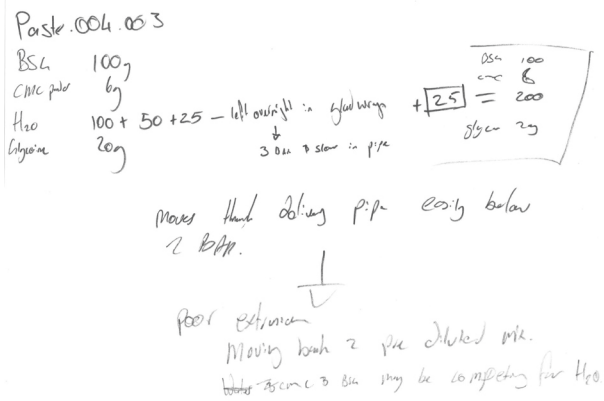
PASTE_003_007

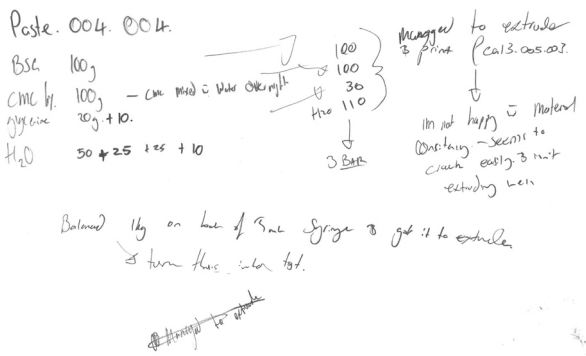
ANCHOR

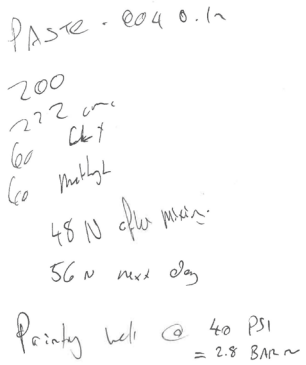
The PASTE_004 series was the final series of pastes used in research questions 2 and 3. The pastes explored finalising the processes for recipe ratios, mixing, extrusion testing, storage, extrusion, drying behaviours and disposal via composting.

EXPERIMENTS









OUTCOME

Several processes were either finalised or developed to creating consistent pastes in regards to extrusion, printing behaviours, and drying. A recipe was finalised (PASTE_004_012), which was predicable and reliable in use. Mixing using a 1000w Kenwood Stick mixer and Puree attachment was most effective after initially mixing the ingredients by hand. It was found that stick mixers could break without manually mixing the ingredients. Processes were developed for quality control and evaluation, such as using a Starr instruments digital force gauge to confirm material consistency (PASTE_004_011). It was found that the paste mixture could be composted (vermicomposting) in 20 days.

ANCHOR

Now that I can print consistently, I am working towards lowering the water content of the paste mixture in an effort to reduce shrinkage.

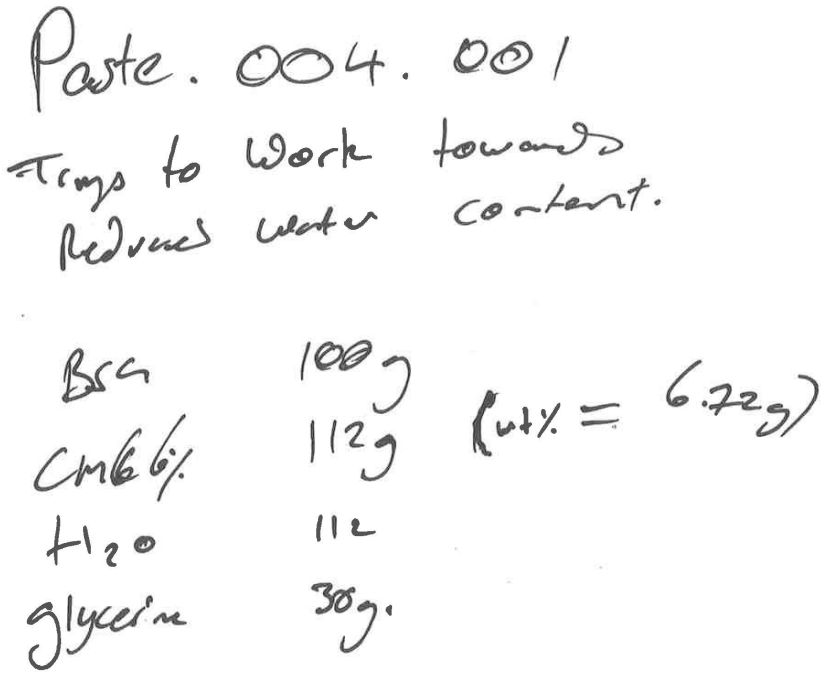
BSG 100g

6% CMC 112g (equals 6.72g of CMC powder)

H2O 112g

GLYCERINE 30g.

EXPERIMENTS



OUTCOME

Moving towards lowering the water content for better drying. Paste printed well. Maybe the Glycerine content can halved back to where I started.

ANCHOR

BSG and CMC powder mixed before adding water with a blender.

Water was added in parts until a ‘usable’ mix was found.

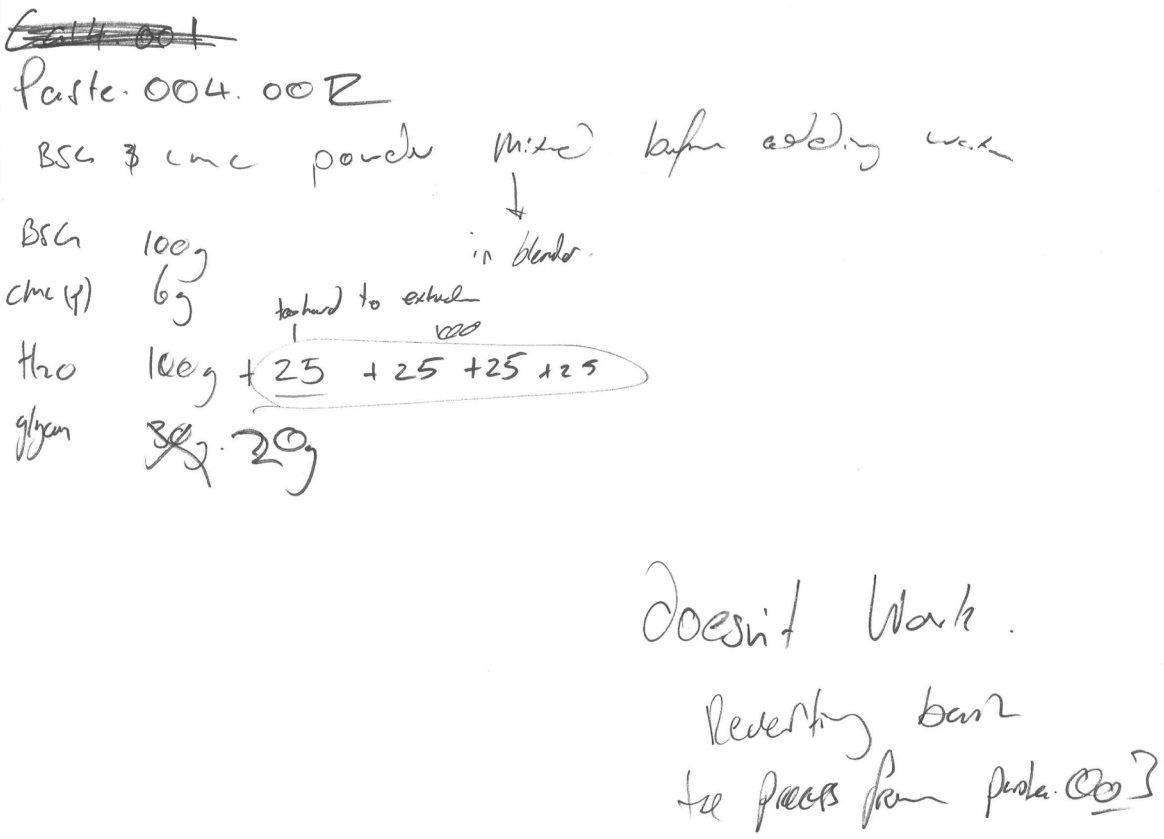
BSG 100g

CMC 6g

Glycerine 20g

Water 100 + 25 + 25 + 25 + 25g

EXPERIMENTS



OUTCOME

This experiment was unsuccessful. CMC needs to absorb the water separately, and for a longer period of time before printing. The BSG and CMC powders absorb water at different rates and need to be processed separately, then mixed, to create an effective paste. After this experiment I went back to mixing CMC in large batches at 6% powder to water.

ANCHOR

BSG 100g

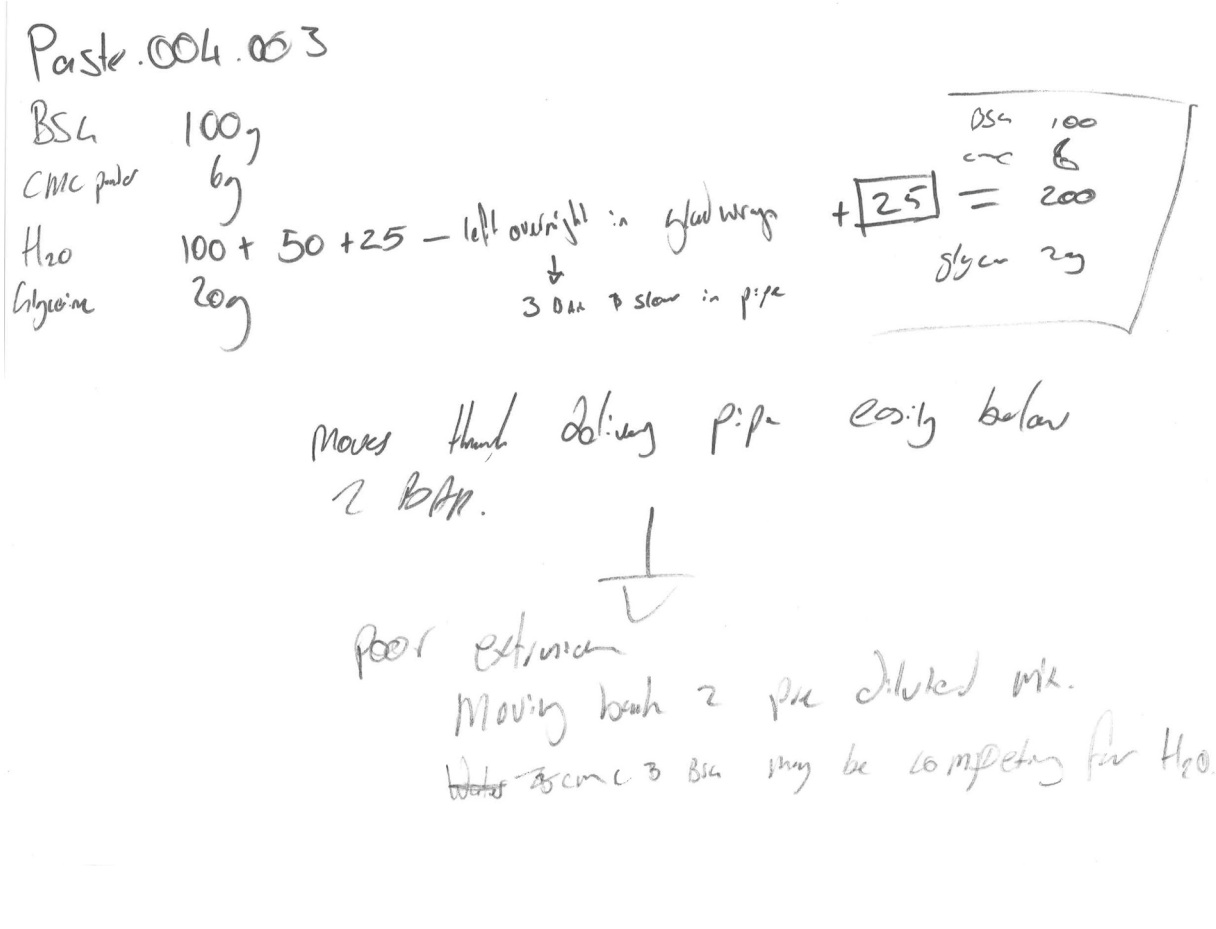
CMC Powder 6g

Glycerine 20g

H20 100 + 50 + 25g - Left Overnight in gladwrap -> 3 BAR and moved very slowly through delivery pipe so i added 25 g more water (200g in total).

200g water mix moved easily through delivery pipe at 2 BAR.

EXPERIMENTS



OUTCOME

Mix extruded poorly, reinforcing findings in PASTE_004_002, where I need to move back to a premix of CMC paste. I think the BSG and CMC powder could be 'competing' for water, and from batch mixing of CMC, lots of force needs to be applied to break up clumping groups of CMC so that it absorbs water equally. CMC mixes also need to be left overnight to full absorb water, and mixing with BSG may be stunting this process.

ANCHOR

BSG 100g

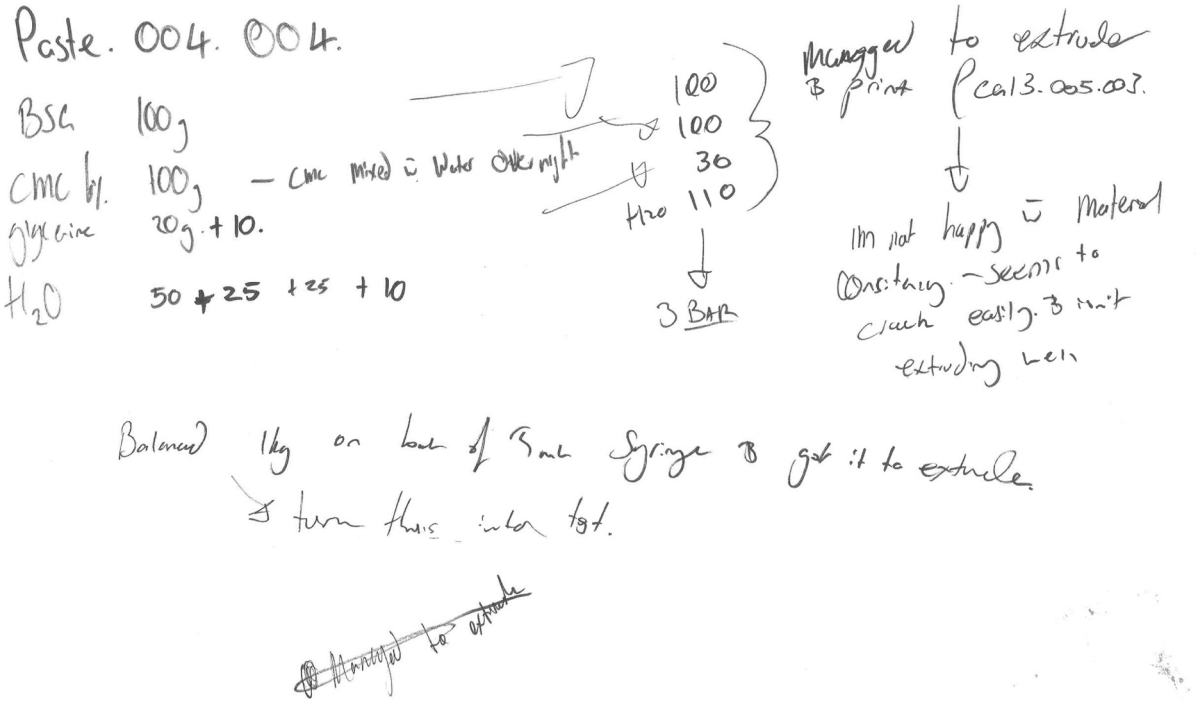
CMC 6% 100g

Glycerine 20 + 10g (30g)

H20 50 + 25 + 25 + 10 (110g)

moved through paste delivery pipe at 3 BAR.

EXPERIMENTS



OUTCOME

After mixing, I balanced 1kg of weights on top of a 5ml syringe and was able to extrude material. I am considering developing this into a more consistent testing method for pre-validating a paste possible printability.

This paste managed to extrude and print in CALIBRATION3.005.003. I am not happy with the material consistency, it seems to crack easily and is not extruding well.

ANCHOR

6% CMC used in previous paste has gone ‘off’ or expired, and has become quite watery. This leads to the possibility that previous pastes using this batch of CMC might not accurately be 6% CMC. I need to work the paste back to being easily extrudable, then I will work on shrinkage.

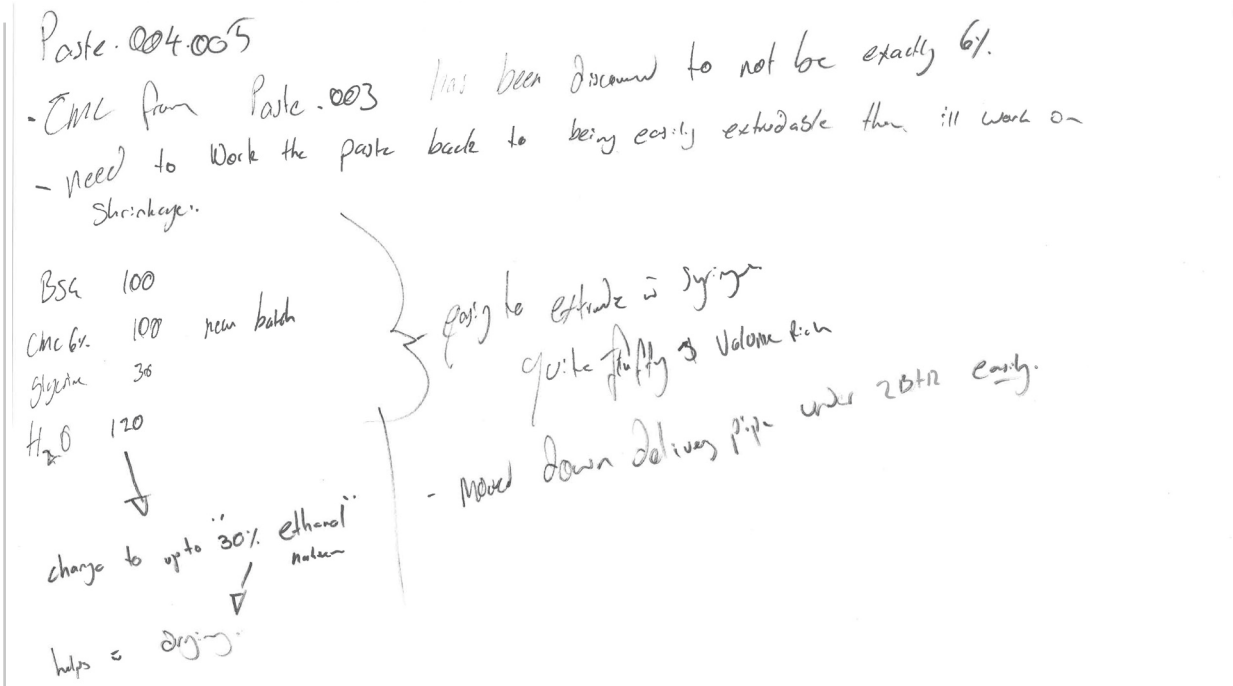
BSG 100g

CMC 6% 100g (new batch)

Glycerine 30g

H20 (considering changing this to up to “30% ethanol” for assistance in drying - recommended by Nahum).

EXPERIMENTS



OUTCOME

Was easy to extrude out of a 5ml syringe by hand. Material was more fluffy and mousey looking then recent pastes. This paste also moved down the delivery pipe under 2 BAR - easily.

ANCHOR

Testing the addition of ethanol (in the form of methylated spirits). Mixing a smaller batch for testing to avoid material waste.

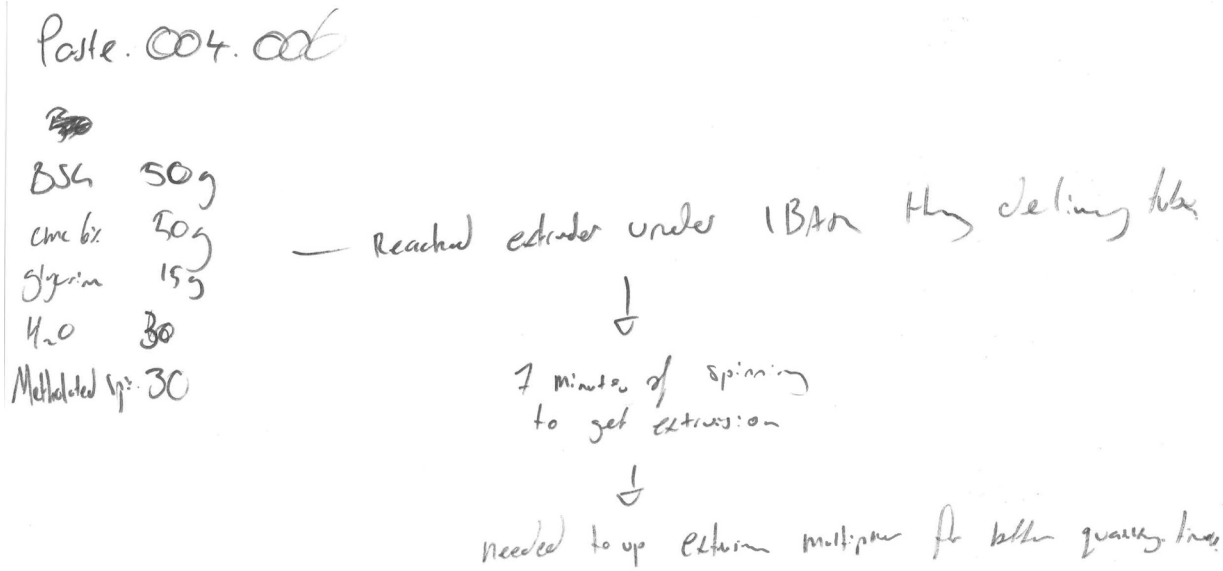
BSG 50g

CMC 50g

Glycerine 15g

H20 30g, Methylated Spirits 30g.

EXPERIMENTS



OUTCOME

Reached extruder under 1 BAR through delivery tube.

7 minutes of 'spinning' to get material to extrude after reaching extruder body.

I also needed to increase the extrusion multiplier in simplyfy3d for more consistent lines.

ANCHOR

FIRST PASTE DEVELOPED FOR ENDER 3 V2 PRINTER WITH 19MM INTERNAL DIAMETER DELIVERY PIPE.

BSG 100g

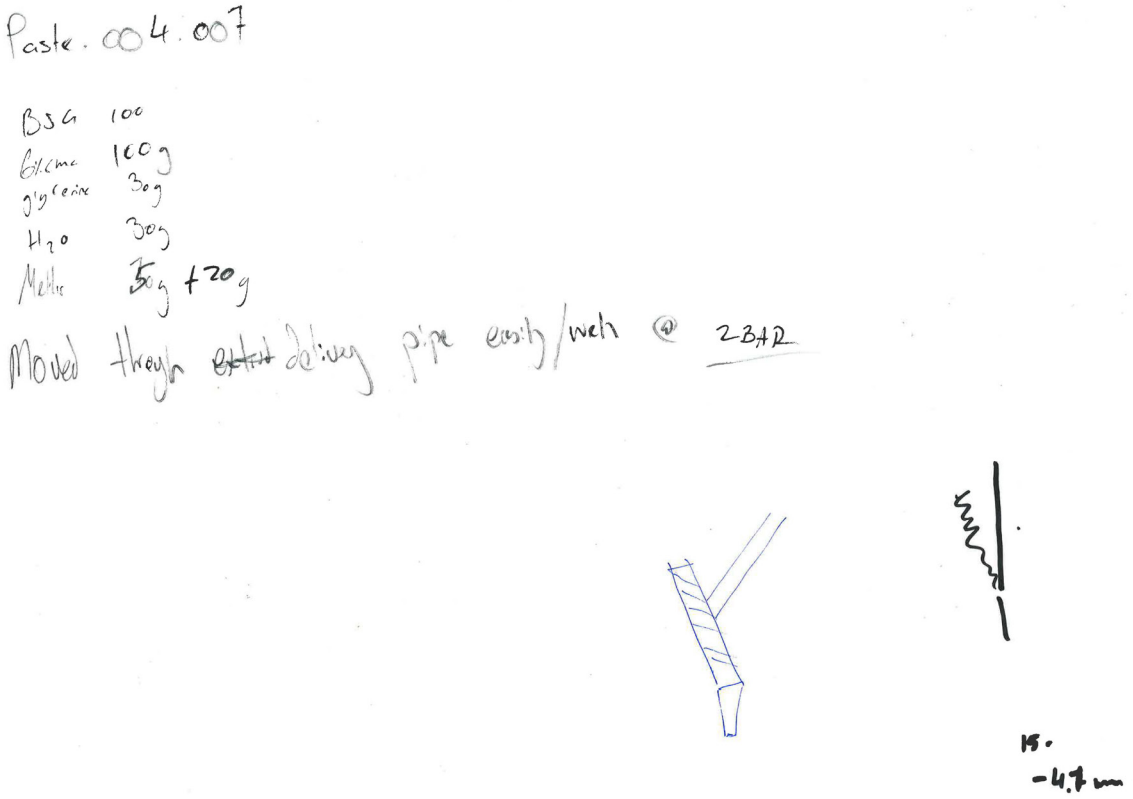
CMC 6% 100g

Glycerine 30g

H20 30g

Methylated Spirits 50 + 20 (70g)

EXPERIMENTS



OUTCOME

Move through 19mm ID delivery pipe easily @ 2 BAR of pressure. A 40mm3 cube was successfully printed as shown in CALIBRATION4.001.001.

ANCHOR

Begginign to try reduce the liquid content with paste delivery system and extruder on the Creality Ender 3 v2 Printer.

BSG 100g

CMC 6% 100g

Glycerine 30g

H20 30g

Methelated Spirits 50g

EXPERIMENTS



OUTCOME

No major change with this. More refinement is needed to delivery system and extruder assembly.

ANCHOR

Paste for 19mm ID paste delivery pipe which may require less water content to allow for delivery to extruder and extrusion.

BSG 100g

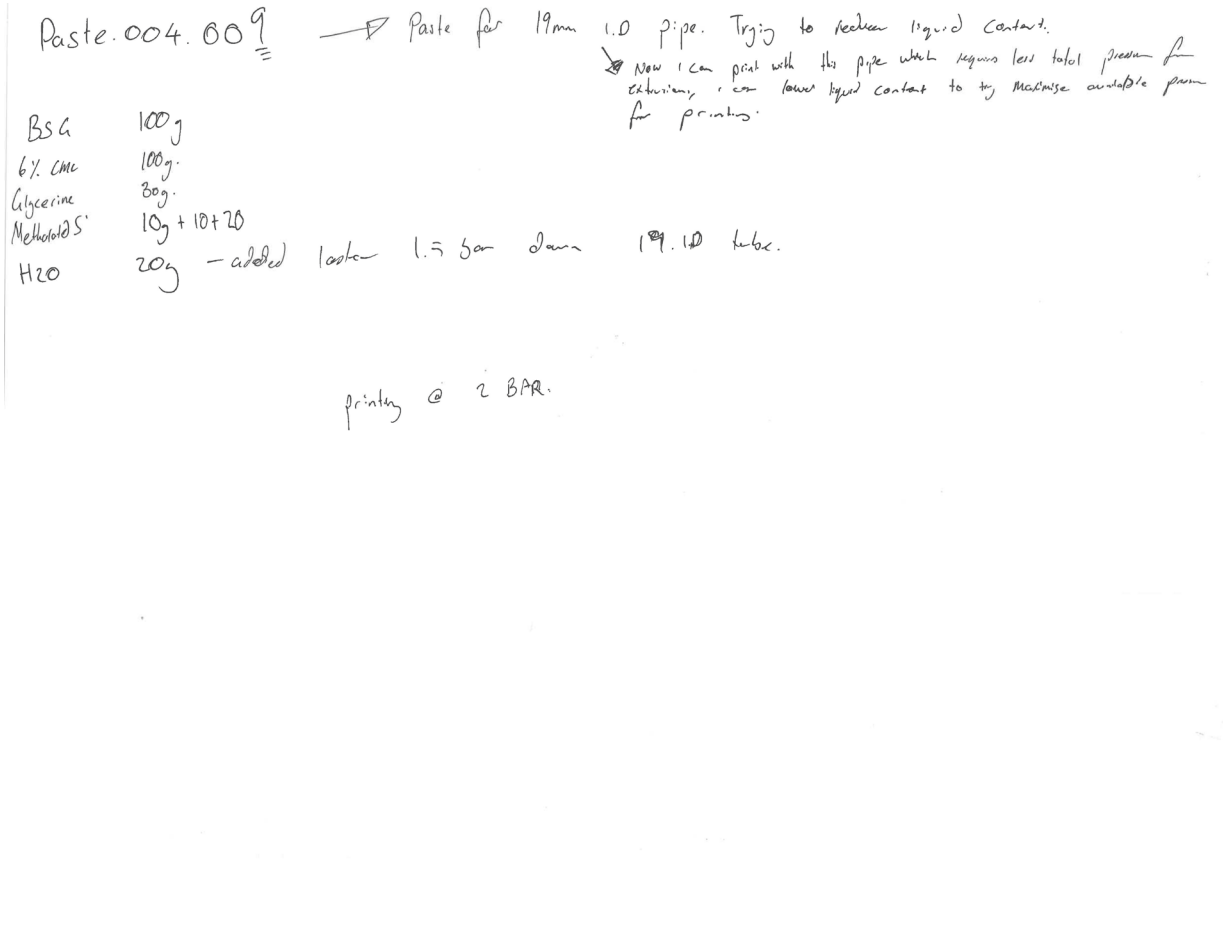
CMC 6% 100g

Glycerine 30g

Methalated Spirits 10 + 10 + 20 (40g)

ADDED 20g H20 after poor extrusion.

EXPERIMENTS



OUTCOME

Once 20g of H20 was added, material moved down 19mm ID tube at 1.5 BAR ,and printed at 2 BAR.

With the 19mm ID tube, I can now print with pipe that requires less total pressure for extrusion, which means I can lower the liquid content to try maximise available pressure for 3D printing more dense pastes which COULD be stronger and dry more consistently.

ANCHOR

making a bigger batch for for increased print size

BSG 200g

CMC 6% 200g

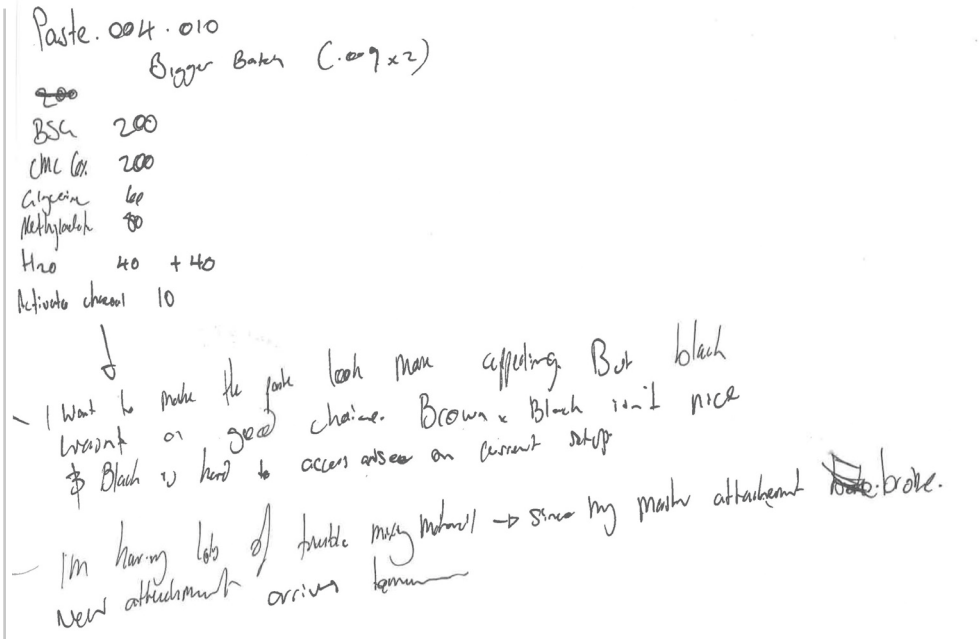
Glycerine 60g

H20 40+ 40g

Methylated Spirits 80g

activated charcoal 10g for colour

EXPERIMENTS



OUTCOME

Activated charcoal was added to this mixture to test altering the colour. People had been commenting on the colour of the brown and I thought a dark brown/black would be visually interesting. Wet, this was not an appealing mix, but dry it looked much better. However the mix was very difficult to mix due, as my puree attachment for my hand mixer broke, which has proven to be an invaluable tool. More care in mixing is needed, where material should be premixed by hand, then mixed with the stick mixer. This will avoid mixing very dense patches that could break the motors and gears.

ANCHOR

EXPERIMENTS

OUTCOME

Exploring mixing and measuring using the force gauge, then leaving the paste overnight and remeasuring. Pastes used days after printing in the past have been more consistent in drying then pastes used mixed straight away. Added H20 will be replaced with Methylated spirits for better drying

BSG 200g

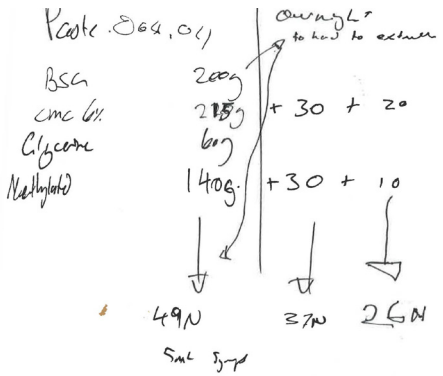
CMC 6% 215g

Glycerine 60g

Methylated Spirits 140g.

49N on forge gauge the morning after.
Added 60 CMC and 30 Methyl lowering to 26N which flowed and extruded well.







This processes showed the paste is best used after it has had adequate time to settle. I think that the CMC and BSG need time to absorb water and settle into each other. Whilst this mixture printed well, water reducing should now be the main focus. I want to try making a paste that prints well near 4 BAR and seeing if this paste dries better.

PASTE_004_011

ANCHOR

BSG 200g

CMC 6% 220

Glycerine 60g

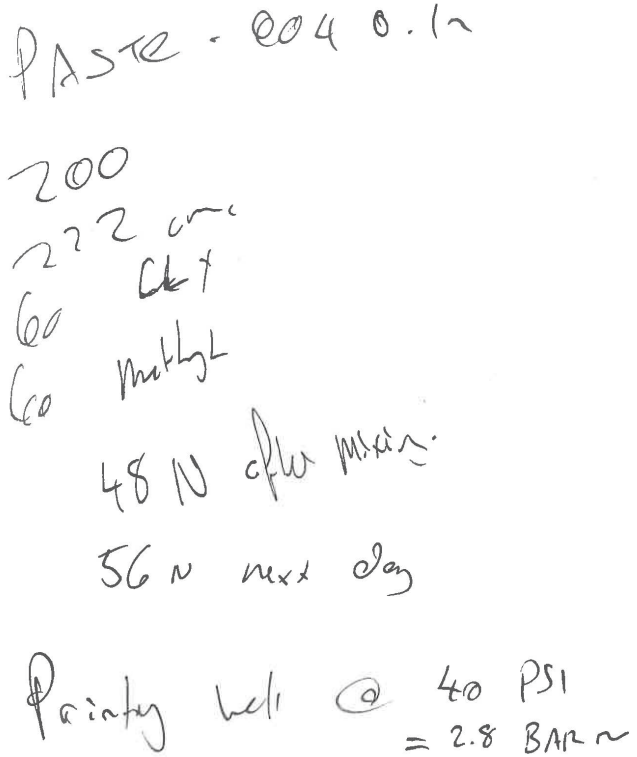
Methylated Spirits 60g

48N after mixing

56N next day

Prinitng at 2.8 BAR (40 PSI)

EXPERIMENTS



OUTCOME

The process of allowing paste to sit overnight after mixing, and this mixture provided the best results thus far, and will be used going forward for consistency in the final sets of experimentation. the material extrudes well at around 2.5-3 BAR, allowing for ample adjustments of the pressure to control line thickness while printing. Further experimentation would look at changing other factors (such as the auger, extruder design, stepper strength), and not the paste alone.

Vermicomposting was tested in domestic worm farms. Two prints, PRODUCT_001_002 and 001_003 were placed in the domestic worm farms which remained in use for regular food scrap composting. Prints were placed in the worm farms on 18/10/23 and were consumed by 07/11/23 (20 days).









The confirmation that the material is compostable is a tremendous result. All ingredients are bioderived, and printed and dried models are still absorb moisture where are also positive. Along with the results of the REANIMATION tests, the material shows significant environmental benefits in terms of reuse and disposal (in comparison to thermoplastics and poly foams). Further development on both reanimation/reuse and composting options of NMC materials would be interesting areas of future research.

ANCHOR

ReAnimation

Reusing dried paste from previous prints, tests, paste batches.

Assuming that all dry matter has a mix of BSG, CMC & Glycerine.

Dry Paste 100g

Methylated Spirits 100g

H20 50g.

EXPERIMENTS









OUTCOME

After mixing I realised I need to turn the dry matter back into powder, using a mill ect. Otherwise there are very hard clumps that are difficult to mix and are not extrudable.

PASTE_005_001

ANCHOR

ReAnimation

Reusing dried paste from previous prints, tests, paste batches.

Assuming that all dry matter has a mix of BSG, CMC & Glycerine.

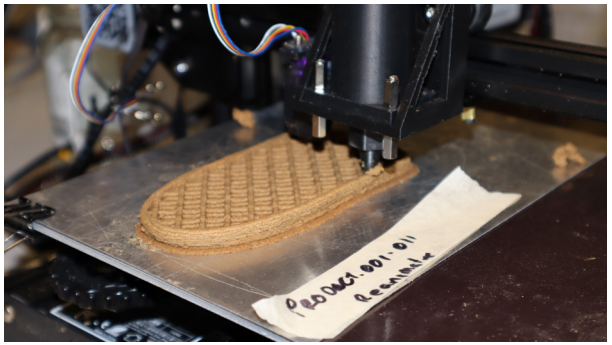
Dry Paste 200g through 40-mesh

Water 270g

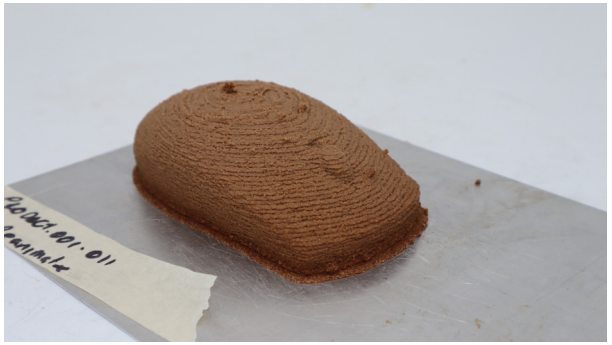
Methylated Spirits 15g after 24 hours

20-24N on force meter.

EXPERIMENTS









OUTCOME

Almost immediately after the water made contact with the ground material, it was back to a thick paste. Whilst the consistency was more liquid than pastes such as those developed in the PASTE_004 series, it was deemed printable through manual extrusion with a 5ml syringe. Whilst this remained true, the prints extruded at 0.1 BAR, indicating that they needed less water. WHilst the prints completed and were comparable to PASTE_004 series prints when wet, they cracked significantly when dried. This again my be tied to the high water content. Future experimentation would explore using less water in mixing, adding more BSG to the mixture, and leaving the mixture overnight to set as per PASTE_004_012.

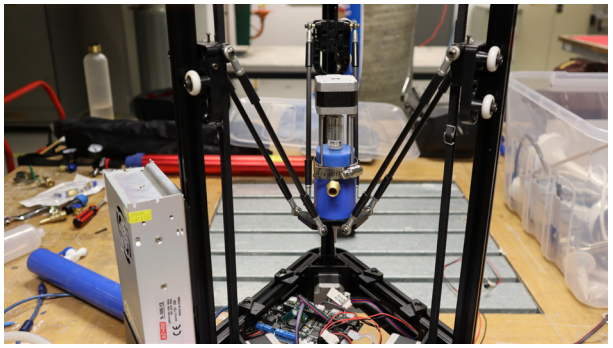
ANCHOR

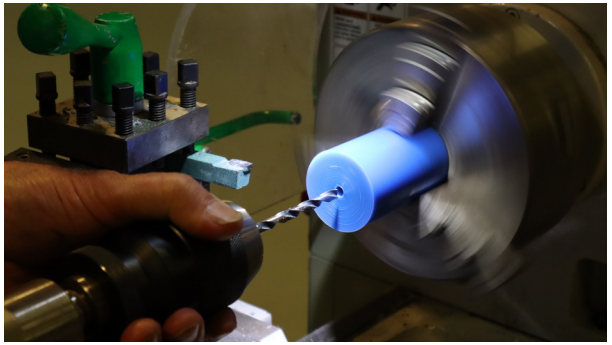
Extruder_001_001 was built based on Jonathan Keeps' "Self Build Clay Printhead" (link below). This printhead allows for complete control from the slicer software as it is connected to the motherboard through the same pins as the original plastic extruder. The printhead mounts to the existing gantry of the 3D printer and receives paste through a separate system fed by compressed air. Through commands by gcode generated in the slicer software, the roofing screw connected to the stepper motor acts as an auger that pushes paste through the printhead in a controlled manner. Andrew Purnell from the UTS fabrication workshop aided in constructing the print head.

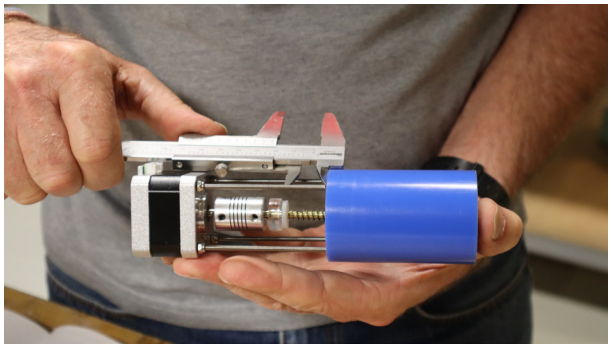
https://wikifactory.com/@jonathankeep/self-build-clay-printhead

EXPERIMENTS









OUTCOME

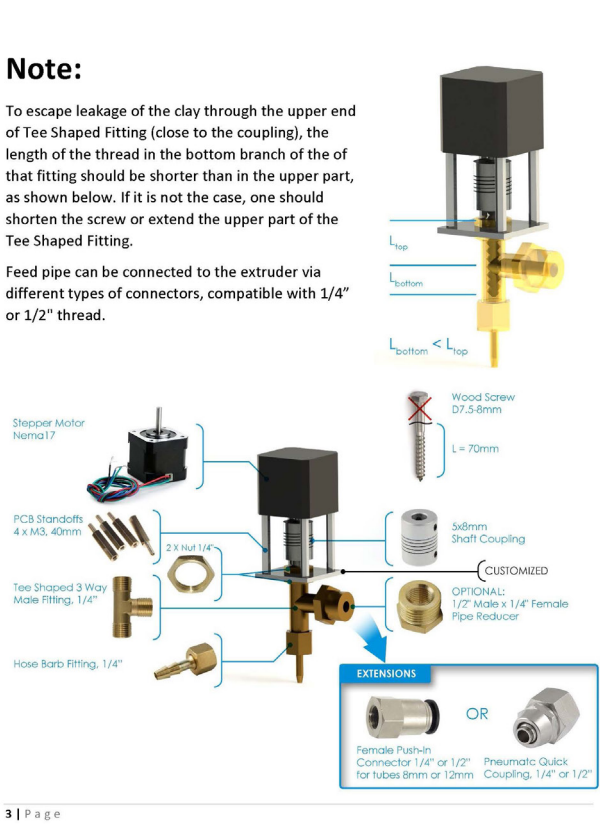
Though successful in extrusion, extruder_001_001 encountered several issues mainly relating to the nylon body. The body seemed too heavy on the gantry, as it was top-heavy with the stepper motor hose clamped to the top of the nylon body. Additionally, nylon became challenging to clean after printing, as the drilled threaded holes began to strip, creating weaker connections between the various components holding the extruder assembly together. Other options that are easier to (dis)assemble and clean need to be considered. Additionally, the construction of extruder_001_001 required some machinery (lathe) that many aspiring designers may not have access to.

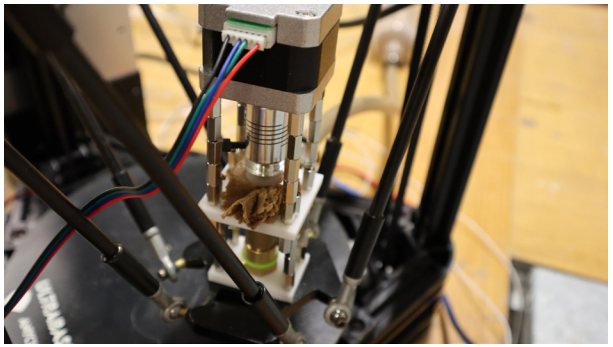
ANCHOR

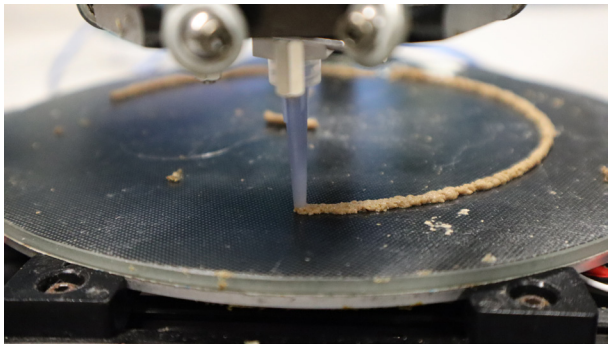
Extruder_002_001 was built according to the open-source design “Clay extruder, prototype V 1.0” hosted by StoneFlower3D (link below). This design can be assembled mostly from readily available components (All components were purchased through eBay, Bunnings and Jaycar) and two simple brackets made from plywood or any sturdy material. One bracket is included in the stoneflower open-source PDF; the other I designed to allow for easier mounting to the gantry and the automatic leving probe designed for the Anycubic Kossel printer to be attached. The brackets were designed in Fusion360 and printed in ABS using a TierTime UP300 3D printer (although they can be printed on the users’ printer prior to modification to a paste system) and are a simple extrude with holes.

https://www.stoneflower3d.com/opensource/

EXPERIMENTS







OUTCOME

Extruder_002_001 was significantly easier to assemble and attach to the AnyCubic Kossell delta printer. The printer does not have a height constraint on the size of the extruder, so the tall stoneflower design does not cause any issues with its height. The assembly and disassembly for clearing processers are much easier than the Jonathan Keep design. The extruder can be easily hand (dis)assembled and can be soaked in hot soapy water to remove any residue leftover in the threaded brass air piping parts.

I found that push-in connectors allowing paste into the tee shaped 3-way fitting can come loose due to pressure built up in the paste delivery system, and I opted for barbed 1/4 inch BSP hose fittings, which allow for significantly stronger holds on the tubing when under pressure. Another modification was an alteration to the customized bracket specified in the stoneflower literature. My bracket was 3D printed, which allowed me to forego the 1/4 inch hex nuts placed on top of the bracket and implement a threaded fitting and cap into the centre of the bracket body. This allows for easier assembly and the creation of a seal above the auger to combat any paste being extruded or pushed out the top of the assembly.

There is still the issue of the assembly tilting to the side where the paste is entering through the tee shape three-way fitting. A rudimentary solution has been employed where the 12 oz syringe holding the paste is being taped on top of a tub of similar height to the extruder.

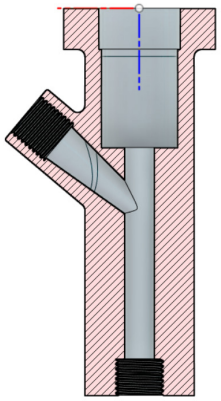
EXTRUDER_002_001

ANCHOR

Extruder_003_001 is a progression from the componentry and design used in Extruder_002_001. 003 was designed using Fusion360 and 3D printed in nylon powder using an HP Jet Fusion 3D printed at the UTS Protospace.

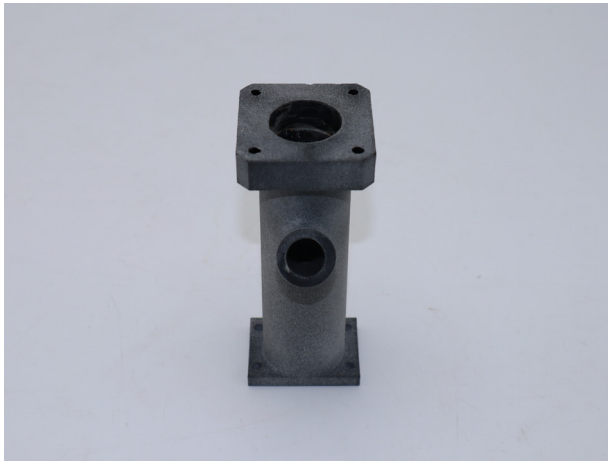
The design turns the many components from previous extruders into a unibody design, allowing for easier assembly, cleaning and reassembly. Additionally, the 3D printed design allowed me to design a 'Y' shaped body with 45 degree angled inlet for the paste. This should allow me to hang the paste syringe above the extruder body and prevent it from being pulled by the weight of the paste delivery system. Lastly, the design allowed me to customise the length and diameter of the auger shaft, allowing me to tailor the design of the shaft to various screw/ auger design, ultimately creating a tighter fit for the auger which should create more control over where paste is deposited via gcode and not through compressed air pressure.

EXPERIMENTS









OUTCOME

The tighter tolerances in the auger section of the extruder made printing under 'screw power' alone very difficult. Paste was not flowing freely, which is was good, but it was still not able to extrude effectively or consistently. Until the events of CALIBRATION3.001.002, it seemed that this extruder was not going to work. Then, after reversing the auger rotation, the extruder worked perfectly, allowing me to print shapes previously impossible. Additionally, the Y angle of the paste inlet and the use of a spring balancer to hold the paste syringe meant that the extruder was not being pulled off axis while printing. Over all this design was a solid time investment. It would be interesting to print this part out of PLA or ABS filaments with a desktop 3D printer, too see if this could be produced at home and printed with.

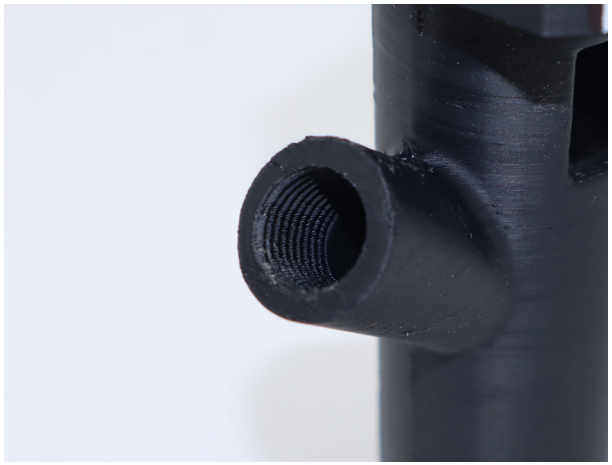
ANCHOR

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EXPERIMENTS









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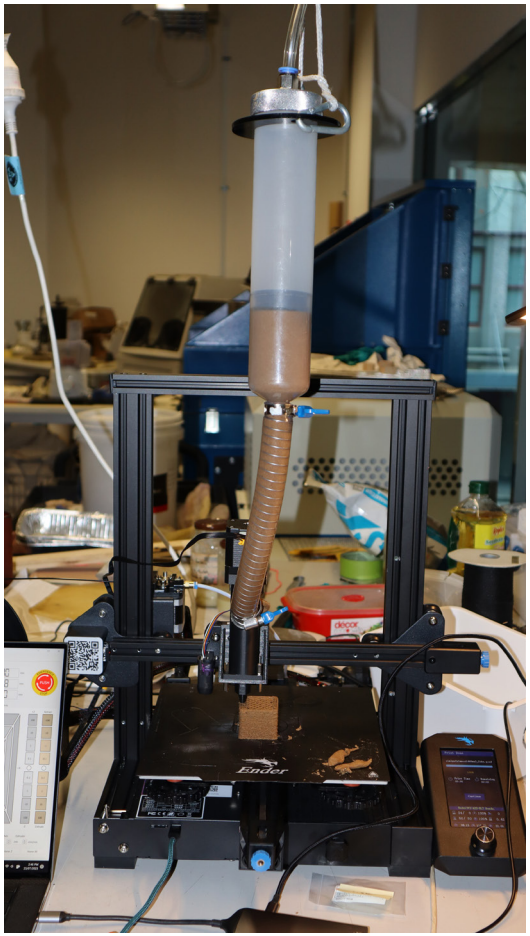
ANCHOR

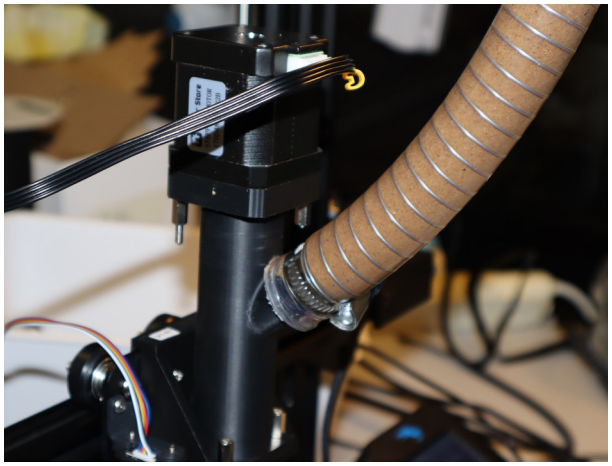
Extruder_003_002 was designed to be used with the Ender 3 V2 printer.

Modifications include a rotation of the base mounting plate by 90 degrees, which was initially designed for mounting to the stock gantry plate on the Anycubic Kossel printer.

The most significant change was the redesign of the paste entry point, which was extended and designed to accommodate hose clamps instead of the previously used internal BSP thread. This design allows for a 19mm internal diameter reinforced hose to be hose clamped over the paste entry point on the extruder, which results in lower pressure needs to delivery paste through the tubing to the printer. This modification is enabled by the added support and strength of the cartesian design of the Ender 3 V2 printer.

EXPERIMENTS







OUTCOME

The new mount and and front paste entry worked extremely well. The gantry and nozzle were unaffected by any movement or the weight of the paste delivery system. The hose clamps need to be closed very tightly, as the pressure pulled the hose lose running prints and emptying the cartridge onto the built plate. A collar was 3d printed which fit tightly around the auger shank and filled the area between the bottom of the coupling and the auger shaft, this stopped excessive paste moving up through the shaft into the coupling section of the assembly.

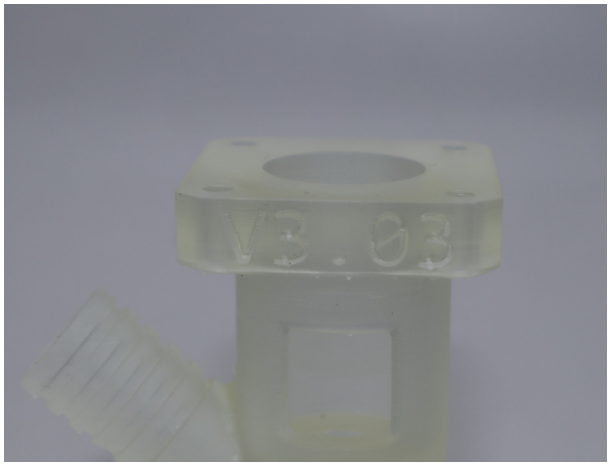
This extruder was used for the final prints in series PRODUCT_001-003.

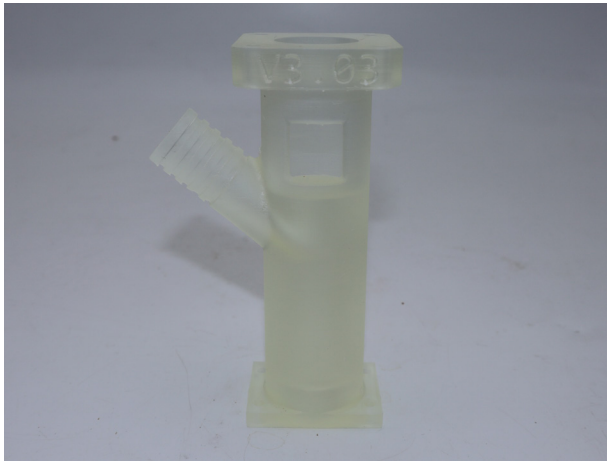
ANCHOR

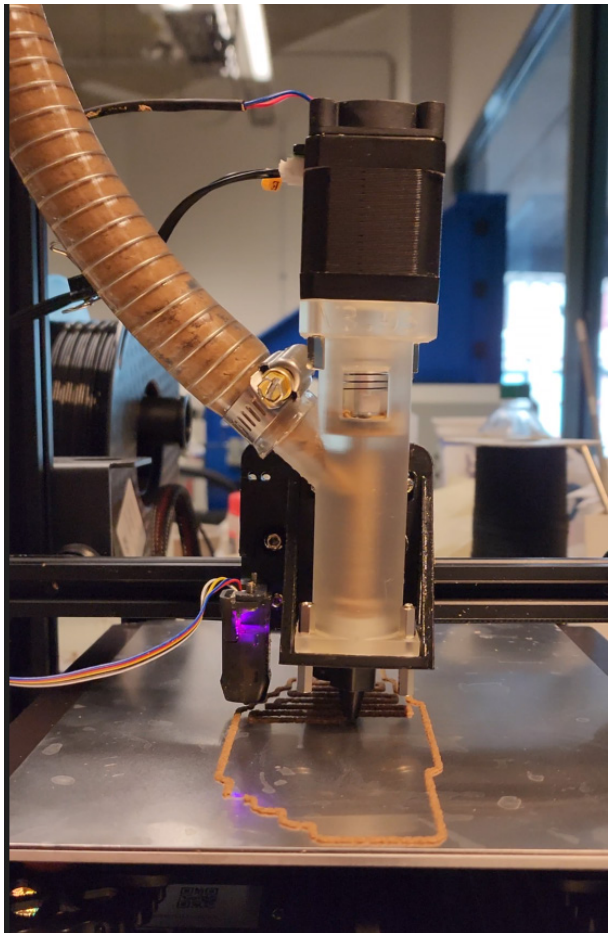
EXPERIMENTS

OUTCOME

Extruder_003_002 was printed in Clear V4 resin using a Formlabs Form 2 printer at the UTS Protospace. The print rotated the paste entry inlet to investigate if this effected print quality while using the spring balancer.





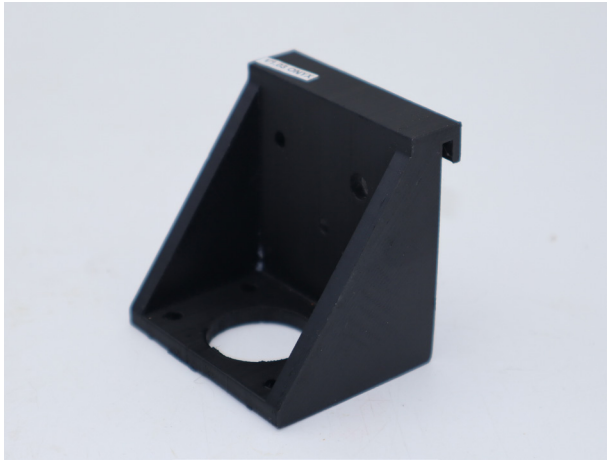


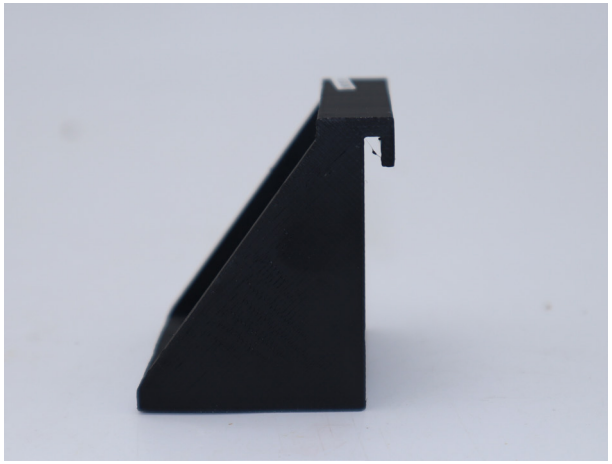
The main purpose of this extruder was to use the clear filament to see the flow of paste into the extruder and its interaction with the auger. This was somewhat achieved, but the print is no fully transparent giving little detail to the augers effect on flow.

ANCHOR

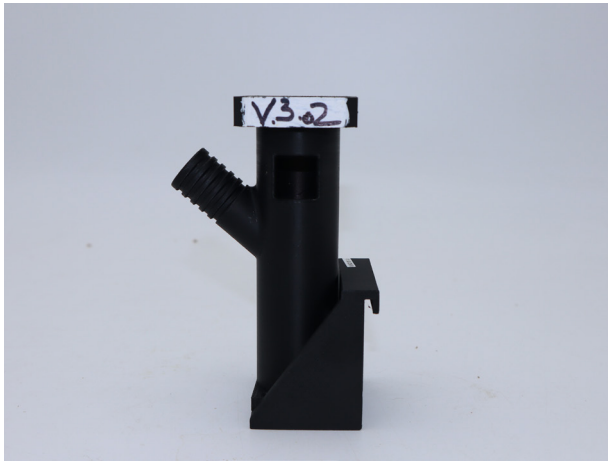
This mount was designed to adapted EXTRUDER_003_002 to be used with a Creality Ender 3 V2 printer with the stop e-plate. The e-plate is essentially the gantry on the X axis (horizontal bar that moves up and down) which holds fans and the hot end. This design slides directly onto the stock e-plate, using the pre-existing screw holes and extrusions for the hot end as a supporting slot. Further a lip was designed which fits over the top of the e-plate for added support. The mount then has the same mounting holes as the AnyCubic Kossel printer previously used, allowing for for easy mounting of existing extruder designs.

EXPERIMENTS









OUTCOME

The mount worked well, and made the transition from the AnyCubic printer to the Ender 3 much easier.

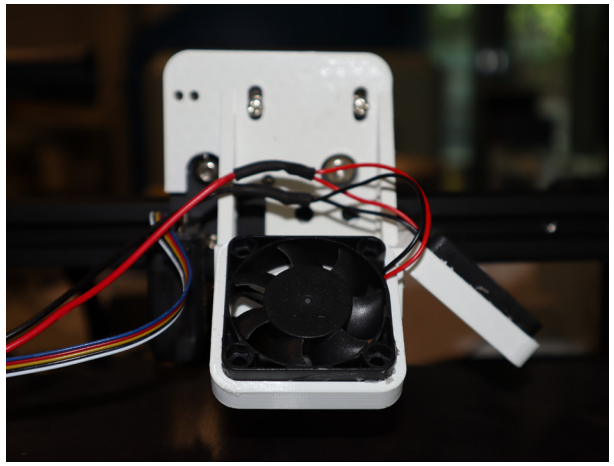
New nozzles were printed as it was found that the mount did not allowed the nozzle to reach the built plate with the auto leveling probe still in use (CR-touch). This was a minor inconvenience as nozzles can be printed in under an hour, and were designed for easy modification in fusion 360.

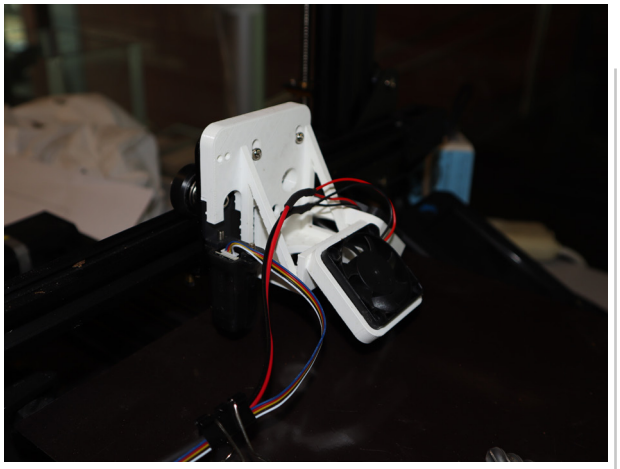
EXTRUDER_003_ENDERMOUNT1

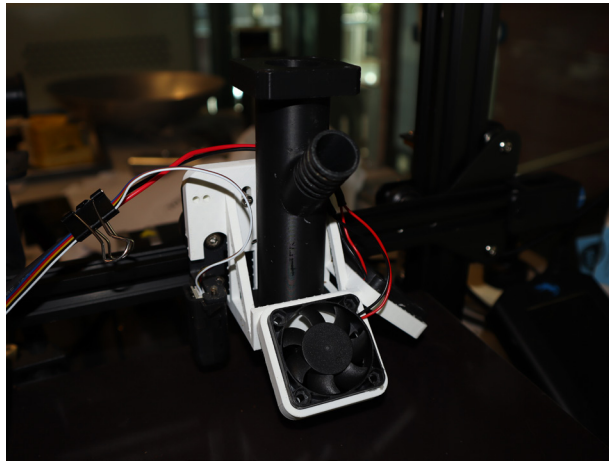
ANCHOR

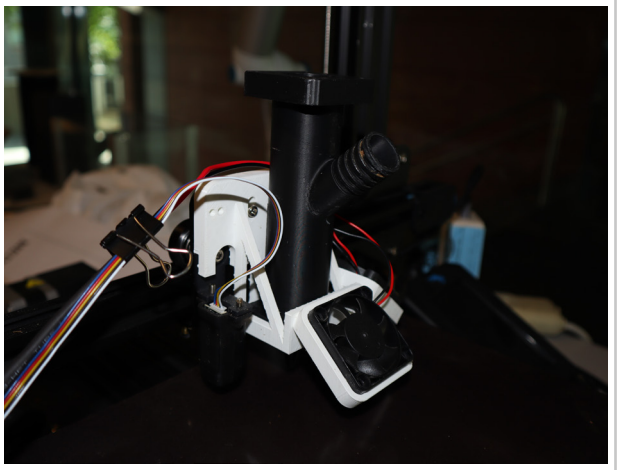
This mount progresses from the first design for the Ender 3 V2, and adds two 40x10x10 fans which run on the same circuit as the cooling fan used on the auger stepper motor. The idea was to apply some level of drying to parts while printing, mainly aiming to begin drying the infill before being sealed by the top layers.

EXPERIMENTS









OUTCOME

The mount and fans worked well. Whilst the fans do not dry the parts significantly, they do give the exterior a layer of 'crust' which makes parts slightly more stable to handle before being removed from the build plate. Further development would look at:

Using heat sources behind or in front of the fans for added drying effect

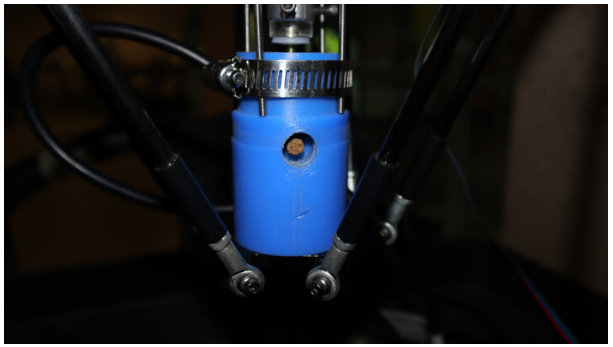
Adding a third fan or moving the side fan slightly as the mount reduces the build volume slightly by hitting the post removing the mount entirely and creating an extruder body that slots and mounts to the existing e-plate.

The assembly and testing of the initial paste delivery system. They were designed based on the work of Jonathan Keep (2020) and the open-source StoneFlower3D extruder.









Several issues became apparent after the first phase of testing. Of particular concern was air escaping from various parts of the system, particularly from the syringe backing, which is the connection point between the compressed air system and the paste delivery system. I managed to find an 'official' part on the Cerambot website, which is a metal screw-on base for the syringe body, which will replace my 100% infill 3D printed base.

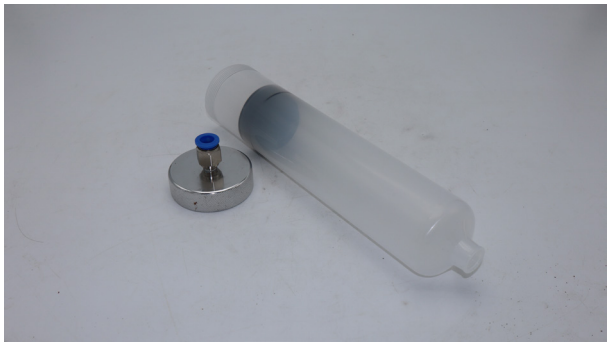
https://youtu.be/Zqo1CbAZup0

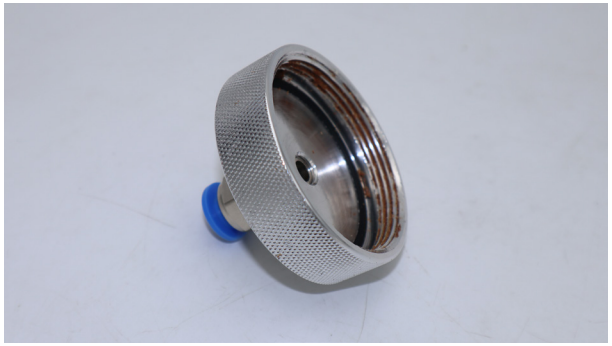
ANCHOR

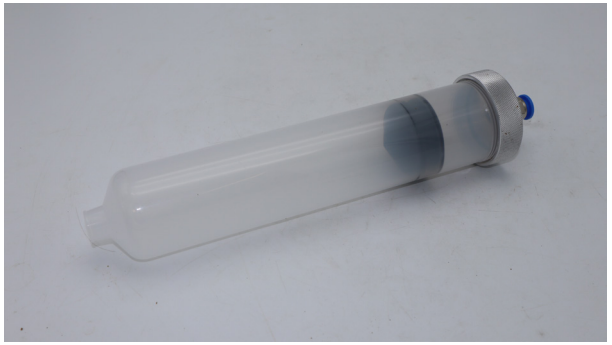
The backplate used to allow air into the cartridge was leaking air. It was 3D printed and seal with epoxy, but was still not air tight enough. The “CERAMBOT Air Clay Cartridge Set” was purchased, which has a metal back cover with a 1/8 inch BSP threaded insert, allowing for press fit fittings to be used.

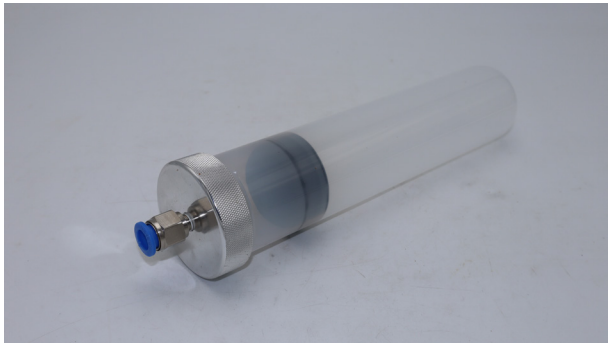
https://www.cerambot.com/product/cerambot-air-clay-cartridge-set/

EXPERIMENTS









OUTCOME

This solution worked perfectly. It would be interesting to find a solution that was cheaper and not reliant on someone else making them, but for time purposes this worked well. Other solutions could be the use of https://vormvrij.nl/lutum/shop/#!/Clay-Cartridge-L/p/137376043/category=47484151 or other offerings from LUTUM but these are very expensive. Ideally, one could buy and modify a “automotive fluid extractor” from Amazon and modify this to be airtight and to allow compressed air entry or purchase and modify a pneumatic caulking gun.

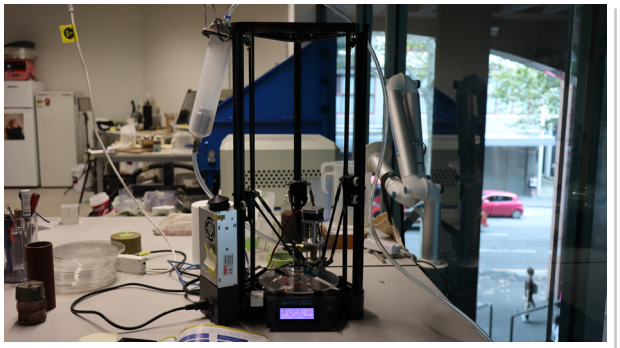
ANCHOR

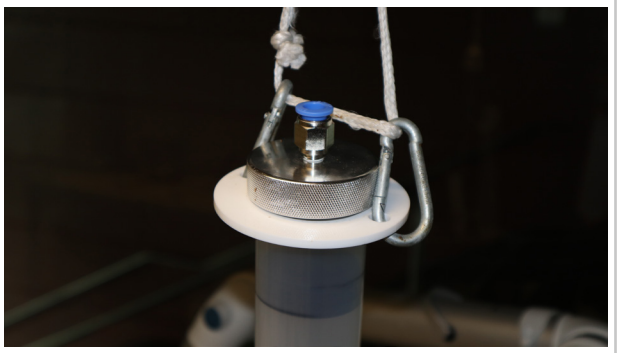
Whilst watching a video of someone using a DELTA WASP 40100 printer, I noticed that the paste cartridge was supported by some sort of count balance system. After more research i found that this was a spring balancer, and ordered one from Amazon that could support 0.5-1.5kg. Then, I lase cut a collar/ mount, that fit around the paste cartridge using the lip of the metal back plate as a stopper. The collar has two holes for carabiners, and these are hanging from a rope which is tied to to the spring balancer.



EXPERIMENTS







OUTCOME

The spring balancer was an immediate success, especially when paired with the Creality Ender 3 V2 printer (PRINTER_002), which has a much more well supported gantry. The system removed most of if not all of the weight off the gantry and extruder assembly, allowing for unencumbered movement and printing of more advanced shapes.

ANCHOR

The spring balancer system was further modified by increasing the dimeter or the cartridge outlet, tubing and inlet of the extruder assembly to 19mm. It was found that smaller diameter piping had increased friction (Nur et al. 2019)

Tubing was sourced online with careful attention being paid to the pressure rating of piping. 19ID helical reinforced PVC tubing was sourced online. 19ID was found to provide the best mix of flexibility and safe working range (around 4 BAR or 60 PSI). Smaller ID piping was more rigid but had higher pressure rating, and larger ID was very flexibly but had very low pressure rating.

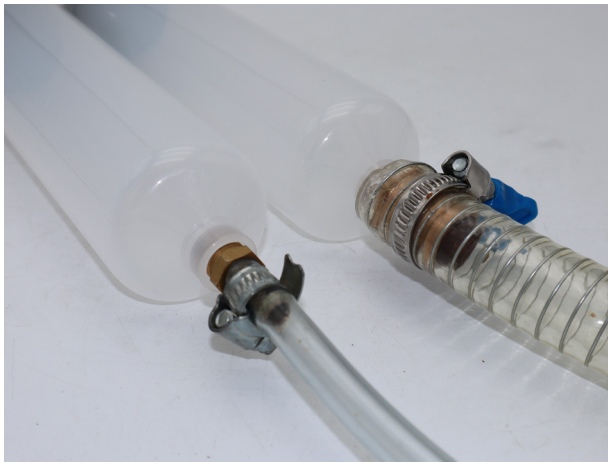
Further, a 1/4 inch BSP to 19mm ID hose barb was sourced cheaply from eBay for use on the cartridge, and hose clamps purchased from local hardware stores

This system was paired with EXTRUDER_003_002

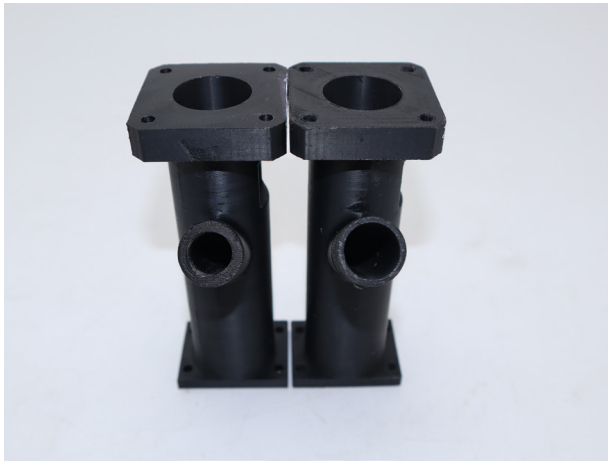
See: Effect of pipe diameter changes on the properties of fluid in closed channels using Osborne Reynold Apparatus by Nur, Afrianita1 and Ramli

EXPERIMENTS









OUTCOME

This system worked well, with a few minor hiccups. Hose clamp[s] needed to be extremely tight, or the hose could come loose. This resulted in the helical wire breaking through the PVC pipe after many uses and did need monitoring.

The system allowed for refilling or replacing cartridges mid print, as the cartridges could be unscrewed from the metal back plate mounted to the spring balancer and unscrewed from the 19mm ID hose barb which was secured to the hose by clamps.

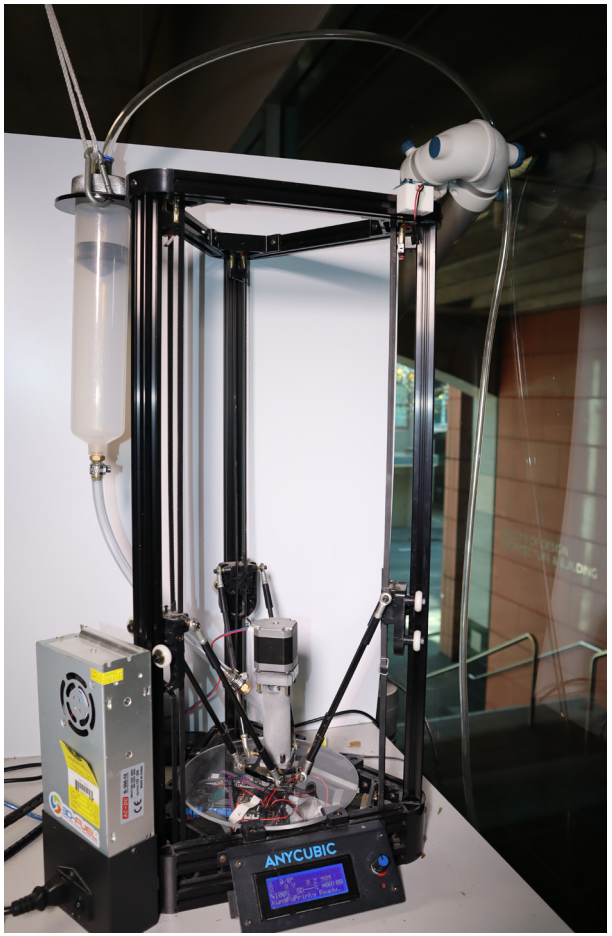
Ultimately this system was used in the majority of experimentation in research question 3 and worked extremely well. It would be used in experimentation going forward with minimal changes if any.

PASTEDEILVERY_002_002

ANCHOR

The first printer used in this research was the AnyCubic Kossel Delta Printer. When it was on sale (it is now discontinued), it was one of the cheaper printers (sub 300 AUD), in part because it required assembly (including wiring the motherboard). It is a delta printer with a cylindrical build platform of 180 x 300mm. I have owned this printer since 2017 and it was used as a prototyping tool during undergraduate studies.
For this experimentation the printer was originally modified in line with Jonathan Keeps Guide to Clay 3D printing. http://www.keep-art.co.uk/Journal/JKeep-Guide%20to%20Clay%203D%20Printing%20-%202020.pdf

EXPERIMENTS





OUTCOME

Delta printers have been used for paste printing due to their tall open build plate, and fast printing speeds (no moving bed), and smooth moving gantry. However, this study aimed to create intricate smaller forms than the vase like structures typically printed using paste-extrusion delta printers, and therefore needed more stability in printer movements. It was also found that the gantry on the Kossel Delta, supported by 3 stepper motors which dried a wheeled pully system, was not strong enough to hold paste extruder assemblies. This printer was not designed for heavy payloads on the gantry, but rather a Bowden tube style setup, where the extruder stepper motor is mounted to the printer frame, the only the hot end and fans are carried on the gantry. The extruders designed for this researched are more closely related to direct-drive extruders which have the stepper motor attached to the same plate as the hot-end and fans, and therefore needed more stability.

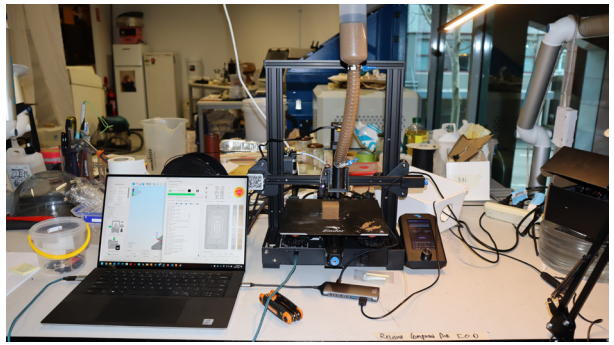
PRINTER_001_001

ANCHOR

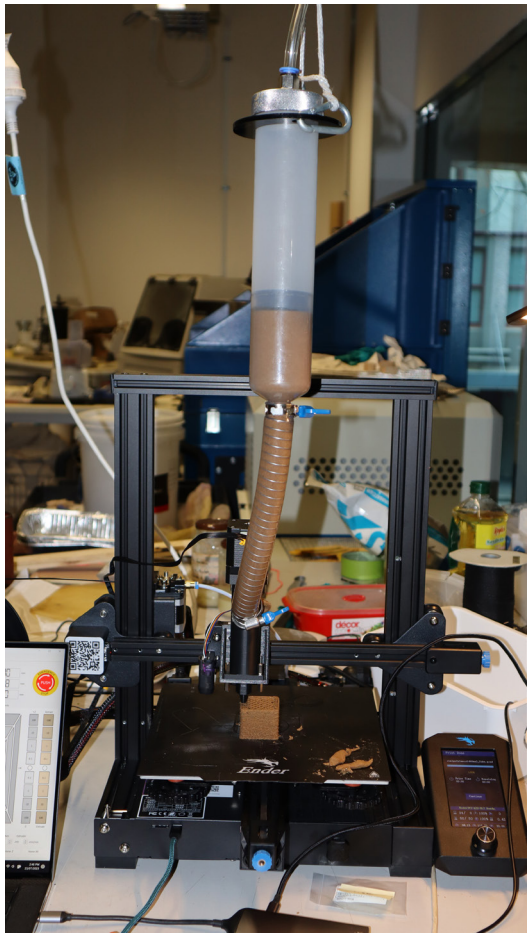
The Creality Ender 3 V2 is a cheap (around 300-350 AUD from Amazon in 2023) consumer 3D printer with a 220 x 220 x 250mm build platform. Part of the low price is that the printer requires some assembly (not wiring) which takes roughly 1-2 hours. The Ender series from Creality is immensely popular with hobbyist, with free printable modifications downloadable from Thingiverse or printables.com, and many purchasable directly from Creality such as direct drive kits, auto levelling tools (Cr-Touch), dual-z upgrade kits and more. The Ender 3 v2 was purchased from Amazon initially as a prototyping tool to produce extruders and nozzles for PRINTER_001, however, it became apparent that it would be better used as a dual purpose machine, printing thermoplastics parts for itself to use as a paste-extrusion printer. To improve the printing experience:

A CR-touch was purchased for bed-mesh and leveling, a Creality direct-drive kit, which comes with a larger e-plate (which holds the extruder assembly). This would be used to mount the paste-extruder and to remove the existing e-motor from the z-axis when not in use (and replace it with the direct drive motor). A dual z-axis kit was purchased for added strength to the z-axis to support the direct-drive and paste-extrusion extruder assembly.

EXPERIMENTS







OUTCOME

The ender 3 v2, paired with EXTRUDER_003_002 and PASTEDELIVERY_002_002 worked extremely well for paste printing, and was used in research question 3 to produce great printed results. The printer was eventually flashed with Professional Firmware" from Miguel Risco-Castillo (username mriscoc) from https://github.com/mriscoc/Ender3V2S1/releases/tag/20230522. This added ease of use in aspect such as bed level visualisation, bed level visualisation and changing the stepper motor rotation between thermoplastic printing and paste-extrusion. Further refinement to the system would be developing a quick change system for extruder assemblies between paste and thermoplastic, a heated chamber design for increasing the range of thermoplastics printable and to explore alternate drying modes for NMC pastes, and a system to mount the spring balancer and filament spool directly above to the system rather than relying on external structures.

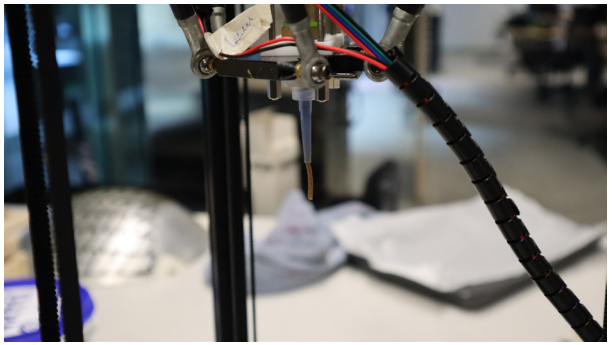
PRINTER_002_001

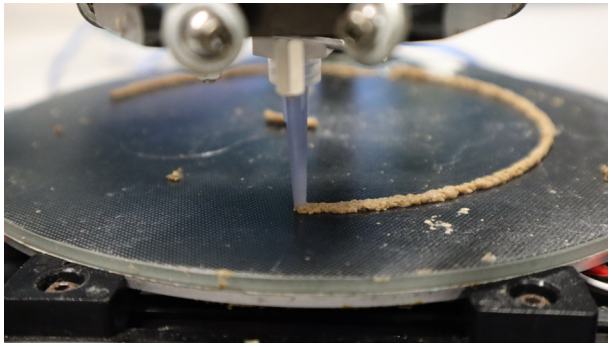
ANCHOR

EXPERIMENTS

OUTCOME

This series documented the first 3D printing attempts utilising the reworked EXTRUDER_002, PASTE_003_001, and the paste delivery system modified to fit the Anycubic Kossel printer. The experiments were a proof of concept that these components could extrude the paste along a path set by slicer software.









The printer was able to extrude the paste into circles, then cylindrical paths. This was controlled through the Cura 3D printer slicer.

Extensive CALIBRATION is needed in order as the results were nonuniform and seemingly random. Specifically the layer heights and Z offset need to be calibrated, as well as control over extrusion.

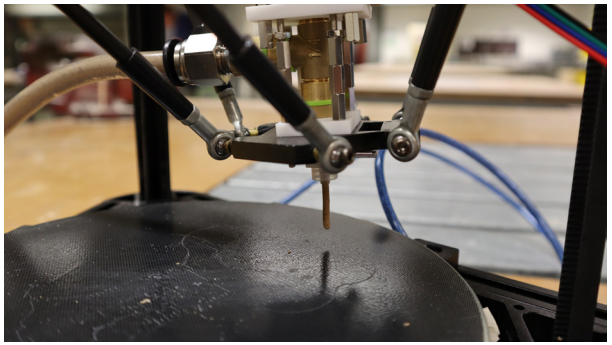
ANCHOR

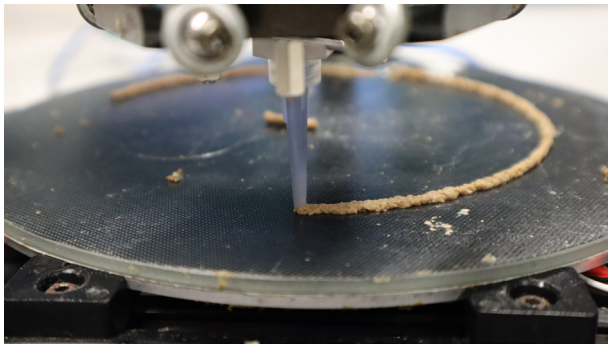
Testing air compressors ability to move paste through piping to extruder. 3 BAR of pressure was the maximum applicable due to air leakage from the 3D printed thread made for the syringe.

Testing if auger and extruder assembly can consitently extrude paste through gcode control.

Adjusting Z offset through Cura 4.13.1 manually to explore first layer adhesion and 'look' (whether the first layer was thick and wide or shaped netly like filament).

EXPERIMENTS









Photographs and videos of the paste delivery and extruder systems being calibrated and tested. Changes to the various systems were done individually and tested before further alterations.

OUTCOME

After many attempts, I achieved some uniform extrusion powered by the paste and extrusion systems working in unison. The first printed shapes were 2-4 layer tall circles, where I focused on the extrusion's uniformity.

Of particular concern was manually measuring the Z-offset - the height from the nozzle to the bed at the start of the print - so this could be input into the slicer and controlled electronically.

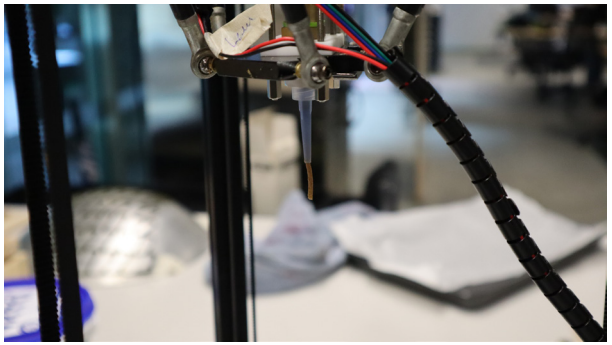
PRINT_001_001

ANCHOR

EXPERIMENTS

OUTCOME

Testing for a consitent flow rate (speed at which the auger turns) to consitently extrude material onto build plate.









Further CALIBRATION to the extrusion system., mainly focused on CALIBRATION and control through the slicer software.
The same 100-diameter hollow disc was printed as earlier CALIBRATION tests.

PRINT_001_002

ANCHOR

EXPERIMENTS

OUTCOME

Further development of the results from PRINT_001, 002 explored settings changes in the slicer software in attempts to print the same model consistently.









Print consistency was incredibly difficult to achieve, and pinpoint issues was a challenge. Reusing successful gcode from a previous print would yield completely different results. I was able to print a shallow thick cylinder, with no base or top, however this result was unsatisfactory when compared to what was displayed in the slicer software.

ANCHOR

EXPERIMENTS

OUTCOME

Testing for a consitent flow rate (speed at which the auger turns) to consitently extrude material onto build plate.









Further CALIBRATION to the extrusion system., mainly focused on CALIBRATION and control through the slicer software.
The same 100-diameter hollow disc was printed as earlier CALIBRATION tests.

PRINT_002_001

ANCHOR

Flow 300%

Print speed 7.5 mm/s

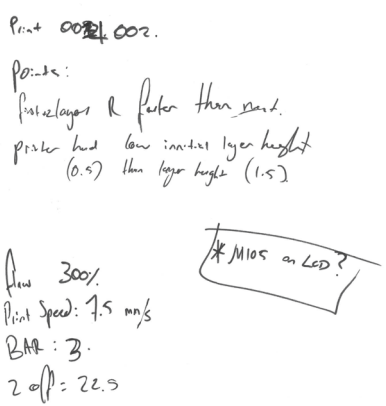
BAR 3

Z offset 22.5 mm

EXPERIMENTS







OUTCOME

First 2 layers are faster than the rest.

Printers first initial layers are lower than the set layer height

– something to look at in settings.

Before printing, there was an M105 error on the Anycubic kossels LCD.

PRINT_002_002

ANCHOR

EXPERIMENTS

OUTCOME

Initial layer height 1.5 mm

layer height 1.5 mm

Print speed 17 mm/s (+10 from 001)

Flow 300%

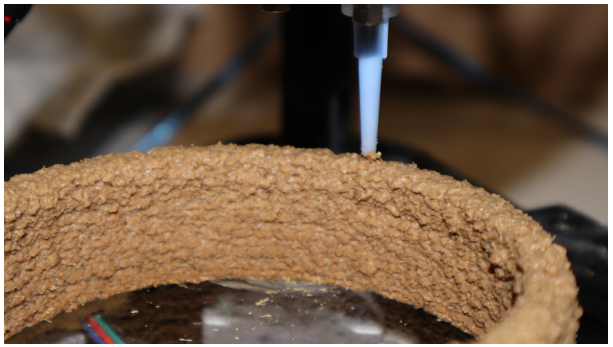
Z offset 22.5 mm

Pressure 3 BAR









Changed the speed, layer height and initial layer height from 002.

*speed could increase?

PRINT_002_003

ANCHOR

EXPERIMENTS

OUTCOME

Travel speed 25 mm/s

Flow 300%







P002.004.
Notes – Increase travel speed increase to
25
Much too fast in 300% flow.
So fast the coupler screws
came loose.

Much too fast with 300% flow –

so fast that the flexible beam coupling screws came loose.

PRINT_002_004

ANCHOR

EXPERIMENTS

OUTCOME

Print speed 20 mm/s

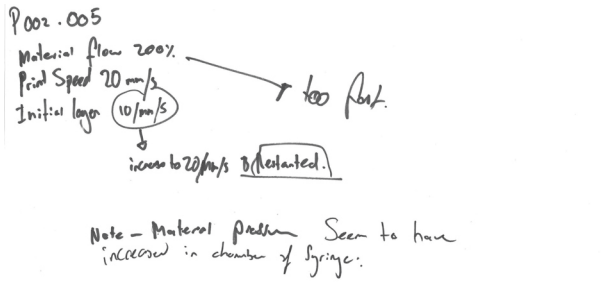
Material flow 200%

Initial layer speed 20 mm/s (match pint speed)









Flow or speed is too fast.

Note – material pressure seems to have increased in the chamber of the syringe.

PRINT_002_005

ANCHOR

‘middle ground’ settings

Flow 100%

trying to control line thickness (increase looks like cement print)

Speed 15 mm/s

increse to 20-25?

Initial layer speed 7.5 mm/s

try 2/3 speed instead of 1/4?

Layer height 1.5 mm

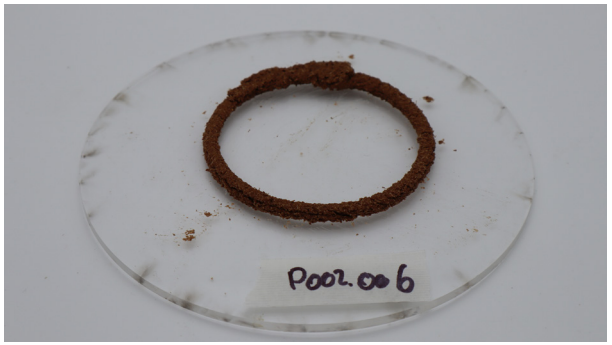
Initial layer height 1.5 mm

Wall line width 2 mm

can this be reduced?

Z offset 22.5 mm

EXPERIMENTS







P002.006.
Middle ground Setting.
flow 100% → try control. → lines are Thick (looks like cement print)
Speed 15 mm/s → increase - (20 - 25)
Initial layer 7.5 mm/s. → try @ 2/3 instead of half.
Layer & initial layer 1.5mm
Wall line width 2 mm → could be Reduced.
Z off 22.5 mm
failed due to air bubbles!

OUTCOME

Print failed due to air bubbles.

It seems as though the less paste in the syringe,

the more chance there is of air bubbles.

PRINT_002_006

ANCHOR

EXPERIMENTS

OUTCOME

I started this series with completely new print settings, as shown in 003_001. Ultimately this is a continuation in the CALIBRATION process where I am dialling in all the components, softwares, and the paste mixtures.









I found that the more settings I changed, the more the printer strained against me.

The print head was jittering/ shaking quite a lot while printing, a problem I seen on other devices with 'logic' issues. This made me think that the printer was struggling to follow the path being set for it.

At this point in the experimentation process I began to consider that the print needed a firmware update, and that I needed to try slicer software's other than cura.

ANCHOR

*moved to 50d x 50h cylinder print

*more paste in the syringe to try to prevent air bubbles

Layer height 1.5 mm

Initial layer height 1.5 mm

Wall line 2 mm

Flow rate 150%

Print speed 20 mm/s

Initial layer speed 15 mm/s

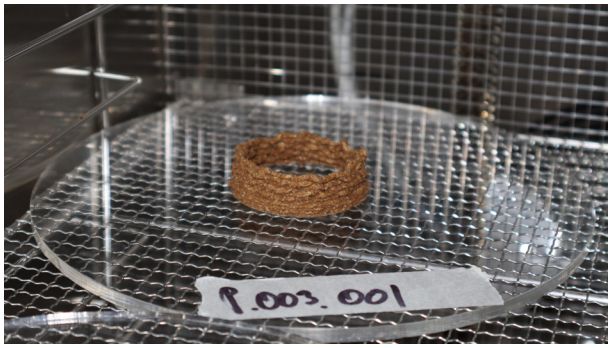
Number of slow layers 2

Z offset 22.2 mm

Pressure 3 BAR

EXPERIMENTS









OUTCOME

First few layers were faster than the rest, which is confusing

due to the initial layer speeds number of slow layers.

Perhaps this has to do with inner & outer wall speed settings,

I should just match these up.

PRINT_003_001

ANCHOR

Layer height 1.5 mm

Initial layer height 1.5 mm

Wall line 2 mm

Flow rate 150%

Print speed 20 mm/s

Initial layer speed 15 mm/s

Outer wall 15mm/s

Inner wall 20 mm/s

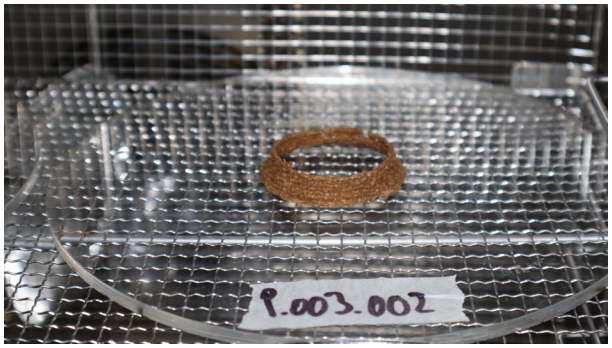
Number of slow layers 2

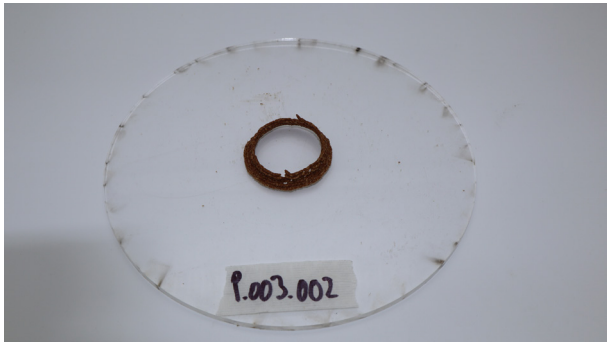
Z offset 22.2 mm

Pressure 3 BAR

EXPERIMENTS









OUTCOME

Reduce speed to 17?

Too fast, breaks the deposits

I am happy with overall quality

PRINT_003_002

ANCHOR

Speed & flow test

Print speed 17 mm/s

Wall speed 8.5 mm/s

Initial layer speed 15 mm/s

Outer wall 12mm/s

Inner wall 25 mm/s

Number of slow layers 2

Z offset 22.2 mm

Pressure 3 BAR

EXPERIMENTS









OUTCOME

Still having tares/breaks in deposits.

Could/should I lower speed more or flow?

PRINT_003_003

ANCHOR

EXPERIMENTS

OUTCOME

Same settings as print_003_003 but with 100d x 50 model









Still having some material breaks and slowing.

I will match the inner/outer wall settings in future.

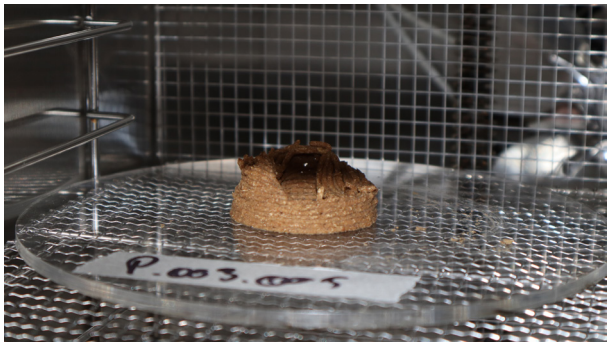
PRINT_003_004

ANCHOR

EXPERIMENTS

OUTCOME

Back to 50d x 50 model









NOTE breaks are happening due layer support/strength beneath that deposit.

This is causing the deposit to stretch and tare.

Nahum (MEDL colleague) points to their only being CMC in the mixture and

that some MFC could help with structural integrity.

PRINT_003_005

ANCHOR

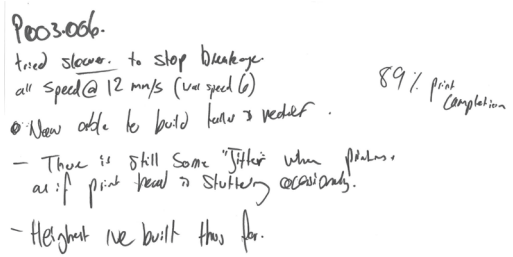
EXPERIMENTS

OUTCOME

ALL SPEEDS TO 12 mm/s

Wall speed 6 mm/s (automatic)

Building taller and higher





Noting there is some 'jittering' when printing like the print head is stuttering.

Highest I've built thus far

89% print completion





The print immediately collapsed upon contact with heat

PRINT_003_006

ANCHOR

EXPERIMENTS

OUTCOME

Trying to print a base to the vase mode.









The BOTTOM layer cannot be set to ‘spiralised outer contour’ (vase mode)

This means the extrusion was lifting and settling back on different parts of the bed -resulting in a mess.

PRINT_003_007

ANCHOR

This series continues in the development of the settings for the printer while problem solving previous issues.

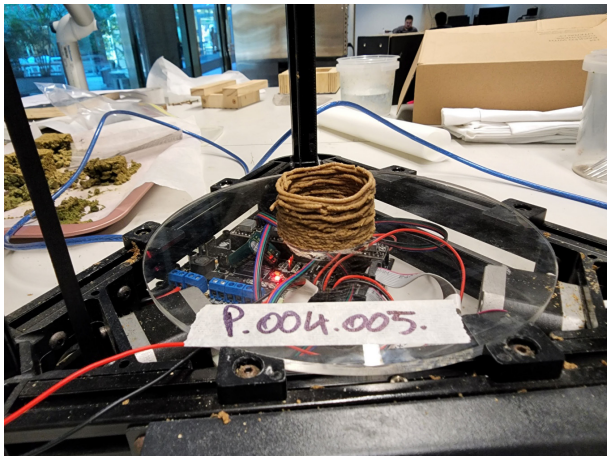
Currently the printer is struggling all round, particularly with

First layer adhesion

Layer size when prints get taller are not uniform

Jitting and stuttering, most likely related to firmware and software limitations.

EXPERIMENTS









https://youtu.be/beqHzQyAlwg

OUTCOME

This series started off poorly with the first four attempts at printing failing. This can be seen through this video link. https://youtu.be/1mpdlrZKiLY.

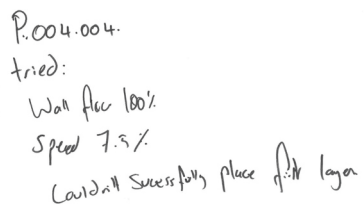
Prints had poor layer adhesion and the printer was struggling to uniformly deposit paste.

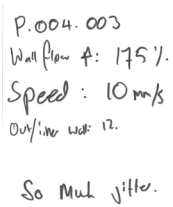
Later prints in the series were able to build some height on thin walls, however this required lowering the printer speed and starting height, increasing the flow; basically relying on the printer to extrude lots of material to make up for any mistakes in layer adhesion.

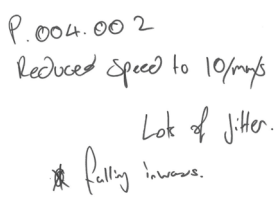
ANCHOR

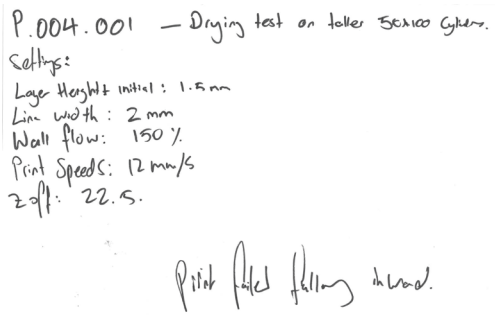
The first four attempts at printing in this sequence all failed. First, the paste was struggling to adhere to the build plate, then, there was no structural strength, and the prints would fall inward on themselves.

EXPERIMENTS









OUTCOME

Not shown in the frame on the videos published, I noticed that the syringe/cartridge was low on material. From this observation, I believe the extrusion issues were due to decreased pressure in the chamber, resulting in less pressure at the extruder.

This shows that the mix of pressure and motion of the auger work together in creating successful extrusions, and though one can print without an auger, it provides a necessary level of control when extruding.

https://youtu.be/1mpdlrZKiLY

PRINT_004_001

ANCHOR

EXPERIMENTS

OUTCOME

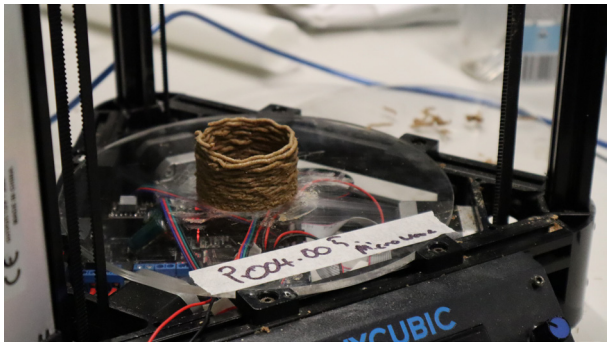
Testing drying methods.

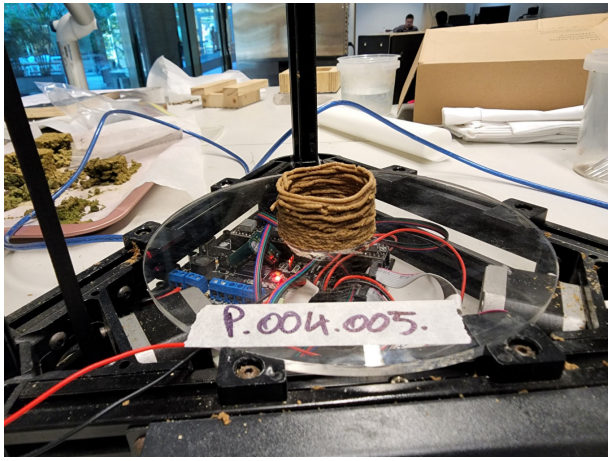
Speed 7.5 mm/s

Layer height 1.5 mm

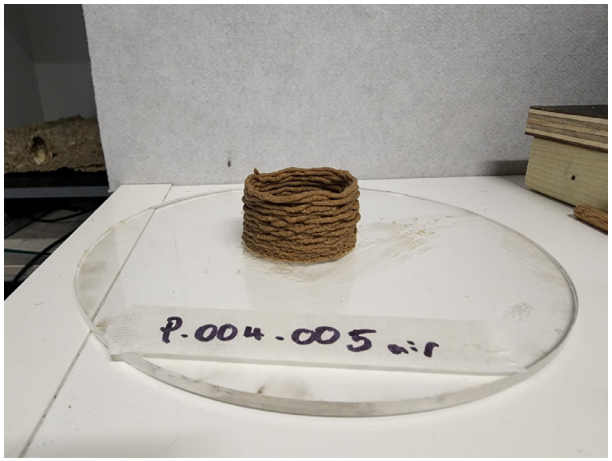
Flow rate 200%

Z offset 22.5 mm









Considering lowering the Z offset.

I tried to print the same 50d x 50 cylinders three times and dry them in the microwave, dehydrator and with air.

The dehydrator was set to 30 degrees C

The microwave was set to 120 seconds – it immediately collapsed in the microwave.

The air drying model was left on my desk overnight.

PRINT_004_005

ANCHOR

EXPERIMENTS

OUTCOME

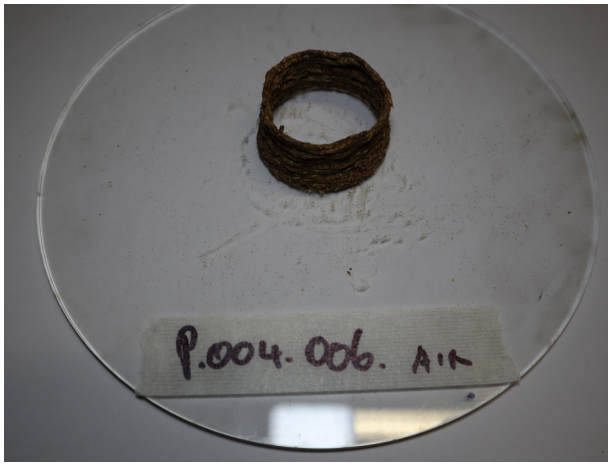
Air dry

Z offset 22.2 mm

Speed 7.5 mm/s

Flow 200%









Good print – note that as it got taller, the pressure[?] slightly

changed the total height of the model

therefore changing the

thickness of the deposited material either through less pressure

being applied above by the print head, or gravity allowing the

material to stretch to more a filament looking cylinder material.

PRINT_004_006

ANCHOR

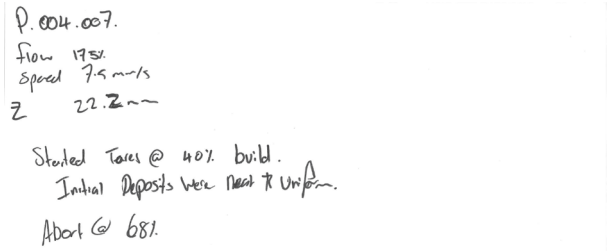
EXPERIMENTS

OUTCOME

Flow 175%

Speed 7.5 mm/s

Z offset 22.2 mm









Aborted at 68%

Visable tares appering at 40% build complesion.

Note initial deposits were neat and uniform

PRINT_004_007

ANCHOR

EXPERIMENTS

OUTCOME

Thick deposit for air and dehydrator

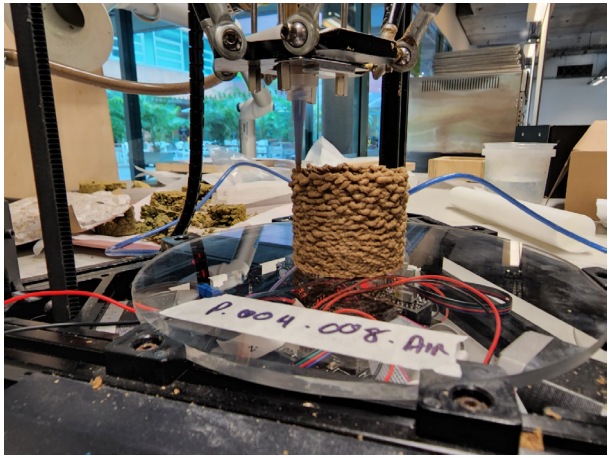
Flow 250%

Speed 7.5mm/s

Z offset 22.2 mm









Break/tares at 60%

Walls are physically moving with deposits.

100% completed print for air drying.

Aborted at 80% for the dehydrator, dried at 50 degrees C overnight

*what is setting ‘number of slow layers’.

PRINT_004_008

ANCHOR

50x50x50 Cube

Layer Height 1.5mm

Line Width 2mm

Wall out/in 250%

Initial Layer 100%

Print Speed 15

Wall Speed 15

Inner Speed 7.5

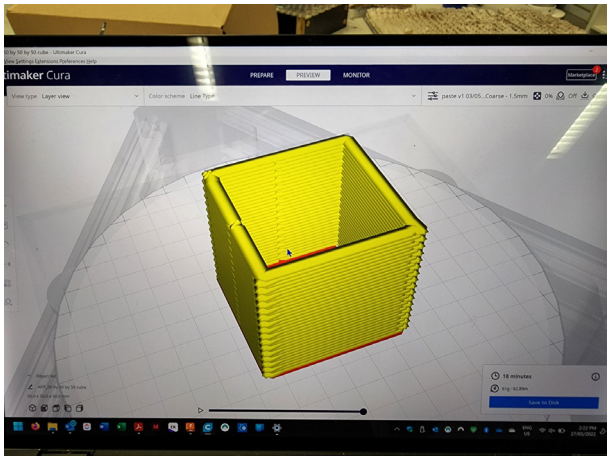
Travel Speed 7.5

Initial Layer Speed 3.75

Slow Layers 2

Z Offset 22.2mm

EXPERIMENTS



P.005 . 001 — Cube
50x50x50.

Settings as ~~[illegible]~~

layer Height : 1.5
Line Width: 2
Wall Out/In : 250%
Initial layer : 100%

Print Speed. ~~15~~ 15
Wall Speed/out : ~~7.5~~ 15
Inner : 7.5
Travel 7.5
Initial 3.75
Slow layer: 2
Z: 22.2mm

Printer Does not Spin extruder.
↳ This is for first few layers.

Seems Cura is Slicing the model weirdly.
→ Only slicing to one layer?

P.005 . 001 — Cube
50x50x50.

Settings as ~~[illegible]~~

layer Height : 1.5
Line Width: 2
Wall Out/In : 250%
Initial layer : 100%

Print Speed. ~~15~~ 15
Wall Speed/out : ~~7.5~~ 15
Inner : 7.5
Travel 7.5
Initial 3.75
Slow layer: 2
Z: 22.2mm

Printer Does not Spin extruder.
↳ This is for first few layers.

Seems Cura is Slicing the model weirdly.
→ Only slicing to one layer?

OUTCOME

It wont print straight lines. There is no explanation as to why the auger does not spin when following a straight path. Cura is also slicing the model very strangely. Perhaps it is time to move to another slicer.

https://youtu.be/tNI25nCMKtA

PRINT_005_001

ANCHOR

Series PRINT_006 continued the investigation into generating consisting prints.

Flow rate at 250% seemed to bring good results in PRINT_005, however the speed of the printer, particularly in the case of laying down a clean first layer which is the foundation of a good print, both thermoplastic and paste.

EXPERIMENTS









OUTCOME

Prints have begun to show some consistency between topping and starting the printer. I am now able to build cylinders which are uniform in shape and that have some height to them.

I am still battling with the printer to allow for smooth extrusion, and don't seem to have control over the extrusion, even with the auger inside the extruder.

ANCHOR

EXPERIMENTS

OUTCOME

Travel speed experiments

Travel speed 15 mm/s

Line width 2 mm

Flow 250%

Z offsest 22.2 mm

Number of slow layers 0









Failing in the 60% range

Aborted at 73%

A global flow rate of 250% has shown to be an effective selection in past prints during the configuration process.

PRINT_006_001

ANCHOR

EXPERIMENTS

OUTCOME

Travel speed 5 mm/s

Line width 2 mm

Flow 250%

Z offsest 22.2 mm

Number of slow layers 0









The print was extremely small at 60 minutes and thus the print was stopped.

PRINT_006_002

ANCHOR

EXPERIMENTS

OUTCOME

Travel speed 10 mm/s

Line width 2 mm

Flow 250%

Z offsest 22.2 mm

Number of slow layers 0









Stopped at 54:35 minutes

“best yet” – comment from colleague Ella Willaims who has done lots of paste printing.

The comments relate to the uniformity and consistent texture to the printed body, with no apparent changes in layers heights or deposition consistency.

PRINT_006_003

ANCHOR

Travel speed 12 mm/s

Line width 2 mm

Flow 250%

Z offsest 22.2 mm

Layer height 1.5 mm

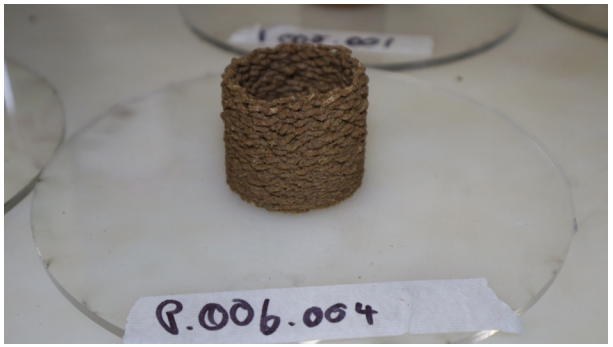
Number of slow layers 0

EXPERIMENTS









OUTCOME

Started missing alignment at 50%.

Aborted at 90%.

I thought of possibly getting a spirit level to place on top of the servo and see if the alignment is off due to tension from the syringe.

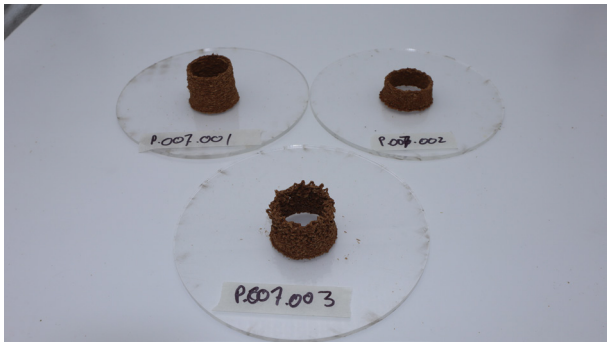
PRINT_006_004

ANCHOR

Building on findings from PRINT_006, this continued the pursuit for uniform, repeatable prints.

This series explored keeping settings uniform as per findings in 006, and experimenting only with the layer heights of prints.

EXPERIMENTS









OUTCOME

The settings used in this series of showed that layer height should be less than the width of the nozzle. A larger layer height caused prints to struggle and fail when building taller models. Lower layer heights print slower, however they make more uniformity in the model as it builds. Layer heights of 1 and 1.5mm seem to be further flattened by the passing nozzle, whilst heights closer to 2mm, which matches the nozzle width, lay down material that is more cylindrical in shape resulting in less surface contact between layers.

The best settings from this series, which can be used as a baseline going forward are:

Flow rate 250% (which is very high and needs solving)

Line Width 2 mm

Print Speed 12 mm/s

ANCHOR

EXPERIMENTS

OUTCOME

Layer height tests

Layer height 1 mm

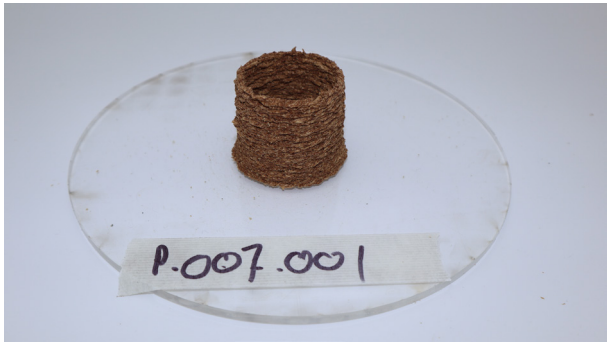
Line width 2 mm

Wall flow 250%

Print speed 12 mm/s









100% printed at 12 minutes

First 'miss' was seen at around 51% on a wider extrude than the body's shape (like oversteer in a car).

Some breaks in the body starting at 85%

PRINT_007_001

ANCHOR

EXPERIMENTS

OUTCOME

Layer height 1 mm

Line width 2 mm

Wall flow 250%

Print speed 10 mm/s









Aborted at 85%

Before changing layer height again, I thought I would change the print speed as I liked the consistency of 1mm layer height.

Previous prints had all been at 1.5mm layer height.

PRINT_007_002

ANCHOR

EXPERIMENTS

OUTCOME

Layer height 2 mm

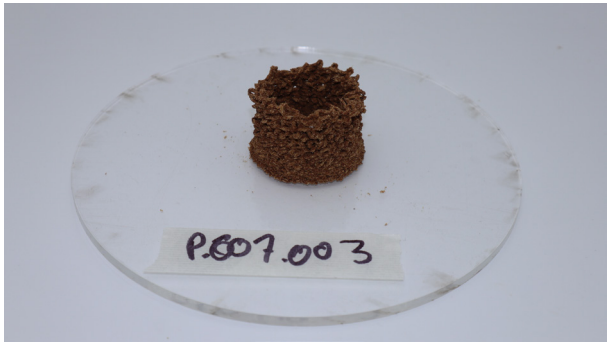
Line width 2 mm

Wall flow 250%

Print speed 12 mm/s









Aborted at 90%

The longer the print went, the larger the gap grew between the nozzle and the model wall.

This gave the deposit a ‘wave’ or ‘woven’ effect as it deposited.

This shows that the flow is too high however, it is interesting to see that the flow-rate can create drastically different shapes to the designated tool path.

PRINT_007_003

ANCHOR

The final instalment in the first PRINT series before revesting machine software and firmware issues, PRINT_008 printed artefacts utilising various of the most consistent settings found in previous experimentation. Settings changes mainly explored flow rate, print speed, layer height and line widths to print uniform and tall cylinders.

EXPERIMENTS









OUTCOME

PRINT_008 specifically explored how alterations to Cura's 'flow-rate' settings affected printed models. It was interesting to see how the GUI representation of models in Cura did not change with flow-rate alteration, reinforcing that the software is visualising thermoplastic printing paths and not thick paste paths.

Of all eight print series conducted thus far, this series had the most consistency. This is because it used variations of the best settings from the previous series in an effort to build towards consistent print outcomes.

Ulimately, while there was some uniformity in the hollow cylinder printers, the outcome of the PRINT series has been unsatisfactory due to the inability to control the material flow and extrusion with the auger.

This consistently has led to me to start exploring upgrading and alerting settings in the printer firmware, using other slicer software such as paid options like Simplyfy3d and free software like PrusaSlicer. Additionally, a new extruder that has a vertical inlet for paste and tighter tolerances in the paste delivery system would help with avoiding any path deviation on the extruder body through pulling from external forces while also providing more control over paste extrusion with the auger fitting tighter in the extruder body.

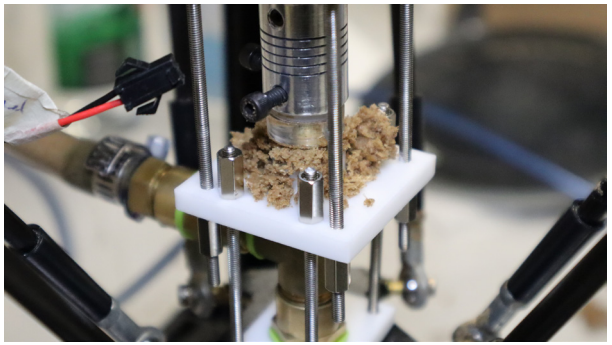
ANCHOR

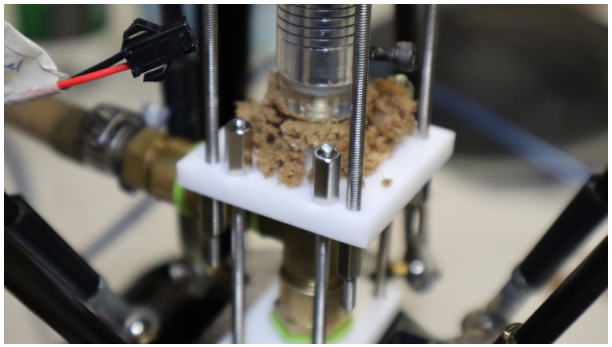
EXPERIMENTS

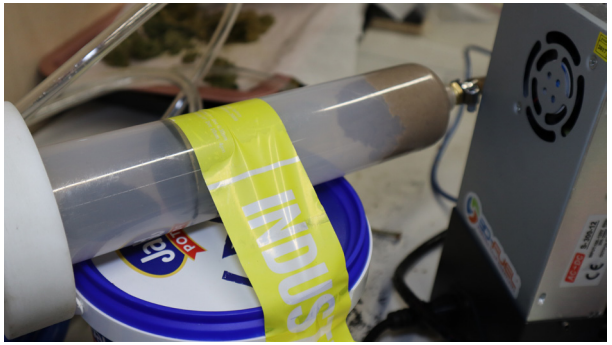
OUTCOME

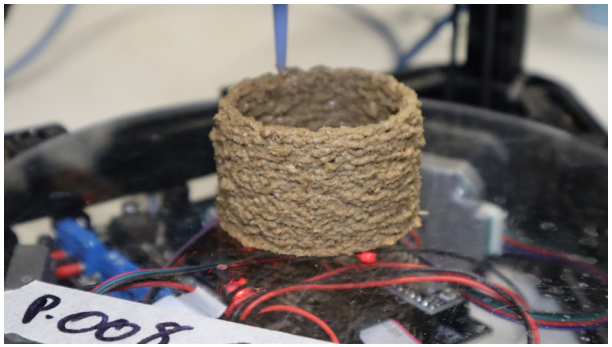
Reoccuring issue of having to secure the 12 oz syringe manually.

The syringe puts some lateral pressure on the extruder, which can cause miss alignment in printing.









After an intense day of printing, I noticed that the hex nuts securing the extruder to the printer had rattled loose. This allowed for some paste to be pushed out the top of the extruder body.

Some problem-solving remains regarding the extruder body and paste delivery system.

The extruder, after long periods of printing, starts to shake loose.

As seen in the images, paste begins to slowly push out the top of the auger body. Hex nuts on both sides of the threaded rod should help this.

The extruder is also being pulled off axis by the paste syringe.

A system/addition will need to be designed and made to securely hold the syringe without affecting the extruder.

PRINT_008_000

ANCHOR

EXPERIMENTS

OUTCOME

Flow rate testing (wall flow)

Wall flow 200%

Print speed 12 mm/s

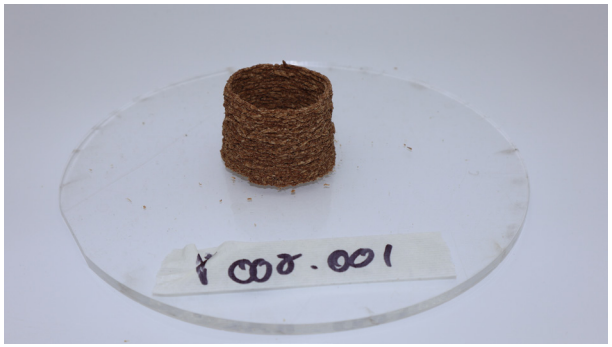
Layer height 1 mm

Line width 2 mm









Print aborted at 85% completion

This initial test started with the settings I had previously been using in other prints.

There is an obvious transition in the quality of the deposits/walls as the print gets taller.

PRINT_008_001

ANCHOR

EXPERIMENTS

OUTCOME

Wall flow 175%

Print speed 12 mm/s

Layer height 1 mm

Line width 2 mm









Wall weakness shown at 30% print

Neat lines and deposits to start with. As the print got taller,

the deposition becomes more ‘filament’ shaped and unpredictable

Printed to 100% completion

PRINT_008_002

ANCHOR

EXPERIMENTS

OUTCOME

Wall flow 150%

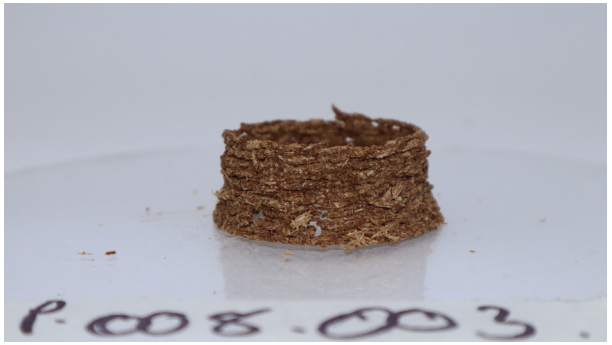
Print speed 12 mm/s

Layer height 1 mm

Line width 2 mm









Significantly less structural integrity was apparent earlier in the print process.

Breaks shown on lower levels

<30% print

Aborted at 50%

PRINT_008_003

ANCHOR

EXPERIMENTS

OUTCOME

Wall flow 225%

Print speed 12 mm/s

Layer height 1 mm

Line width 2 mm









This run was suncessfully completed to 100%.

However, the layers do change in appearance at the top layers, suggesting changes in nozzle height to the body of the print.

Wall breaks/misses starting at at 75%

100% print completion

PRINT_008_004

ANCHOR

EXPERIMENTS

OUTCOME

Wall flow 225%

Print speed 10 mm/s

Layer height 1 mm

Line width 2 mm









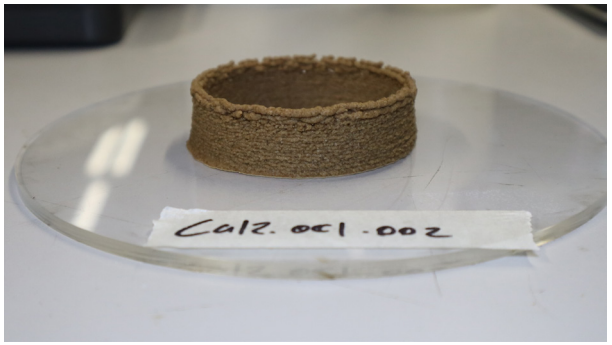
This prints settings are the culmination of the ‘best’ settings from what I had witnesssed in the days print tests.

PRINT_008_005

ANCHOR

CALIBRATION2 is a continuation of the PRINT_002-008 series, in that it focusses on 'dialling' the printing into a workflow and settings which result in a consistent printing experience. The series continued with printing hollow cylinders, but with a focus on moving towards one set of settings that can print a tall structure with unform layer heights and wall consistency.

EXPERIMENTS









OUTCOME

Prints began to have some consistently following settings:

In Cura
Z Offset 21.5 mm
Layer Height 1.5-1.8 mm
Jerk 10 Acceleration 1500_
Relative Extrusion turned on

2 Bar of pressure, which is too high and causes material to push out of the top of the extruder body where the stepper motor is.

The EXTRUDER_002 was showing its limitations in a few aspects. First the parallel to the ground paste inlet was continently pulling the extruder off axis due to the weight of the piping and syringe with paste. This needs to be fixed in order to allow for smooth movement of the extruder body and gantry. Further, the thickness of the auger is not equal to close to the thickness of the inside of body of the extruder, allowing paste to flow around and and past the auger reducing its control of the extrusion.

Lastly, it seems like the printer cannot print straight lines, in that the stepper motor will not spin when a straight line path is presented to it in the the gcode. This is important to fix however the paste extrusion issues in general need to be addressed first.

ANCHOR

EXPERIMENTS

OUTCOME

Print of 75mm tall Cylinder with 75 diameter

Speed 10mm/s

Z Offset 21.5mm

Layer Height 1mm

Line Width 2mm

1 Bar of pressure









Aborted at 46%. Layer Height is either too low because the material seem thin. The rubber pusher inside the cylinder was also not touching the material but paste was able to be extruded. Paste is also coming for the top of the extruder - I assume this is because the pressure is too high.

CALIBRATION2_001_001

ANCHOR

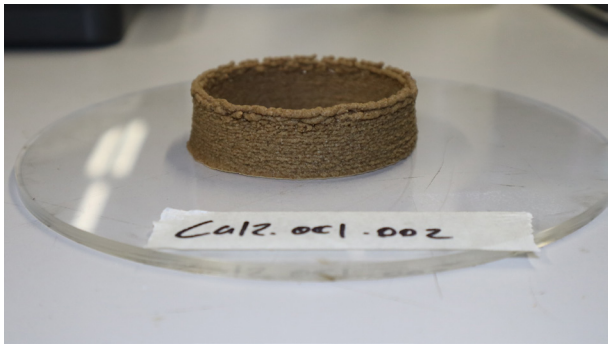
EXPERIMENTS

OUTCOME

Same as cal2_001_001 but trying to investigate 'thin' layers'

Z Offset 22mm









At 65% progress there began to be deposit issues. Aborted at 73%

Speed could go up

Paste too thin

Layer heights looked good.

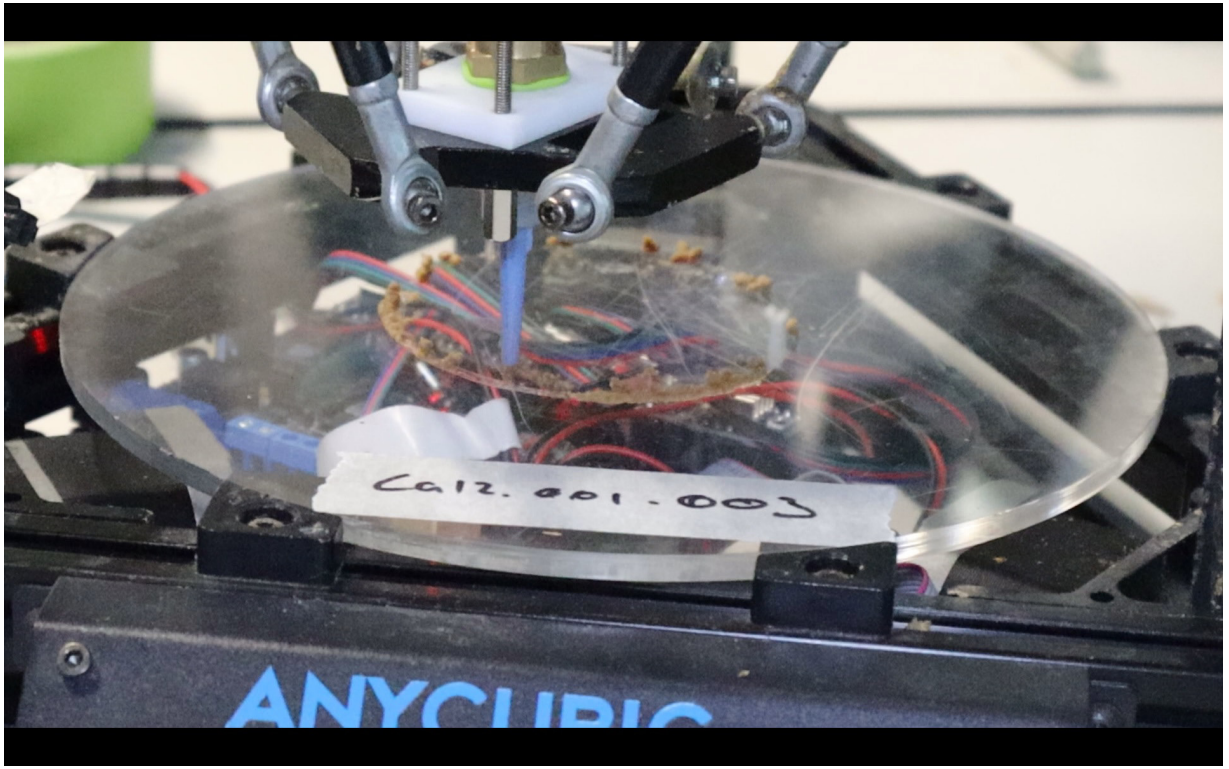
ANCHOR

EXPERIMENTS

OUTCOME

Z Offset 21.85 mm

Speed 12.5mm/s



Couldn't get first layer or good adhesion. Changing settings for next experiment

CALIBRATION2_001_003

ANCHOR

Z offset 21.80mm

Speed 10 mm/s

EXPERIMENTS

No Photos due to print failure

OUTCOME

Extruder_002 has lots of paste coming out of the top where the auger meets the stepper motor.

ANCHOR

EXPERIMENTS

OUTCOME

New Paste Mix + 1 Bar of pressure

Z offset 22mm







Flow rate issues possible causes

Pressue - paste leak and inconsistent layer deposits

FLow rate settings might help

Layer height could also be an issue. Lower heights may enable more consistency when prints get taller.

CALIBRATION2_001_005

ANCHOR

Begin testing flow rate settings.

FLow rate value raised to 250% from 225%.

EXPERIMENTS

No Photos due to print failure

OUTCOME

Could not get consistent extrusion or layer adhesion. Printer began stuttering in CALIBRATION2_001_006 and 001.007.

CALIBRATION2_001_006

ANCHOR

Trying to reduce printer stuttering - this led to me learn about settings called ‘jerk’ which may help.

Printer Jerk reduced from 20 to 10

Printer acceleration reduced from 3000 to 1500

Setting called Relative Extrusion was enabled in Cura as well.

EXPERIMENTS









OUTCOME

Relative Extrusion seemed to help with some of the shake.

I need to maybe lower layer heights for more consistent adhesion and extrusion uniformity.

CALIBRATION2_001_007

ANCHOR

EXPERIMENTS

OUTCOME

Same settings as .001.007









Need to lower the layer heights more. The jerk and stuttering issues are still very bad.

CALIBRATION2_001_008

ANCHOR

EXPERIMENTS

OUTCOME

Z offset 21.75









I am coming to terms wit that the stuttering issue must be firmware (printer coded settings) or software (slicer settings).

Large strands missing as the build gets taller.

CALIBRATION2_001_009

ANCHOR

EXPERIMENTS

OUTCOME

Z Offset 21.5









Pressure needs to go down as well as layer heights.

Pressue is extracting H2O from paste as it sits still not printing. I need to turn off the tank and disconnect if I take extended breaks.

CALIBRATION2_001_010

ANCHOR

EXPERIMENTS

OUTCOME

Z offset 21.5mm

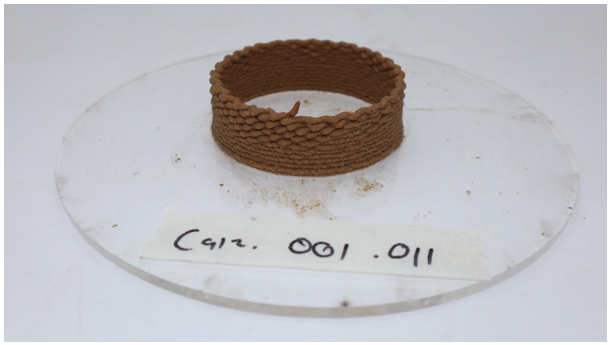
Layer Height 1.8mm

Jerk 10

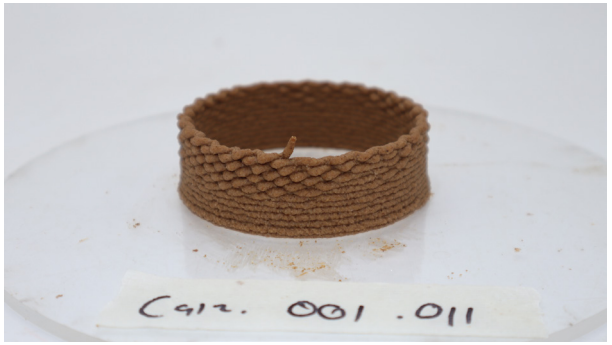
Acceleration 1500

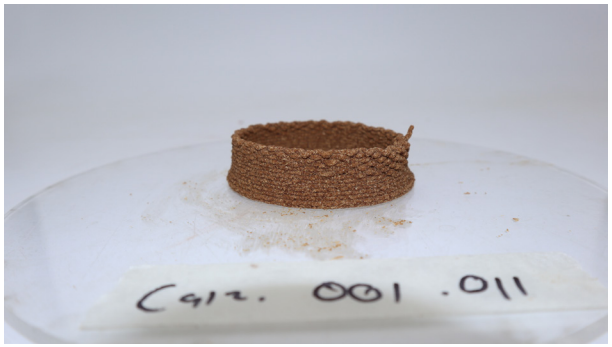
Relative Extrusion ON

2 BAR.









While a nice looking artefact, similar but lesser in quality to the ‘standard’ 3D printed vase, I am not happy with my control over the extrusion.

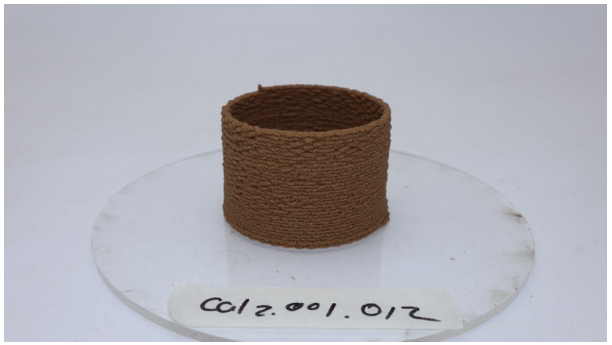
CALIBRATION2_001_011

ANCHOR

EXPERIMENTS

OUTCOME

All settings the same as CALIBRATION.001.011, but Layer was dropped to 1.5mm.









I want to be able to build taller - but I do not have enough control over extrusion or the printer to do infill yet. I want more structural integrity and uniformity in the extrusion.

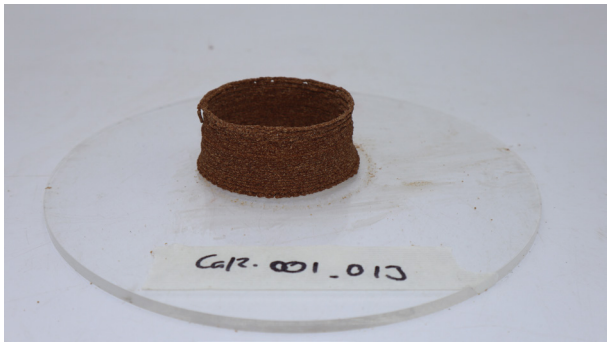
CALIBRATION2_001_012

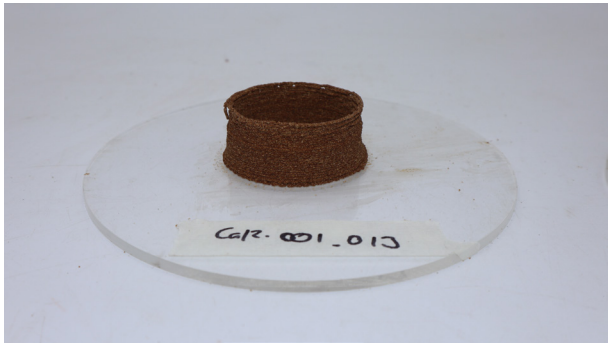
ANCHOR

EXPERIMENTS

OUTCOME

Exact Same as .012









I liked the outcome from 0.12 so I printed it again to see if I could get a similar result. I was pleasantly surprised that they printed similarly.

CALIBRATION2_001_013

ANCHOR

I tried to print a simple slot.....

EXPERIMENTS

No Photos due to print failure

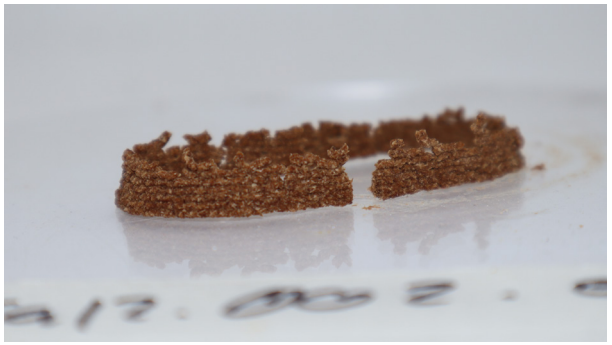
OUTCOME

but it wont print the straight lines????????????

ANCHOR

CALIBRATION2.002 documents the transition of slicer software from Cura to Simplyfy3D. When comparing the Gcode between the two slicers, Simplyfy3D's output showed promising signs that it produce straight lines on the 3D printer, a problem found was encountered multiple times in Cura (see PRINT_005_001 & CALIBRATION2_001_014).

EXPERIMENTS









OUTCOME

For unknown reasons, models with straight lines loaded into Simplify3D were able to be printed on the printer. This series of prints documents the various settings tested and the changes in settings values from Cura to Simplify3D. Settings differences were:

Nozzle 2mm

Extrusion Multiplier 10 with auto width (this would be similar to flow rate from Cura)

Layer Height 1.5mm

Perimeter Shells 1

Corkscrew ON (vase mode)

First Layer Settings all at 100%

Extruder temp 0

Cooling 0

Z offset 6mm (firmware differences from Cura)

Speed 30mm/s

ANCHOR

Slot attempt v2.

Printed with PASTE_003_004.

MOVED FROM CURA TO SIMPLYFY3D

Nozzle 2mm

Extrusion Multiplier 10 with auto width

Layer Height 1.5mm

Perimeter Shells 1

Corkscrew ON

First Layer Settings all at 100%

Extruder temp 0

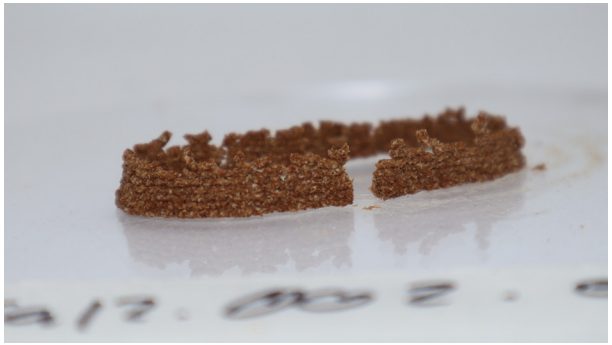
Cooling 0

Z offset 6mm (firmware differences from Cura)

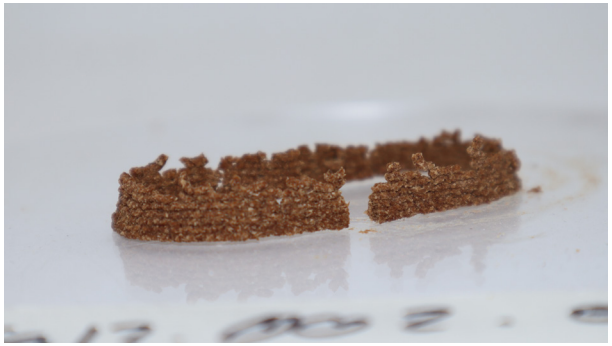
Speed 30mm/s

EXPERIMENTS









OUTCOME

Something still seems off, but I can now print straight lines. I need to find a way to override the speed settings as they seem to be ignored when set in slicer software. I imagine this is something I will need to change in the printer firmware (marlin) eventually.

CALIBRATION2_002_001

ANCHOR

EXPERIMENTS

OUTCOME

Z offset 5.75









Layer heights too low and the flow rate was too high.

Slowly learning about different gcode commands that i can send from the terminal in simplfy3d. This terminal also has GUI controls from moving the extruder around as well as extruding material

CALIBRATION2_002_002

ANCHOR

EXPERIMENTS

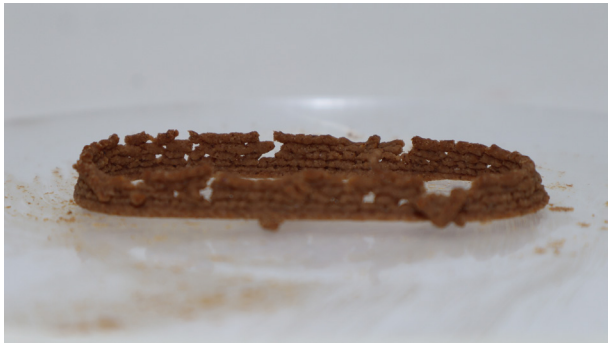
OUTCOME

2 BAR









I need to make more consistent material and pack the material more consistently in the syringe and design a new extruder body.

The current body is really struggling particularly because it is being pulled stage right by the weight of the syringe which is laying next to the printer. If I could hang the syringe body and have the inlet to the extruder be at a Y angle, I believe this would help with smoother extrusion.

CALIBRATION2_002_003

ANCHOR

EXPERIMENTS

OUTCOME

Layer Height 1mm adjusted from 1.5

2 BAR









Slowing adjusting the pressure BAR while printing - Starting at 2 BAR and slowly moving down. This is only a Band-Aid to the problems.

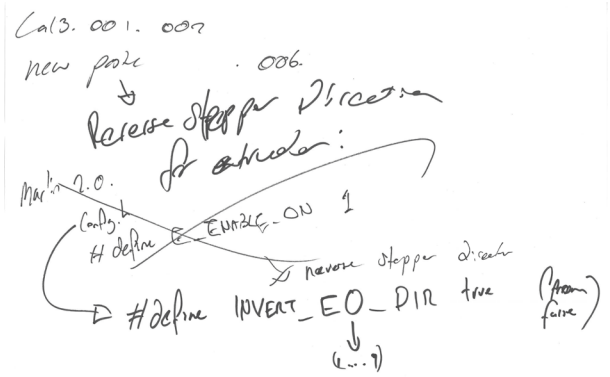
CALIBRATION2_002_004

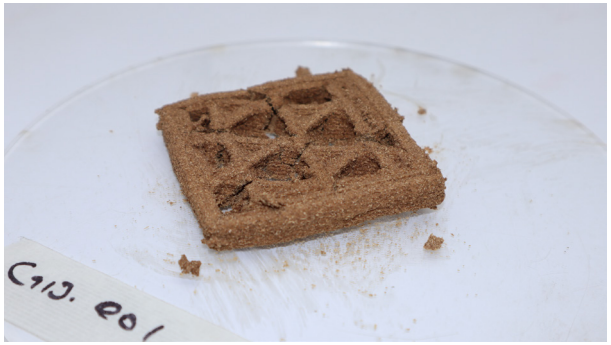
ANCHOR

CALIBRATION3 continues on the findings from CALIBRATION2, developing a set of best settings to use in Simplyfy3D. This series also feature the first use of a custom designed and 3D printed extruder for the printer and paste, EXTRUDER_003_001.

The series of CALIBRATION3 explores many forms and settings, from hollow cubes and cylinders, to cubes with various infill settings. This is all made possible by the move from Cura to Simplyfy3D, which inexplicably enabled the printer to extruder straight lines.

EXPERIMENTS





OUTCOME

There was a learning curve when using Simplyfy3D and EXRTUDER_003. First, new Z offset heights needed to be measured; however, this proved difficult as the nozzle was now further away from the gantry, beyond the software enable limitations enabled by the printer to avoid collision with the bed. This meant I had to upgrade and change settings in the printers Marlin firmware. I also generated new starting gcode, stored in the slicer software, which defines the Z Offset without crashing the printer, as shown in CALIBRATION3_001_006.

While changing settings in Marlin 2.0, the new firmware, I disabled features relating to the software end-stops, which limited how close the gantry body can get to the bed, I also changed settings related to the unused heating elements which occasionally created error messages halting or stopping prints.

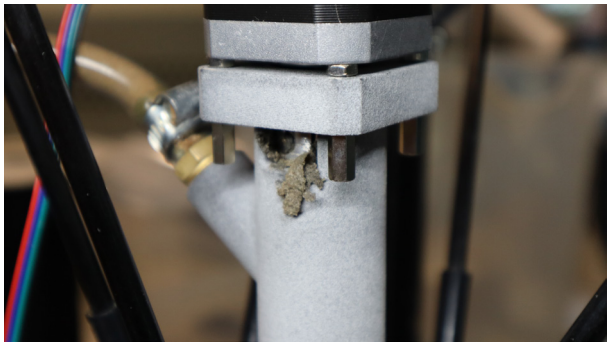
The most significant, and project altering change was noted in CALIBRATION3_001_002, in which I reversed the stepper motor direction. While watching the printer struggle to print, I was playing with a screw that I considered using as an auger. I spun the screw in between my fingers and noticed that the screw moved away from me if I spun it clockwise, the opposite direction it was currently spinning on the stepper motor. This meant that the current counter clockwise spin was pulling material towards the stepper motor, rather than pushing it away. I tested this in the Simplyfy3D printer controller GUI, and a string of smooth extracted material was released when spinning the auger clockwise. I changed the auger spin direction in the firmware by inverting all ‘E’ motor directions. This enabled smooth and controller extrusion and enabled the ability to create infill and do retraction between deposits.

ANCHOR

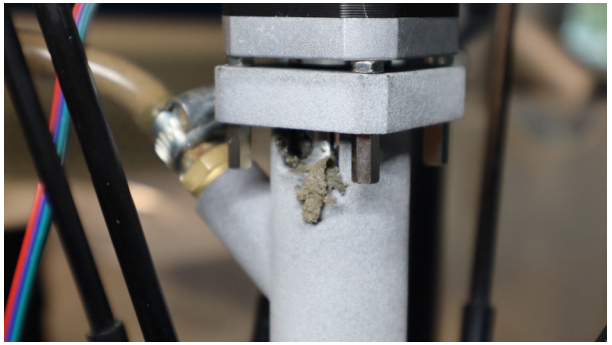
EXPERIMENTS

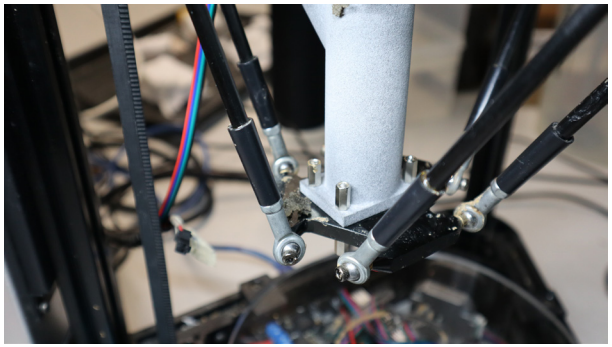
OUTCOME

A persistent problem where liquid paste escapes from the top of the extruder through both the side outlet (which I designed for air to escape and to monitor the spin speed of the auger, and through the top of the beam coupling.









This problem is possibly happening for a few reasons. There is possibly a pressure difference between the amount of paste entering the extruder assembly and the amount of paste being extruded through the nozzle. Liquid and excess paste then finds a way out of the extruder assembly. The paste may be too liquid. What I should explore is trying to find the ‘sweet spot’ of extrusion and paste delivery speed, and work towards reducing the water content in the paste to avoid liquid moving through the extruder assembly.

ANCHOR

EXPERIMENTS

OUTCOME

Using new nylon 3d Printed EXTRUDER_003_001 and FDM printed nozzles

2 BAR







Material is still escaping through the top of the extruder body.
I think this can be solved by creating a tight seal between and separating the auger section with the coupling section. An O-ring and perhaps another seal above that. Andrew in the workshop described this as creating a collar which may fit snug around the auger while also going inside the auger hole to stop material coming back up. This is also probably a high pressure and watery paste issue.

I also went to bunnings and bought 7 drill bits for new augers. I cut these to size for fitting in the coupling and the extruder body. I think maybe the tips of these can be an issue, but the other auger and the amount of material that is allow to flow between section seems important. Screws with more thread may enable more control of material flow through the auger sections of the extruder body.

CALIBRATION3_001_001

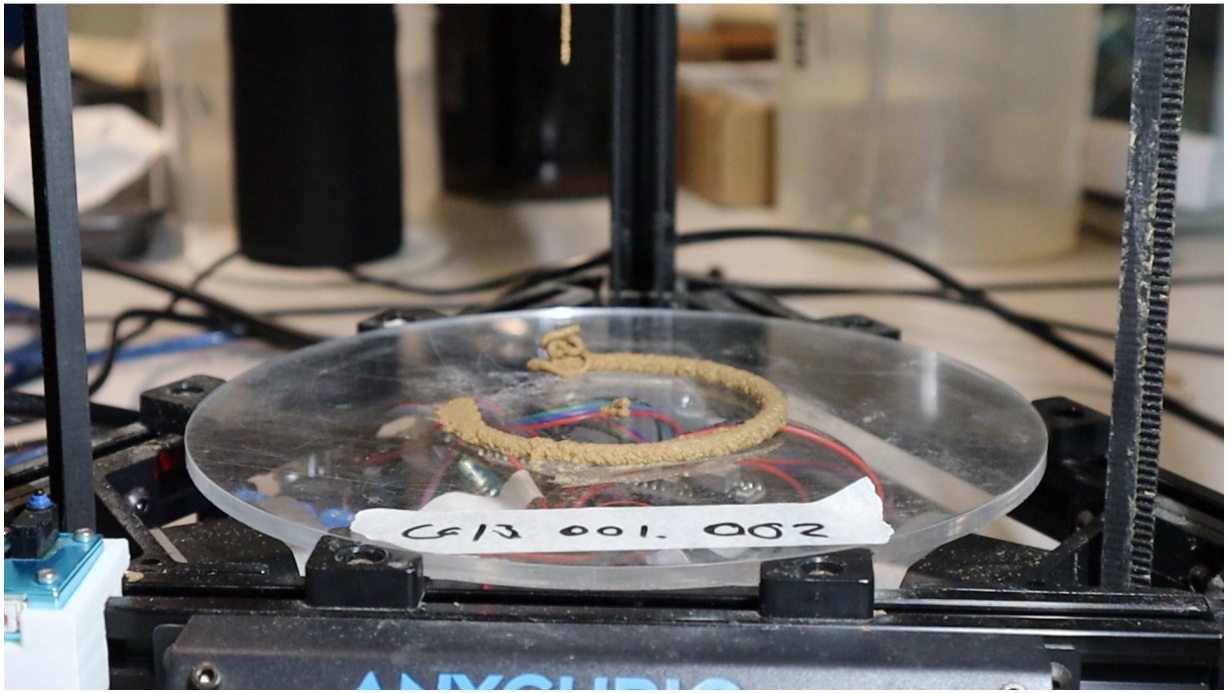
ANCHOR

EXPERIMENTS

OUTCOME

Extrusion Multiplier reduced from 7.5 to 2 while using new FDM printed 2mm nozzle.

Using PASTE_003_006.



Limited Photos due to print failure

Too much flow from 2mm nozzle.

I am trying to experiment with reversing stepper motor direction to see if this does anything for the extrusion issues. I updated the printed to marlin 2.0 firmware from a file I found online. I also changed in the configuration #define INVERT_E0_DIR true- this is a change from false value.

CALIBRATION3_001_002_change direction

ANCHOR

Trying to calibrate EXTRUDER_003_001.

Particularly layer heights_Z offset_Material Flow

EXPERIMENTS









OUTCOME

I need to improve

upwards leak into coupling area

Nozzles

Material make up, it could have less water. I will return to using PASTE.003.005

CALIBRATION3_001_003

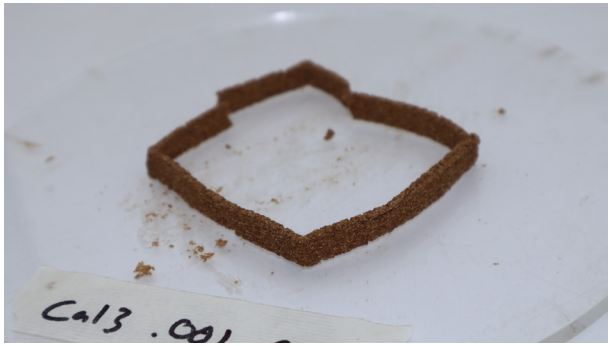
ANCHOR

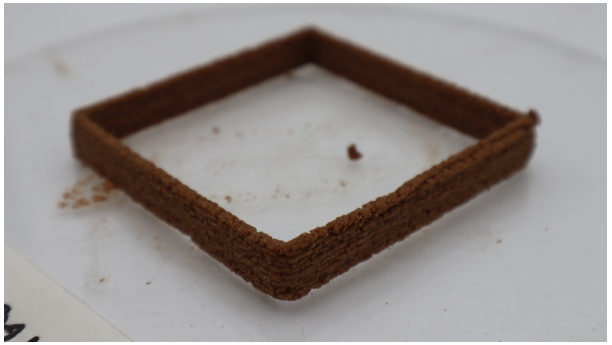
EXPERIMENTS

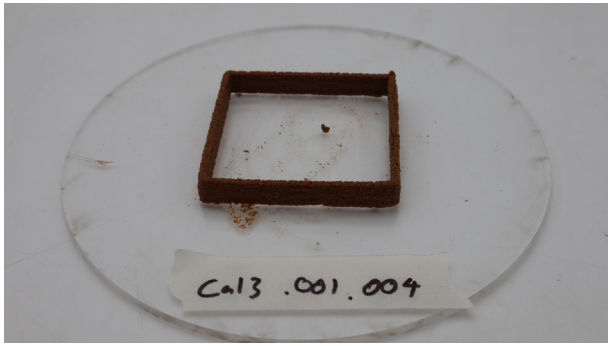
OUTCOME

Attempt at a cube. New Z offset.









Happy I could print the corners and straight lines. The dried part broke.

CALIBRATION3_001_004

ANCHOR

EXPERIMENTS

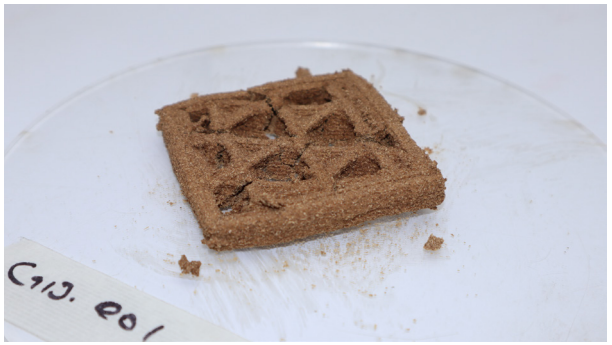
OUTCOME

Cube

1 bottom layer

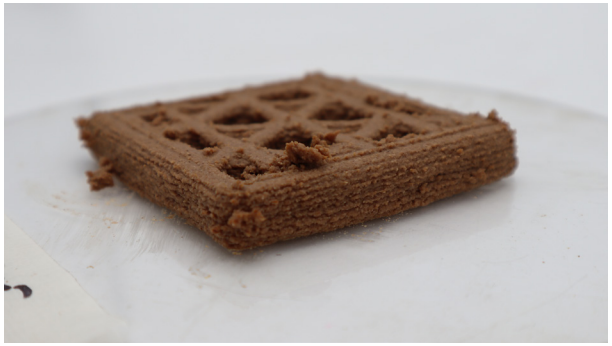
2 walls

50%@ infill.









I think its starting to work!
Reversing the direction of auger allows for significantly more flow._
Material is accumulating on nozzle body, I assume from dragging.

CALIBRATION3_001_005_INFILL

ANCHOR

Cube

1mm Nozzle

Extrusion Multiplier 2.0

Retraction 5mm and 60mm/s

Layer height 0.75mm to accommodate smaller nozzle

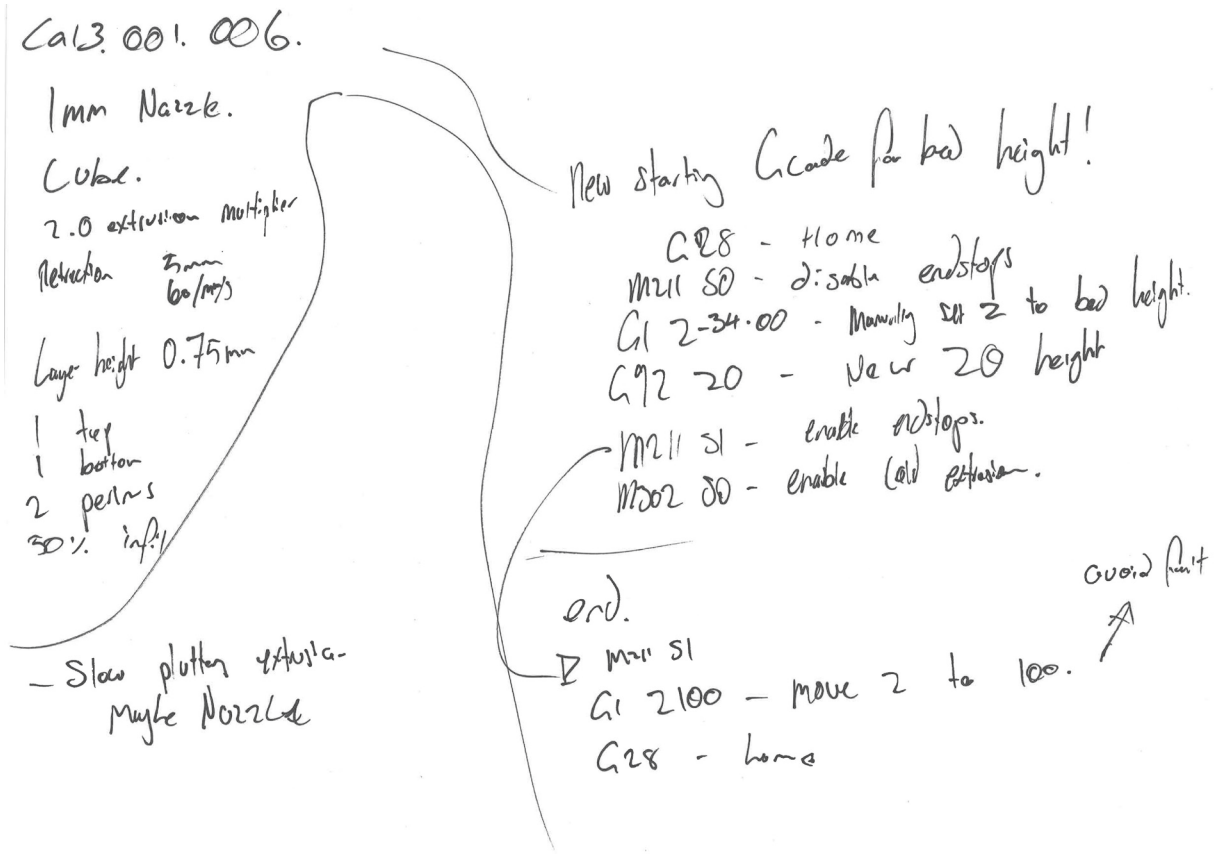
Top 1

Bottom 1

Perimeters 2

50% infill

EXPERIMENTS



No Photos due to print failure

OUTCOME

New Starting Gcode for settings bed height below minimum height allowed by firmware

G28 autohome

M211 S0 disables endstops

G1 Z-34 manually lowers z to height of negative 34 which was calculated as an appropriate height for z offset

G92 Z0- set current height as new Z0 height. M211 S1 enable software endstops

M302 S0 enable cold extrusion

New ending gcode

M211 S1 enable endstops

G1 Z100 move Z to height of 100 which helps avoid the printer failing when trying to find home

G28 auto home.

I think the print failed because of the 1mm nozzle.

CALIBRATION3_001_006

ANCHOR

EXPERIMENTS

OUTCOME

Back to 2mm Nozzle

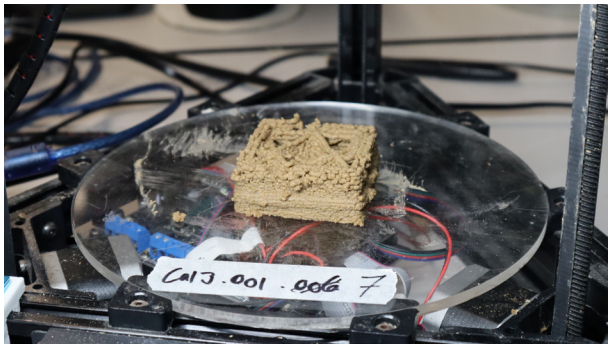
50mm Cube

Extrusion Multiplier 2.0

Layer Height 1mm

Speed 20mm/s









This print shows that the change in extrusion direction (from CALIBRATION3.001.002) has completely changed the print quality for the better. This print has infill, straight lines and had a smoother extrusion then anything else previously. I stopped it from getting too tall as there was some drag from the nozzle which can be fixed with more finetuning of settings.

CALIBRATION3_001_007

ANCHOR

EXPERIMENTS

OUTCOME

Cube 40mm3

Infill at 100% in grid format.









Another print which shows that the proof of concept of changing the direction of the auger rotation has been a successful change. A print with straight lines and infill is a great step in the direction.

CALIBRATION3_001_008

ANCHOR

CALIBRATION3.002 applied the findings from CALIBRATION3.001 to more complex forms, all printed with infill, extra wall counts, and top and bottom layers.

EXPERIMENTS









OUTCOME

CALIBRATION3.002 showed that more complex forms, print paths and manoeuvres were now achievable for the printer and paste. This series features dense cubes and with high infill, inward leaning structures with support layers such as a pyramid, and a failed but information rich attempt at printing a 3DBenchy at 150% scale.

Best practice and settings were now taking shape that showed the way forward for the project for attempt at more complex shapes and tool paths.

Settings:

Nozzle 2mm
Extrusion Multiplier 4
Retraction 5mm at 60mm/s with 0.5mm lift
Layer Height 1mm
Top layers 2
Bottom Layers 2
Perimeters 2
Infill 50%
Infill Pattern ‘traingle’
Infill width 100%
Infill Overlap 25%
Speed 20 mm/s

No speed alterations between layers.

ANCHOR

Using PASTE_003_007

Cube 40mm3

Nozzle 2mm

Extrusion Multiplier 7.5 (up from 2.0)

Retraction 5mm at 60mm/s with 0.5mm lift to try stop dragging

Layer Height 1mm

Top layers 1

Bottom Layers 1

Perimeters 1

Infill 100%

Infill Pattern ‘aligned’

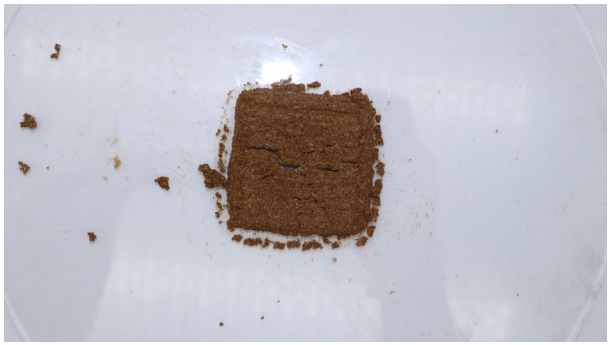
Infill width 100%

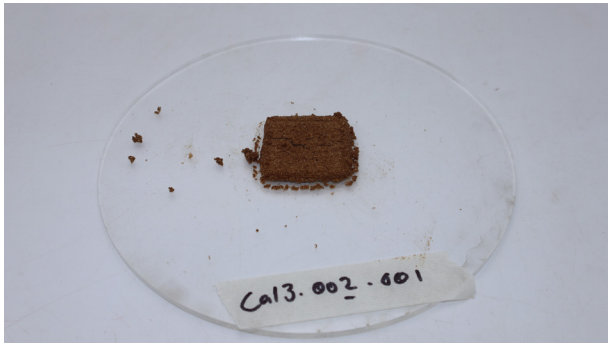
Infill Overlap 25%

Speed 20 mm/s

No speed alterations between layers.

EXPERIMENTS









OUTCOME

100% infill was not a good idea, but it was great to see that I could get decent layer adhesion.

CALIBRATION3_002_001

ANCHOR

EXPERIMENTS

OUTCOME

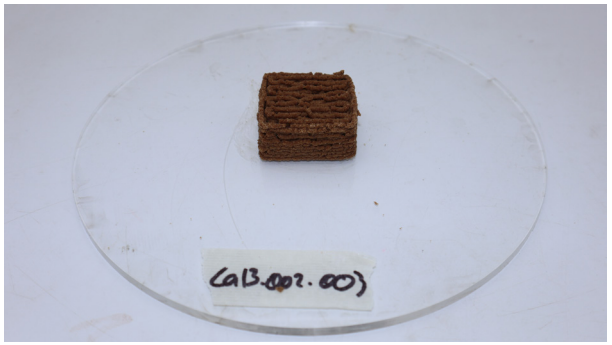
Multiplier 2

Layer Height 1.5

Speed 30 mm/s

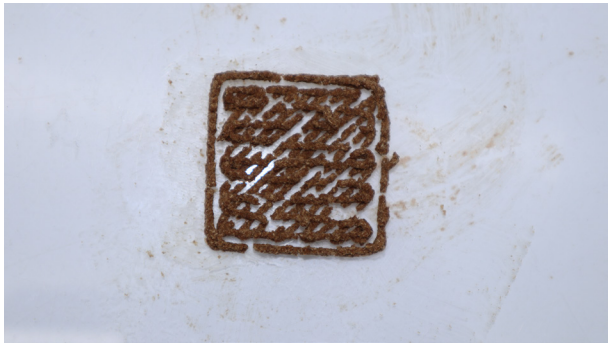
Infill 60%

Overlap 0%









Really happy with this. The printer was able to lay down a decent amount of infill layers and is starting to create more intricate patterns.

CALIBRATION3_002_002

ANCHOR

EXPERIMENTS

OUTCOME

Same settings as CALIBRATION3.002.002 but with

Multiplier 4









At 07:00 minutes there seems to be some structural integrity issues and issues with paste layer adhesion. I think more perimeter layers would help - the same if I were printing with a plastic. More walls makes more strength.

CALIBRATION3_002_003

ANCHOR

EXPERIMENTS

OUTCOME

Perimeters 2

Infill Pattern triangle









COMPLETED WITH TOP SURFACE!! This was a huge breakthrough. A cube, which I previously country print with cura, infill, which I couldn't do, extra walls, smooth adhesion. I was very happy with this print.

This confirmed that the previous changes had been for the good.

https://youtu.be/UhWQPVbL0EM

CALIBRATION3_002_004

ANCHOR

EXPERIMENTS

OUTCOME

Same settings as CALIBRATION3.002.004

Pyramid with 40mm base and 35mm height.









A complete print!

https://youtu.be/a9v-_3vZB0g

CALIBRATION3_002_005

ANCHOR

EXPERIMENTS

OUTCOME

Using settings from CALIBRATION3_002_004

Trying to print the 3DBenchy model at 150% scale,the model is designed by and distributed freely by Creative Tools. I thought that I could print one once in a while to benchmark my process against a difficult to print model which is associated with calibrating MEX 3D printers.









Started to miss layers especially on the front of the ship which has some overhang. A huge success was the noticeable retraction action happening during the printing process. I stopped the print as it was clearly failing. I didn't let it try do the bridging sequence which finishes a roof structure above the boat. The weight of the front literally tore the print in half.

CALIBRATION3_002_006 Benchy

ANCHOR

EXPERIMENTS

OUTCOME

Cylinder 50mm3









I stopped the print to observe the triangular infill and how this would dry. It cracked a lot and I would think this is from the high water content of the paste used.

CALIBRATION3_002_007

ANCHOR

EXPERIMENTS

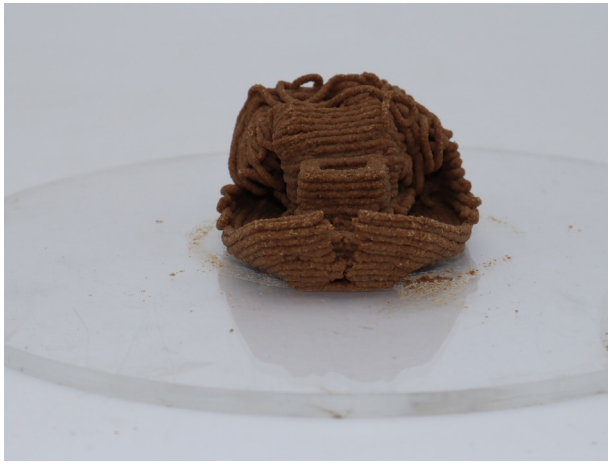
OUTCOME

This series experimented with the settings from CALIBRATION3_002_004, which provided great results. These settings were applied to another 3DBenchy and a cylinder.









The cylinder produced during this series was a fantastic benchmark for how far the capabilities of the printer has come. The 3DBenchy is an indicator that the project should move towards refining the paste mixture to create something stronger.

ANCHOR

EXPERIMENTS

OUTCOME

Cylinder using settings from CALIBRATION3_002_004.









Really happy with this. I need to play with top layer settings to try cover holes.

CALIBRATION3_003_001

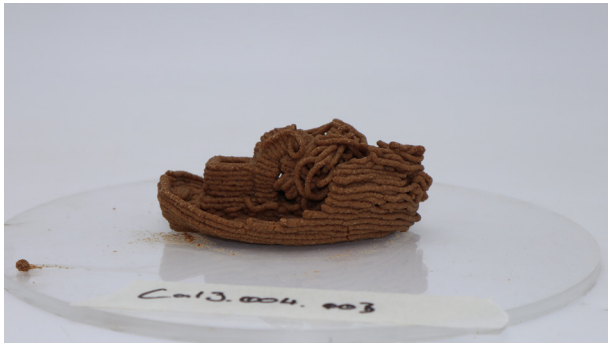
ANCHOR

EXPERIMENTS

OUTCOME

Benchy using settings from CALIBRATION3_002_004.









I let this one print to the end. It failed on the front overhangs again but did a surprisingly good job on the back of the boat. I need to experiment with drying while printing to try get objects to hold their intended shape. This print slumped a lot on the edges.

CALIBRATION3_003_002 Benchy

ANCHOR

There was a quick change from Series .003 to CALIBRATION3.004, due to a change in the paste mixture. The paste was remixed to try combat some of the deficiencies seen in the drying from the high water content. Prints continued to investigate the effects of infill and wall settings on the outcomes of parts. Different nozzles were also used to test how a finer extrusion would effect the finished artefacts.

EXPERIMENTS









OUTCOME

While pleased with the wet printed results, the dried artefacts were ruined in the dehydrator. The same heat and time settings were used as with previous prints, however the dehydrator turned off and left the prints too cool, resulting in uneven and cracked parts.

Additionally, the smaller nozzle prints were unsatisfactory, being very stringy and struggling with layer adhesion. This may be changed with a less viscous paste however, in the meantime thin extrusions will be avoided. New nozzles at 1.5mm and 1.75mm were 3D printed for future testing.

ANCHOR

EXPERIMENTS

OUTCOME

Using PASTE_004_001 which has more CMC.

Nozzle 2mm

Multiplier 4

Retraction 5mm, 60mm/s with 0.5mm lift

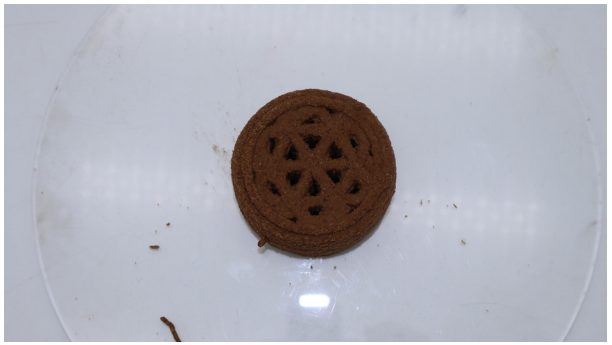
Layer height 1.5mm

Top layers 2

Bottom Layers 1

Perimeters 2

Infill 60% in triangles









I am happy with this print however, the lines are quite thick, this may have something to do with the extrusion multiplier.

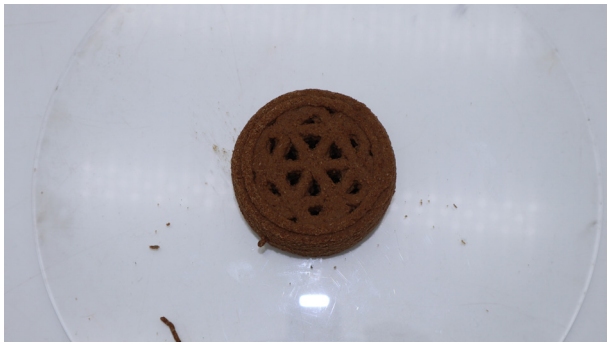
CALIBRATION3_004_001

ANCHOR

EXPERIMENTS

OUTCOME

Extrusion Multiplier dropped to 2 from 4









Slight over extrusion and left over paste on the bed before printing which slightly interfered with layer 1. Overall this print completed and looked good. The dehydrator which I have been drying prints in turned off with all prints from this series in it, resulting in uneven drying results with lots of cracks.

CALIBRATION3_004_002

ANCHOR

EXPERIMENTS

OUTCOME

Same settings as CALIBRATION3_004_002 printing another benchy.









Happy with this one, better holding of total shape. Some slumping of the front of the ship.

CALIBRATION3_004_003 benchy

ANCHOR

EXPERIMENTS

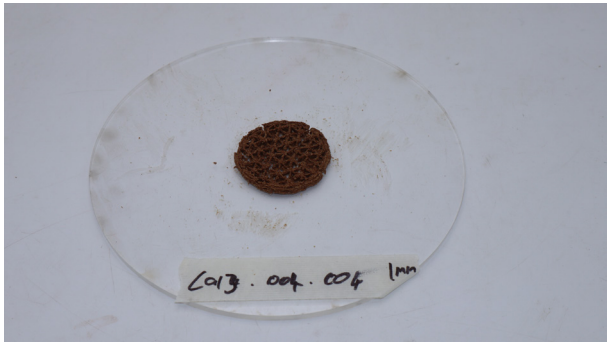
OUTCOME

1mm Nozzle

1mm Layer height









1mm nozzle is possibly too fine. I should reduce the layer height from being equal to the nozzle site. Could try again with lower extrusion multiplier but 1mm doesn't visually look to be a good fit for this material.

CALIBRATION3_004_004

ANCHOR

EXPERIMENTS

OUTCOME

Layer height dropped to 0.75mm.

Z offset was lowered to match new layer height.





I wasn't happy with this one and think it reaffirms that 1mm is too fine a nozzle diameter. I will 3D print new nozzles at 1.5 and 1.75mm to test as an in-between size between 2 and 1 mm.

ANCHOR

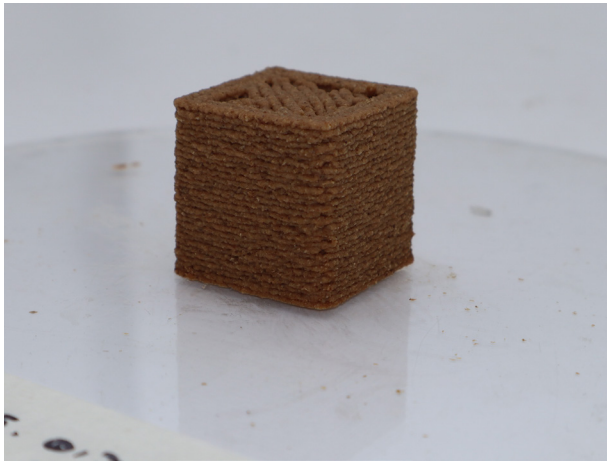
EXPERIMENTS

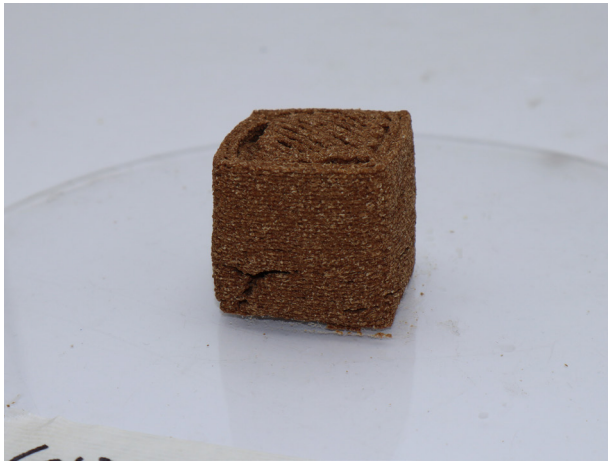
OUTCOME

This series explored further development of slicer settings and the extruder set up.
Cubes with infill were primary investigated as a target shape to evaluate printer performance through ‘neatness’ and uniformity between prints.









This series showed strong progression towards consistent and reliable printing results.
Neat cubes with infill were successfully printed, however drying behaviours still need to be understood and adjusted towards.
Interaction between internal and external walls (infill and perimeters) needs to be better understood to avoid delamination in drying.

ANCHOR

50mm3 Cube, Testing new 1.75mm Nozzle and Print Shrinkage

Using PASTE_004_001

1.75mm Nozzle

4 Extrusion Multiplier

1mm Layer Height

2x Top, Bottom, Perimeters

60% triangular infill

30 mm/s Speed

EXPERIMENTS

OUTCOME

Paste is moving and extruding poorly; Extruding poorly in ‘dotted line’ rather thin as a smooth wall/ line. I will move back to an older paste mix.

ANCHOR

Using PASTE.004.003 which used powdered CMC and BSG mixed with water together.

2mm Nozzle

2.0 extrusion multiplier

1mm Layer Height

20 mm/s speed

EXPERIMENTS

OUTCOME

Still bad extrusion, possible from poor mixing between dried BSG and CMC powdered. I am going to move back to premixed 6% CMC paste.

CALIBRATION3_005_002

ANCHOR

40mm3 Cube

Using PASTE.004.004

2mm Nozzle

3.0 Extrusion Multiplier

5mm Retraction

1mm Layer Height

2x Top, Bottom, Perimeters

60% Triangle Infill

30mm/s Speed

3 BAR

EXPERIMENTS







OUTCOME

Exploring playing with first layer height through Z offset changes.

I need to control the extrusion more, there is lots of shake and bottle from both the extrusion stepper motor, the extruder body sway from paste delivery, and table shake from the air compressor.

CALIBRATION3_005_003

ANCHOR

40mm3 Cube

2mm Nozzle

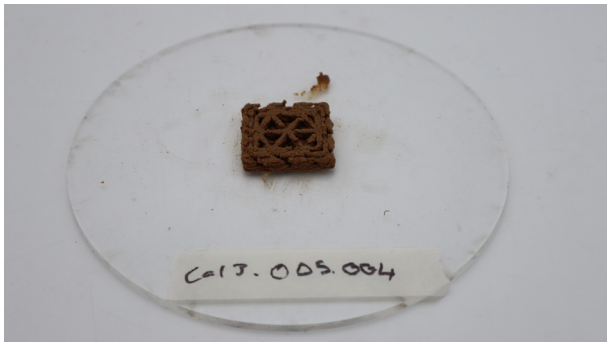
3.5 Extrusion Multiplier

1mm Layer

2x Top, Bottom, Perimeters

60% Triangular Infill

EXPERIMENTS









OUTCOME

Exploring playing with first layer height through Z offset changes.

I need to control the extrusion more, there is lots of shake and bottle from both the extrusion stepper motor, the extruder body sway from paste delivery, and table shake from the air compressor.

CALIBRATION3_005_004

ANCHOR

EXPERIMENTS

OUTCOME





40MM Clyinder file

4x Extrusion Multiplier





The extruder is still not vert stable and the outline layers of the cylinder are messy.

CALIBRATION3_005_005

ANCHOR

EXPERIMENTS

OUTCOME

40mm3 Cube

2mm Nozzle

3.5 Extrusion Multiplier

1mm Layer

2x Top, Bottom, Perimeters

60% Triangular Infill









The extruder needs more refinement. Particularly in stability, paste processing. Additionally the stepper motor that controls the auger needs to be held more securely, as it slowly loosens the hex nuts that hold it to the extruder body, and then begins rocking back and forth as it prints. It is clearly under a lot of stress and could possibly be under powered.

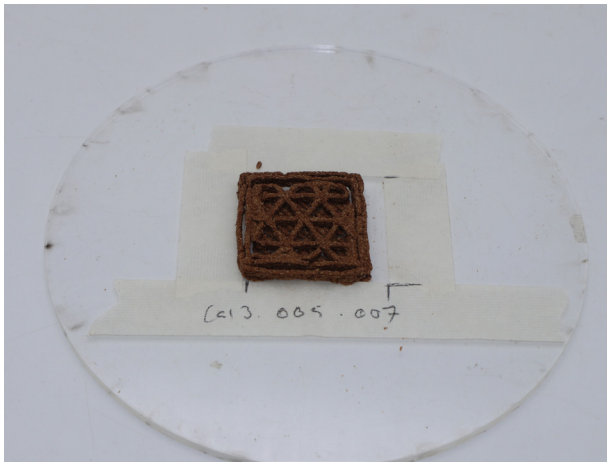
CALIBRATION3_005_006

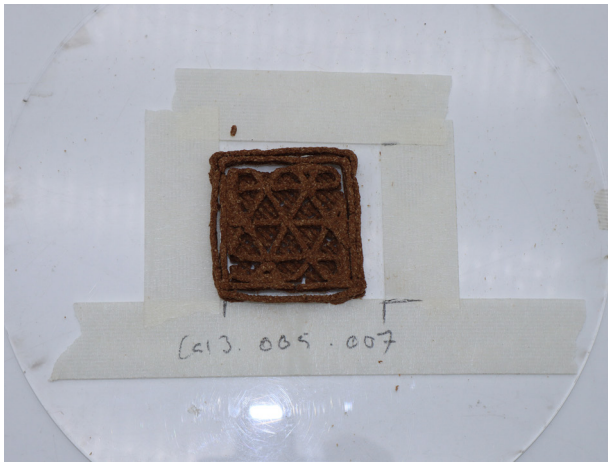
ANCHOR

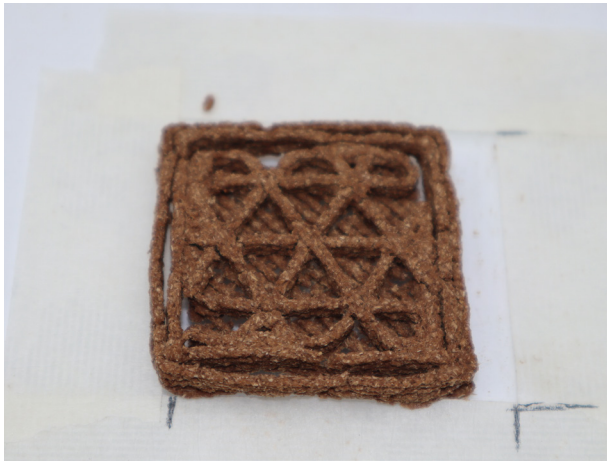
EXPERIMENTS

OUTCOME

Same Settings as 005.005.







Print Stopped Early to observe infill and infill drying behaviour.

CALIBRATION3_005_007

ANCHOR

50mm3 Cube

Using PASTE.004.004

2mm Nozzle

4 Extrusion Multiplier

5mm Retraction Distance @ 60mm/s

1mm Layer Height

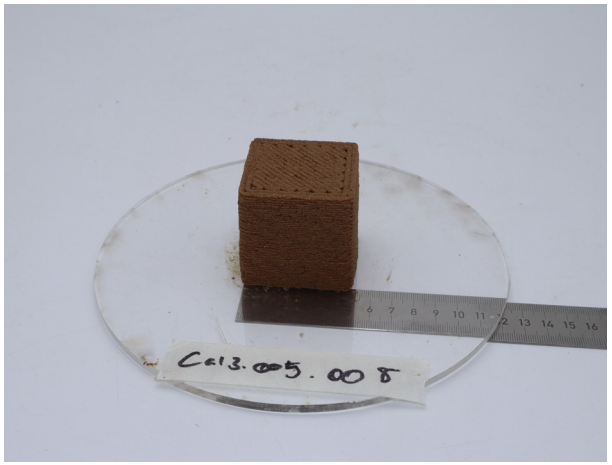
2x Top, Bottom, Perimeters

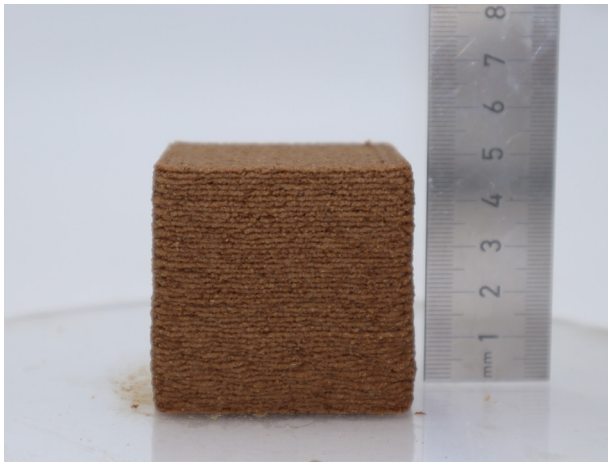
100% All Layer Heights

60% Triangular Infill @ 100% Extrusion Width

30mm/s All Speeds

EXPERIMENTS









OUTCOME

Artefacts in the print are from auger stepper motor movement while printing.

Shrinkage after drying in dehydrator for 24 hours at 35-45 degrees -> lots of cracking.

At Widest

H: 41mm = 18% shrink

L & W: 51mm = -2.4%

At Slimmest L & W : 47.4mm

CALIBRATION3_005_008

ANCHOR

50mm3 Cube

Using PASTE.004.005

2mm Nozzle

4.0 Extrusion Multiplier

5mm Retraction @ 60mm/s

1mm Layer Height

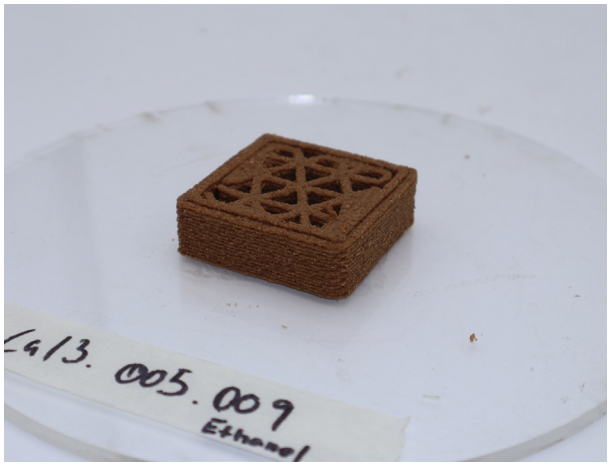
2x Top, Bottom, Perimeters

100% Layer Heights

60% Triangular Infill @ 100% Width

30mm/s Speed

EXPERIMENTS









OUTCOME

Printer connection failed at 17mm Z height. I think this is from vibrations from the compressor (a first mid print).

CALIBRATION3_005_009

ANCHOR

50mm Cube

Using PASTE.004.006 - Implementing Methylated Spirits as a water replacement for lower temperature drying.

5.5 Extrusion Multiplier (raised from pervious value of 4.0 in previous print 005.008 using PASTE.004.005)

2mm Nozzle

5mm Retraction @ 60mm/s

1mm Layer Height

2x Top, Bottom, Perimeters

100% Layer Heights

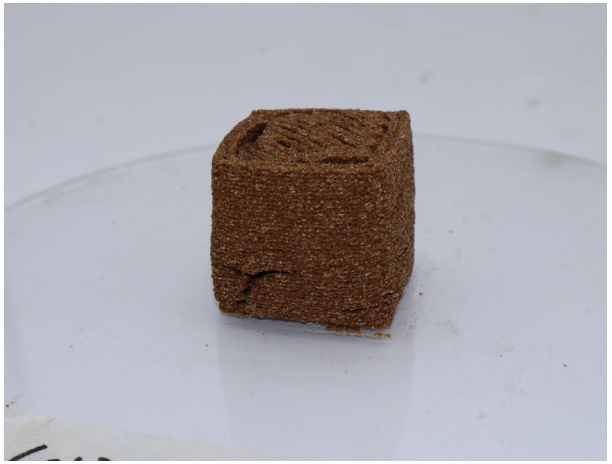
60% Triangular Infill @ 100% Width

30mm/s Speed

EXPERIMENTS









OUTCOME

Print time to complete 60 minutes.

CAL3.005.009/010 put in dehydrator @ 35 degrees until dry.

I am noticing that the base/ bottom layer of prints are struggling to dry. This is possibly because of the lack of airflow as the bases used are solid 4.5mm acrylic. Perhaps a perforated bed could assist in drying.

Less cracking was noticed on the pastes which have ethanol content than those without.

Shrinkage: H: 34.9 = 12.75%

L & W: Ranged between 40.8 and 41.8 = -2 to -4.5%.

These shrinkage results have led to me believe that vertical slump caused by weight results in height loss and horizontal stretching. How do I stop the slumping: Possibly through more active drying while printing with fans and a heated bed could help.

ANCHOR

40mm3 Cube

ALL SETTINGS &
PASTE THE SAME AS
CALIBRATION3.005.009 WHICH
FAILED DUE TO A PRINTER
DISCONNECTION.

EXPERIMENTS

OUTCOME

print failed

CALIBRATION3_005_011

ANCHOR

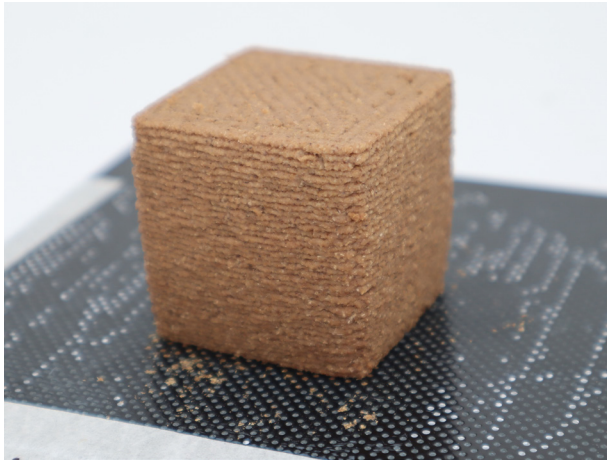
EXPERIMENTS

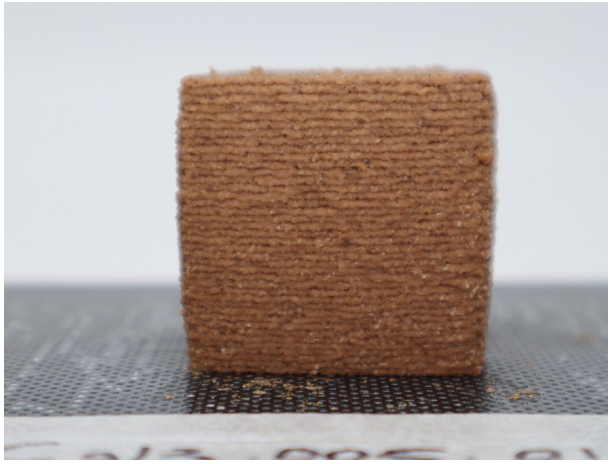
OUTCOME

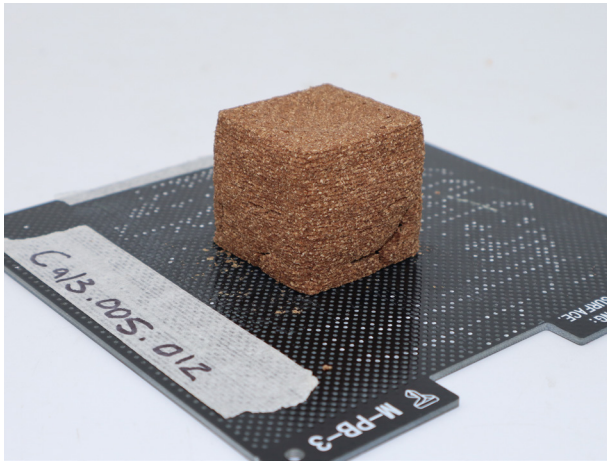
SAME SETTINGS AS CAL3.005.010/011

Printing onto a perforated be to test if this improves the speed and consistency of drying of the bottom layers.

6.5 Extrusion Multiplier









I am really happy with this print, whilst the dried print did slightly warp and crack, the wet print was very 'neat' and was a good representation of the CAD file and print settings. Further understanding of drying is needed but this is a good milestone.

CALIBRATION3_005_012

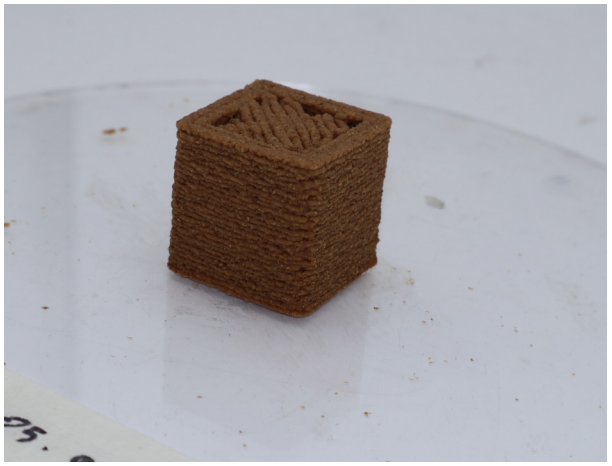
ANCHOR

Print started with very little paste left in cartridge, so a cube of 30mm3 was loaded.

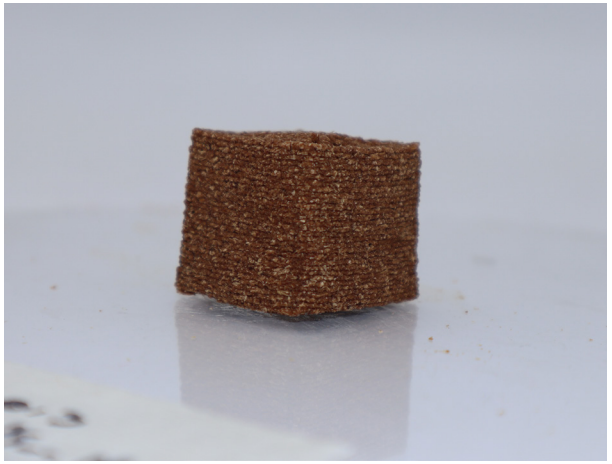
1.75 mm nozzle was used

30% Triangular Infill

EXPERIMENTS









OUTCOME

While printing, some of the layers/ depositions were missing, starting at the point where infill should be interesting with the wall features. This can be changed in slicer settings.

Infill separated during dehydration/drying process.

The 1.75mm nozzle created uniform and neat layers and will be used instead of the 2mm nozzle going forward.

CALIBRATION3_005_013

ANCHOR

This series documented the set up and use of a new printer, the Creality Ender 3 v2 (PRINTER_002) and a revised design of the extruder assembly (EXTRUDER_003_002. The print is much more sturdy than the delta printer used in previous experimentation, and the new extruder was modified to feature a new inlet design which acts as a hose clamp for larger inlet hoses (19mm ID). The system change is intended to add more structural support to the extruder assembly during printing processes, and the extruder update aimed to minimise friction on paste movement by increasing the diameter of delivery tubing.

EXPERIMENTS









OUTCOME

This series documents the moments of transition between research question 2 and 3, where the capabilities of the paste and system was realised to the extent of a possible role they could fulfill in product design prototyping practices.

First, the change to the Creality Ender 3 v2 was an immediate success, prints were more consistent and printer movements were more confident and exact. The printer gantry could handle the weight of the weight of the extruder assembly, and printer results were much more representative of the capacities of thermoplastic printing with larger filaments diameters.

The Printed results, particularly in the 3DBenchy progression and the Logitech G1 gaming mouse, showed the project was ready to explore the explorative prototyping capabilities such as form prototyping exercises.

ANCHOR

This is the first print using the newly modified Creality Ender 3 V2 printer, with a custom mount allowing for relatively quick changes between my extruder design (extruder series 3) and the plastic extruder standard to the Ender 3 V2. This print uses a newer version of extruder 3, which uses a hose clamp connection to the paste delivery pipe rather than the screw in hose barb I had been previously been using. This new system allows for large diameter pipes to be used on the printer (through extruder design and printer stability), which allows for denser pastes to be extruded under lower pressure requirement.

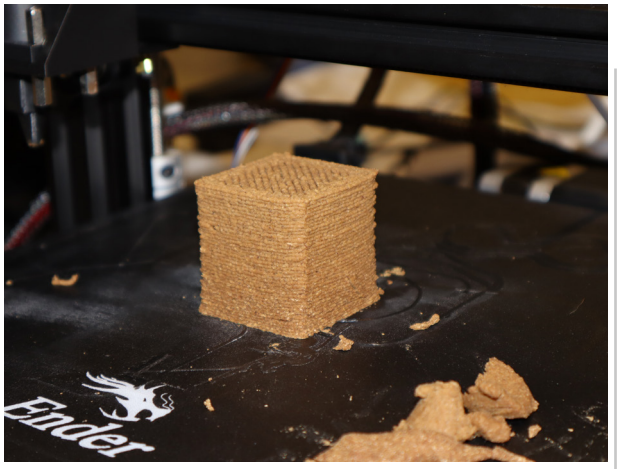
Using PASTE.004.007 which had been in the fridge, cling wrapped for 2 weeks. 1 BAR using 19mm ID hose.

1.75 mm Nozzle
1mm Layer Height
4mm Retraction @ 40mm/s (printer default through Simplyfy3D profile)
50% Rectilinear infill with 50% overlap on perimeter layers
50 degrees C heated bed
40mm/s Speed (using default profiles of 50% out wall speed, 80% inner wall speed, 80% solid infill speed).

It was noticed that there is a slight Z offset difference between the plastic extruder and the paste extruders (+0.42 for the paste nozzle and -1.64 for the plastic nozzle).

EXPERIMENTS









OUTCOME

The benefits of the ENDER 3 v2 compared to the ANYCUBIC Kossel were immediately apparent. Whilst further calibration was needed, the ENDER 3 v2 moves much more smoothly and confidently under load. There is no worry of the print head plummeting into finished parts after printing, or the cartridges responsible for movement coming loose under load.

CALIBRATION4_001_001

ANCHOR

Using PASTE.004.008

Dialling in workflow with the printer.

10.00 Extrusion Multiplier

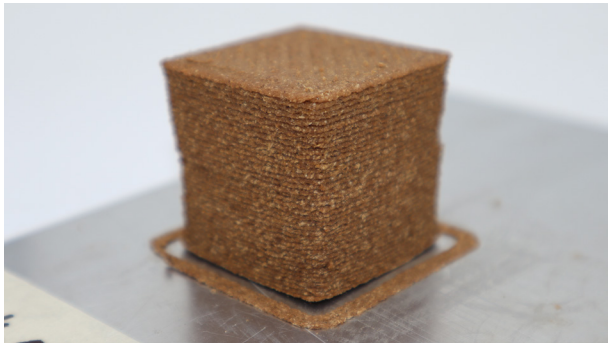
Z offset @ -2.2

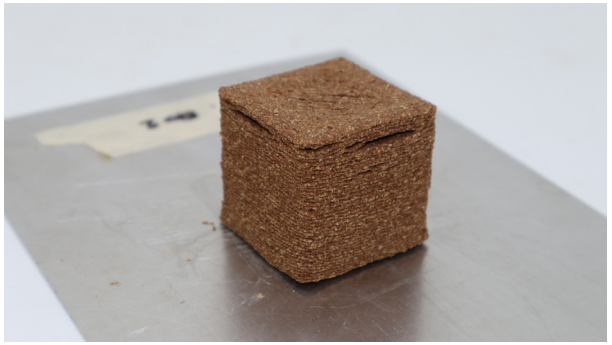
2 x skirts with 2mm offset from parts, removes need for purge line in starting gcode.

50 degree heated bed

EXPERIMENTS









OUTCOME

It took very long to dial in the Z offset. I need to figure out if this is faster to do through the slicer firmware/ gcode or through the control screen on the printer.

M302 S0 was added to opening gcode to enable cold extrusion.

I need to make perimeter walls overlap more with each other to avoid delamination.

At Z 24.00 I lowered the bed temperature from 50 to 30 degrees C to avoid warping or missing of higher layers from the now shrinking dried lower layers.

I put a small heater on the table to try create more airflow to commence the drying process before the print is placed in the dehydrator to avoid shrinkage and cracking.

Print was placed in the dehydrator at 40 degrees C until dry.

ANCHOR

I decided that if perimeter walls were delaminating during drying, that eliminating the amount of perimeter walls and increasing the overlap between infill would result in more uniform constructing. So in this print I decided to use only 1 Perimeter Wall, with 50% overlap on infill touch points.

1 perimeter wall

6.5 Extrusion Multiplier (too low, previously it had been 10)

30% rectilinear infill @ 50% overlap.

EXPERIMENTS









OUTCOME

The first attempted failed because I bumped the bed. Second attempt looked great but cracked a lot during drying.

ANCHOR

EXPERIMENTS

OUTCOME

3DBenchy @ 150%

7.25 Extrusion Multiplier

Bed heating program to avoid shrinkage on print bed (Celsius):

50 @ Layers 1-5

40 @ 5-10

35 @ 10-15

25 @ 15 onwards









I turned off the heated bed at layer 26 (Z height 26.00).

Unfortuantely I had to stop the print because I moved the print bed while trying to fix a loose screw on the extruder. I need to find a more secure bed solution for the ender 3 - maybe I find more magnetic removable beds.

CALIBRATION4_001_004_BENCHY

ANCHOR

25mm3 Cube with PASTE.004.009. Looking at extruding and printing with less liquid.

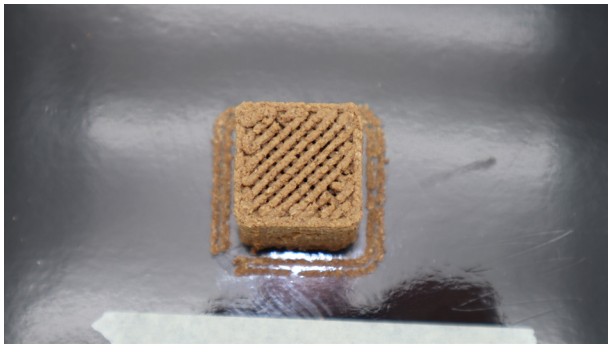
I also reduced the layer height from 1mm to 0.875mm, which is half of the nozzle size (1.7mm). The thought being that lower layers will be stronger and adhere to the bed easier as they are pushed more into the bed.

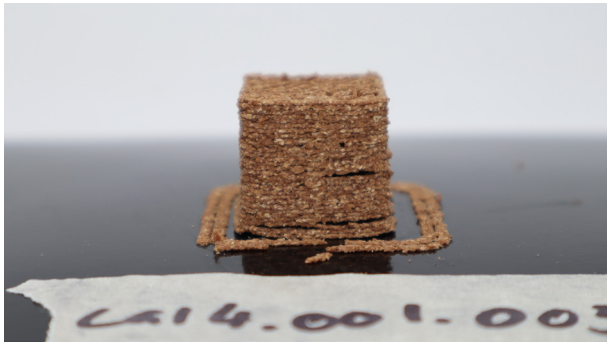
10.00 Extrusion Multiplier

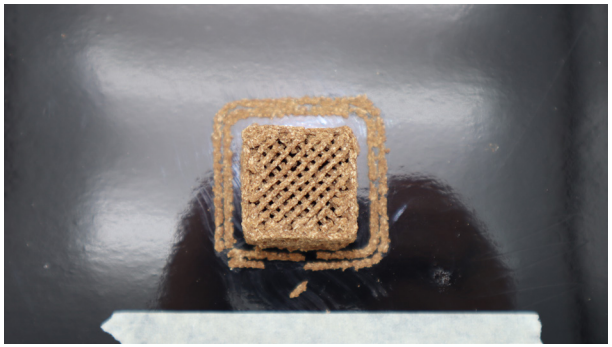
0.875 layer Height

EXPERIMENTS









OUTCOME

Though a small test print, I was happy with the results of using 'layer height = half nozzle diameter'.

ANCHOR

EXPERIMENTS

OUTCOME

Sphere of 40mm diameter, sliced by lowering the sphere model through the bed in the slicer.

Same settings as 001.005.









Whilst there are some small cracks in the dried print, it did not warp significantly or slump which is very interesting. Further, the base of the print was extremely smooth after drying, almost like a film had been applied between it and the base.

CALIBRATION4_001_006

ANCHOR

3DBenchy at 105% scale using settings from CAL4.001.005:

1.75mm Nozzle

0.875 Layer Heights

10.0 Extrusion Multiplier

Bed heating program as per CAL4.001.004

1 Perimeter Wall

2 Bottoms and Tops

30% Rectilinear Infill @ 50% Overlap

40mm/s Speed (using default profiles of 50% out wall speed, 80% inner wall speed, 80% solid infill speed)

EXPERIMENTS









OUTCOME

Printed very well with results exceeding the capabilities of previous prints on the ANYCUBIC DELTA KOSSEL printer.

Failed during retraction and movement processes on the small parts where the model needs to build the 'cabin' or indoor area. I need to play with retraction settings in order to avoid this.

https://youtu.be/fkgB_nKB64M

CALIBRATION4_001_007_BENCHY

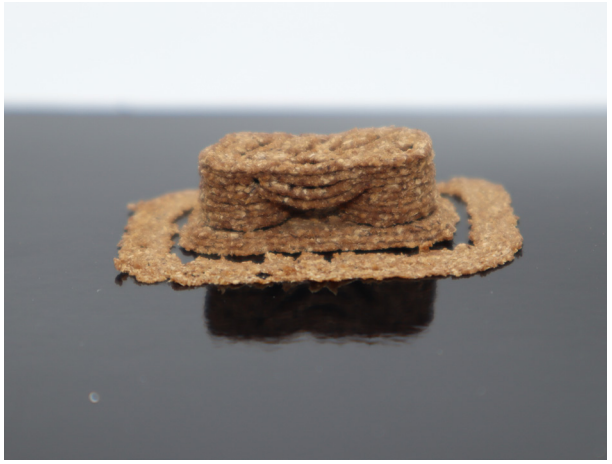
ANCHOR

Bridging test of 5mm expanse between bodies

Settings from CAL4.001.005 & PASTE.004.009

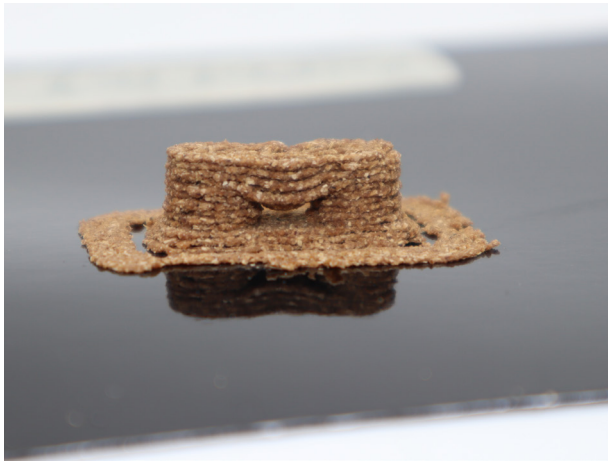
Model designed in Fusion360, testing the capabilities of the printer and paste to build unsupported paths between bodies (bridging).

EXPERIMENTS









OUTCOME

Results were interesting, in that the first few layers of bridging slumped, but ultimately acted as support for the top layers, where were relatively flat. This prompted me to try a longer bridging test of 7mm.

ANCHOR

Bridging test of 7mm expanse between bodies

Settings from CAL4.001.005 & PASTE.004.009

Model designed in Fusion360, testing the capabilities of the printer and paste to build unsupported paths between bodies (bridging).

EXPERIMENTS









OUTCOME

Results were interesting, in that the first few layers of bridging slumped, but ultimately acted as support for the top layers, where were relatively flat. This prompted me to try a longer bridging test of 7mm.

CALIBRATION4_001_009

ANCHOR

Model used is of a scanned Logitech computer mouse from thingiverse: thing #4398925

Ender 3 v2 with Dual Z Axis Modification

Using extruder_003_002 (extruder v3.02) which uses a hose clamp to attach a 19mm ID spiral reinforced PVC tube

1.75 Nozzle

0.875 Layer Height

12.0 Extrusion Multiplier

3mm Lift on Retraction movements to avoid nozzle dragging in material on longer passes

3 Top Layers

2 Bottom Layers

1 Perimeter

40% Rectilinear Infill @ 100% width with 50% overlap

40mm/s ALL Speeds

EXPERIMENTS









https://youtu.be/ATUXITBxAQ8

OUTCOME

Initially it took hours of troubleshooting to get consistent layer adhesion and paste flow. There was also a scratching noise coming from the extruder body, and an occasionally high pitch squeak coming from Z axis lead screws which move the gantry up and down.

I think the squeak is due to the new weight from the extruder, paste, paste delivery system, and stepper motor. I will be removing the stepper motor for the plastic extruder and replacing it with different style of extruder called a 'direct drive', which situated the extruder and hot end in close proximity ,allowing me to remove all weight and plastic printing components quickly before replacing them with paste extrusion components.

For this print, which initially failed due to the hose clamp for the paste delivery coming loose, I increased the 'lift' of the nozzle on retraction movements, which should avoid future situations where the nozzle drags through material when moving between paths.

I am also looking to increase the print speed, and found through reddit posts that I can increase to up to 60-70mm/s from the current 40mm/s.

CALIBRATION4_001_010

ANCHOR

PRODUCT_001 series explored the development of printer settings, processes and post processing capabilities of the BSGNMC paste and system. The prints continued from the success of CALIBRATION4.001.010, and Computer mice were the primary subject, with the first 23 experiments printing from a scan of a Logitech G1, 1 print of a Razer Basilisk V3, and 3 prints of a Logitech MX Master 3 for comparison with a physical model.

EXPERIMENTS









OUTCOME

Through this series, it was determined that the printer and BSGNMC paste were suitable for sustainable explorative prototyping practice. Dried parts can have close dimensional accuracy to cad files, and can be extensively post-processed through hand and machine methods such as sanding and cutting. Further, it was found that the system is capable of quickly outputting parts, where drying is the limiting factor.

ANCHOR

Model used is of a scanned Logitech computer mouse from thingiverse: thing #4398925

Ender 3 v2 with Dual Z Axis Modification

Using extruder_003_002 (extruder v3.02) which uses a hose clamp to attach a 19mm ID spiral reinforced PVC tube

Nozzle 1.75mm

Layer Height 0.875mm

Extrusion Multiplier 12.0

Vertical Lift on Retraction 3.0mm to avoid nozzle dragging on longer movements

Top Layers 3

Bottom Layers 2

Perimeter Layers 1

Infill 40% Rectilinear with 50% overlap

Speeds 40mm/s all

EXPERIMENTS









https://youtu.be/ATUXITBxAQ8

OUTCOME

Initially it took hours of troubleshooting to get consistent layer adhesion and paste flow. There was also a scratching noise coming from the extruder body, and an occasionally high pitch squeak coming from Z axis lead screws which move the gantry up and down.

I think the squeak is due to the new weight from the extruder, paste, paste delivery system, and stepper motor. I will be removing the stepper motor for the plastic extruder and replacing it with different style of extruder called a 'direct drive', which situated the extruder and hot end in close proximity ,allowing me to remove all weight and plastic printing components quickly before replacing them with paste extrusion components.

For this print, which initially failed due to the hose clamp for the paste delivery coming loose, I increased the 'lift' of the nozzle on retraction movements, which should avoid future situations where the nozzle drags through material when moving between paths.

I am also looking to increase the print speed, and found through reddit posts that I can increase to up to 60-70mm/s from the current 40mm/s.

ANCHOR

Based on Thing:4398925
Logitech G1 Mouse Scan

Nozzle 1.75mm

Extrusion Multiplier 10 (I needed to raise the max e-steps (in mm/s) to allow this setting to have full effect)

Retraction 4mmm @ 40mm/s with 2.5 vertical lift

Layer Height 0.875mm

Tops 3

Bottoms 2

Perimeter Walls 1

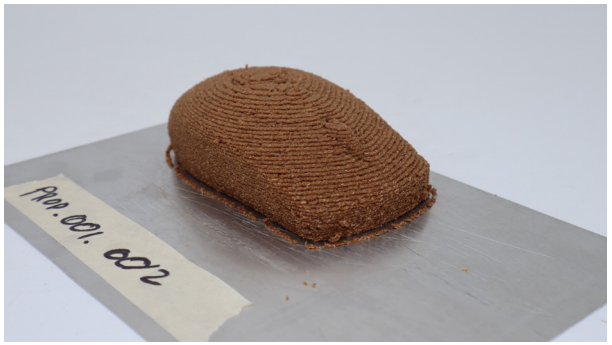
Infill 40% rectilinear, 10% width with 50% overlap

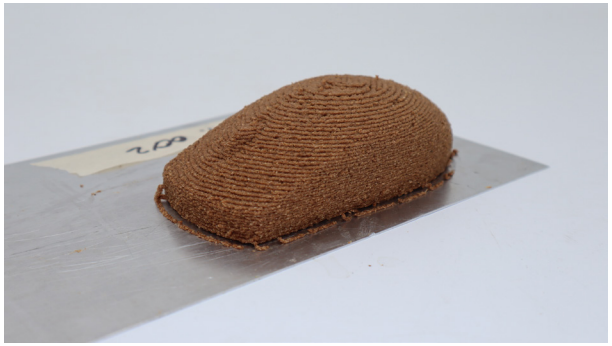
Speed 55mm/s (80% all speeds)

Total time: 47 minutes

Drying Dehydrator at 0 degrees C

EXPERIMENTS









OUTCOME

Initially extrusion multiplier was not seeming to have significant effect on the auger rotations. E-step max speed was increased in through the printer screen which allowed the auger to spin much faster (as it effects the maximum rotational speed of the auger). The intersection of factors that effect line deposits and print quality was emerging, particularly around print speed, auger speed, paste mixture and paste flow. Variable, such as the paste mixture, once controlled can then be controlled or altered through other settings. Paste consistency is a key variable to have reliability from, allowing further control to be through the machine.

ANCHOR

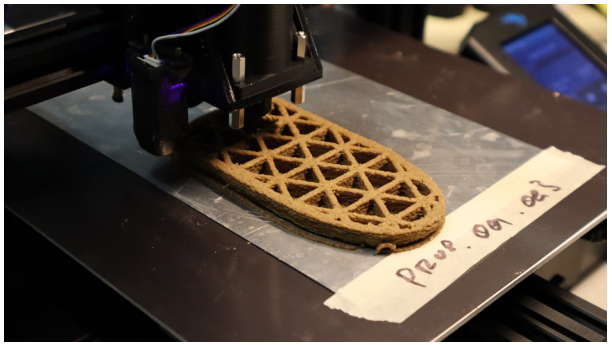
EXPERIMENTS

OUTCOME

Infill changed:

Infill Triangular at 40%

Print time 52 minutes









The wet print looked great, but the dried result cracked significantly. This is possibly due to the paste or infill settings.

ANCHOR

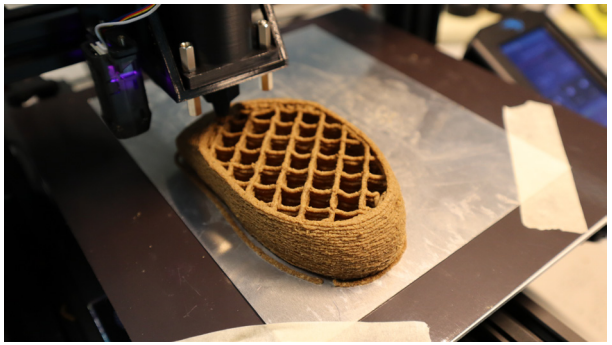
EXPERIMENTS

OUTCOME

Exploring infill and drying

Infill 20% rectilinear

Print Time 36 minutes









Whilst this print was printed incredibly fast, at 36 minutes, it cracked significantly in drying. Infill seems to have a connection to the drying behaviour of models.

ANCHOR

EXPERIMENTS

OUTCOME

Infill 30% rectalinear

Print time 43 minutes









Dried prints were taken to the UTS Fabrication Workshop for sanding. They were sanded by hand starting with 120-grit, moving through to 150 and then 240g. Prints responded well to sanding, similar to soft woods. They could hand the pressure applied to them without deforming, and were left with very smooth and lighter coloured exteriors. Gaps between top layers become more apparent as material was taken away, however it was thought that this could be ‘puttied’ with paste leftover form printing. This was a significant progression into realising a functional role that this material and process could fill for product designers.

ANCHOR

Exploring print time in relation to print speed and infill

Overall print speed increased to 60mm/s (80% speeds for all settings)

Infill at 25% rectilinear

Print Time 39 minutes

EXPERIMENTS









OUTCOME

Whilst the wet print was satisfactory, small gaps in the top layers were noticed, as the paste struggles to bridge the larger gaps in less dense infill settings. This then becomes more apparent in drying where significant cracking occurs.

This print was sanded with PRODUCT_001_005 and continued that experiment in that it was puttied with paste from printing. this was then dried with a hot air gun. the final product was smooth and had no holes. This was another major success in finding an application for the material and printing system, as these practices could be used in product design form prototyping.

ANCHOR

EXPERIMENTS

OUTCOME

Speed back to 55 mm/s (80% to all)

Infill 25% rectalinear

Print Time 39 minutes









This print explored slightly modifying my current drying procedures. The print was removed from the sheet metal print surface using fishing wire, a process inspired by how potters remove objects from their wheel. Next, prints were placed on steel mesh and placed in the dehydrator with no added heating. It was thought that using mesh would allow for better airflow in and out of prints. The final results was great, in that the print had very few holes - but seemed to shrink the same amount.

PRODUCT_001_007

ANCHOR

Testing the printers retraction ability by printing two parts at once (008 and 009)

No settings were changes between previous prints

Print Time 1 hour 18 minutes (78 minutes)

When dry, PRODCUT_001_008 was coated in a xyz paste (developed by Nahum McLean) exploring the application of extra barriers against waster absorption and reinforcement to parts.

EXPERIMENTS









OUTCOME

The printer performed flawlessly in printing two components, an exiting development in printing of assemblies or batches of components. Further the coating applied gave print a new finish quality which is an interesting avenue for further exploration. The coatings ability for preventing water absorbing and improving structural reinforcement was not tested.

https://youtu.be/i3ulKbZ0JhE

PRODUCT_001_008_RETRACTION

ANCHOR

EXPERIMENTS

OUTCOME

Printing with PRODUCT_001_008. This print was placed on the lowest setting in a domestic microwave and run for 2 minutes and off until satisfactory.









Microwaving, or at least this method of low pulse and short spurt microwaving, caused the wet print to deform. The print did not dry uniformly and cracked and warped during this process. The experiment was stopped after 30 minutes of on and off 2 minutes microwave spurts.

ANCHOR

EXPERIMENTS

OUTCOME

Holes in prints were drilled with electric drills. Prints were then cut in half with a band saw.









Prints responded well to heavier post processing such as drilling and cutting. This may come into use for building multi part assemblies or parts that require additional post processing.

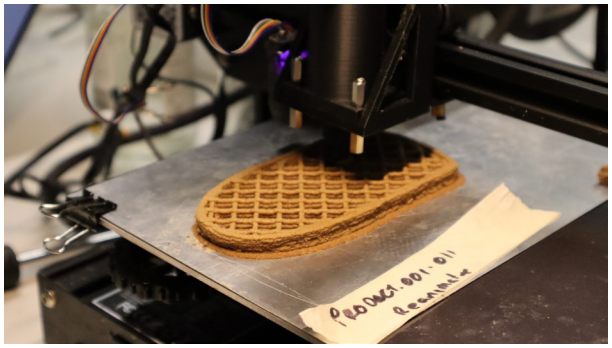
ANCHOR

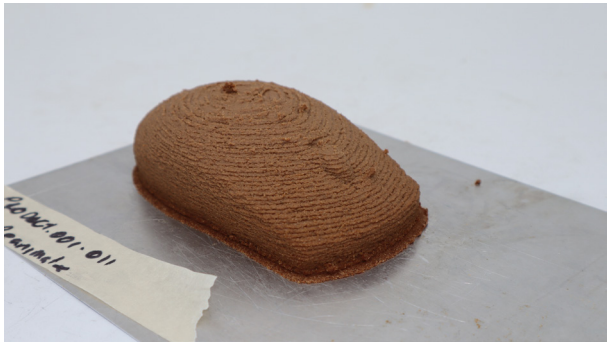
Printed using REANIMATE_001_002, a mixture of dried and ground old prints and paste and water.

Mixture was very ‘watery’, extruding and printing at 0.1 BAR (1.0 PSI).

EXPERIMENTS









OUTCOME

The print was successful, but drying of this high water content material proved to be an issue, where it cracked extensively. Further refinement to the mixture is needed however this proof of concept was a success.

ANCHOR

EXPERIMENTS

OUTCOME

Using the same settings as PRODUCT_001_007

When dried, the print was coated with 6% CMC, smeared on by hand.









This print was done to mimic the processes undertaken in PRODUCT_001_008 whilst removing many of the additives in Nahum's starch and cellulose mixture. once dried, there was no obvious physical difference between dried prints with or without CMC coating, however, visually the model looked improved due to the glossy finish. I imagine this will look good on well sanded and hand finished models.

PRODUCT_001_012_CMC

ANCHOR

Using the same settings as previous prints, the overall dimension of the 3D model were increased in Simplyfy3D, to match the shrinkage rates recorded in previous prints.

1:1 scale Logitech G1 Scan

L 116.94mm

W 61.70mm

H 37.31

Dried prints

L 103.50mm (11.5% shrink)

W 57.23mm (7.2% shrink)

H 25.93mm (30.5% shrink)

This print used the shrinkage rates to increase dimensions to:

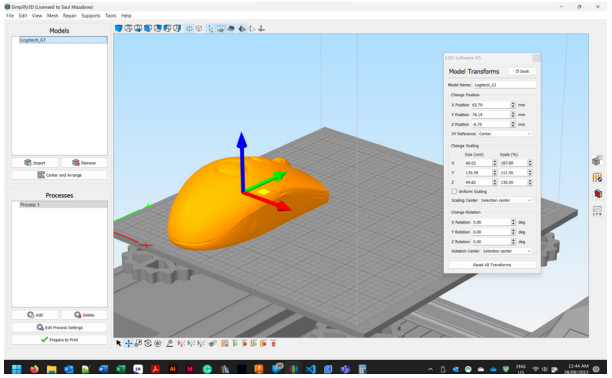
L 130.4mm

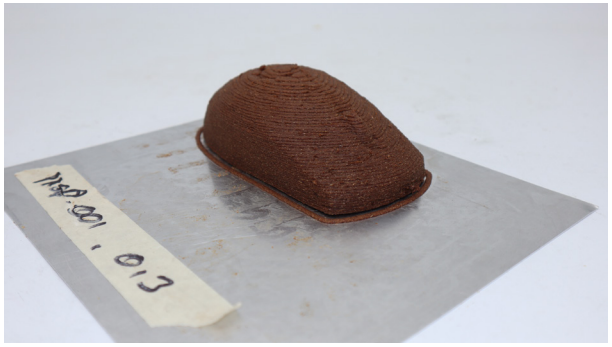
W 66.16mm

H 48.709mm.

Prints were dried at 40 degrees C in the dehydrator until dry.

EXPERIMENTS









OUTCOME

Dried dimensions:

L 117.78mm (-1% off 1:1)

W 58.05mm (6% off 1:1)

H 28.24mm (24% off 1:1)

These shrinkage rates show that vertical slumping is the key factor to solve in shrinkage, as it effects the others. This will need further investigation into factors such as material water content and drying environment which effect the drying time, as well all wall thickness, infill type and percentage. Perhaps slumping can be mitigated by better structural stability from the infill during the drying/shrinking processes.

PRODUCT_001_013_ENLARGED

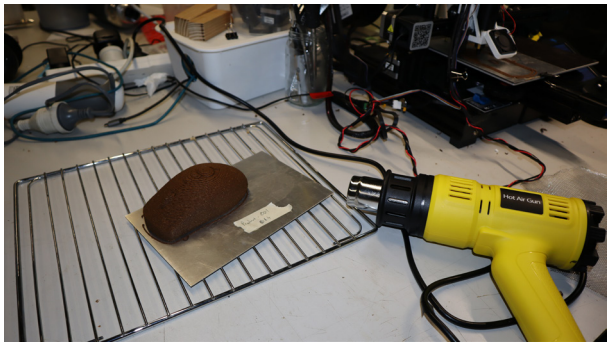
ANCHOR

Using the same enlarged print settings as PRODUCT_001_013, exploring faster ways to dry the print to avoid slumping.

Once printed, the model was crusted with a hot air gun for easy removal from the build plate, then placed in a Breville toaster oven at 180 degrees C on ‘bake”.

After 25 minutes, the print was burnt and the room was starting to smell. THe print was then placed in the dehydrator at 90 degrees C.

EXPERIMENTS









OUTCOME

The high temperature of the oven caused a delamination effect, where the perimeter walls broke away from the infill. This is particularly interesting in that there is a 50% overlap between the perimeter wall and infill layers. Perhaps a lower a lower temperature would more be suitable.

ANCHOR

Exploring faster drying. The thought being that if the outer body can dry, then it will prevent slumping while the infill is drying.

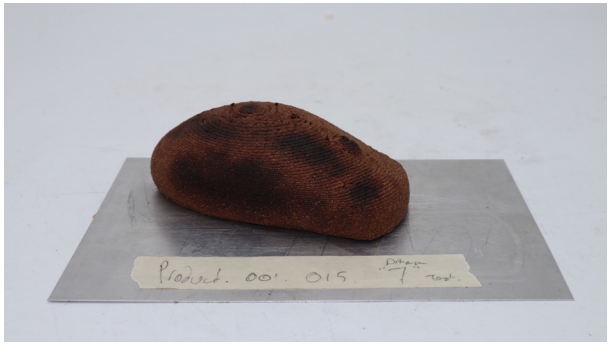
Using the same settings as PRODUCT_001_013.

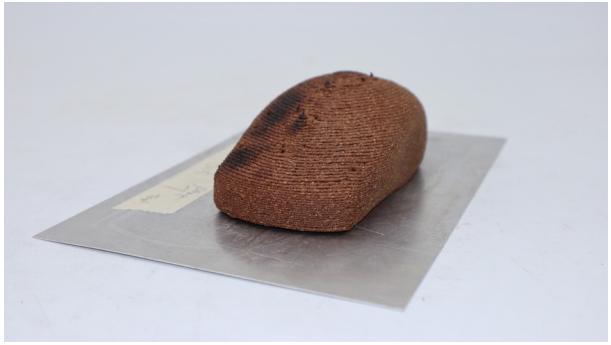
Once printed and removed from the build plate, this print was placed in the same Breviile toaster oven, on 'toasting' mode at the highest setting '7 Dark'.

EXPERIMENTS









OUTCOME

Like 001_014, the high temperature of the toaster function significantly deformed the print, and ruined the exterior layers. One of the walls delaminated from the temprature, and one side of the print was black and burnt. Lower heat is needed.

PRODUCT_001_015

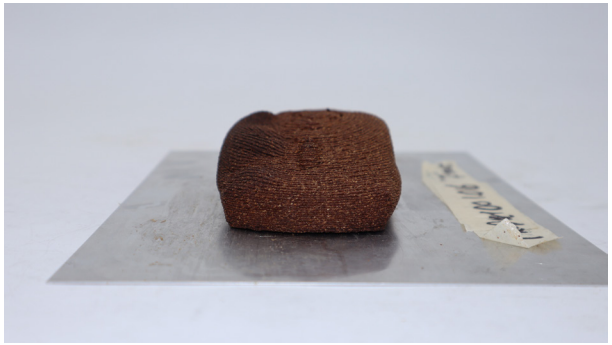
ANCHOR

EXPERIMENTS

OUTCOME

Using the same procedure and settings at PRODUCT_001_015, then placed in the dehydrator at 90 degrees C.









This print had the same outcome at previous tests as the drying temperatures were too high. More attention was paid while monitoring the print during toasting actions but this did not prevent burning and delamination.

PRODUCT_001_016

ANCHOR

EXPERIMENTS

OUTCOME

Drying Testing

This print explored allowing greater airflow into models by manually poking holes in the bottom of prints. Holes were aimed to create air channels through infill sections.









While there was still significant slumping in the print, a drying time was slightly improved through the creation of air holes. These seem to allow air and moisture to escape the infill sections of the model. However, they did also create a slight 'warp' in the print. This could also be due to the 90 degree c drying environment in the dehydrator.

ANCHOR

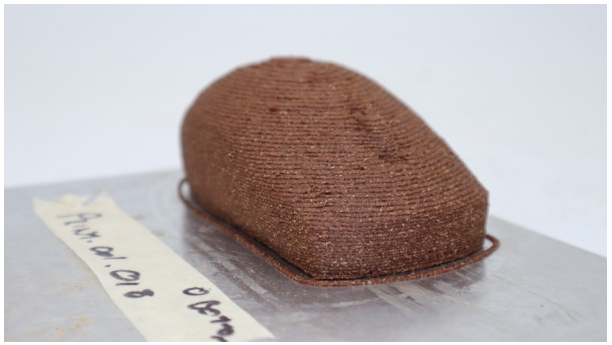
EXPERIMENTS

OUTCOME

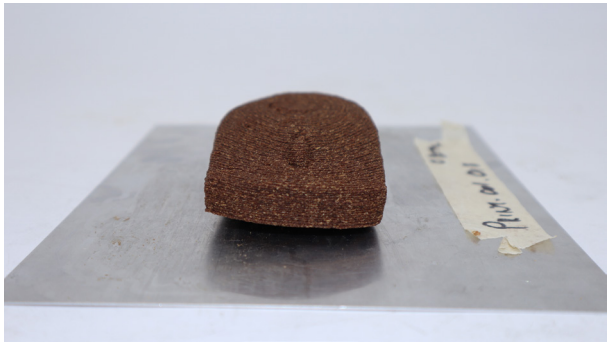
Same settings as PRODUCT_001_013

Bottom Layers zero

Continueing from the interesting results of 001_018, this print was printed with 0 bottom layers to allow greater airflow to the infill layers of the model. This model was dehydrated at 60 degrees C.









The model printed well without a bottom layer; however, it was immediately obvious that the model had less overall strength then models with a bottom. The dried print shows that the bottom layer is vital in structural rigidity during drying. The print underwent significant deformation in all axis during drying. It slumped and lost uniformity.

PRODUCT_001_018

ANCHOR

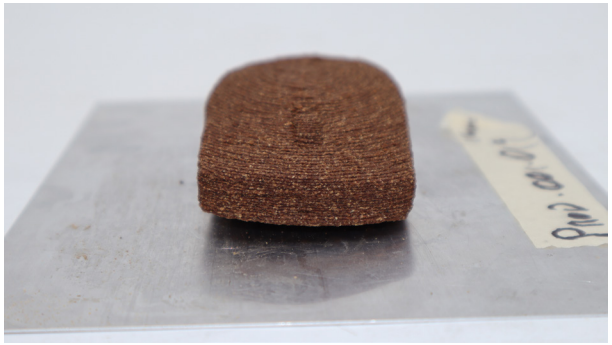
Drying Testing

Bottom Layers 1

Progressed from 001_017 and 001_018, in that a single bottom was used and had holes manually poked into it after removing from build plate. Holes were aimed to create air channels through infill sections.

EXPERIMENTS









OUTCOME

Keeping a single bottom layer allowed for increased structural rigidity, and the holes slightly improved drying time in the dehydrator. It is become apparent that more advanced drying technologies are needed for significantly faster drying times. Focus should be back to slumping and dimensional accuracy.

ANCHOR

EXPERIMENTS

OUTCOME

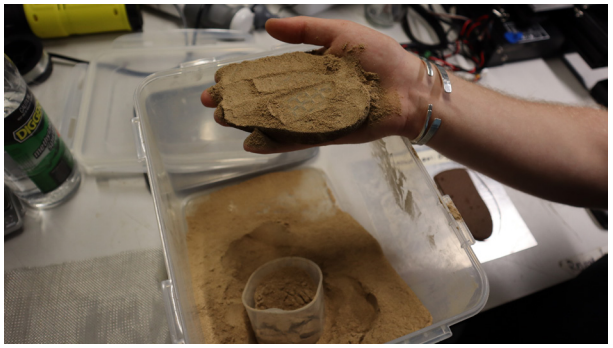
Drying and Slump Testing

Exploring the concept of filling parts with dry matter to prevent slumping.

Using the same settings as PRODUCT_001_013, two bodies were printed; a three layer tall base, and a body missing the bottom 3 layers.

Once removed from the build plate, the main body was filled with dried BSG. Prints were the placed in the dehydrator. Once dried, they were joined using 6% CMC as a glue and seal to prevent BSG from falling out.









The dried print warped and slumped significantly, with the front of the model lifting significantly. This could be a result of high dehydrator temperature (60 degrees C), and the missing structural rigidity of a full external ‘skin’ provided by the outer layers of the models. Further, the parts shrunk at different rates, were the separately printed bottom was smaller than the bottom surface area of the model.

The model has more weight to it and feels dense, which adds a nice presence to it while handling.

It was only realised afterwards that the print was using a the 1:1 scale model and not the enlarged print, showing that slumping was improved through the use of packed infill. Shrinkage was around 23%.

PRODUCT_001_020 _DRY INFILL

ANCHOR

EXPERIMENTS

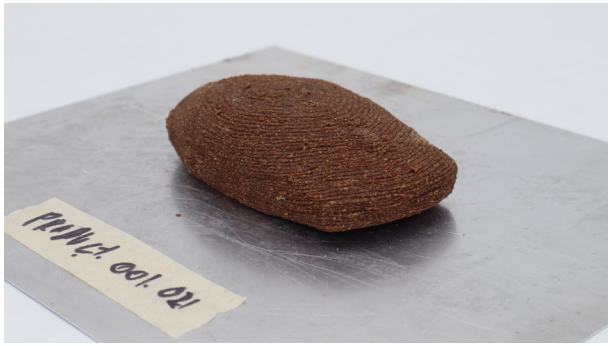
OUTCOME

Drying and Slump Testing

Looking for improved structural rigidity drying drying to avoid slumping

Infill 50% Triangular Pattern









The increased infill (50%) and triangular pattern SEEMED to slightly improve slumping behaviours. However it was only realised afterwards that the print was using the 1:1 scale and not enlarged design.

ANCHOR

Exploring triangular infill

1:1 scale

Infil 40% trianglular

Perimeter 1

Top 2

Bottom 0

Filled with dry BSG after printing.

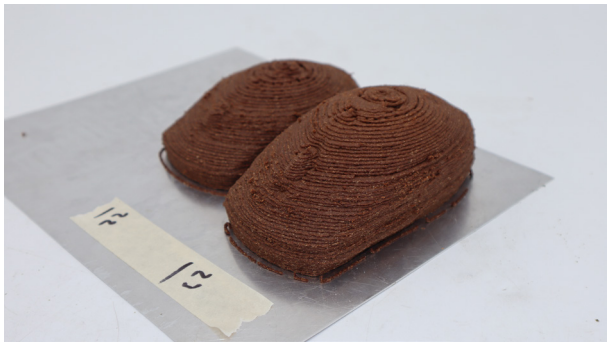
Dried Dimensions:

L 107.73 (8% Shrink)

W 55.14 (11% shrink)

H 31.55 (15% Shrink)

EXPERIMENTS









OUTCOME

Triangular infill proved to be superior in drying than rectangular. Filling the model with dried material after printing has also shown to be a possible avenue for assisting slumping reduction. However, without a base the model does warp on the front which has less material.

ANCHOR

Infill 35% Triangular with 50% overlap with perimeters

2 top and bottom layers

1 Perimeter_ENLARGED CAD in slicer to

L 130.4

W 60.16

H 48.71

EXPERIMENTS









OUTCOME

This experiment showed significant improvement in reaching 'dimensional accuracy' Whilst not the direct point of experimentation, which was to deem the material and system as suitable for use in product design practice, the final outcome is very close to being satisfactory in terms of accurately representing 3d shapes . Final Dried size of

L 116.6 (0.29% from goal)

W 59.7 (3% from goal)

H 31.09 (17% from goal).

ANCHOR

Printing a mouse with more complicated geometry,
the Logitech Master MX 3 (Thingiverse thing:4907929 by Scout 339)Scale 1:1

Nozzle 1.75mm

Layer Height 0.875mm

Extrusion Multiplier 10.0

Retraction 4.0mm at 40mm/s with 2.5mm Vertical Lift

Skirt 1 Layer with 3.0mm offset and 1 outline

Top Layers 2

Bottom Layers 2

Perimeter Layers 1

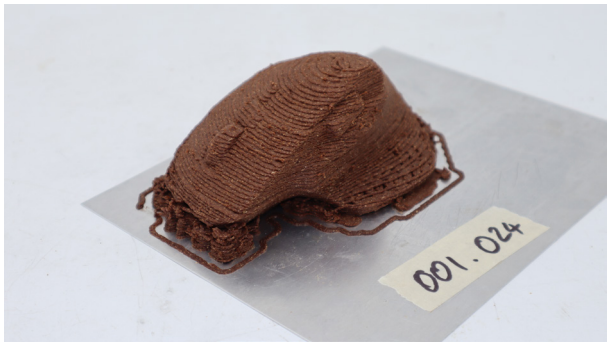
Infill Triangular at 35% with 50% overlap

Support Triangular at 80% with 3.0mm inflation (this makes support materials cover larger areas)

Speeds 55mm/s with 70% outer speed and everything else 80%

Print Time 1 hour 13 minutes (73 minutes)
Weight 183g wet on plate

EXPERIMENTS









OUTCOME

This print was a success in that the more complex shape of the Logitech MX Master 3 was printed without fail. Further, support material functioned perfectly and supported more extreme overhangs. Intricate features were well represented in the final form, such as the shape of the middle mouse button scroll wheel, the thumb scroll wheel, the textured slope on the thumb side wall, and the placement of the back and forwards thumb buttons (though faded). Slumping occurred during drying but this was not a concern in relation to the printers ability to produce more detailed and organic shapes that the simple shape of the Logitech G1.

ANCHOR

Using the same settings as PRODUCT_001_024, a 1:1 Razer Basilisk V3 (from the same Thingiverse pack) was printed.

This model has more severe angles and a different typology and theme than the Logitech mice previously printed.

EXPERIMENTS









OUTCOME

The printer was able to print Razer Blasitik V3, which has a more severe and sharp angles than the Logitech mice. The layer heights and changes are more prominent in this model, leaving an interesting pattern on the top of the mouse. Support material worked well, holding the sharp angles on the mouse buttons up during printing and drying. There are some gaps on the top of the mouse were the layers did not have enough contact with one another due to the angles and layer heights, but overall this is a successful print. The system was able to produce the complex form and the form is representative of the digital design.

ANCHOR

Printing the Logitech Master MX 3 based on shrinkage rates from PRODUCT_001_024.

Infill Triangular 40%

3D Model Dimension:

L 124.61mm

W 84.33mm

H 50.31mm

Enlarged Dimensions

L 136.13mm

W 96.44mm

H 61.38mm

Print Time 1 Hour 51 Minutes (111 minutes)

EXPERIMENTS









OUTCOME

Dried Dimensions:

L 85.36mm (11.49% shrink and -1.2% of goal)

W 126.66 (6.96% shrink and -1.6% of goal)

H 45.05 (26.6% shrink and +10.5% from goal)

This print showed fantastic improvement in managing slumping, however further calculations and calibration is needed. This may also change per print, but could open an interesting area of research and development. Slicers already do this in their software calculations for Gcode, what would this look like for a paste printer/system. The model looks very much like like its true form, and has a good level of details for a form prototyping experimentation.

ANCHOR

Printing the Logitech Master MX 3 based on shrinkage rates from PRODUCT_001_026.

Infill Triangular 40%

3D Model Dimension:

L 124.61mm

W 84.33mm

H 50.31mm

Enlarged imensions

L 133.00mm

W 96.44mm

H 70.00mm

Print Time 1 Hour 51 Minutes (111 minutes)

EXPERIMENTS









OUTCOME

Dried Dimensions:

L 87.07m (9.3% shrink and -3.25% of goal)

W 120.37 (9.5% shrink and 3.4% of goal)

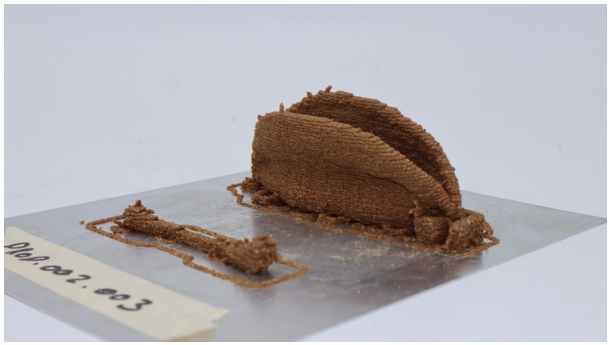
H 46.52 (33.54% shrink and 7.5% from goal)

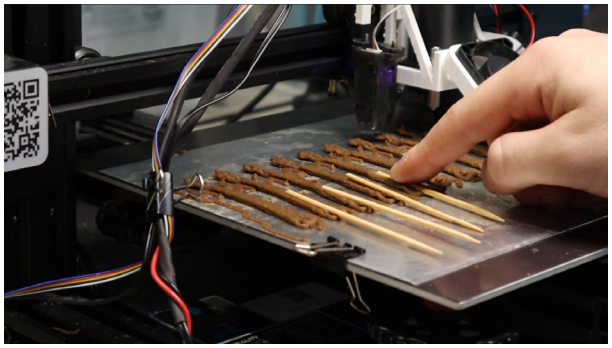
Whilst still not achieving 100% dimensional accuracy, the print was a success. Confirmed through 3D scanning the dried print and compared to the digital files, the shrinking can be assessed, planned and further developed for future experimentation. Overall, the model is roughly within 10% range of the desired size, showing significant progression in controlling of shrinkage behaviour.

ANCHOR

PRODUCT_002 explored methods of quickly producing batches of prototypes, including post processing, for a series of kurrajong seedpods to be displayed in Lucy Simpsons Belle Room commission at the MCA. The subject of PRODUCT_002, the kurrajong seedpod, was based off a scan provided by Lucy.

EXPERIMENTS









OUTCOME

Through the series, methods postprocessing and improving the visual quality of parts were found. A process was developed for postprocessing which unfolds through the 9 experiments in the series. These tie together into a single process of part preparation where prints can be dried, sanded, puttied, glued and joined, and coated.

ANCHOR

I was approached by artist Lucy Simpsons to produce a set of prints using a 3D scan of a Kurrajong Seedpod. This print was a proof of concept that the system was capable of printing the organic shape of the main body and the thin shape of the 'tail'.

Seepod was printing at 1:1 scale in two parts (front and tail).

Using the same settings as PRODUCT_001_001

Nozzle 1.75mm

Layer Height 0.875mm

Extrusion Multiplier 12.0

Vertical Lift on Retraction 3.0mm

Top Layers 3

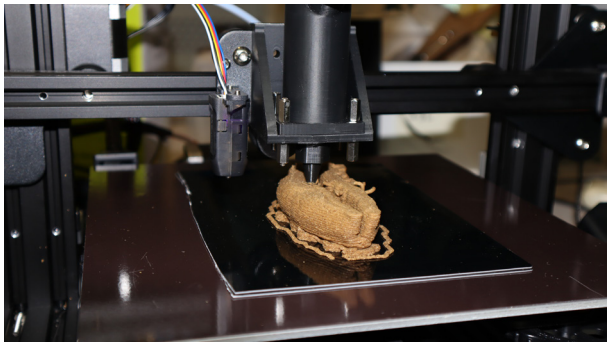
Bottom Layers 2

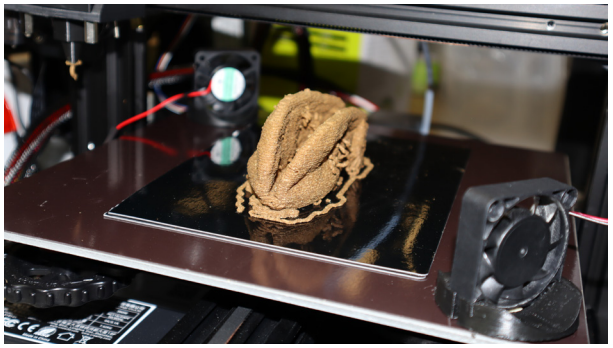
Perimeter Layers 1

Infill 40% Rectilinear with 50% overlap

Speeds 40mm/s all

EXPERIMENTS









OUTCOME

The print was a success, the sloped side walls printed well and included slight details and ridges like the scan. The bottom of the seedpod would need further post processing as the printer did not create a smooth or fully closed layer. Further, the tail was very delicate and would need problem solving to attach it to the main body. Even if they were printed as 1 piece, the tail would be weak.

ANCHOR

Seedpod printed all-in-one:

Nozzle 1.75mm

Layer Height 0.875mm

Extrusion Multiplier 10.0

Retraction 4.0mm at 40mm/s with 2.5mm vertical lift

Tops 3

Bottoms 2

Perimeter Walls 1

Infill 25% rectilinear with 50% overlap

Support 30% rectilinear infill with 10mm inflation distance

Default Speed 55mm/s (80% all speeds)

Print Time 51 minutes

EXPERIMENTS





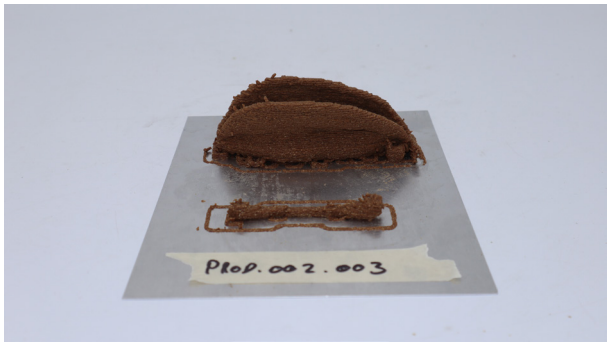


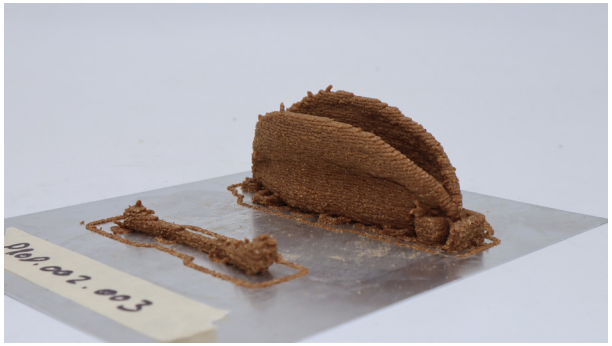


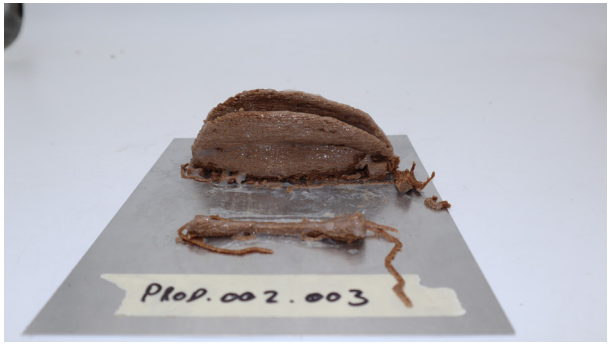
OUTCOME

The print was successful, and the support material held the body and tail well. There was some misses in layer adhesion due to the material needing the 'bridge' the distance of the support. more dense support would be needed to print these parts. Overall the use of this much support is a waste if the model could be printed in parts which may also enable better part strength if a reinforcement rod or wire was embedded in the tail.

Printing the seedpod in the parts, front and back (tail), using the same settings as PRODUCT_002_002. Testing the effect on print time of infill.









The seedpod printed in two parts printed 15 minutes faster than all-in-one with infill. The Overall time for this print was 36 minutes in comparison to 51 minutes for PRODUCT_002_002. Further the tail was of much better quality than the all-in-one print as it did not need to bridge the gaps in support material.

ANCHOR

EXPERIMENTS

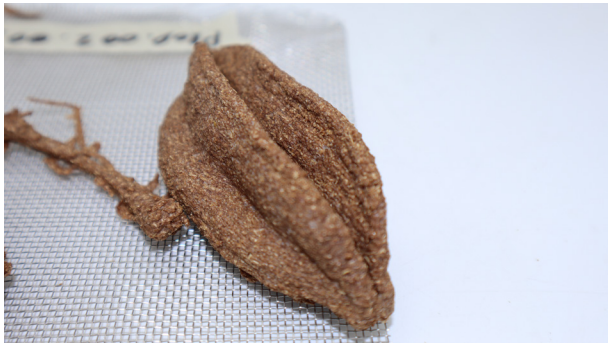
OUTCOME

Using the same settings as previous prints in this series, two seedpod fronts and tails were printed at the same time.









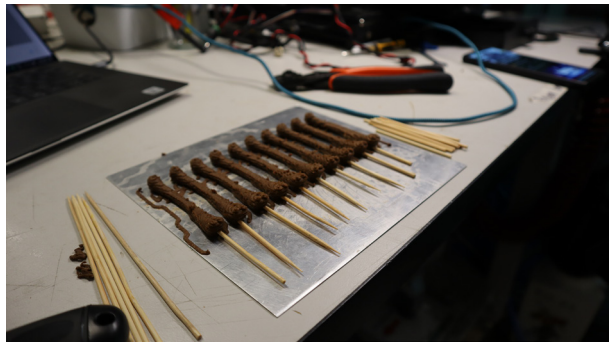
This print showed the printers ability to print multiple complex bodies at once, and retract for longer movements between components. This is a milestone moment in the development of the system for batch production of prototypes and end-use parts such as the seedpods.

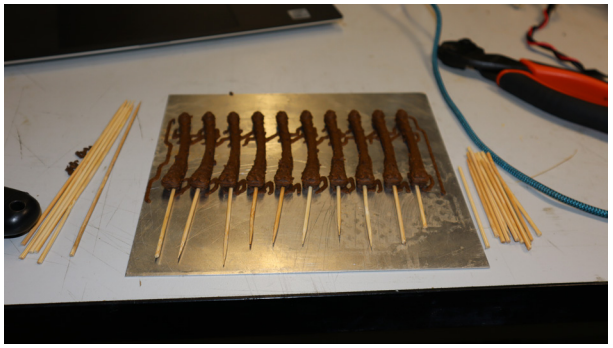
Post processing needs still need to be explored, such as reinforcing the tails and joining them to the bodies (which I will try with CMC paste, the paste used for printing and bamboo skewers), and sanding for a smooth surface quality. Further the bottoms of the parts need post processing which may need putting or intense sanding.

ANCHOR

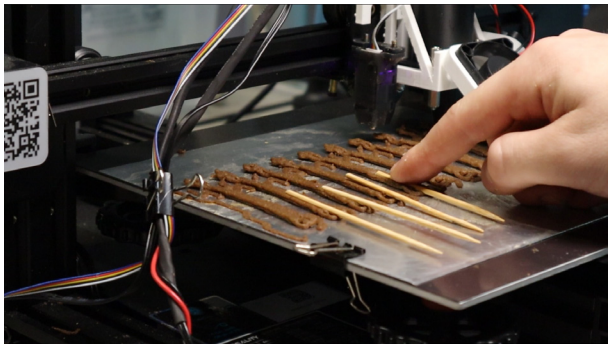
Exploring adding 3mm bamboo skewers into the tails for added structural support and as a method for joining to the front when dry. The print was paused using simplyfy3d's contorl panel after 3 layers and skewers were manually added.

EXPERIMENTS









OUTCOME

The process worked well. This progressed into alternating the scale of each tail for a more natural and odd size group of seedpods. The skewers were kept long and clipped as needed when fitting with the front of the seedpod.

ANCHOR

EXPERIMENTS

OUTCOME

Once printed and dried the seedpod front needed their support material removed and their bodies sanded before any further post processing. The support material was easily removed with a snipping tool, and excess material was collected for future use or composting. It was decided that a Dremel with a sanding drum attachment would be tested as a mode of reducing the amount of time and labour needed to sand 21 seedpods. THis process took place on a downdraft table and while wearing a mask for safety.









The sanding with the Dremel worked very well, and made the process of sanding prints in bulk much less labour intensive then manual sanding. THe material responded very well to the process.

ANCHOR

Once sanded, the front of the seedpod was prepared for joining with the tail. First, a 3mm hole was drilled where the tail would connect. Then, paste was packed around the drilled hole on the front, and the tail was joined slowly pushing the skewer through the hole (and trimmed if needed). Paste was then packed around any visible seems and blended by hand around the tail and front to create a smooth seamless body. Last, the front of the seedpod was puttied using wet paste, then the entire assembly was placed in the dehydrator.

EXPERIMENTS









OUTCOME

This process worked well, albeit messy, it was very enjoyable to manually work with the printed and sanded parts. The tails connected well, occasionally they had to be removed to trim the skewer long, which was sometimes longer then the drilled hole or visible through the inside cavity of the seedpod.

ANCHOR

Final post processing followed the following steps: dried and assembled seedpods (from 002_009), were sanded again using the Dremel with 120 and 240 grit sanding bands. Careful attention was paid to the tail and joining point making sure to keep these areas smooth. Then, the interior cavity of the seedpod was cleaned and sanded using the Dremel with cone shaped tungsten carbide burs. Last, body was coated with a 6% CMC solution, the inside using a thin brush to reach all tight corners, and the outside by hand. Seedpods were then placed in the dehydrator to dry the CMC layer.

EXPERIMENTS









OUTCOME

This process has created a strong proof of concept for future post processing to make assemblies and increase prototype fidelity with NMC pastes. The material has responded well to intensive post processes with power tools (drills, rotatory tools), and it would be interesting to explore making more consumer product prototype assemblies with this workflow.

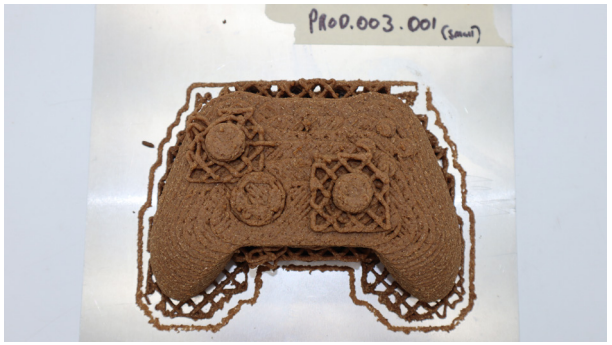


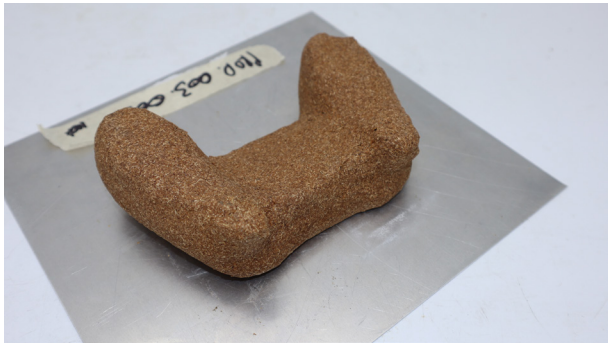
Seedpods were displayed at Lucy Simpon's Belle Room commission at the MCA in Sydney.

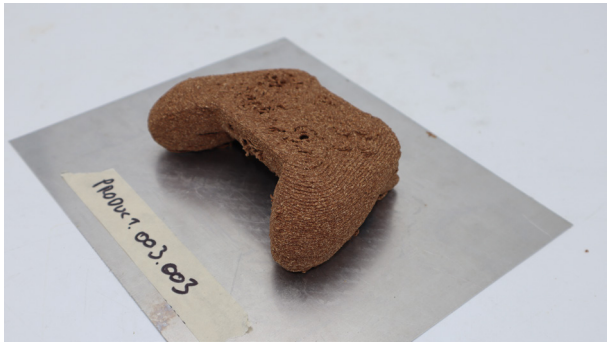
ANCHOR

This series explored producing more complex shapes which have variable layers of support material and extensive infill. The Xbox controller was chosen to be the subject due to the larger overhanging area on the bottom of the controller, organic shape, and small details such as the buttons and thumb sticks.

EXPERIMENTS









OUTCOME

The series required the configuration of new settings such as infill percentage and shape, support material density and type. Further, post processing such as the removal of support material and sanding and puttying behaviours of the dried prints and paste were explored.

Most interesting was the use of ‘inflation’ settings of support, which helps support building overhangs, and would be a setting to use going forward on more complex structures.

Further, PRODUCT_003_004 showed that transitioning settings from PRODUCT_001 for dimensional accuracy was a useful foundation, but did not provide the same level of dimensional accuracy, and that settings changes and scaling would need to shift between product sand sizes for dimensional accuracy.

ANCHOR

XBOX Controller - THING: 41837344 by GIULIA1999 Thingiverse

Nozzle 1.75mm

Layer Height 0.875mm

Extrusion Multiplier 10.00

Retraction 4mm with 2.5mm lift @ 40mm/s

Tops 3

Bottoms 3

Perimeter Walls 1

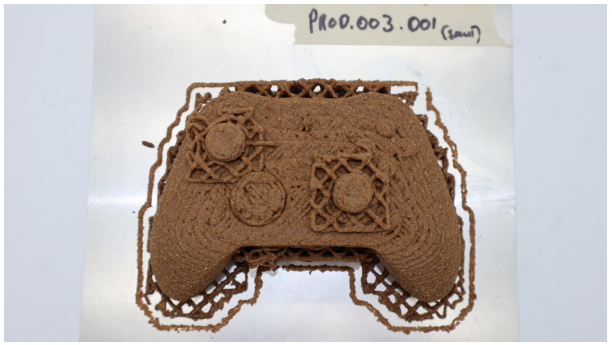
Infill 25% with 50% Overlap of Perimeter

SUPPORT 30% rectilinear with 10mm inflation

Speed 55mm/s (default) with 60% outer, 80% inner, 60% solid infill, 80% spares infill, 70% dense infill

Total time 91 minutes

EXPERIMENTS









OUTCOME

This print explored the printer and pastes capabilities to produce complex shapes and the performance of support material. Whilst it was noted that the print was scaled a bit smaller then 1:1, it was a success and printed to completion including complex shapes such as the significant overhang under the body of the controller, and the overhangs of the thumb sticks on the top. Support inflation was a useful settings which increases the area covered by individual support structures, which is particularly useful here as the slicer does not interpret the size of the material being deposited and does not scale supports correctly.

Further, support was relatively easy to remove using snipper tools, but does cause superficial damage to the body of the print. This requires further sanding and it was found that the BSGNMC paste can be reapplied as a putty on the the model to plug or rebuild holes made during post processing.

ANCHOR

100% scaled controlled based on overall measurements found online.

Width 152.90mm

Depth 103.17mm

Height 61.00mm

Support overhang angle @ 20.00 degrees with 4mm pillar size

Support inflation reduced to 5.00mm

EXPERIMENTS









OUTCOME

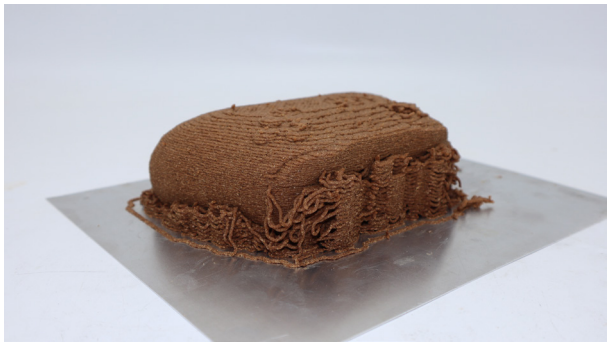
During this print I wanted to try pause and replace the empty cartridge with a full one. However, after pressing 'pause' using the printers display and loading in a new cartridge, the printer got stuck in an endless loop of reheating, which is something coded into the onboard pause function. This meant that the print could not resume and i could not print the detailed top layers of the controller. This did give insights into other options of loading material, such as testing using the simplyfy3d control panel for controlling pause and resume functions. Further ,the part was puttied extensively using wet BSGNMC paste and was give a crusted outer layer using a head gun for quickly handling of the model once puttied.

ANCHOR

Using the same settings as PRODUCT_003_002 but with a full cartridge to start.

Printed for 135 minutes (2 hours 15 minutes) before running out of material.

EXPERIMENTS









OUTCOME

This print had to be stopped earlier as the cartridge ran out of material and the print was run using the onboard controller. The print was very close to finishing, and just had the thumb sticks left. I was very happy with the surface quality and details of what was produced, with the gradient of layers looking quite interesting ,and the buttons on the top of the controlled showing well. Further the support material was simply to remove the holes were patched with BSGNMC paste.

This model was displayed at Sydney Design Week and was interacted with by the general public. People like interacting and handing the model showing use as a explorative ergonomic model.

Further experimentation should explore printing a full controller with a pause function for paste reloading, and methods for dealing with shrinkage and slumping for dimensional accuracy.

ANCHOR

Exploring getting dimensional actuary through enlarging the part in the slicer to match shrinkage rate_based on shrinkage of PRODUCT_001 and of other PRODUCT_003 prints:

L 170.00mm (9% increase from 155.28 1:1)

W 117.81 (9% increase from 155.28 1:1)

H 72.27 (22.51% increase from 56.00 1:1)

Nozzle 1.75m

Layer Height 0.875mm

Retraction 4mm @ 40mm/s with 2.5mm lift

Top and Bottoms 2

Perimeters 1

Infill 40% triangular with 50% overlap of perimeter

Support 60% triangular with 3.0mm inflation

Speed 55mm/s with 70% outer perimeter speed, all others 80%

Printed via Simplyfy3D from computer to control pause function for loading of extra material

Print Time 220 minutes (3 hours 40 minutes)

EXPERIMENTS









OUTCOME

The final model completed and showed interesting details into the capabilities of the system. Shrinkage of the length and with reached under 1% of the intended 1:1 models dimension, whereas the vertical shrink was 16%. Further exploration of infill and external support to control slumping is needed for full dimensional accuracy. Pausing the print using the simlpyfy3d controller allowed for refilling the paste cartridge mid print, exploring ways of doing this with the onboard controller would also be useful to minimise wires and possible lose connection failures. The surface quality of the part was very good, and would be useable in scenarios where users needed to handle the prototype. Further exploration of infill and support material is needed, first to control slumping, and second in relation to bridging movements where the top layers of the print struggling to cover the distance needed in closing the top layers. Overall this print shows good progression of the settings, system and material for producing explorative prototypes with improvement needed mainly to shrinkage calculations.

ANCHOR

3D Benchy at 125% scale

PASTE_004_011

Nozzle 1.75mm

Layer Height 0.875mm

Extrusion Multiplier 10.0

Retraction 4.0mm at 40mm/s with 2.5mm Vertical Lift

Skirt 1 Layer with 3.0mm offset and 1 outline

Top Layers 3

Bottom Layers 3

Perimeter Layers 1

Infill Rectilinear at 25% with 50% overlap

S

Speeds 55mm/s with 60% outer, 80% inner, 60% infill, 80% sparse infill, 70% dense support

EXPERIMENTS









OUTCOME

A relatively successful print, where the majority of the benchy was printed. The slicer does not recognise the chimney at this nozzle thickness and layer height. At 1:1 scale the smallest the nozzle size can be for printing the chimney seems to be 1.1mm and layers heights of 0.55. I am a ways off that. The print also shows that air pressure can determine the thickness of the deposits.

ANCHOR

EXPERIMENTS

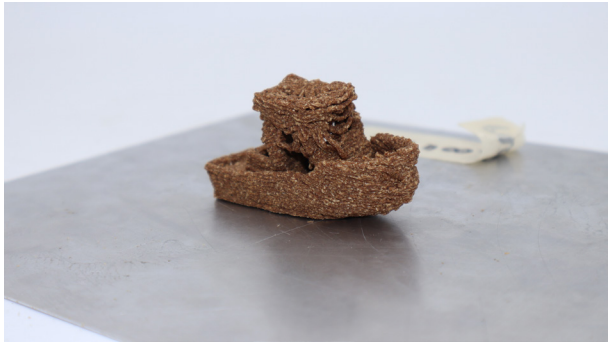
OUTCOME

Same settings as PRODUCT_004_001, but I lowered the pressure as the paste was extruding quick thick in 004_001.









This print shows that line thickness is in part determined by the air pressure of the print in combination with the paste consistency, material flow and nozzle size and layer height. More work is needed for the thin walls that build up the roof of the cabin. I think this has to do with retraction speeds and bridging speeds. the only setting I have changed from default is the lift to stop dragging on large movements, but when watching the printer try bridge and build these parts, retraction isn't happening fast enough or forceful enough to break the string of material which then can pull the walls.

PRODUCT_004_002

ANCHOR

Images are tagged as print 004_004, this is incorrect.

150% scale to try print chimney

Inceased speed for bridging movements to 150%

Completed with chimney at 27 minutes.

EXPERIMENTS









OUTCOME

This print was quite exciting, showing the progression and development of the system in comparison to earlier attempts at benchys. As reflected in the wet model, the printer and BSGNMC paste printed the benchy at 150% scale in less time than it takes to print a 100% model with filament, and was capable of building the structure without support material. The dried model does slump, but the printer and material has progressed quite a long way. Drying will need to be addressed as an aspect of the final frontier to implementation.

ANCHOR

BASED ON "3 paste creationg_ 1 first paste through collaboration"

Ingredients
100g Base cellulose glue
65g CMC 6%
26g MFC 10%
9g Water
200g CMC 6% solution
180g dried BSG
50g Cationic starch 4% solution
160g Water

Process
Mix all ingredients together with a stick mixer
Once well combined, form mixture into a ball and flatten to desired thickness on baking paper
Bake at 60 degrees

Notes
Cationic starch solution was added to increase bonding strength, this could be substituted for tapioca starch or a similar kind of starch (I would choose one with higher levels of amylose pecin) or you could even omit this entirely and use water. Note that the starches have to been 'cooked' or gelatinised before using.

In the process of using a stick mixer to combine the BSG does get a bit finer which should increase bond strength.

Total weight = 690g
DMC = 200.5g
Email from Nahum McLean

EXPERIMENTS



The paste was placed between two measuring cups from the same set, creating a thin-walled mould.

Additionally, the paste was cut with a square cookie cutter. Both shapes were oven-dried.

OUTCOME

This experiment, the first in a series of moulding tests, functioned as a

test to confirm the 'usability' of the initial paste mix designed with my

colleague Nahum McLean. The resulting vessels gave me hope for the future

development of an organic BSG paste.

The cookie cutter mould was course to the touch and structurally

strong enough to withstand bending or breaking for hand and finger force.

The cup mould had fragile walls, mainly due to human error in the packing of

BSG paste between the two measuring cups. Additional moulding experiments were

conducted in parallel and will give more insight into the usability of the paste.

MOULDS_001_001

ANCHOR

BASED ON "3 paste creationg_ 1
first paste through collaboration"

Ingredients
100g Base cellulose glue
65g CMC 6%
26g MFC 10%
9g Water
200g CMC 6% solution
180g dried BSG
50g Cationic starch 4% solution
160g Water

Process
Mix all ingredients together with a stick mixer
Once well combined, form mixture into a ball and flatten to desired thickness on baking paper
Bake at 60 degrees

Notes
Cationic starch solution was added to increase bonding strength, this could be substituted for tapioca starch or a similar kind of starch (I would choose one with higher levels of amylose pecin) or you could even omit this entirely and use water. Note that the starches have to been 'cooked' or gelatinised before using.

In the process of using a stick mixer to combine the BSG does get a bit finer which should increase bond strength.

Total weight = 690g
DMC = 200.5g
Email from Nahum McLean

EXPERIMENTS









Dried and unground BSG being weighed and prepared for mixing.
The mix of BSG, CMC, MFC, water and cationic starch before blending and mixing.
A stick mixer was the most effective kitchen appliance for mixing the ingredients into a paste.
The paste was shaped into a slab sized at roughly 245mm x 185mm x 25mm (L x W x H).
After roughly six days baking at 60 °C (on and off), the slab was complete.
A comparison of the size and finish of the slab to an iPhone 6 with a leather case.

OUTCOME

Various elements and enquiries were investigated in this 'freestyle' branch experimentation. At this point of the research, I became inspired by the work and feedback of my colleagues in the Material Ecologies Design Lab (MEDL) and decided to create moulds with novel BSG mixtures. My colleague Nahum McLean created the recipe (listed in the Anchor section) in his investigations into creating organic and novel foams.

Slab size was determined in response to the research assistant work that I was undertaking. The research investigated sustainable and recycled materials (such as BSG) as possible insulation materials. In addition to the insulation results (to be reported in another entry), I was particularly interested in investigating the following; the shrinkage rate of the mix, drying time, material strength and feel, and water solubility.

Upon initial inspection, the slab had shrunk somewhere between 20-30% and weighed 192g, meaning it had lost 72% of the mixes starting weight. This is mostly water weight, as the altered cellulose in the recipe are mostly high percentages of water mixed with cellulose. Additionally, there is 160g of water in the recipe to facilitate easier mixing. The slab had a rough tactile feel similar to rough timber and sounded like a wooden cricket bat when knocked on with a knuckle. No strength testing was performed; however, the slab could not be bent while I applied large amounts of force to both sides with my hands.

MOULDS_001_002

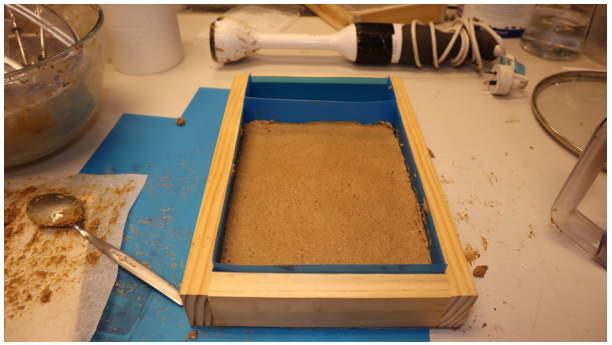
ANCHOR

MOULDS.001.003 explores the effects of minor recipe alterations from that in MOULDS.001.002. The primary objective of this experiment was to create a less dense and more 'foamy' BSG slab. Alterations to the recipe used in 001.002 were: swapping the weight values for the cellulose glue and the CMC, using a mix of half milled BSG with dried BSG, additional water and sodium lauryl sulfate powder. These changes and additions were implemented to inspire a more aerated and foamy paste. In theory, reducing CMC and increasing MFC should create more structural rigidity within the more aerated slab. MFC creates stronger connections due to its fibrillated structure, whilst CMC increases viscosity and is commonly used as a thickening agent. SLS powder is a commonly used surfactant, which lowers the surface tension between ingredients and acts as a foaming agent. The milled BSG was added to lower the surface area of the mix, and extra water was required to allow for easier mixing of ingredients.

MOULD.001.003 took longer to mix than 001.002. This could be due to the additional MFC needing additional force to mix with the other ingredients. Also, additional water was added to the mix to speed up the mixing process, which resulted in a larger body of paste. The increased water content meant that the slab would take longer to dry. Nahum designed a mesh mould for the slab. The mesh allowed for increased airflow to the base of the slab whilst it was in the oven, and we hoped it would speed up the drying process. Due to the alterations to the recipe, the drying speed could not be compared accurately to the previous test.

The slab generated for this experiment had a significantly less uniform surface finish on one of its sides. In addition, the slab, which was thicker than 001.002, had many large cracks on its outer layers. On the slabs more 'uniform' side, the surface finish is improved over 001.002. Additionally, the slab exhibits more flexion when pressed with a thumb or finger. Furthermore, the slab sounds more hollow when tapped or knocked with a fist, showing that the structure is more aerated.

EXPERIMENTS









OUTCOME

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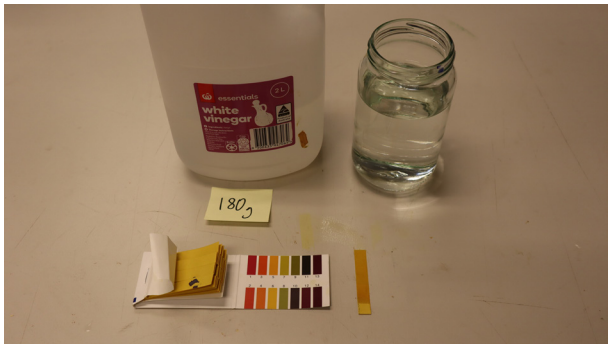
ANCHOR

A titration involves performing a controlled reaction between a solution of known concentration (the titrant) and a solution of unknown concentration (the analyte). Here, the titrant is an aqueous solution of ~0.1 M sodium hydroxide (NaOH) and the analyte is vinegar. When mixed, a neutralization reaction occurs between sodium hydroxide and the acetic acid in vinegar:

Caustic Soda+ Vinegar ? Sodium Acetate + Water

Santa Monica College (2020)

EXPERIMENTS





a. The Ph of Sodium Hydroxide.

b. The Ph of white vinegar.

c. Neutral Ph of a solution made up of a 1:1 mix of sodium hydroxide and white vinegar.

OUTCOME

NaOH (sodium hydroxide, also known as caustic soda or lye) is a corrosive chemical commonly used in manufacturing and cleaning (National Center for Biotechnology Information, 2021). NaOH has many uses and applications; NaOH is a key chemical in manufacturing household bleach (NaOH is mixed with chlorine), soap and detergent manufacturing. NaOH is used as a drain cleaner, pharmaceutical production, water treatment, fuel cell production and paper manufacturing. Moreover, NaOH can be purchased in various purities from hardware stores and online retailers, making it an easily accessible chemical for cellulose isolation from home.

NaOH pretreatment is used on biomasses to break down their protective lignin layer and its connection to hemicellulose (Lee et al., 2015). NaOH pretreatment affects lignin and hemicellulose; its primary purpose as a pretreatment is to remove hemicellulose (Binod et al., 2012). In the NaOH pretreatment, the bonds between the lignin and hemicellulose are broken, enabling the NaOH to hydrolise (dissolve) the hemicellulose. Additionally, this reaction causes the lignocellulosic particles (lignin, hemicellulose and cellulose) to swell, resulting in a larger surface area and accessibility to the cellulose Lee et al., 2015).

Similar to bleach, NaOH is often used as a drain cleaner or cleaning chemical. NaOH can be hazardous to the users, the environment, and aquatic organisms due to its corrosive nature. NaOH corrosive to metals and tissues and should be handled with care. The National Center for Biotechnology Information (2021) states that a dose of 10 grams of NaOH orally can be fatal, as NaOH is corrosive to all tissues. Vapours from NaOH can cause serious harm to the eyes and respiratory system.

Additionally, NaOH coming into direct contact with the skin can result in hair loss, necrosis and blisters. Personal protective equipment should be worn at all time while working with NaOH. Long gloves, glasses and a mask should be worn at all times. Special care should be taken to keep NaOH away from children, and signage should be used to help others identify that powdered NaOH or liquid with NaOH in it is extremely dangerous.

The National Center for Biotechnology Information (2021) states that small amounts of NaOH (dissolved in water) are safe to dispose of down the drain; however, it is recommended to neutralise and dilute the solution before disposal. NaOH is neutralised by acetic acid at a ratio of 1:1 (Department of Physical Sciences Kingsborough Community College The City University of New York, 2013). Acetic acid is found in vinegar in concentrations typically between 5-8%. In cellulose isolation, NaOH is usually diluted in low percentages; therefore, the ratio of acetic acid needed to neutralise the NaOH is easy to calculate. Ph level can be tested with litmus paper, and once a neutral Ph has been reached, the solution can be disposed of.

A titration involves performing a controlled reaction between a solution of known concentration (the titrant) and a solution of unknown concentration (the analyte). Here, the titrant is an aqueous solution of ~0.1 M sodium hydroxide (NaOH) and the analyte is vinegar. When mixed, a neutralisation reaction occurs between sodium hydroxide and the acetic acid in vinegar:

NaOH(aq)+HC2H3O2(aq)?NaC2H3O2(aq)+H2O(l)
Caustic Soda+ Vinegar ? Sodium Acetate + Water
Santa Monica College (2020)

ANCHOR

“One gram of ascorbic acid will neutralize 1 milligram per liter of chlorine per 100 gallons of water. The reaction is very fast. The chemical reaction (Tikkanen and others 2001) of ascorbic acid with chlorine is shown below:

C5H5O5CH2OH + HOCL ? C5H3O5CH2OH + HCl + H2O

Ascorbic acid + Hypochlorous acid ? Dehydroascorbic acid + Hydrochloric acid + water

Approximately 2.5 parts of ascorbic acid are required for neutralizing 1 part chlorine. Since ascorbic acid is weakly acidic, the pH of the treated water may decrease slightly in low alkaline waters.
Land (2005)

“Even SH pretreatment has permitted to reach good lignin losses, comparable to ECA solution, alone or in combination with organosolv. Anyway, in a perspective of practical use, it is worthwhile pointing out that sodium hypochlorite is a chemical reagent that needs to be removed from the solution at the end of the reaction, hypochlorous acid naturally decades to chloride after 48–72 h (experimental evidence), reducing the overall environmen...

EXPERIMENTS









OUTCOME

Bleach is a corrosive chemical commonly used in industrial and domestic cleaning procedures. It has many uses: drain and floor cleaning, whitening of fabrics, and its implementation in the papermaking industry. Bleach is the generic name used for the chemical sodium hypochlorite (NaOCl), a widely available chlorine-based cleaning product. These domestic cleaning solutions are usually diluted to 42g of NaOCl per 1L. In papermaking, wood pulp is ‘bleached’ with hydrogen peroxide (H2O2). This process is twofold, bleaching paper pulp removes lignin from biomass and lightens the colour of the pulp. Costa et al. (2018) found that sodium hypochlorite achieved comparable (over 80% lignin reduction) results to those from hypochlorous acid mixed with either ethanol or acetic acid and acetone, making it a suitable chemical for my experimentation.

Bleach is often used as a drain cleaner

however, pouring excess bleach into a drainage system should be avoided. This is due primarily to the possibility of bleach reactin...

ANCHOR

"Dried BSG (P0) was extracted with 0.1 M NaOH at 60 °C for 60 min (17% w/v) with continuous stirring at 30 rpm. Centrifugation was done at 2000 rpm for 10 min at 4 °C to separate the protein extract from lignocellulosic part."
Pawan Kumar et al. (2016)

"The extractive free straw was treated with an aqueous solution of 5% (w/v) sodium hydroxide (NaOH) for fibre separation and bond breaking using methods projected for soybean hulls [25] but adapted here for Eucalyptus lenceolata."
Rehman et al. (2018)

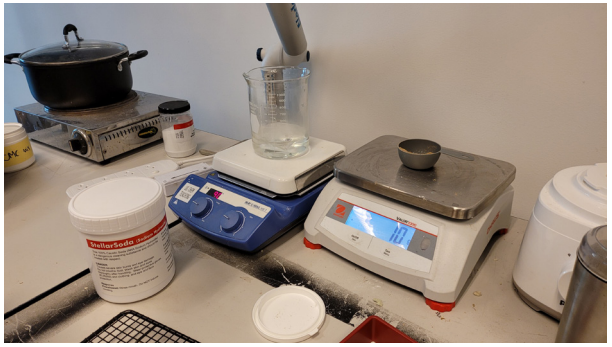
"... then pretreated by dilute sulfuric acid and subsequently by sodium hydroxide solutions, to remove the protective hemicellulose-lignin wrapper... 2% w/v NaOH solution in a 1:20 g:g solid:liquid ratio, 120 °C for 90 min (Mussatto et al. 2006b). After each reaction the residual solid material was separated and washed with water (until neutral pH) to be used in the next step."
Mussatto et al. (2008)

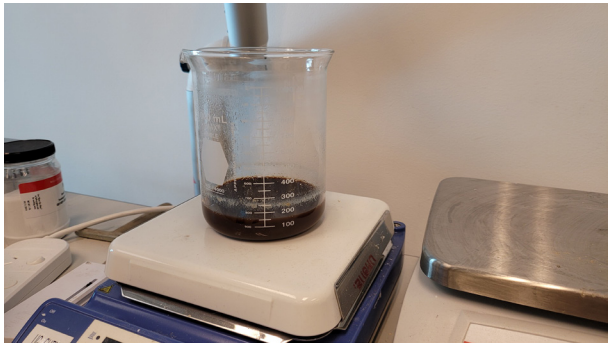
"BSG was extracted according to the method described by Celus et al. (2007), with modification. BSG was mixed with 10 volumes of 0.1N NaOH (v/w) and stirred at 70 °C for 3 h."
Lee et al. (2015)

"Initially, the dried BSG was treated with a 2% (w/w) sodium hydroxide aqueous solution in a solid:liquid ratio of 1:20 (w:v) for 2h at 90°C, as reported by Mussatto et al. (2006b) with some modifications."
Santos et al. (2015)

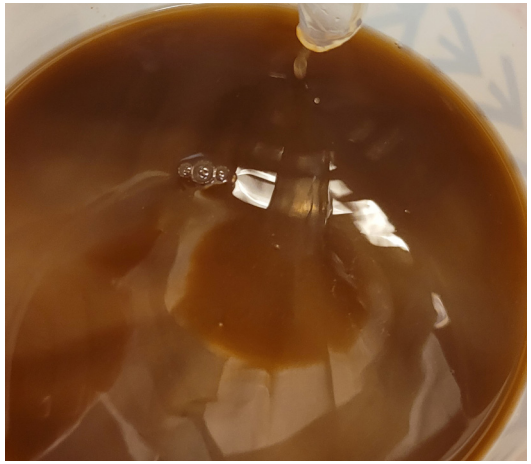
"Generally alkali pretreatment removes lignin from the lignocellulosic biomass, leaving cellulose and hemicelluloses fraction in the solid residue. Acid pretreatment removes hemicelluloses that can be separated from solid residue in soluble form."
Binod et al. (2012)

EXPERIMENTS









a. Experiment set up showing Caustic Soda, scales and the magnetic stirrer and heat plate.
b. Tearaway paper is placed into a funnel to catch BSG post alkali treatment.
c. A close-up photograph of the brown and cloudy liquid after separation.
d. Post alkali treatment drying BSG. BSG was milled before processing to less than one micron.

OUTCOME

According to Binod et al. (2012), "alkali pretreatment removes lignin from the lignocellulos biomass." Alkali pretreatment refers to the exposure of biomass to sodium hydroxide (NaOH), also known as caustic soda, a common cleaning chemical. 1Kg of 100% NaOH was purchased from an online brewery supply shop "Kegland". NaOH is a harmful corrosive chemical and should be used with personal protective equipment such as glasses, gloves and a mask.

Initial testing followed the methods of Santos et al. (2015), in which BSG was treated with 2% (weight to weight) NaOH and a solid to liquid ratio of 1:20 (weight / volume). This mixture was heated and stirred on a IKA magnetic stirrer for two hours at 90 °C. The same procedure could be conducted on a regular oven with careful temperature monitoring and regular stirring.

After two hours, the dark brown residue was rinsed and washed until a neutral Ph was reached. First the residue was poured through a fabric sieve, and subsequent washes used tap water through the same fabric and funnel. After washing, BSG was placed in a domestic oven at 50°C until it was dry to the touch and brittle. Further experimentation and development needs to be applied to the washing techniques, as most researches referenced used an autoclave for separation and washing.

ANCHOR

"...it is an acid-catalysed autohydrolysis of lignocellulosic materials... Microwave irradiation could be easily combined with chemical reaction and can accelerate the chemical reaction rate [16]."

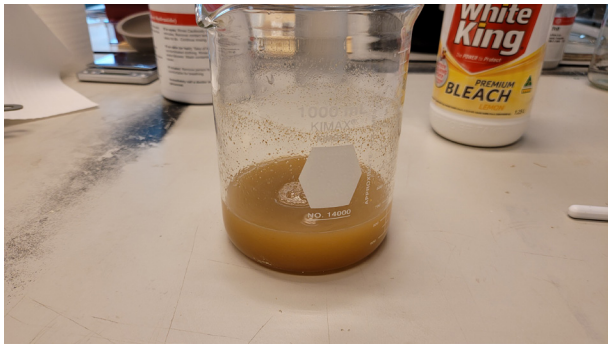
"Microwave-alkali pretreatment (MAL) was carried out using 1% NaOH as pretreatment reagent. 10% biomass was loaded to this alkaline solution in a stoppered flask and subjected to microwave pretreatment at varying power consumption 850W, 600W, 450W, 300W, 180Wand 100W for different residence time varying from 1 min to 30 min. After pretreatment, biomass was thoroughly washed with water till pH 6.0 and dried in air."

"Generally alkali pretreatment removes lignin from the lignocellulosic biomass, leaving cellulose and hemicelluloses fraction in the solid residue. Acid pretreatment removes hemicelluloses that can be separated from the solid residue in soluble form."
Binod et al. (2012)

"MAA was carried out following the procedure described by Binod et al. (2012) with minor modifications... 1% (w/v) biomass was loaded to 0.5% NaOH (w/v) solution in a stoppered flask and subjected to microwave radiation at varying power settings of 400 W, 560W and 800W for different residence time varying from 30 s, 60 s and 120 s. After pretreatment, the biomass was thoroughly washed with distilled water till pH 6.0 and dried in air."
Ravindran et al. (2018)

EXPERIMENTS









a. Notes taken in preparation for experimentation. b. The vessel post microwave pretreatment. c. Preparation of the funnel and fabric to catch the treated BSG. d. Homemade teabag containing treted BSG. e. Post treatment and dried BSG.

OUTCOME

Mercerization is a common treatment applied to cotton fabrics in which the fabric is exposed to NaOH solution in short bursts. Mercerization results in increased textile strength, dye affinity and other benefits. Similar treatments have been applied to biomass, resulting in the removal of lignin from lignocellulosic biomass. ISOLATION_001_002 explores a microwaved assisted various of the methods explored in ISOLATION_001_002. Binod et al. (2012) investigated microwave-assisted reactions in comparison to traditional pretreatments used on lignocellulosic materials. Binod et al. argue that traditional methods are limited due to their high energy consumption. They found that microwave-alkali pretreatment used less power, reduced reaction time and better cellulose yield than traditional methods.

ISOLATION_001_002 follows the procedures listed by Ravindran et al. (2018), in which 1% (w/v) of BSG was exposed to 0.5% NaOH (w/v) at 440W for one minute in a domestic microwave. This experiment allowed for further refinement of my washing technique. I found that if I created a teabag out of the tearaway fabric I was using as a sieve, I could easily wash the treated BSG in a sink under running water rather than pouring water into the sieve and waiting for it to filter through.

After washing, the makeshift teabag was emptied onto a baking tray and dried at 50°C until crisp to the touch. Further scientific analysis needs to be applied to this sample to understand if the MAA pretreatment was effective.

ISOLATION_001_002

ANCHOR

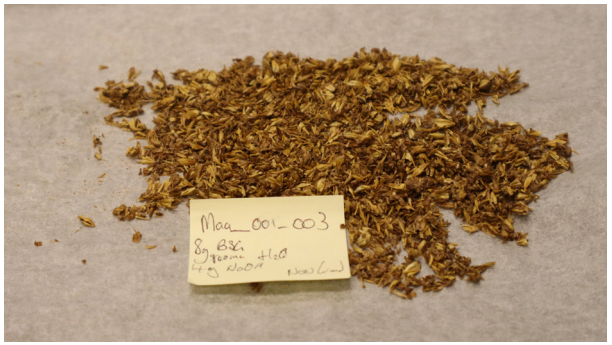
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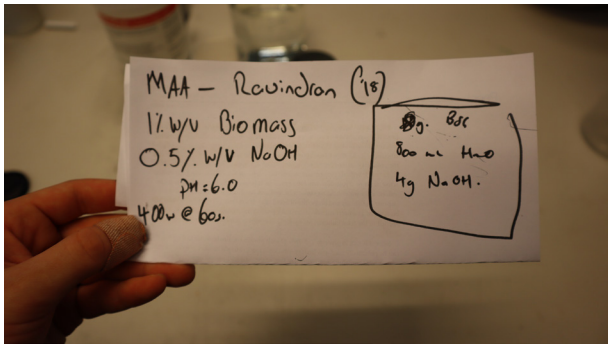
"Microwave-alkali pretreatment (MAL) was carried out using 1% NaOH as pretreatment reagent. 10% biomass was loaded to this alkaline solution in a stoppered flask and subjected to microwave pretreatment at varying power consumption 850W, 600W, 450W, 300W, 180Wand 100W for different residence time varying from 1 min to 30 min. After pretreatment, biomass was thoroughly washed with water till pH 6.0 and dried in air."

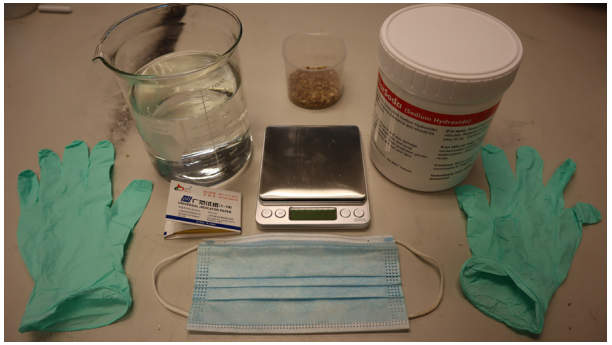
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EXPERIMENTS









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After washing, the makeshift teabag was emptied onto a baking tray and dried at 50°C until crisp to the touch. Further scientific analysis needs to be applied to this sample to understand if the MAA pretreatment was effective.

ISOLATION_001_003

ANCHOR

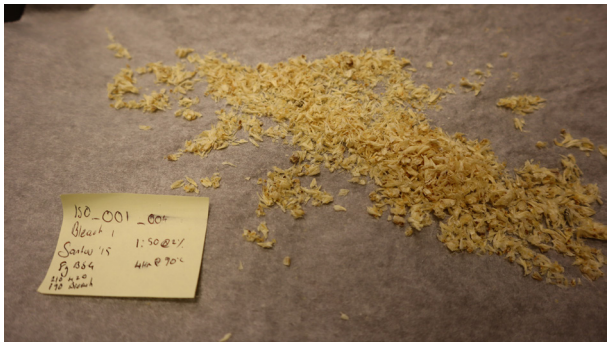
"Initially, the dried BSG was treated with a 2% (w/w) sodium hydroxide aqueous solution in a solid:liquid ratio of 1:20 (w:v) for 2h at 90°C, as reported by Mussatto et al. (2006b) with some modifications."

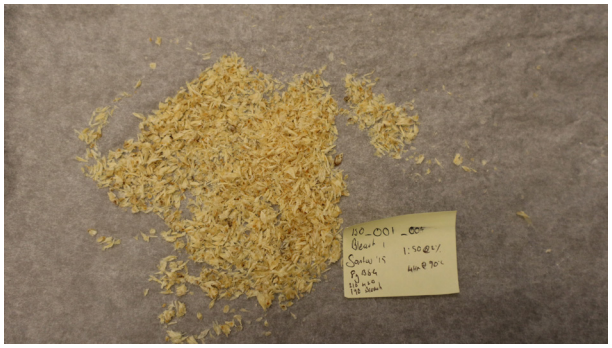
Santos et al. (2015)

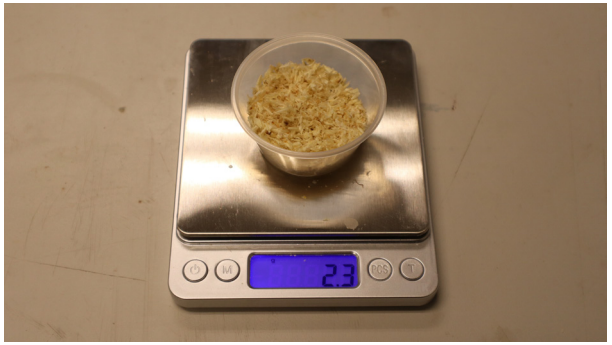
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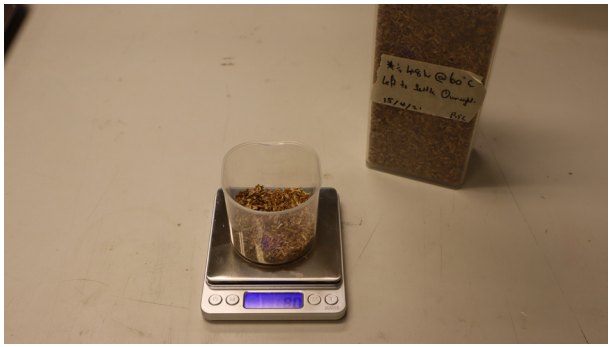
Binod et al. (2012)

EXPERIMENTS









8 grams of dried BSG before the bleaching process.

Notes and calculations taken before experimentation.

After bleaching, 2.3 grams of bleached BSG. Note the 71% weight reduction.

OUTCOME

Initial testing followed the methods of Santos et al. (2015):

I mixed 80 grams of dried BSG with 210 grams of tap water and 190 grams of store-bought liquid bleach. This was heated to 90 degrees C and stirred at temperature for 4 hours.

The resulting liquid was a mirky golden fluid, which was filtered through fabric to retain the solid material inside. This was washed until a neutral PH and placed in the oven until dry.

The dried material was a course yellowish husk-like material - further analysis is required to identify the cellulose content truly. However, this was put on hold due to COVID lockdowns.

ANCHOR

"...it is an acid-catalysed autohydrolysis of lignocellulosic materials... Microwave irradiation could be easily combined with chemical reaction and can accelerate the chemical reaction rate [16]."

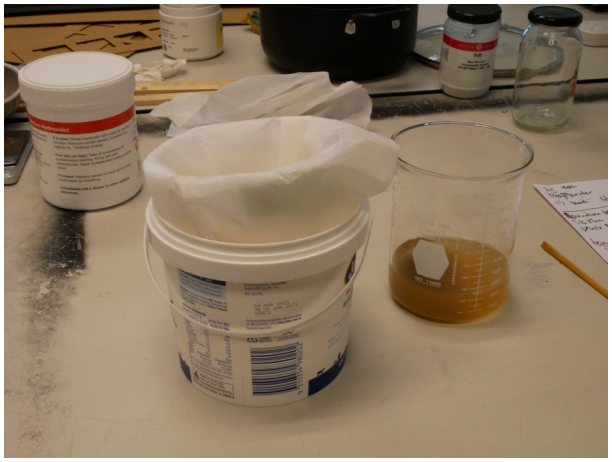
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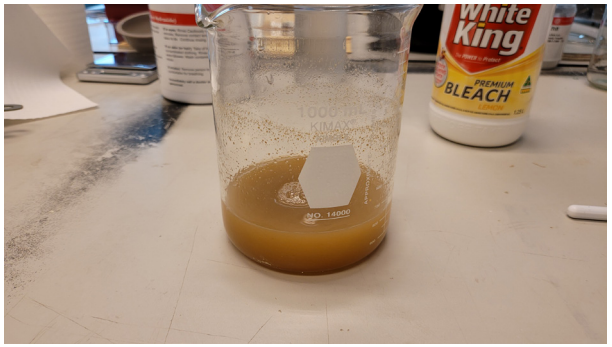
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EXPERIMENTS





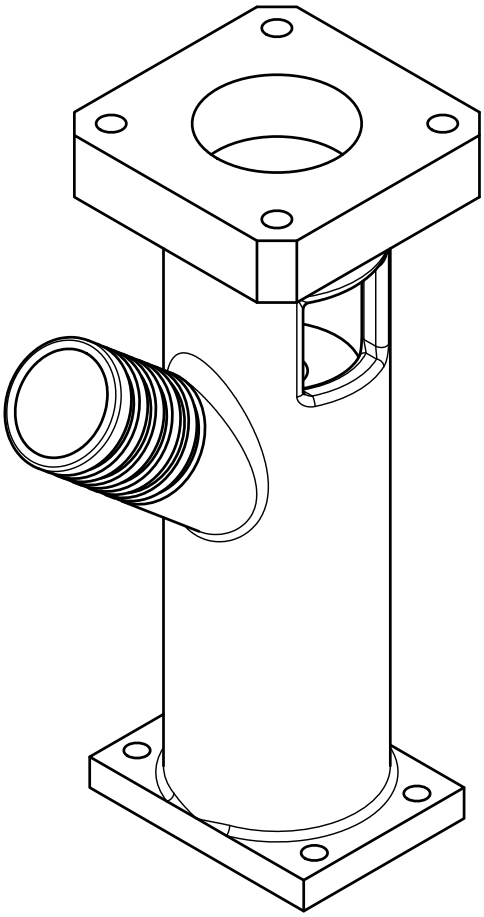




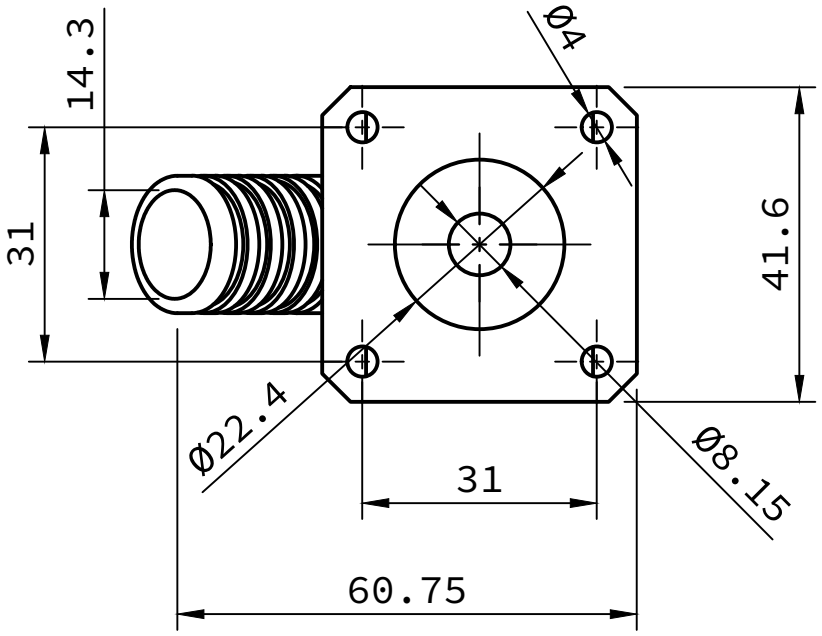
OUTCOME

Put on hold due to COVID, and will not be revistted until later in the thesis.

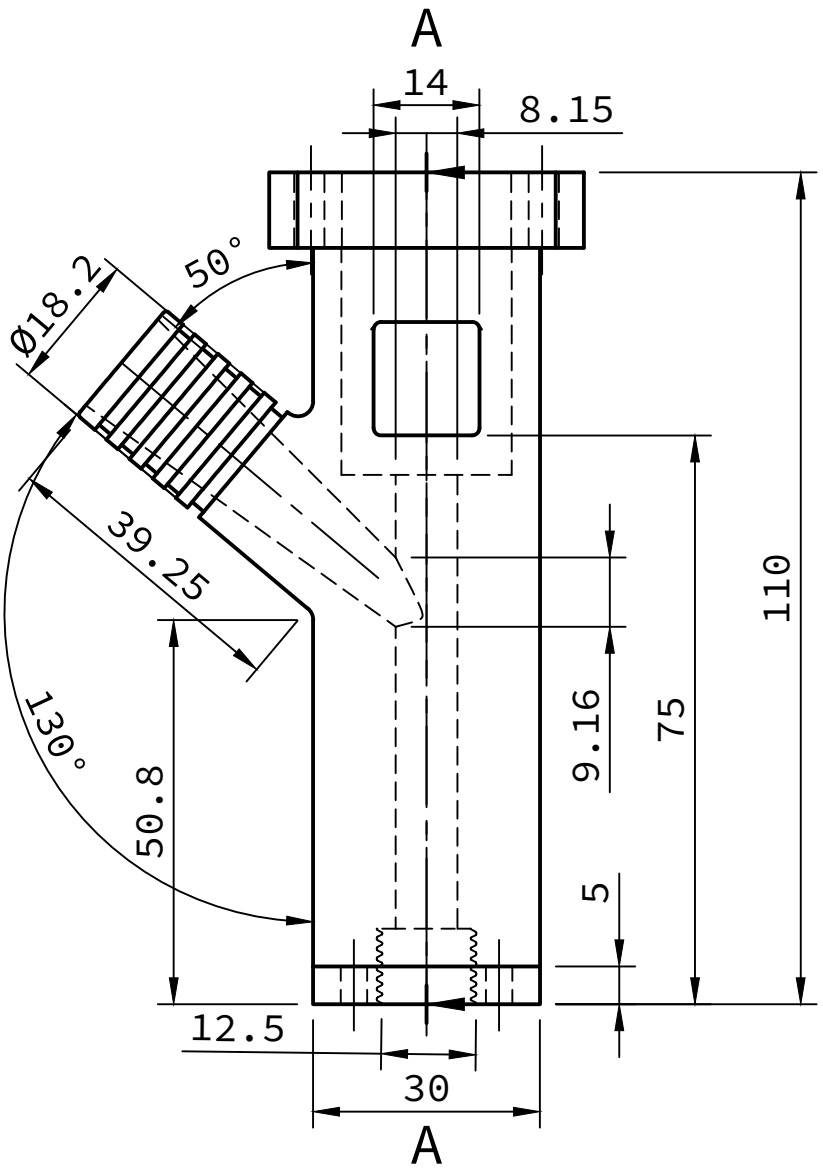
Appendix D



EXTRUDER_003_002



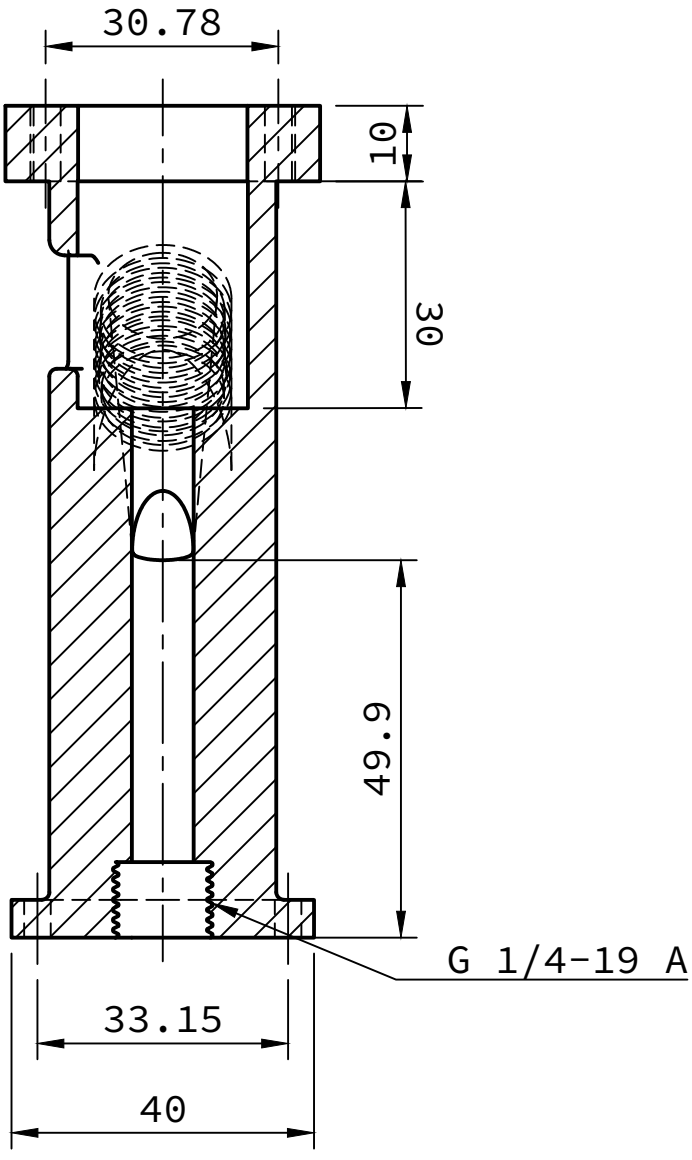
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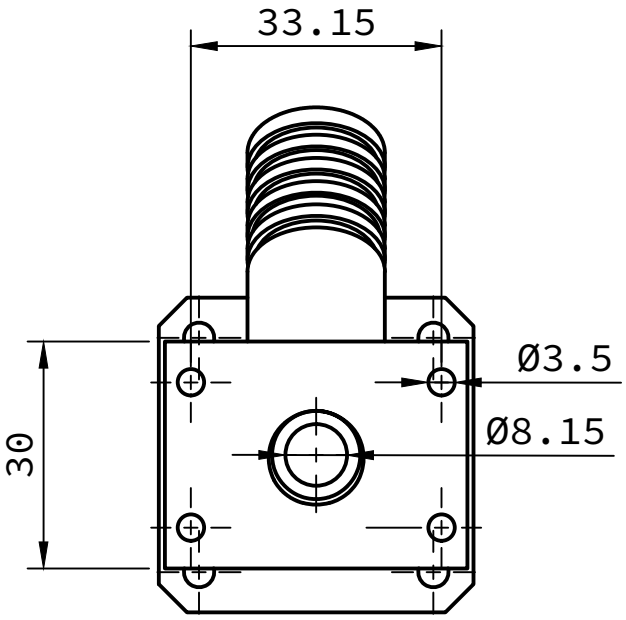


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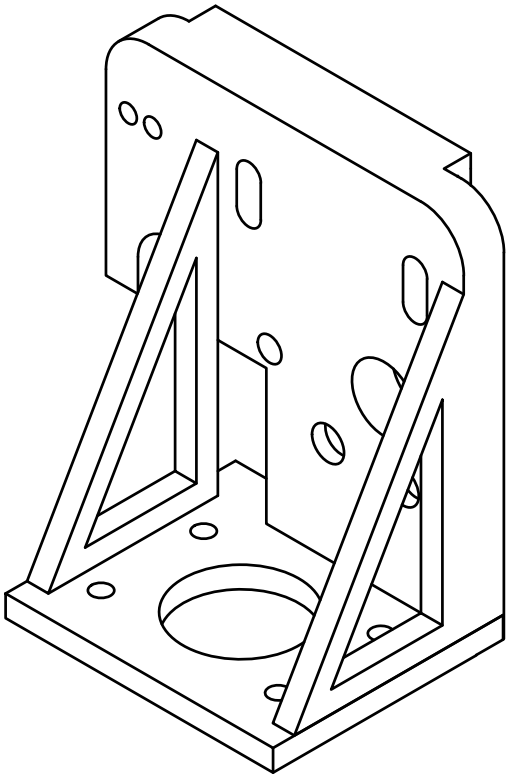
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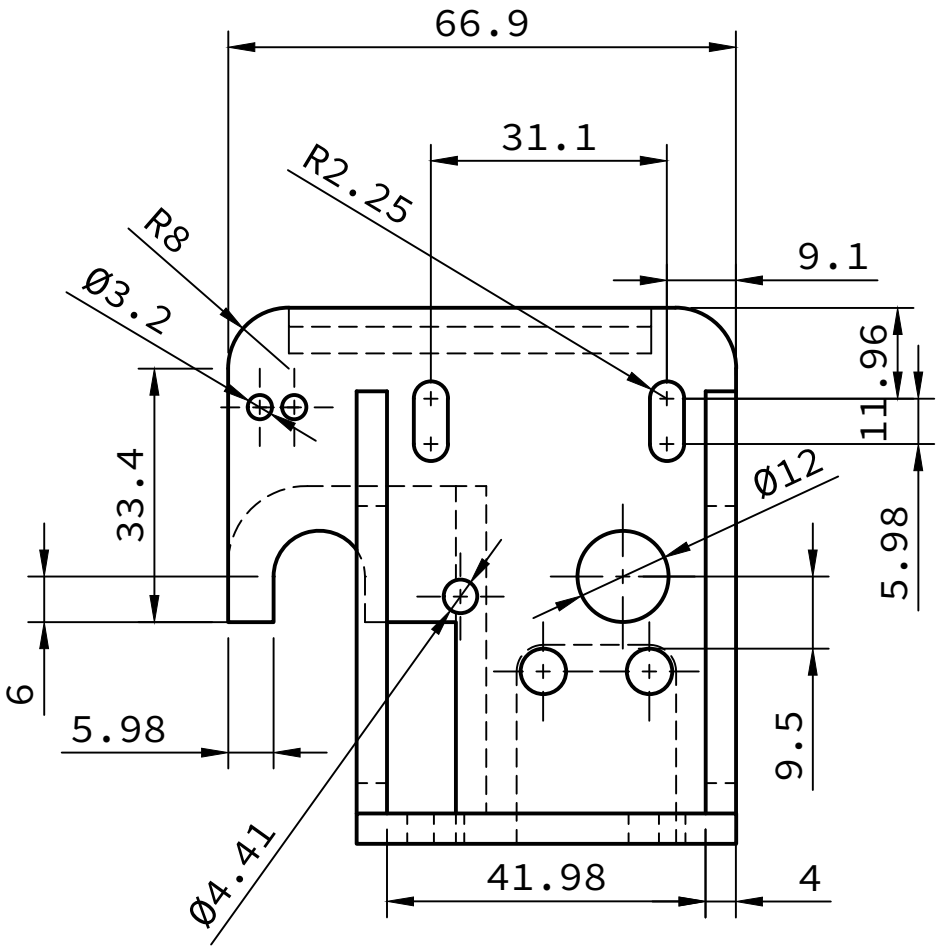




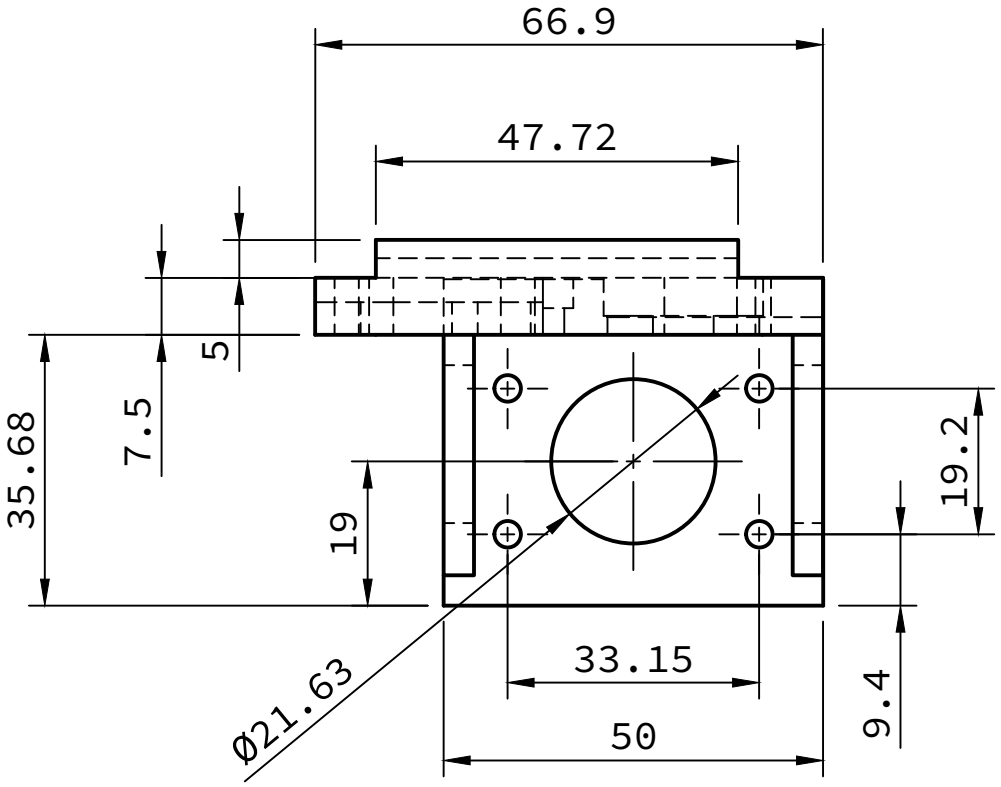
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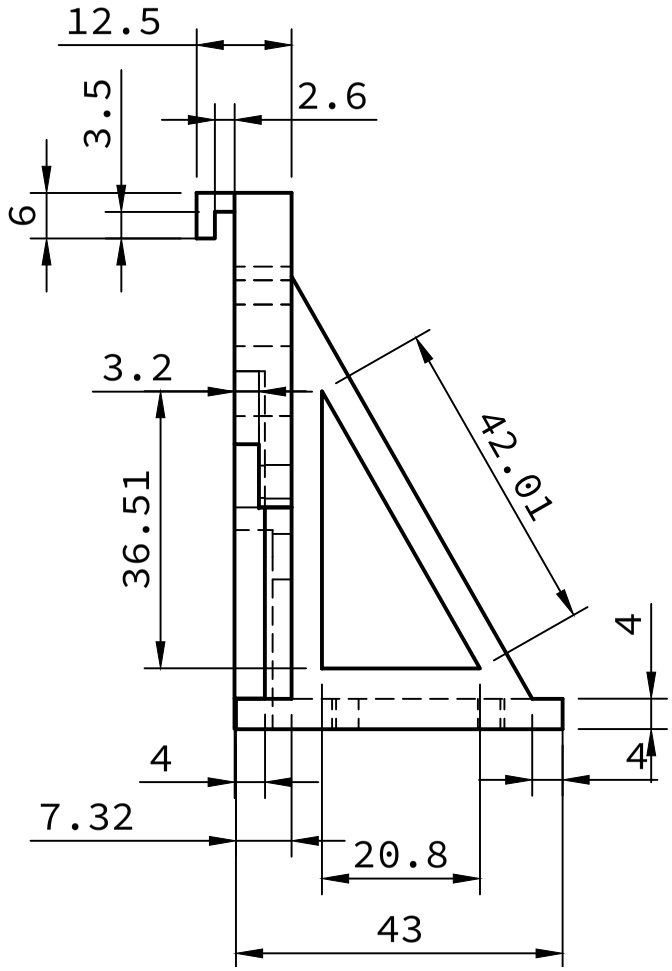


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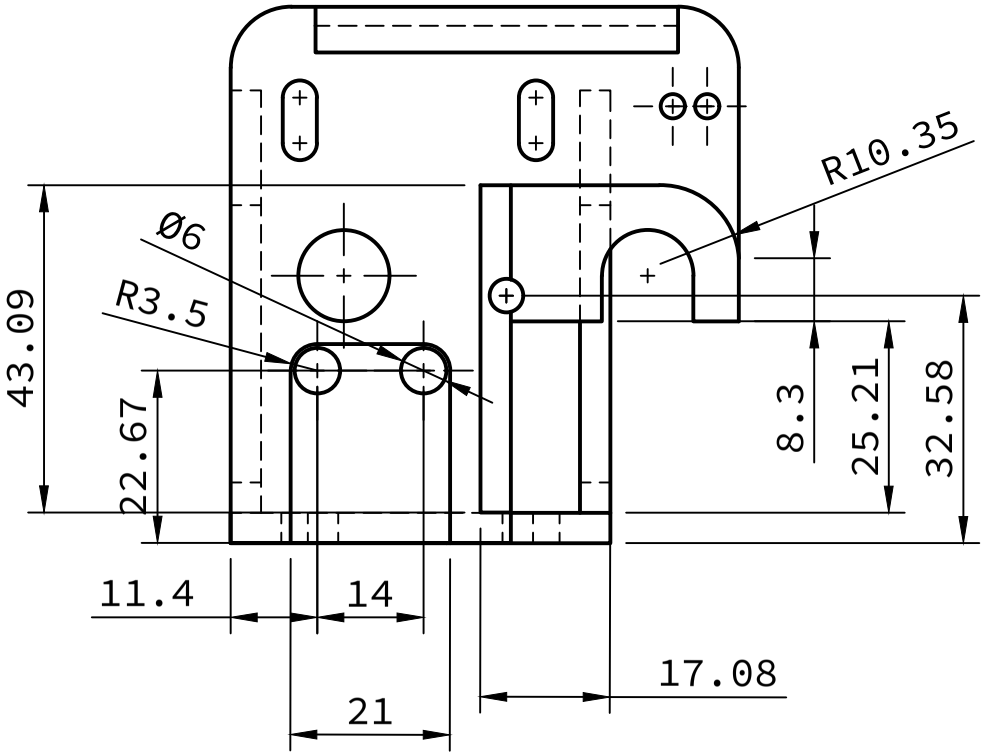


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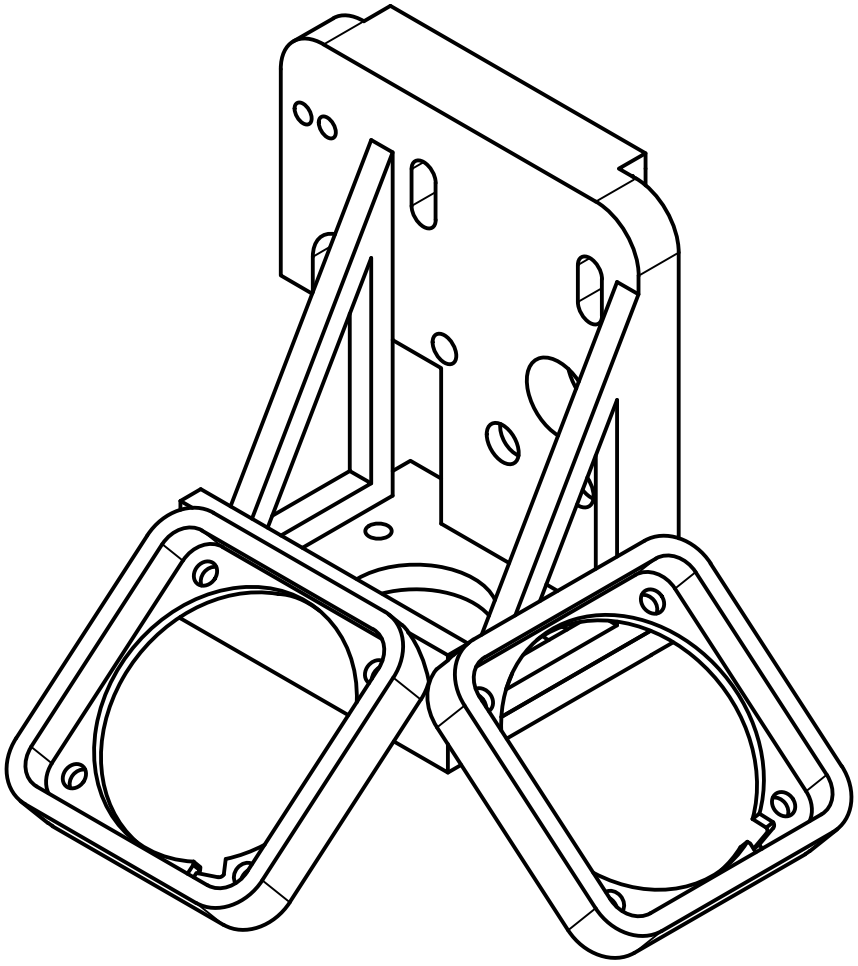
EXTRUDER_003_002_ENDERMOUNT


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3.5
6
3.2
36.51
42.01
4
4
4
7.32
20.8
43

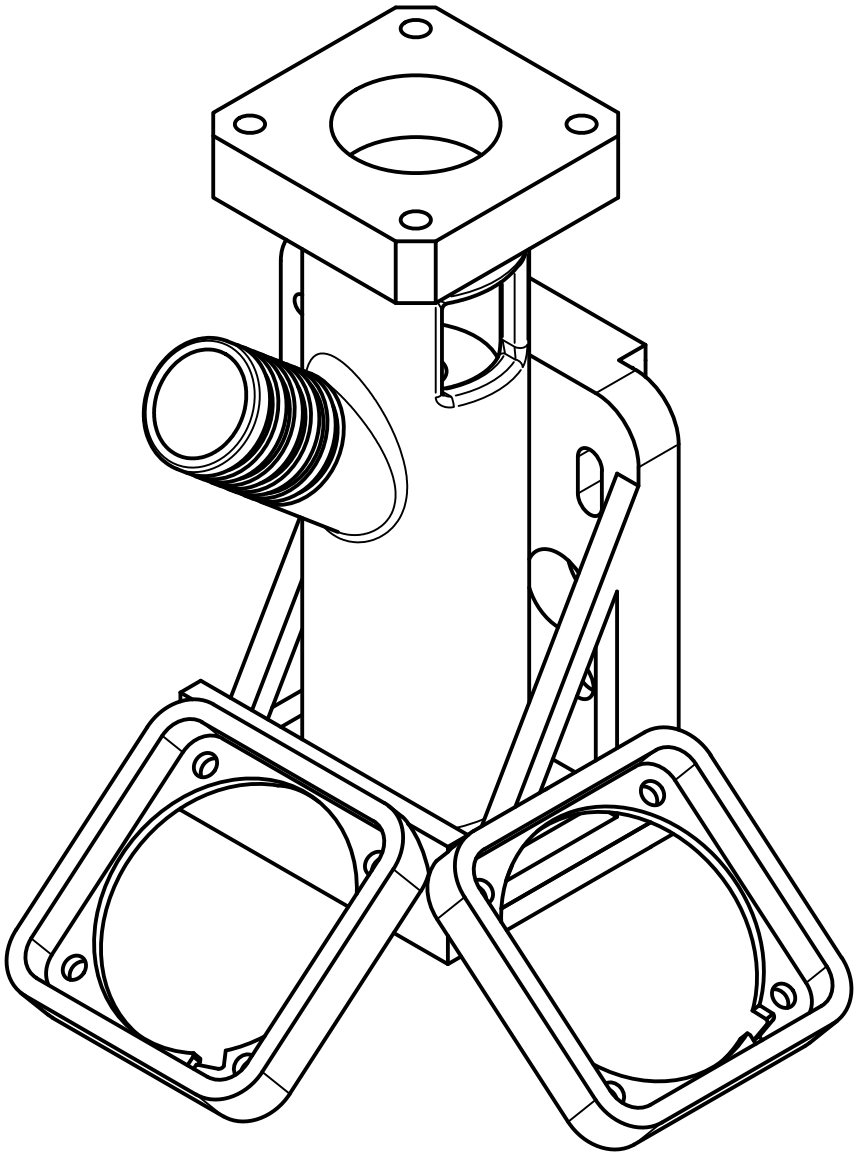
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Ø6
R3.5
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8.3
25.21
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11.4
14
17.08
21

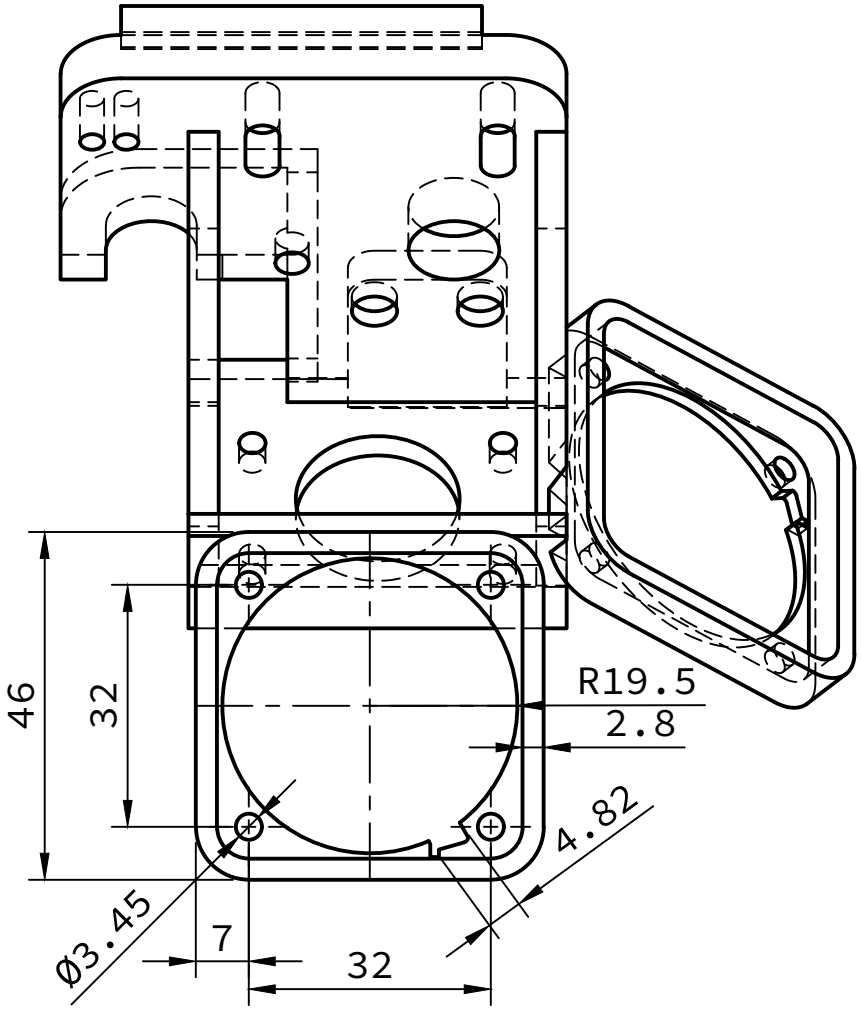
BACK



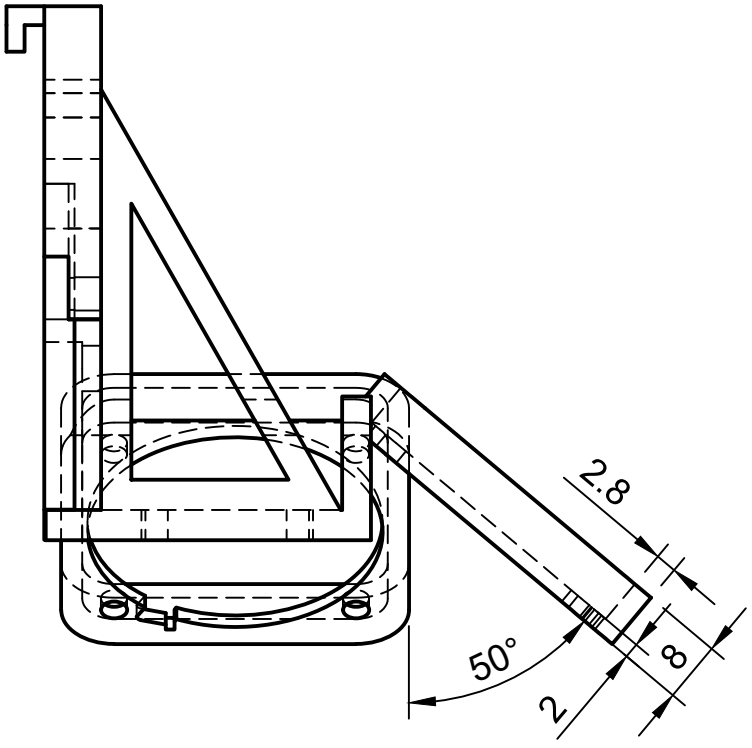
EXTRUDER_003_002_FANMOUNT



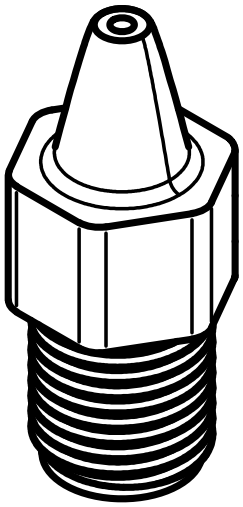
EXTRUDER_003_002_FANMOUNT



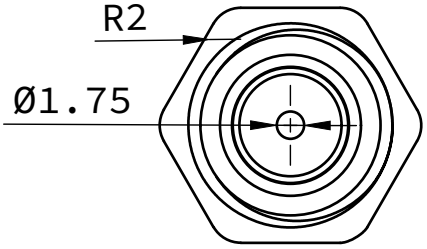
FRONT, TILTED 50 DEGREE



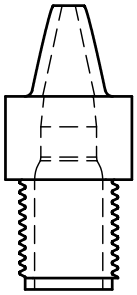
SIDE



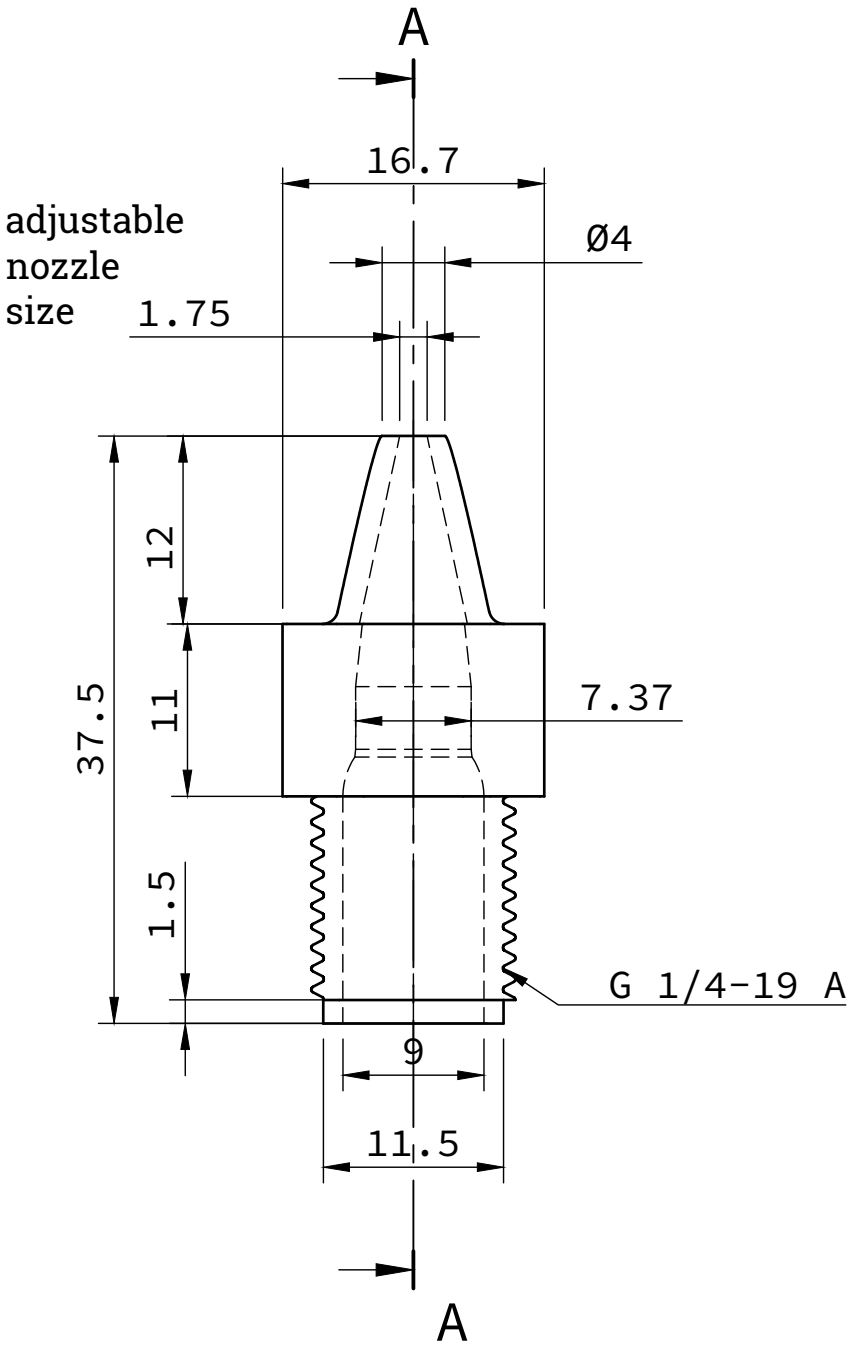
ADJUSTABLE NOZZLE



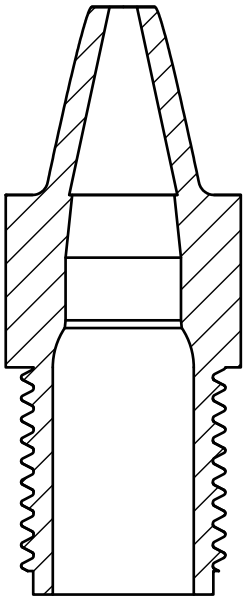
TOP



ACTUAL SIZE



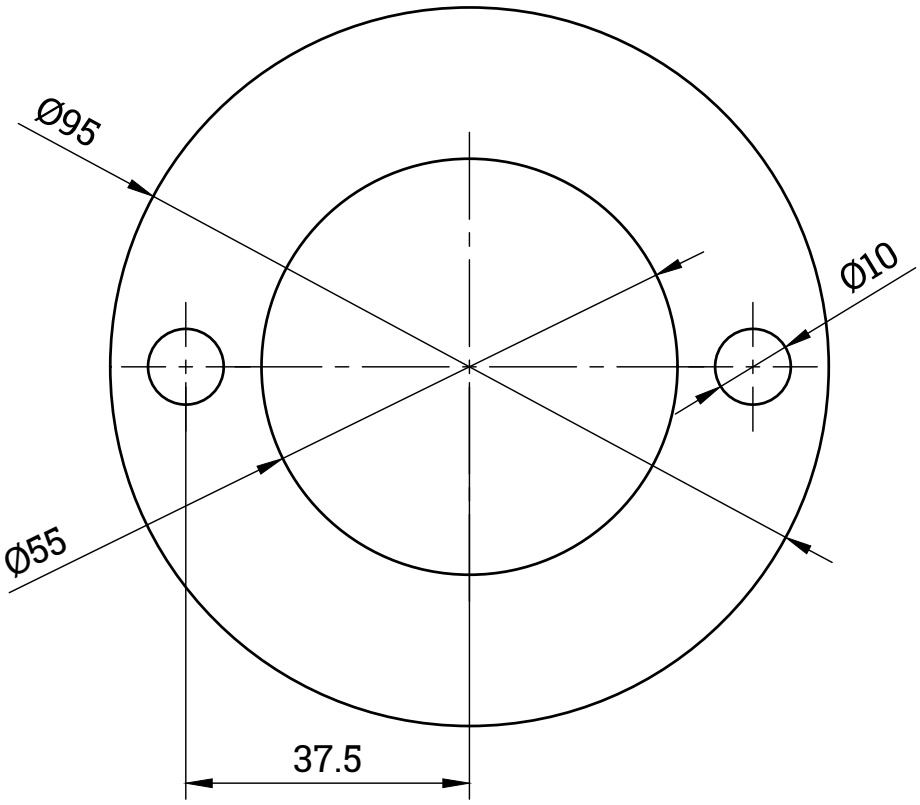
FRONT



A-A (2.1)

ADJUSTABLE NOZZLE 2:1

The part should be laser cut or 3D printed at around 4mm thick.
It needs to support the suspended weight of a full paste cartidge.



TOP

PASTE CARTRIDGE COLLAR

References

Gelatin. (2020). In: Encyclopædia Britannica Inc.

3D Pottter. (2023). *3D PotterBot 10 Micro*. 3D Potter, Inc. Retrieved 8 January from https://3dpotter.com/printers/potterbot-micro-10

3D Printer Universe. (2023). *Anycubic Kossel Delta DIY 3D Printer*. Retrieved 29 December from https://3dprinteruniverse.com/products/anycubic-kossel-delta-diy-3d-printer?variant=27861634482281

3d Printing Gear. (2023). Original Prusa I3 MK3S+ Assembled. In O. P. I. M. S. ASSEMBLED (Ed.). Melbourne, Australia.

3D-Fuel. (2020). *Buzzed - Beer Filament*. Retrieved 10 November from https://www.3dfuel.com/collections/buzzed/products/buzzed-beer-filament

3DPrintBeginner. (2020). *Flow Rate Calibration - Improve Print Accuracy*. Retrieved 04 December from https://3dprintbeginner.com/flow-rate-calibration/

ABARES. (2024). *Production volume of barley in New South Wales, Australia from financial year 2010 to 2024 (in 1,000 kilotons) [Graph]*. Statista. Retrieved 10 May from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/1350536/australia-barley-production-volume-nsw/

ABARES. (2024). *Production volume of wheat in New South Wales, Australia from financial year 2010 to 2024 (in 1,000 kilotons) [Graph]*. Statista. Retrieved 09 May from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/1350483/australia-wheat-production-volume-nsw/

Abdulraheem, M. (2015). *Waste plastic bottles and other types of plastic waste at the Thilafushi waste disposal site*. The World Bank. https://datatopics.worldbank.org/what-a-waste/tackling_increasing_plastic_waste.html

Agriculture, U. D. o. (2020). *Principal sugar exporting countries in 2019/2020 (in million metric tons)*. Statista. Retrieved 8 December from https://www.statista.com/statistics/273437/exported-amount-of-sugar-in-leading-countries/

AgriFutures Australia. (2024). *Growing industrial hemp in New South Wales – finding the right varieties*. Retrieved 09 May from https://agrifutures.com.au/wp-content/uploads/2024/02/24-036-Growing-industrial-hemp-in-NSW.pdf

AgSales Australia. (n.d.). *Wheat Straw Header Tailings*. Retrieved 24 November from https://www.agsalesaustralia.com/item/hay-grain/straw/wheat-straw-header-tailings/

Ajala, E. O., Ighalo, J. O., Ajala, M. A., Adeniyi, A. G., & Ayanshola, A. M. (2021). Sugarcane bagasse: a biomass sufficiently applied for improving global energy, environment and economic sustainability. *Bioresources and Bioprocessing*, *8*(1), 87. https://doi.org/10.1186/s40643-021-00440-z

Aliverti, P., Maietta, A., Justo, P. D., Polcan, E., & Salvatori, D. (2015). *The Maker's Manual : A Practical Guide to the New Industrial Revolution*. Maker Media, Inc. http://ebookcentral.proquest.com/lib/uts/detail.action?docID=2011361

Aljazeera. (2021). *Why manufacturing is the biggest hurdle in climate change fight*. Retrieved 30 August from https://www.aljazeera.com/economy/2021/2/16/why-manufacturing-is-the-biggest-hurdle-in-climate-change-fight

Al-Oqla, F. M., Hayajneh, M. T., & Aldhirat, A. (2021). Tribological and mechanical fracture performance of Mediterranean lignocellulosic fiber reinforced polypropylene composites. *Polymer Composites*, *42*(10), 5501-5511. https://doi.org/https://doi.org/10.1002/pc.26241

Alterfact Studio. (2023). *One of a Kind Vase*. Retrieved 30 December from https://www.alterfact.net/purchase/one-of-a-kind-vase

Amazon. (2023). *Microsoft Wireless Controller - Black for Xbox One*. Retrieved 30 from https://www.amazon.com.au/Wireless-Controller-Bluetooth-Black-889842114584/dp/B01LPZM7VI

Amza, C. G., Zapciu, A., & Popescu, D. (2017). Paste Extruder—Hardware Add-On for Desktop 3D Printers. *Technologies*, *5*(3), 50. https://www.mdpi.com/2227-7080/5/3/50

Andrady, A. L., & Neal, M. A. (2009). Applications and societal benefits of plastics. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *364*(1526), 1977-1984. https://doi.org/doi:10.1098/rstb.2008.0304

Andres, A. I., Petron, M. J., Lopez, A. M., & Timon, M. L. (2020). Optimization of Extraction Conditions to Improve Phenolic Content and In Vitro Antioxidant Activity in Craft Brewers' Spent Grain Using Response Surface Methodology (RSM). *Foods*, *9*(10).

AnyCubic. (2023). ANYCUBIC Kossel Plus. In: AnyCubic.com.

Aravamudhan, A., Ramos, D. M., Nada, A. A., & Kumbar, S. G. (2014). Chapter 4 - Natural Polymers: Polysaccharides and Their Derivatives for Biomedical Applications. In S. G. Kumbar, C. T. Laurencin, & M. Deng (Eds.), *Natural and Synthetic Biomedical Polymers* (pp. 67-89). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-396983-5.00004-1

Archer, B. (1995). The nature of research. *Co-Design Journal*(2), 6-13.

Ashby, M. F., & Johnson, K. (2013). *Materials and Design: The Art and Science of Material Selection in Product Design*. Elsevier Science. https://books.google.com.au/books?id=lyDEACMTtUEC

Assandri, D., Pampuro, N., Zara, G., Cavallo, E., & Budroni, M. (2020). Suitability of composting process for the disposal and valorization of brewer's spent grain. *Agriculture*, *11*(1), 2.

Augustin, S., Augustin, S., & Coleman, C. (2011). *The designer's guide to doing research: applying knowledge to inform design* (1 ed.). WILEY.

Austrade. (2019). *Export value of leading agricultural commodities produced in Australia in 2018 (in billion Australian dollars)*. Statista. Retrieved 26 October from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/738858/australia-export-value-of-agricultural-goods/

Australia, W. (2024). *National Vintage Report*. https://www.wineaustralia.com/getmedia/9f5366e6-88bd-4bd6-b664-9458be8a641f/MI_VintageReport2023_full-report.pdf

Australian Bureau of Agricultural and Resource Economics. (2020). *Value of wine exports from Australia in financial year 2019, by country (in million Australian dollars)*. Statista. Retrieved 8 December from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/794126/australia-wine-exports-by-country/

Australian Bureau of Agricultural and Resource Economics and Sciences [ABARES]. (2023). *Area for crop production in Australia in financial year 2020 and 2024, by crop (in 1,000 hectares) [Graph].* Statista. Retrieved 06 May from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/1093773/australia-agriculture-crop-area-by-crop/

Australian Bureau of Statistics. (2021). *Sugarcane, experimental regional estimates using new data sources and methods*. Retrieved 09 May from https://www.abs.gov.au/statistics/industry/agriculture/sugarcane-experimental-regional-estimates-using-new-data-sources-and-methods/latest-release#interactive-map-showing-production-of-sugarcane-by-statistical-area-level-2

Avramia, I., & Amariei, S. (2021). Spent Brewer's Yeast as a Source of Insoluble β-Glucans. *Int J Mol Sci*, *22*(2). https://doi.org/10.3390/ijms22020825

Azimi, P., Zhao, D., Pouzet, C., Crain, N. E., & Stephens, B. (2016). Emissions of Ultrafine Particles and Volatile Organic Compounds from Commercially Available Desktop Three-Dimensional Printers with Multiple Filaments. *Environmental science & technology*, *50*(3), 1260-1268. https://doi.org/10.1021/acs.est.5b04983

Azoulay, D., Villa, P., Arellano, Y., Gordon, M. F., Moon, D., Miller, K. A., Thompson, K., & Kistler, A. (2019). *Plastic & health: the hidden costs of a plastic planet*. CIEL Geneva.

BarthHaas GmbH & Co. KG. (2023). *Barthhaas Report 2022 / 23*.

Beaman, J., Bourell, D., & Wallace, D. (2014). Special Issue: Additive Manufacturing (AM) and 3D Printing. *Journal of Manufacturing Science and Engineering*, *136*(6). https://doi.org/10.1115/1.4028670

Beldman, G., Hennekam, J., & Voragen, A. G. J. (1987). Enzymatic hydrolysis of beer brewers' spent grain and the influence of pretreatments. *Biotechnology and Bioengineering*, *30*(5), 668-671. https://doi.org/https://doi.org/10.1002/bit.260300511

Berliner Stadtreinigungsbetriebe. (2023). All Rubish Bins In Overview. In. Berlin, Germany: Berliner Stadtreinigungsbetriebe,.

Bertrams, N. (2021). Workers risk their health for little pay rummaging through the trash. In. Bonn, Germany: Deutsche Welle (DW).

Besoain, M. J., & Weiss, A. (2018). *Beer spent grain biocomposite*. Materiom. Retrieved 10 November from https://materiom.org/recipe/61

Bianco, A., Fancello, F., Garau, M., Deroma, M., Atzori, A. S., Castaldi, P., Zara, G., & Budroni, M. (2022). Microbial and chemical dynamics of brewers' spent grain during a low-input pre-vermicomposting treatment. *Science of The Total Environment*, *802*, 149792. https://doi.org/https://doi.org/10.1016/j.scitotenv.2021.149792

Big Circle Studios. (2022). *Biochar Biomaterial*. Materiom. Retrieved 27 July from https://materiom.org/recipe/666

Big Circle Studios. (2022). *Coffee Husk/Chaff Biomaterial*. Materiom. Retrieved 27 July from https://materiom.org/recipe/665

Blikstein, P. (2013). Digital fabrication and 'making'in education: The democratization of invention. *FabLabs: Of machines, makers and inventors*, *4*(1), 1-21.

Bonaccorsi, L., Ferraro, E., & Manassé, M. (2022). *Oil companies in disguise: the impact of mandatory reporting of indirect emissions on car companies'*

valuation. E. F. f. T. a. Environment. https://www.transportenvironment.org/discover/oil-companies-in-disguise-carmakers-are-a-ticking-carbon-bomb-for-investors/

Boulaala, M., Elmessaoudi, D., Buj, I., el Mesbahi, J., Ezbakhe, O., Astito, A., El Mrabet, M., & el Mesbahi, A. (2020). Towards design of mechanical part and electronic control of multi-material/multicolor fused deposition modeling 3D printing. *The International Journal of Advanced Manufacturing Technology*, *110*. https://doi.org/10.1007/s00170-020-05847-0

Bozkurt, Y., & Karayel, E. (2021). 3D printing technology; methods, biomedical applications, future opportunities and trends. *Journal of Materials Research and Technology*, *14*, 1430-1450. https://doi.org/https://doi.org/10.1016/j.jmrt.2021.07.050

Bragato Research Institute. (2020). *Covid-19 research fund invests in grape waste*. Retrieved 24 November from https://bri.co.nz/2020/05/22/covid-fund-marc/

Brandt, E. (2004). Action research in user-centred product development. *AI & society*, *18*(2), 113-133. https://doi.org/10.1007/s00146-003-0271-0

Browder, R. E., Aldrich, H. E., & Bradley, S. W. (2019). The emergence of the maker movement: Implications for entrepreneurship research. *Journal of Business Venturing*, *34*(3), 459-476. https://doi.org/https://doi.org/10.1016/j.jbusvent.2019.01.005

Brown, J. (2019). *Old brewery building in Sydney nominated for world architecture award*. Commercial Real Estate. Retrieved January 20 from https://www.commercialrealestate.com.au/news/old-brewery-building-in-sydney-nominated-for-world-architecture-award-29374/

Buglass, A. J. (2011). *Handbook of alcoholic beverages; technical, analytical and nutritional aspects; 2v* (Vol. 26). Ringgold Inc. https://www.proquest.com/docview/869979687?accountid=17095&parentSessionId=Iq7nbjsy7UKf9x3AUIWxO6sEgw2WMi2fbAORfut%2FN0s%3D

Bulut, C., Nazli, M., Aydin, E., & Haque, A. U. (2021). The effect of environmental concern on conscious green consumption of post-millennials: the moderating role of greenwashing perceptions. *Young Consumers*, *22*(2), 306-319. https://doi.org/10.1108/YC-10-2020-1241

Bürdek, B. E. (2015). *Design : History, Theory and Practice of Product Design*. Walter de Gruyter GmbH. http://ebookcentral.proquest.com/lib/uts/detail.action?docID=4001442

Burg Giebichenstein University of Art and Design Halle. (2014). *3D Paste Printing Workshop with Jonathan Keep*. Halle, Germany. Retrieved 03 April from https://www.burg-halle.de/en/university/facilities/burg-gestaltet/archiv/project/3d-paste-printing-workshop-with-jonathan-keep/

Burton, R. A., Andres, M., Cole, M., Cowley, J. M., & Augustin, M. A. (2022). Industrial hemp seed: from the field to value-added food ingredients. *Journal of Cannabis Research*, *4*(1), 45. https://doi.org/10.1186/s42238-022-00156-7

Camburn, B., Viswanathan, V., Linsey, J., Anderson, D., Jensen, D., Crawford, R., Otto, K., & Wood, K. (2017). Design prototyping methods: state of the art in strategies, techniques, and guidelines. *Design Science*, *3*, e13, Article e13. https://doi.org/10.1017/dsj.2017.10

Camere, S., & Karana, E. (2018). Fabricating materials from living organisms: An emerging design practice. *Journal of Cleaner Production*, *186*, 570-584. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.03.081

Carlo Ratti Associati. (2019). *Feel The Peel*. Retrieved 29 January from https://carloratti.com/project/feel-the-peel/

Carlson, C. (2020). *Mater designs stool made with leftover grain from beer and plastic insulin pens*. Dezeen. Retrieved 9 November from https://www.dezeen.com/2020/09/04/mater-mask-stool-earth-studio-eva-karlou-beer-carlsberg-sustainable/

CDRinfo. (2006). *Logitech G1 Optical Mouse*. Retrieved 29 December from https://www.cdrinfo.com/d7/content/logitech-g1-optical-mouse

Celma, A. R., Rojas, S., & López-Rodríguez, F. (2007). Waste-to-energy possibilities for industrial olive and grape by-products in Extremadura. *Biomass and Bioenergy*, *31*(7), 522-534. https://doi.org/https://doi.org/10.1016/j.biombioe.2006.08.007

Central Park Sydney. (n.d.). *Chippendale: A Rich History*. Retrieved 30 January from https://www.centralparksydney.com/explore/chippendale-a-rich-heritage

CERAMBOT. (2023). *CERAMBOT Air Clay Cartridge Set*. Qingdao Eazao Intelligent Technology Co., Ltd. Retrieved 10 November from https://www.cerambot.com/product/cerambot-air-clay-cartridge-set/

Civancik-Uslu, D., Ferrer, L., Puig, R., & Fullana-i-Palmer, P. (2018). Are functional fillers improving environmental behavior of plastics? A review on LCA studies. *Science of The Total Environment*, *626*, 927-940. https://doi.org/https://doi.org/10.1016/j.scitotenv.2018.01.149

Comgrow Store. (2022). *Comgrow Creality Ender 3 3D Printer Aluminum DIY with Resume Print 220x220x250mm*. Amazon. Retrieved 28 July from https://www.amazon.com.au/Comgrow-Creality-Ender-Aluminum-

220x220x250mm/dp/B07BR3F9N6/ref=sr_1_6?crid=XPBTBSV76Y0L&keywords=3d+printer&qid=1658971722&sprefix=3d+print%2Caps%2C204&sr=8-6

Corbin, K. R., Hsieh, Y. S., Betts, N. S., Byrt, C. S., Henderson, M., Stork, J., DeBolt, S., Fincher, G. B., & Burton, R. A. (2015). Grape marc as a source of carbohydrates for bioethanol: Chemical composition, pre-treatment and saccharification. *Bioresource Technology*, *193*, 76-83.

Corbin, K. R., Hsieh, Y. S. Y., Betts, N. S., Byrt, C. S., Henderson, M., Stork, J., DeBolt, S., Fincher, G. B., & Burton, R. A. (2015). Grape marc as a source of carbohydrates for bioethanol: Chemical composition, pre-treatment and saccharification. *Bioresource Technology*, *193*, 76-83. https://doi.org/https://doi.org/10.1016/j.biortech.2015.06.030

Core Jr. (2010). *Ariane Prin takes a fresh look at the hairdryer*. Core77. Retrieved 11 January from https://www.core77.com/posts/16732/Ariane-Prin-takes-a-fresh-look-at-the-hairdryer

Creative Tools. (2020). *#3DBenchy The jolly 3D printing torture-test*. Retrieved 27 January from http://www.3dbenchy.com/wp-content/uploads/2015/04/3DBenchy_Broschure_3DBenchy.com_.pdf

Creative Tools. (2020). *The jolly 3D printing torture-test*. Retrieved 21 Novemeber from http://www.3dbenchy.com/

Cross, N. (2008). *Engineering design methods : strategies for product design* (4th ed.). J. Wiley.

Cruz Sanchez, F. A., Boudaoud, H., Camargo, M., & Pearce, J. M. (2020). Plastic recycling in additive manufacturing: A systematic literature review and opportunities for the circular economy. *Journal of Cleaner Production*, *264*, 121602. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.121602

Cuffaro, D., & Zaksenberg, I. (2013). *The Industrial Design Reference and Specification Book: Everything Industrial Designers Need to Know Every Day*. Quarto Publishing Group USA.

Curventa. (2023). *Motorola Office*. Retrieved 30 December from https://www.curventa.com/motorola-office

Dai, L., Cheng, T., Duan, C., Zhao, W., Zhang, W., Zou, X., Aspler, J., & Ni, Y. (2019). 3D printing using plant-derived cellulose and its derivatives: A review. *Carbohydrate Polymers*, *203*, 71-86. https://doi.org/https://doi.org/10.1016/j.carbpol.2018.09.027

Dalsgaard, P., & Halskov, K. (2012). *Reflective design documentation* Proceedings of the Designing Interactive Systems Conference, Newcastle Upon Tyne, United Kingdom. https://doi.org/10.1145/2317956.2318020

de Coninck, H., A. Revi, M. Babiker, P. Bertoldi, M. Buckeridge, A. Cartwright, W. Dong, J. Ford, S. Fuss, J.-C. Hourcade, D. Ley, R. Mechler, P. Newman, A. Revokatova, S. Schultz, L. Steg, & Sugiyam, T. (2018). Strengthening and Implementing the Global Response. In *Global Warming of 1.5°C: IPCC Special Report on Impacts of Global Warming of 1.5°C above Pre-industrial Levels in Context of Strengthening Response to Climate Change, Sustainable Development, and Efforts to Eradicate Poverty* (pp. 313-444). Cambridge University Press. https://doi.org/DOI: 10.1017/9781009157940.006

Department of Agriculture, W. a. t. E. (2020). Broad land use in New South Wales. In B. l. u. i. N. S. Wales (Ed.). Department of Agriculture, Water and the Environment: Department of Agriculture, Water and the Environment.

Department of Agriculture Water and the Environment. (2020). *Sugar*. Retrieved 27 October from https://www.agriculture.gov.au/ag-farm-food/crops/sugar#sugar-industry-assistance-and-reform

Despeisse, M., Baumers, M., Brown, P., Charnley, F., Ford, S. J., Garmulewicz, A., Knowles, S., Minshall, T. H. W., Mortara, L., Reed-Tsochas, F. P., & Rowley, J. (2017). Unlocking value for a circular economy through 3D printing: A research agenda. *Technological Forecasting and Social Change*, *115*, 75-84. https://doi.org/https://doi.org/10.1016/j.techfore.2016.09.021

Diegel, O., Kristav, P., Motte, D., & Kianian, B. (2016). Additive Manufacturing and its Effect on Sustainable Design. In S. S. Muthu & M. M. Savalani (Eds.), *Handbook of Sustainability in Additive Manufacturing: Volume 1* (pp. 73-99). Springer Singapore. https://doi.org/10.1007/978-981-10-0549-7_5

Dilberoglu, U. M., Gharehpapagh, B., Yaman, U., & Dolen, M. (2017). The Role of Additive Manufacturing in the Era of Industry 4.0. *Procedia Manufacturing*, *11*, 545-554. https://doi.org/https://doi.org/10.1016/j.promfg.2017.07.148

Dougherty, D. (2012). The maker movement. *Innovations: Technology, governance, globalization*, *7*(3), 11-14.

Duncan, S. s. (2023). *Mouse Shape Tester Megapack*. Printables. Retrieved 15 November from https://www.printables.com/model/113133-mouse-shape-tester-megapack/comments

Dunn, K. M. (2017). *Prototyping Models of Climate Change: New Approaches to Modelling Climate Change Data. 3D printed models of Climate Change research created in collaboration with Climate Scientists*

Dyson, J. (2001). *Against the odds : an autobiography* (New ed.). Texere.

E6PR. (2017). *Eco Six Pack Ring*. Retrieved 10 November from https://www.e6pr.com/

Eazao. (2022). *Cartridge for Eazao Zero*. Retrieved 29 July from https://www.eazao.com/product/cartridge-for-eazao-zero/

Eazao. (2022). *Ceramic 3D Printer Air Kit | Eazao Air Kit*. Retrieved 28 July from https://www.eazao.com/product/ceramic-3d-printer-air-kit-eazao-air-kit/

El Mesbahi, J., Buj-Corral, I., & El Mesbahi, A. (2021, 2021//). Ceramic Paste Extruder of 3D Printing: Status, Types, and Prospects. Advances in Integrated Design and Production, Cham.

El-Shafey, E. I., Gameiro, M. L. F., Correia, P. F. M., & Carvalho, J. M. R. d. (2004). Dewatering of Brewer's Spent Grain Using a Membrane Filter Press: A Pilot Plant Study. *Separation Science and Technology*, *39*(14), 3237-3261. https://doi.org/10.1081/SS-200028775

Enck, J., & Dell, J. (2022). *Plastic Recycling Doesn't Work and Will Never work*. The Atlantic. Retrieved February from https://www.theatlantic.com/ideas/archive/2022/05/single-use-plastic-chemical-recycling-disposal/661141/

Falcone Jr., J. S. (2000). Fillers. In *Kirk-Othmer Encyclopedia of Chemical Technology*. https://doi.org/https://doi.org/10.1002/0471238961.0609121206011203.a01

Faludi, J., Van Sice, C. M., & Shi, Y. (2022). *Mica bioprint*. Materiom. Retrieved 27 July from https://materiom.org/recipe/586

Faludi, J., Van Sice, C. M., Shi, Y., Bower, J., & Brooks, O. M. K. (2019). Novel materials can radically improve whole-system environmental impacts of additive manufacturing. *Journal of Cleaner Production*, *212*, 1580-1590. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.12.017

FAO. (2020). *Leading sugar cane producers worldwide in 2018, based on production volume (in million metric tons)*. Statista. Retrieved 8 December from https://www.statista.com/statistics/267865/principal-sugar-cane-producers-worldwide/

FAO. (2020). *World sugar cane production from 1965 to 2018 (in million metric tons)*. Statista. Retrieved 27 October from https://www.statista.com/statistics/249604/sugar-cane-production-worldwide/

FAO, & US Department of Agriculture. (2019). *Worldwide production of grain in 2018/19, by type (in million metric tons)*. Statista. Retrieved 2 November from https://www.statista.com/statistics/263977/world-grain-production-by-type/

Farago, C. V., de Melo, G. B., Escher, G. B., Marcon, M. V., Granato, D., & Danesi, E. D. G. (2021). Cereal bars made from brewers' spent grain, apple and Spirulina platensis: antioxidant activity and antihyperglycaemic effects. *Research, Society and Development*, *10*(5).

Felfil. (2023). Felfil Evo Filament Extruder Fully Assembled from Kit. In. Torino, Italy: Felfil.com.

Fisher, G. J. (2022). How Will Self-Manufacture and the Maker Movement Reshape Consumer Preferences? *Research-Technology Management*, *65*(4), 18-26. https://doi.org/10.1080/08956308.2022.2071063

Food and Agriculture Organization of the United Nations [FAO]. (2024). *Food and agriculture data*. Retrieved 07 May from https://www.fao.org/faostat/en/#home

Food Standards Australia New Zealand. (2019). *Temperature control* Retrieved 15 July from https://www.foodstandards.gov.au/consumer/safety/faqsafety/pages/foodsafetyfactsheets/charitiesandcommunityorganisationsfactsheets/temperaturecontrolma1477.aspx

Ford, S., & Despeisse, M. (2016). Additive manufacturing and sustainability: an exploratory study of the advantages and challenges. *Journal of Cleaner Production*, *137*, 1573-1587. https://doi.org/https://doi.org/10.1016/j.jclepro.2016.04.150

Forti, V., Baldé, C. P., Kuehr, R., & Bel, G. (2020). The global e-waste monitor 2020. *United Nations University (UNU), International Telecommunication Union (ITU) & International Solid Waste Association (ISWA), Bonn/Geneva/Rotterdam*, *120*.

Frayling, C. (1994). Research in art and design (Royal College of Art Research Papers, vol 1, no 1, 1993/4).

Freitas, L., Simões, R., Miranda, I., Peres, F., & Ferreira-Dias, S. (2022). Optimization of Autohydrolysis of Olive Pomaces to Obtain Bioactive Oligosaccharides: The Effect of Cultivar and Fruit Ripening. *Catalysts*, *12*(7), 788. https://www.mdpi.com/2073-4344/12/7/788

Gadhave, R. V., Srivastava, S., Mahanwar, P. A., & Gadekar, P. T. (2019). Recycling and disposal methods for polyurethane wastes: A review. *Open Journal of Polymer Chemistry*, *9*(2), 39-51.

Galanakis, C. M. (2018). *Sustainable recovery and reutilization of cereal processing by-products*. Woodhead Publishing.

Galdon, F., & Hall, A. (2022). (Un) Frayling design research in design education for the 21st Century. *The Design Journal*, *25*(6), 915-933.

Ganter, M., & Storti, D. (2011). *Rice Flour Printing*. Mechanical Engineering Department on the University of Washington. Retrieved 14 May from http://depts.washington.edu/open3dp/2011/06/rice-flour-printing/

Gardan, J. (2017). Additive manufacturing technologies: state of the art and trends. *Additive Manufacturing Handbook*, 149-168.

Gardner, D. J., Oporto, G. S., Mills, R., & Samir, M. A. S. A. (2008). Adhesion and surface issues in cellulose and nanocellulose. *Journal of adhesion science and technology*, *22*(5-6), 545-567.

Garmulewicz, A., & Corbin, L. (2018). *Materiom: Nature's Recipe Book*. Retrieved 20 January from https://materiom.org/

Garmulewicz, A., Holweg, M., Veldhuis, H., & Yang, A. (2018). Disruptive Technology as an Enabler of the Circular Economy: What Potential Does 3D Printing Hold? *California Management Review*, *60*(3), 112-132. https://doi.org/10.1177/0008125617752695

Gaver, B., & Bowers, J. (2012). Annotated portfolios. *interactions*, *19*(4), 40–49. https://doi.org/10.1145/2212877.2212889

Gaver, W. (2012). *What should we expect from research through design?* Proceedings of the SIGCHI Conference on Human Factors in Computing Systems, Austin, Texas, USA. https://doi.org/10.1145/2207676.2208538

Gebler, M., Schoot Uiterkamp, A. J. M., & Visser, C. (2014). A global sustainability perspective on 3D printing technologies. *Energy Policy*, *74*, 158-167. https://doi.org/https://doi.org/10.1016/j.enpol.2014.08.033

Giorgetti, N. (2019). Feel the Peel: Bioplastic cups from orange peels. In. carloratti.com: Carlo Ratti Associati.

Girdis, J., Gaudion, L., Proust, G., Löschke, S., & Dong, A. (2016). Rethinking Timber: Investigation into the Use of Waste Macadamia Nut Shells for Additive Manufacturing. *JOM*, *69*. https://doi.org/10.1007/s11837-016-2213-6

Glanville, R. (2014). The sometimes uncomfortable marriages of design and research. In *The Routledge Companion to Design Research*. Routledge. https://doi.org/10.4324/9781315758466.ch1

Goel, V., Luthra, P., Kapur, G. S., & Ramakumar, S. S. V. (2021). Biodegradable/Bio-plastics: Myths and Realities. *Journal of Polymers and the Environment*, *29*(10), 3079-3104. https://doi.org/10.1007/s10924-021-02099-1

Gomes, M. M., Sakamoto, I. K., Silva Rabelo, C. A. B., Silva, E. L., & Varesche, M. B. A. (2021). Statistical optimization of methane production from brewery spent grain: Interaction effects of temperature and substrate concentration. *Journal of Environmental Management*, *288*, 112363. https://doi.org/https://doi.org/10.1016/j.jenvman.2021.112363

Greenpeace. (2017). Men selecting electronic waste from used cellular phones at a workshop in Bantar Gebang area, Bekasi, West Java. In: Greenpeace Australia,.

Hadil. (2022). *Turkish Coffee Waste | Agar Agar*. Materiom. Retrieved 27 July from https://materiom.org/recipe/618

Hallgrimsson, B. (2012). *Prototyping and modelmaking for product design*. Hachette UK.

Hallgrimsson, B. (2019). *PROTOTYPING AND MODELMAKING FOR PRODUCT DESIGN* (Second ed., Vol. 2023). Hachette.

Halverson, E. R., & Sheridan, K. (2014). The maker movement in education. *Harvard educational review*, *84*(4), 495-504.

Hamilton, L. A., & Feit, S. (2019). *Plastic & climate: The hidden costs of a plastic planet* (A. Kistler & C. Muffertt, Eds.). Center For International Environmental Law (CIEL). https://www.ciel.org/plasticandclimate/

Harkness, M. (2022). *Matters of Concern: A Critical Investigation of Bioplastics, 3D Printing, and the Maker Movement* UNSW Sydney].

Hardin, T. (2021). *Plastic: It's Not All the Same*. Plastic Oceans. Retrieved 11 October from https://plasticoceans.org/7-types-of-plastic/

Hassan, S. S., Ravindran, R., Jaiswal, S., Tiwari, B. K., Williams, G. A., & Jaiswal, A. K. (2020). An evaluation of sonication pretreatment for enhancing saccharification of brewers' spent grain. *Waste Management*, *105*, 240-247. https://doi.org/https://doi.org/10.1016/j.wasman.2020.02.012

Heinberg, R. (2018). The Problem of Economic Growth. In J. L. Caradonna (Ed.), *Routledge Handbook of the History of Sustainability* (1 ed., Vol. 1, pp. 322-338). Routledge. https://doi.org/10.4324/9781315543017-20

Heinrich-Böll-Stiftung, & Break Free From Plastic. (2020). *Plastic Atlas; Facts and figures about the world of synthetic polymers* (L. Fuhr & M. Franklin, Eds.). Heinrich-Böll-Stiftung, Break Free From Plastic,.

Hejna, A. (2020). Poly(ε-Caprolactone)/Brewers' Spent Grain Composites—The Impact of Filler Treatment on the Mechanical Performance. *Journal of Composites Science*, *4*(4), 167. https://www.mdpi.com/2504-477X/4/4/167

Hejna, A., Barczewski, M., Skórczewska, K., Szulc, J., Chmielnicki, B., Korol, J., & Formela, K. (2020). Sustainable upcycling of brewers' spent grain by thermo-mechanical treatment in twin-screw extruder. *Journal of Cleaner Production*, 124839. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.124839

Hendry, J., & Dumas, A. (1988). What do you do with an industrial designer? *Cranfield School of Management,*.

Herz, E., Moll, P., Schmitt, C., & Weiss, J. (2023). Binders in foods: Definition, functionality, and characterization. *Food Hydrocolloids*, *145*, 109077. https://doi.org/https://doi.org/10.1016/j.foodhyd.2023.109077

Hirz, M., & Nguyen, T. T. (2022). Life-Cycle CO2-Equivalent Emissions of Cars Driven by Conventional and Electric Propulsion Systems. *World Electric Vehicle Journal*, *13*(4), 61. https://www.mdpi.com/2032-6653/13/4/61

Hitti, N. (2020). *Nataša Perković makes textured furniture from palm oil byproducts*. DeZeen. Retrieved 16 January from https://www.dezeen.com/2020/06/13/natasa-perkovic-palm-oil-homeware-design/

Holter, I. M., & Schwartz-Barcott, D. (1993). Action research: what is it? How has it been used and how can it be used in nursing? *J Adv Nurs*, *18*(2), 298-304. https://doi.org/10.1046/j.1365-2648.1993.18020298.x

Hoornweg, D., & Bhada-Tata, P. (2012). What a waste: a global review of solid waste management.

Hossain, R., Islam, M. T., Ghose, A., & Sahajwalla, V. (2022). Full circle: Challenges and prospects for plastic waste management in Australia to achieve circular economy. *Journal of Cleaner Production*, *368*, 133127. https://doi.org/https://doi.org/10.1016/j.jclepro.2022.133127

Hunt, E. J., Zhang, C., Anzalone, N., & Pearce, J. M. (2015). Polymer recycling codes for distributed manufacturing with 3-D printers. *Resources, Conservation and Recycling*, *97*, 24-30. https://doi.org/https://doi.org/10.1016/j.resconrec.2015.02.004

Hustwit, G. (2018). *Objectified* San Francisco, California, USA, Film First Corp.

Igini, M. (2022). *How Waste Management in Germany is Changing the Game*. Earth.Org Ltd. Retrieved 06 February from https://earth.org/mission-statement/

Independent Brewers Association. (2021). *2020-21 Annual Report*.

Intergovernmental Panel on Climate Change [IPCC]. (2022). *AR6 Synthesis Report: Climate Change 2022*.

Intergovernmental Panel on Climate Change [IPCC]. (2022). *Climate Change 2022: Mitigation of Climate Change*.

International Organisation of Vine and WIne [OIV]. (2020). *Wine consumption worldwide in 2019, by country (in million hectoliters)**. Statista. Retrieved 26 October from https://www.statista.com/statistics/858743/global-wine-consumption-by-country/

International Organisation of Vine and WIne [OIV]. (2020). *Wine production worldwide in 2019, by country (in million hectoliters)**. Statista. Retrieved 26 October from https://www.statista.com/statistics/240638/wine-production-in-selected-countries-and-regions/

International Organisation of Vine and WIne [OIV]. (2022). *Leading countries in wine export worldwide in 2022, based on volume (in million hectoliters) [Graph]*. Statista. Retrieved 07 May from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/240649/top-wine-exporting-countries-since-2007/

International Organisation of Vine and WIne [OIV]. (2023). *Wine production worldwide in 2022, by country (in million hectoliters) [Graph]*. Statista. Retrieved 13 May from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/240638/wine-production-in-selected-countries-and-regions/

International Organization for Standardization. (2021). ISO/ASTM 52900:2021(en) Additive manufacturing — General principles — Fundamentals and vocabulary. In (Vol. 52900:2021).

Jakovlev, I. (2019). Recipe 20 Patterning Cellulose pp. 106-107. In. shop.aalto.fi: Aalto University.

Jefferies, S. (2022). *Australian Industrial Hemp Strategic RD&E Plan*. AgriFutures Australia https://agrifutures.com.au/wp-content/uploads/2022/03/22-030.pdf

Jones, M. (2022). *PETG/PLA Recycling: How to Recycle 3D printer Waste*. All3DP. Retrieved 11 October from https://all3dp.com/2/3d-printer-recycled-plastic-tips-for-your-waste-plastic/

Jones, R., Haufe, P., Sells, E., Iravani, P., Olliver, V., Palmer, C., & Bowyer, A. (2011). RepRap – the replicating rapid prototyper. *Robotica*, *29*(1), 177-191. https://doi.org/10.1017/S026357471000069X

Julier, G. (2017). Economies of design. SAGE Publications Ltd.

Junai. (2023). *Extruder Kit*. Retrieved 04 December from https://www.junai.earth/3d-printers

Junai. (2023). *Extruder Kit - Assembled*. Retrieved December 2023 from https://www.junai.earth/product/extruder-kit-direct-drive

Kääriäinen, P., Tervinen, L., Riutta, N., Vuorinen, T., & Aalto University. (2020). *The CHEMARTS Cookbook* (P. Kääriäinen, R. N., L. Tervinen, T. Vuorinen, & A. University, Eds.). Aalto University publication.

Kääriäinen, P., Tervinen, L., Riutta, N., Vuorinen, T., & Aalto University. (2020). The CHEMARTS Cookbook. In. shop.aalto.fi: Aalto University.

Kango. (2023). *Kango 8mm HSS Drill Bit*. Bunnings. Retrieved 8 January from https://www.bunnings.com.au/kango-8mm-hss-drill-bit_p0354532

Kango. (2023). *Kango 8mm x 150mm Masonry Drill Bit*. Bunnings. Retrieved 8 January from https://www.bunnings.com.au/kango-8mm-x-150mm-masonry-drill-bit_p0354568

Kanoski, C. (2018). *THE INFORMATION NEEDED TO BUILD YOUR PROTOTYPE*. Priority Prototypes. Retrieved 08 January from https://prototypes.prioritydesigns.com/2018/07/30/the-information-needed-to-build-your-prototype/

Karana, E., Barati, B., Rognoli, V., & Zeeuw Van Der Laan, A. (2015). Material driven design (MDD): A method to design for material experiences. *International journal of design*, *9*(2), 35-54.

Kariz, M., Sernek, M., Obućina, M., & Kuzman, M. K. (2018). Effect of wood content in FDM filament on properties of 3D printed parts. *Materials Today Communications*, *14*, 135-140. https://doi.org/https://doi.org/10.1016/j.mtcomm.2017.12.016

Kaza, S., Yao, L., Bhada-Tata, P., & Van Woerden, F. (2018). *What a waste 2.0: a global snapshot of solid waste management to 2050*. World Bank Publications.

Keep, J. *MAKE YOUR OWN 3D DELTA PRINTER FOR CERAMIC*. www.keep-art.co.uk. Retrieved 25 December from http://www.keep-art.co.uk/Self_build.html

Keep, J. (2020). *Guide to Clay 3D Printing*. WikiFactory. Retrieved 28 July from https://wikifactory.com/@jonathankeep/guide-to-clay-3d-printing/files

Keep, J. (n.d.). *MAKE YOUR OWN CLAY AUGER PRINTHEAD WITH MECHANICAL RAM DELIVERY*. keep-art.co.uk. Retrieved 22 March from http://www.keep-art.co.uk/printhead.html

Keep, J. (N.D.). *Studio Journal*. Retrieved 08 December from http://www.keep-art.co.uk/journal_1.html

Kellens, K., Mertens, R., Paraskevas, D., Dewulf, W., & Duflou, J. R. (2017). Environmental Impact of Additive Manufacturing Processes: Does AM Contribute to a More Sustainable Way of Part Manufacturing? *Procedia CIRP*, *61*, 582-587. https://doi.org/https://doi.org/10.1016/j.procir.2016.11.153

Kellogg (Aust.) Pty. Ltd. (2024). *OUR STORY - Celebrating 100 Years of Good Mornings in Australia*. Kellanova. Retrieved 10 May from https://www.kelloggs.com.au/en_AU/our-story.html

Kellogg (Aust.) Pty. Ltd. (2024). *Pick Your Taste*. Kellanova. Retrieved 10 May from https://www.kelloggs.com.au/en_AU/food.html

Kemmis, S. (2009). Action research as a practice-based practice. *Educational action research*, *17*(3), 463-474. https://doi.org/10.1080/09650790903093284

Kemona, A., & Piotrowska, M. (2020). Polyurethane Recycling and Disposal: Methods and Prospects. *Polymers (Basel)*, *12*(8). https://doi.org/10.3390/polym12081752

Kenwood. (2023). *Triblade XL HBM40.006WH*. Retrieved 29 December from https://www.kenwoodworld.com/en-au/handblender-triblade-xl-hbm40-006wh/p/HBM40.006WH

Kidd, S. A., & Kral, M. J. (2005). Practicing participatory action research. *Journal of counseling psychology*, *52*(2), 187.

Kim, S. i. (2020). *Scan-A-Mouse: Logitech G1*. Thingiverse. Retrieved 16 November from https://www.thingiverse.com/thing:4398925

Kim, Y., McCoy, L. T., Feit, C., Mubarak, S. A., Sharma, S., & Minko, S. (2021). Carboxymethyl Cellulose Enhanced Production of Cellulose Nanofibrils. *Fibers*, *9*(9), 57. https://www.mdpi.com/2079-6439/9/9/57

Kintel, M. (2022). *OpenSCAD*. OpenSCAD. Retrieved 12 January from http://openscad.org/about.html

Kjeldsen, P., & Scheutz, C. (2003). Short- and Long-Term Releases of Fluorocarbons from Disposal of Polyurethane Foam Waste. *Environmental science & technology*, *37*(21), 5071-5079. https://doi.org/10.1021/es026385y

Kleemola, N. (2012). Cardstock 1:1 model with smaller prototypes in the background. In Cantilevered Plywood Chair by Nicholas Kleemola & O. Carleton University (Eds.), (pp. page 87). London: Laurence King Publishing.

KOKONIC. (2023). *KOCONIC 800G Multi-Functional Stainless Steel Grain Grinder*. Amazon. Retrieved 29 December from https://www.amazon.com.au/KOCONIC-Multi-Functional-Stainless-Efficient-High-Speed/dp/B0BNH4LQYP?c=ts&ts_id=5017210051

Koskinen, I., Binder, F. T., & Redström, J. (2008). Lab, field, gallery, and beyond. *Artifact: Journal of Design Practice*, *2*(1), 46-57.

Krill Design. (2023). *Krill Design* Retrieved 17 January from https://www.krilldesign.net/

Krill Design. (2023). "The Origin of Ohmie". Krill Design claiming without providing evidence. In. Milano, Italy: Krilldesign.net.

KUKA. (2022). The KR QUANTEC arm was equipped with a nozzle to extrude concrete for the Besix3D company. In: 3DNatives.com.

Lauff, C. A., Kotys-Schwartz, D., & Rentschler, M. E. (2018). What is a Prototype? What are the Roles of Prototypes in Companies? *Journal of Mechanical Design*, *140*(6). https://doi.org/10.1115/1.4039340

Lavoine, N., Desloges, I., Dufresne, A., & Bras, J. (2012). Microfibrillated cellulose – Its barrier properties and applications in cellulosic materials: A review. *Carbohydrate Polymers*, *90*(2), 735-764. https://doi.org/https://doi.org/10.1016/j.carbpol.2012.05.026

Le Duigou, A., Castro, M., Bevan, R., & Martin, N. (2016). 3D printing of wood fibre biocomposites: From mechanical to actuation functionality. *Materials & Design*, *96*, 106-114. https://doi.org/https://doi.org/10.1016/j.matdes.2016.02.018

Lee, J.-H., Lee, J.-H., Yang, H.-J., & Song, K. B. (2015). Preparation and characterization of brewer's spent grain protein-chitosan composite films. *Journal of Food Science and Technology*, *52*(11), 7549-7555. https://doi.org/10.1007/s13197-015-1941-x

Liu, H., He, H., Peng, X., Huang, B., & Li, J. (2019). Three-dimensional printing of poly(lactic acid) bio-based composites with sugarcane bagasse fiber: Effect of printing orientation on tensile performance. *Polymers for Advanced Technologies*, *30*(4), 910-922. https://doi.org/10.1002/pat.4524

LuchschenF. (2018). color plastic PLA and ABS filament for printing on a 3D printer. In *Adobe Stock*: Adobe Stock.

Ma, X., Cheng, Y., Qin, X., Guo, T., Deng, J., & Liu, X. (2017). Hydrophilic modification of cellulose nanocrystals improves the physicochemical properties of cassava starch-based

nanocomposite films. *LWT*, *86*, 318-326. https://doi.org/https://doi.org/10.1016/j.lwt.2017.08.012

Mahmud, M. A., & Anannya, F. R. (2021). Sugarcane bagasse - A source of cellulosic fiber for diverse applications. *Heliyon*, *7*(8), e07771. https://doi.org/10.1016/j.heliyon.2021.e07771

Mahtani, R., Umstead, K., & Gill, C. (2019). Efficacious Prototyping For Early Stage Industrial Design: Understanding What Matters in Prototyping to Make Prototyping Matter More. DS 95: Proceedings of the 21st International Conference on Engineering and Product Design Education (E&PDE 2019), University of Strathclyde, Glasgow. 12th-13th September 2019,

Maine, E., Probert, D., & Ashby, M. (2005). Investing in new materials: a tool for technology managers. *Technovation*, *25*(1), 15-23. https://doi.org/https://doi.org/10.1016/S0166-4972(03)00070-1

Make Community LLC. (2022). *How many people attend Maker Faires around the world?* . Make Community LLC. Retrieved 12 January from https://help.make.co/hc/en-us/articles/204141969-How-many-people-attend-Maker-Faires-around-the-world-

MakerBot Industries LLC. (2022). *Thingiverse*. Retrieved 12 January from https://www.thingiverse.com/

Malik, A., Ul Haq, M. I., Raina, A., & Gupta, K. (2022). 3D printing towards implementing Industry 4.0: sustainability aspects, barriers and challenges. *Industrial robot*, *49*(3), 491-511. https://doi.org/10.1108/IR-10-2021-0247

Malindra Group. (2024). *OUR FACILITIES*. Retrieved 10 May from https://www.manildra.com.au/manildra-facilities/

Materials Design Map. (2024). *Materials Design Map; For a circular local economy*. WeVux. Retrieved 3 October from https://www.materialsdesignmap.com/

Marten, B., & Hicks, A. (2018). Expanded Polystyrene Life Cycle Analysis Literature Review: An Analysis for Different Disposal Scenarios. *Sustainability (New Rochelle, N.Y.)*, *11*(1), 29-35. https://doi.org/10.1089/sus.2017.0015

Mater Design. (2020). *Mask Stool | Natural edition*. Retrieved 9 November from https://materdesign.com/collections/2020-news/products/mask-stool-natural-edition

McConnell, R. (2020). *Content in the product design process - articulating our role*. Medium.com. https://uxdesign.cc/content-in-the-design-process-articulating-our-role-8a3d882a5550

McElroy, K. (2016). *Prototyping for designers: Developing the best digital and physical products*. " O'Reilly Media, Inc.".

McElroy, K. (2016). *Prototyping for physical and digital products*. O'Reilly Media.

McLean, N. J. (2018). *Material kin: a maker's guide*

Mehrpouya, M., Vosooghnia, A., Dehghanghadikolaei, A., & Fotovvati, B. (2021). Chapter 2 - The benefits of additive manufacturing for sustainable design and production. In K. Gupta & K. Salonitis (Eds.), *Sustainable Manufacturing* (pp. 29-59). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-12-818115-7.00009-2

Mendes, L., Kangas, A., Kukko, K., Mølgaard, B., Säämänen, A., Kanerva, T., Flores Ituarte, I., Huhtiniemi, M., Stockmann-Juvala, H., Partanen, J., Hämeri, K., Eleftheriadis, K., & Viitanen, A.-K. (2017). Characterization of Emissions from a Desktop 3D Printer. *Journal of Industrial Ecology*, *21*(S1), S94-S106. https://doi.org/https://doi.org/10.1111/jiec.12569

Mikula, K., Skrzypczak, D., Izydorczyk, G., Warchoł, J., Moustakas, K., Chojnacka, K., & Witek-Krowiak, A. (2021). 3D printing filament as a second life of waste plastics—a review. *Environmental Science and Pollution Research*, *28*(10), 12321-12333. https://doi.org/10.1007/s11356-020-10657-8

Millati, R., Cahyono, R. B., Ariyanto, T., Azzahrani, I. N., Putri, R. U., & Taherzadeh, M. J. (2019). Chapter 1 - Agricultural, Industrial, Municipal, and Forest Wastes: An Overview. In M. J. Taherzadeh, K. Bolton, J. Wong, & A. Pandey (Eds.), *Sustainable Resource Recovery and Zero Waste Approaches* (pp. 1-22). Elsevier. https://doi.org/https://doi.org/10.1016/B978-0-444-64200-4.00001-3

Milosevic, M., Stoof, D., & Pickering, K. L. (2017). Characterizing the Mechanical Properties of Fused Deposition Modelling Natural Fiber Recycled Polypropylene Composites. *Journal of Composites Science*, *1*(1). https://doi.org/10.3390/jcs1010007

Milton, A., & Rogers, P. (2017). *Research methods for product design*. Laurence King.

Model No. (2023). *Our Materials*. Retrieved 16 January from https://model-no.com/product/our-materials

Montalvo Navarrete, J. I., Hidalgo-Salazar, M. A., Escobar Nunez, E., & Rojas Arciniegas, A. J. (2018). Thermal and mechanical behavior of biocomposites using additive manufacturing. *International Journal on Interactive Design and Manufacturing (IJIDeM)*, *12*(2), 449-458. https://doi.org/10.1007/s12008-017-0411-2

Monteiro, C. C. F., Monteiro, A. R. G., & da Silva, F. M. (2020, 2020//). Product Development with Biopolymers Made from Brewers' Spent Grain (BSG) and Carboxymethylcellulose (CMC),

Using 3D Food Printer. Advances in Manufacturing, Production Management and Process Control,

Morrison, L. R. (2000). Glycerol. In *Kirk-Othmer Encyclopedia of Chemical Technology*. John Wiley & Sons, Inc. https://doi.org/https://doi.org/10.1002/0471238961.0712250313151818.a01

Mounde, A. A. (2020). Understanding the maker in academic makerspaces. *AFRICA HABITAT REVIEW*, *14*(1), 1745-1752.

Muhlack, R. A., Potumarthi, R., & Jeffery, D. W. (2018). Sustainable wineries through waste valorisation: A review of grape marc utilisation for value-added products. *Waste Management*, *72*, 99-118. https://doi.org/https://doi.org/10.1016/j.wasman.2017.11.011

Muratovski, G. (2016). *Research for designers : a guide to methods and practice*. Sage Publications.

Mussatto, S., Dragone, G., & Roberto, I. (2004). Brewers' Spent Grain: Generation, Characteristics and Potential Applications. *Journal of Cereal Science*, *43*, 1-14. https://doi.org/10.1016/j.jcs.2005.06.001

Mussatto, S. I., Dragone, G., Fernandes, M., Milagres, A. M. F., & Roberto, I. C. (2008). The effect of agitation speed, enzyme loading and substrate concentration on enzymatic hydrolysis of cellulose from brewer's spent grain. *Cellulose*, *15*(5), 711. https://doi.org/10.1007/s10570-008-9215-7

Næss, P., & Høyer, K. G. (2009). The Emperor's Green Clothes: Growth, Decoupling, and Capitalism. *Capitalism Nature Socialism*, *20*(3), 74-95. https://doi.org/10.1080/10455750903215753

Narancic, T., Verstichel, S., Reddy Chaganti, S., Morales-Gamez, L., Kenny, S. T., De Wilde, B., Babu Padamati, R., & O'Connor, K. E. (2018). Biodegradable Plastic Blends Create New Possibilities for End-of-Life Management of Plastics but They Are Not a Panacea for Plastic Pollution. *Environmental science & technology*, *52*(18), 10441-10452. https://doi.org/10.1021/acs.est.8b02963

Nascimento, T. A., Calado, V., & Carvalho, C. W. P. (2017). Effect of Brewer's spent grain and temperature on physical properties of expanded extrudates from rice. *LWT - Food Science and Technology*, *79*, 145-151. https://doi.org/https://doi.org/10.1016/j.lwt.2017.01.035

National Center for Biotechnology Information. (2022). *PubChem Compound Summary for CID 7272, 3,6-Dimethyl-1,4-dioxane-2,5-dione*. Retrieved 29 September from https://pubchem.ncbi.nlm.nih.gov/compound/3_6-Dimethyl-1_4-dioxane-2_5-dione

National Center for Biotechnology Information. (2022). *PubChem Compound Summary for CID 7501, Styrene*. Retrieved 29 September from https://pubchem.ncbi.nlm.nih.gov/compound/Styrene

Nay, L. (2020). In good company: Engaging in the maker movement alongside campus partners. *College & Undergraduate Libraries*, *27*(2-4), 326-338. https://doi.org/10.1080/10691316.2020.1865859

Ngo, T. D., Kashani, A., Imbalzano, G., Nguyen, K. T., & Hui, D. (2018). Additive manufacturing (3D printing): A review of materials, methods, applications and challenges. *Composites Part B: Engineering*, *143*, 172-196.

Niaki, M. K., Torabi, S. A., & Nonino, F. (2019). Why manufacturers adopt additive manufacturing technologies: The role of sustainability. *Journal of Cleaner Production*, *222*, 381-392. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.03.019

Noblit, G., & Hare, R. (1988). *Meta-Ethnography*. Sage Publications. https://doi.org/10.4135/9781412985000

Norman, H. (2023). *Logitech MX Master 3 Wireless Mouse for Mac*. Retrieved Australia from https://www.harveynorman.com.au/logitech-mx-master-3-wireless-mouse-for-mac.html

Nur, A., Afrianita, R., & Ramli, R. D. T. F. (2019). Effect of pipe diameter changes on the properties of fluid in closed channels using Osborne Reynold Apparatus. *IOP Conference Series: Materials Science and Engineering*, *602*(1), 012058. https://doi.org/10.1088/1757-899X/602/1/012058

Nyhan, L., Sahin, A. W., Schmitz, H. H., Siegel, J. B., & Arendt, E. K. (2023). Brewers' Spent Grain: An Unprecedented Opportunity to Develop Sustainable Plant-Based Nutrition Ingredients Addressing Global Malnutrition Challenges. *Journal of Agricultural and Food Chemistry*, *71*(28), 10543-10564. https://doi.org/10.1021/acs.jafc.3c02489

OECD. (2020). *Environment at a Glance 2020*. Organisation for Economic Co-operation and Development. https://doi.org/doi:https://doi.org/10.1787/4ea7d35f-en

OECD. (2022). *Municipal solid waste material recovery rates worldwide in 2020, by select country* Statista. Retrieved 02 February from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/1052439/rate-of-msw-recycling-worldwide-by-key-country/

Ogunjobi, J., Taiwo, A., Lajide, L., Olugbenga, O., & Adebayo, A. (2018). Synthesis and Application of Carboxymethyl Cellulose from Gliricidia sepium and Cola gigantea. *Bioresources*, *13*.

Oliveira, G., Passos, C. P., Ferreira, P., Coimbra, M. A., & Gonçalves, I. (2021). Coffee By-Products and Their Suitability for Developing Active Food Packaging Materials. *Foods*, *10*(3). https://doi.org/10.3390/foods10030683

Osman, M. A., & Atia, M., R. A.,. (2018). Investigation of ABS-rice straw composite feedstock filament for FDM. *Rapid Prototyping Journal*, *24*(6), 1067-1075. https://doi.org/10.1108/RPJ-11-2017-0242

Otero, A. (2022). *Eggshell paste for 3d printing*. Matriom. Retrieved 27 July from https://materiom.org/recipe/601

O'Toole, C. (2007). *Frasers buys CUB brewery for $208m*. Australian Financial Review. Retrieved 20 January from https://www.commercialrealestate.com.au/news/old-brewery-building-in-sydney-nominated-for-world-architecture-award-29374/

Öztürk, S., Özboy, Ö., Cavidp lu, I., & Köksel, H. (2002). Effects of Brewer's Spent Grain on the Quality and Dietary Fibre Content of Cookies. *Journal of The Institute of Brewing*, *108*, 23-27.

Pakkanen, J., Manfredi, D., Minetola, P., & Iuliano, L. (2017). *About the use of recycled or biodegradable filaments for sustainability of 3D printing* International conference on sustainable design and manufacturing, DOI: 10.1007/978-3-319-57078-5_73

Panagiotopoulou, V. C., Stavropoulos, P., & Chryssolouris, G. (2022). A critical review on the environmental impact of manufacturing: a holistic perspective. *The International Journal of Advanced Manufacturing Technology*, *118*(1), 603-625. https://doi.org/10.1007/s00170-021-07980-w

Panthapulakkal, S., & Sain, M. (2014). The use of wheat straw fibres as reinforcements in composites. In O. Faruk & M. Sain (Eds.), *Biofiber Reinforcements in Composite Materials* (pp. 423 - 453). Woodhead Publishing. https://doi.org/10.1533/9781782421276.4.423

Parisi, S., Rognoli, V., & Sonneveld, M. (2017). Material Tinkering. An inspirational approach for experiential learning and envisioning in product design education. *The Design Journal*, *20*(sup1), S1167-S1184.

Pawan Kumar, M., Gregor, T., & Wimmer, R. (2016). Utilising Brewer's Spent Grain as a Source of Cellulose Nanofibres Following Separation of Protein-based Biomass. *Bioresources*, *12*(1), 107-116. https://doi.org/10.15376/biores.12.1.107-116

Pedgley, O. (2007). Capturing and analysing own design activity. *Design Studies*, *28*(5), 463-483. https://doi.org/https://doi.org/10.1016/j.destud.2007.02.004

Pedgley, O., & Wormald, P. (2007). Integration of Design Projects within a Ph.D. *Design Issues*, *23*(3), 70-85. https://doi.org/10.1162/desi.2007.23.3.70

Peng, T., Kellens, K., Tang, R., Chen, C., & Chen, G. (2018). Sustainability of additive manufacturing: An overview on its energy demand and environmental impact. *Additive Manufacturing*, *21*, 694-704. https://doi.org/https://doi.org/10.1016/j.addma.2018.04.022

Pickin, J., Randell, P., Trinh, J., & Grant, B. (2018). *National Waste Report 2018*. B. E. P. Ltd. https://www.environment.gov.au/system/files/resources/7381c1de-31d0-429b-912c-91a6dbc83af7/files/national-waste-report-2018.pdf

Pickin, J., Wardle, C., O'Farrell, K., Stovell, L., Nyunt, P., Guazzo, S., Lin, Y., Caggiati-Shortell, G., Chakma, P., Edwards, C., Lindley, B., Latimer, G., Jenny, D., & Axiö, I. (2022). *National Waste Report 2022*. E. The Department of Climate Change, the Environment and Water, & Blue Environment Pty Ltd.

Plastics Europe, & European Association Of Plastic Recycling and Recovery Organisations. (2021). Plastics - the Facts 2021. https://plasticseurope.org/wp-content/uploads/2021/12/Plastics-the-Facts-2021-web-final.pdf

Pollon, F., & Healy, G. (1988). *The Book of Sydney suburbs*. Angus & Robertson.

Polymer Service GmbH Merseburg. (2023). Multi-purpose test specimen 1A and other types of specimens for the tensile test. In. Merseburg, Germany: Polymer Service GmbH Merseburg.

Purkiss, D., Allison, A. L., Lorencatto, F., Michie, S., & Miodownik, M. (2022). The Big Compost Experiment: Using citizen science to assess the impact and effectiveness of biodegradable and compostable plastics in UK home composting [Original Research]. *Frontiers in Sustainability*, *3*. https://doi.org/10.3389/frsus.2022.942724

Rachwał, K., Waśko, A., Gustaw, K., & Polak-Berecka, M. (2020). Utilization of brewery wastes in food industry. *PeerJ*, *8*. https://doi.org/10.7717/peerj.9427

Rael, R., & San Fratello, V. (2011). Developing concrete polymer building components for 3D printing. *ACADIA*, 152-157.

Rael, R., & San Fratello, V. (2015). The Utah Tea Set. In. emergingobjects.com: Emerging Objects.

Rael, R., & San Fratello, V. (2017). Clay Bodies: Crafting the Future with 3D Printing. *Architectural Design*, *87*, 92-97. https://doi.org/10.1002/ad.2243

Rael, R., & San Fratello, V. (2018). *Printing architecture : innovative recipes for 3D printing*. Princeton Architectural Press.

Rahman, M. S., Hasan, M. S., Nitai, A. S., Nam, S., Karmakar, A. K., Ahsan, M. S., Shiddiky, M. J. A., & Ahmed, M. B. (2021). Recent Developments of Carboxymethyl Cellulose. *Polymers (Basel)*, *13*(8). https://doi.org/10.3390/polym13081345

Ravindran, R., Jaiswal, S., Abu-Ghannam, N., & Jaiswal, A. K. (2018). A comparative analysis of pretreatment strategies on the properties and hydrolysis of brewers' spent grain. *Bioresource Technology*, *248*, 272-279. https://doi.org/https://doi.org/10.1016/j.biortech.2017.06.039

Rejeski, D., Zhao, F., & Huang, Y. (2018). Research needs and recommendations on environmental implications of additive manufacturing. *Additive Manufacturing*, *19*, 21-28. https://doi.org/https://doi.org/10.1016/j.addma.2017.10.019

Revert, A., Reig, M., Seguí, V. J., Boronat, T., Fombuena, V., & Balart, R. (2017). Upgrading brewer's spent grain as functional filler in polypropylene matrix. *Polymer Composites*, *38*(1), 40-47. https://doi.org/https://doi.org/10.1002/pc.23558

Risco-Castillo, M. (2023). *Professional Firmware for the Creality Ender 3 V2/S1 Printers*. GitHub. Retrieved 13 November from https://github.com/mriscoc/Ender3V2S1

Risk Management Technologies. (2022). *Bagasse Safety Data Sheet*. WILMAR BIOETHANOL (AUSTRALIA) PTY LTD. https://sds.chemalert.com/company/10002830/download/3029590_001_001.pdf

Rognoli, V., Bianchini, M., Maffei, S., & Karana, E. (2015). DIY materials. *Materials & Design*, *86*, 692-702. https://doi.org/https://doi.org/10.1016/j.matdes.2015.07.020

Sackett, P. d. (2021). *Flow Rate/Extrusion Multiplier Test Tower*. Thingiverse. Retrieved 05 December from https://www.thingiverse.com/thing:4983669

Säde, S. (2001). *Cardboard Mock-ups and Conversations: Studies on User-centered Product Design*. University of Art and Design. https://books.google.com.au/books?id=9cpyOwAACAAJ

Sadokierski, Z. (2019, 19-22 March). *Critical Journal / Contextual Portfolio: A framework for documenting and disseminating RtD as scholarly research* RTD2019: Method and Critique, The Netherlands. http://hdl.handle.net/10453/135917

Safe Work Australia. (2023). *Preparing safety data sheets*. Retrieved 04 November from https://www.safeworkaustralia.gov.au/safety-topic/hazards/chemicals/safety-data-sheets/preparing-safety-data-sheets

Santana, L., Lino Alves, J., & da Costa Sabino Netto, A. (2017). A study of parametric calibration for low cost 3D printing: Seeking improvement in dimensional quality. *Materials & Design*, *135*, 159-172. https://doi.org/https://doi.org/10.1016/j.matdes.2017.09.020

Santos, D. M. d., Bukzem, A. d. L., Ascheri, D. P. R., Signini, R., & Aquino, G. L. B. d. (2015). Microwave-assisted carboxymethylation of cellulose extracted from brewer's spent grain. *Carbohydrate Polymers*, *131*, 125-133. https://doi.org/https://doi.org/10.1016/j.carbpol.2015.05.051

Santos, L. G., & Martins, V. G. (2024). Functional, thermal, bioactive and antihypertensive properties of hot trub derived from brewing waste as an alternative source of protein. *Food Hydrocolloids*, *146*, 109292. https://doi.org/https://doi.org/10.1016/j.foodhyd.2023.109292

Sathish, T., Vijayakumar, M. D., & Krishnan Ayyangar, A. (2018). Design and Fabrication of Industrial Components Using 3D Printing. *Materials Today: Proceedings*, *5*(6, Part 2), 14489-14498. https://doi.org/https://doi.org/10.1016/j.matpr.2018.03.036

Sauerwein, M. *Reprintable Mussel shell-alginate composite material*. Materiom. Retrieved 12 August from https://materiom.org/recipe/599

Sauerwein, M. (2020). *Additive Manufacturing for Design in a Circular Economy* Delft University of Technology]. https://pure.tudelft.nl/ws/portalfiles/portal/83717548/MaritaSauerwein_thesis.pdf

Sauerwein, M. (2023). Mussel Shell - sucrose composite. In: Materiom.org.

Sauerwein, M., Doubrovski, E., Balkenende, R., & Bakker, C. (2019). Exploring the potential of additive manufacturing for product design in a circular economy. *Journal of Cleaner Production*, *226*, 1138-1149. https://doi.org/https://doi.org/10.1016/j.jclepro.2019.04.108

Sauerwein, M., & Doubrovski, E. L. (2018). Local and recyclable materials for additive manufacturing: 3D printing with mussel shells. *Materials Today Communications*, *15*, 214-217. https://doi.org/https://doi.org/10.1016/j.mtcomm.2018.02.028

Sauerwein, M., Zlopasa, J., Doubrovski, Z., Bakker, C., & Balkenende, R. (2020). Reprintable Paste-Based Materials for Additive Manufacturing in a Circular Economy. *Sustainability*, *12*(19), 8032. https://www.mdpi.com/2071-1050/12/19/8032

Schmuck, D., Matthes, J., & Naderer, B. (2018). Misleading Consumers with Green Advertising? An Affect–Reason–Involvement Account of Greenwashing Effects in Environmental Advertising. *Journal of Advertising*, *47*(2), 127-145. https://doi.org/10.1080/00913367.2018.1452652

Schon, D. A. (2016). *The reflective practitioner : how professionals think in action*. Routledge. https://doi.org/10.4324/9781315237473

Schumer, C., Boehm, S., Fransen, T., Hausker, K., & Dellesky, C. (2022). *6 Takeaways from the 2022 IPCC Climate Change Mitigation Report* World Resources Institute. Retrieved 30 August from https://www.wri.org/insights/ipcc-report-2022-mitigation-climate-change

Sculpteo. (2020). *Leading uses of 3D printing from 2015 to 2020*. Statista. Retrieved 5 February from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/560271/worldwide-survey-3d-printing-uses/

Sculpteo. (2020). *The State of 3D Printing*. Sculpteo. https://info.sculpteo.com/hubfs/downloads/state%202020/The%20State%20of%203D%20Printing_2020%20edition.pdf

Sears, J. (2021, 27 November 2021). *Xbox One Controller - Revopoint pop scan*. Thingiverse. Retrieved 23 November from https://www.thingiverse.com/thing:5147790

Senthil Muthu Kumar, T., Senthilkumar, K., Chandrasekar, M., Subramaniam, S., Mavinkere Rangappa, S., Siengchin, S., & Rajini, N. (2020). Influence of Fillers on the Thermal and Mechanical Properties of Biocomposites: An Overview. In A. Khan, S. Mavinkere Rangappa, S. Siengchin, & A. M. Asiri (Eds.), *Biofibers and Biopolymers for Biocomposites: Synthesis, Characterization and Properties* (pp. 111-133). Springer International Publishing. https://doi.org/10.1007/978-3-030-40301-0_5

Shaqour, B., Abuabiah, M., Abdel-fattah, S., Juaidi, A., Abdallah, R., Abuzaina, W., Alqarout, M., Verleije, B., & Cos, P. (2021). Gaining a better understanding of the extrusion process in fused filament fabrication 3D printing: a review. *The International Journal of Advanced Manufacturing Technology*, *114*. https://doi.org/10.1007/s00170-021-06918-6

Shen, M., Huang, W., Chen, M., Song, B., Zeng, G., & Zhang, Y. (2020). (Micro)plastic crisis: Un-ignorable contribution to global greenhouse gas emissions and climate change. *Journal of Cleaner Production*, *254*, 120138. https://doi.org/https://doi.org/10.1016/j.jclepro.2020.120138

shopplaywood. (2019). plastic waste resin codes recycling icons. In *Adobe Stock*: Adobe Stock.

Sigloch, H., Bierkandt, F. S., Singh, A. V., Gadicherla, A. K., Laux, P., & Luch, A. (2020). 3D Printing - Evaluating Particle Emissions of a 3D Printing Pen. *JoVE*(164), e61829. https://doi.org/doi:10.3791/61829

Singh, N., & Ogunseitan, O. A. (2022). Disentangling the worldwide web of e-waste and climate change co-benefits. *Circular Economy*, *1*(2), 100011. https://doi.org/https://doi.org/10.1016/j.cec.2022.100011

Singh, R. K., & Singh, A. K. (2013). Optimization of reaction conditions for preparing carboxymethyl cellulose from corn cobic agricultural waste [Article]. *Waste and Biomass Valorization*, *4*(1), 129-137. https://doi.org/10.1007/s12649-012-9123-9

Skleničková, K., Abbrent, S., Halecký, M., Kočí, V., & Beneš, H. (2022). Biodegradability and ecotoxicity of polyurethane foams: A review. *Critical Reviews in Environmental Science and Technology*, *52*(2), 157-202. https://doi.org/10.1080/10643389.2020.1818496

Smith, R. S. H., Bader, C., Sharma, S., Kolb, D., Tang, T.-C., Hosny, A., Moser, F., Weaver, J. C., Voigt, C. A., & Oxman, N. (2020). Hybrid Living Materials: Digital Design and Fabrication of 3D Multimaterial Structures with Programmable Biohybrid Surfaces. *Advanced Functional Materials*, *30*(7), 1907401. https://doi.org/10.1002/adfm.201907401

Stappers, P. J. (2007). Doing Design as a Part of Doing Research. In R. Michel (Ed.), *Design Research Now: Essays and Selected Projects* (pp. 81-91). Birkhäuser Basel. https://doi.org/10.1007/978-3-7643-8472-2_6

Stappers, P. J., Sleeswijk Visser, F., & Keller, L. (2015). The role of prototypes and frameworks for structuring explorations by research through design. In P. Rodgers & J. Yee (Eds.), *The Routledge Companion to Design Research* (pp. 179-190). Routledge. https://doi.org/10.4324/9781315758466-20

Starr, D. (2016). *Just 90 companies are to blame for most climate change, this 'carbon accountant' says*. American Association for the Advancement of Science [science.org],. Retrieved 30 Augst from https://www.science.org/content/article/just-90-companies-are-blame-most-climate-change-carbon-accountant-says

Starr Instruments. (2023). *FGD-Manual Stand*. Retrieved 20 December from https://starrinstruments.co.nz/force-gauge/21-fgd-stand.html

Stephens, B., Azimi, P., El Orch, Z., & Ramos, T. (2013). Ultrafine particle emissions from desktop 3D printers. *Atmospheric Environment*, *79*, 334-339. https://doi.org/https://doi.org/10.1016/j.atmosenv.2013.06.050

Stern, A., & Siegelbaum, S. (2019). Design and neoliberalism. In (Vol. 11, pp. 265-277): Taylor & Francis.

Stoll, N., & Schrempf, T. (2020). *Trebodur*. Retrieved 10 November from https://trebodur.de/

StoneFlower3D. (2022). *Open source print head for clay StoneFlower*. Retrieved 11 March from https://www.stoneflower3d.com/opensource/

Stoof, D., Pickering, K., & Zhang, Y. (2017). Fused Deposition Modelling of Natural Fibre/Polylactic Acid Composites. *Journal of Composites Science*, *1*(1), 8. https://www.mdpi.com/2504-477X/1/1/8

Sun, L. M. P., & To, A. C.-Y. (2023). Inexpensive DIY Bioprinting in a Secondary School Setting. *Journal of Microbiology & Biology Education*, *24*(2), e00124-00122. https://doi.org/doi:10.1128/jmbe.00124-22

Sutton Tools. (2023). *Sutton Tools 8 x 160mm 2 Cut SDS Plus Masonry Drill Bit*. Bunnings. Retrieved 8 January from https://www.bunnings.com.au/sutton-tools-8-x-160mm-2-cut-sds-plus-masonry-drill-bit_p0188180

Sutton Tools. (2023). *Sutton Tools 8mm Viper Jobber Drill Bit*. Bunnings. Retrieved 8 January from https://www.bunnings.com.au/sutton-tools-8mm-viper-jobber-drill-bit_p6354831

Sutton Tools. (2023). *Sutton Tools 170 x 8mm Short Auger Bit*. Bunnings. Retrieved 8 January from https://www.bunnings.com.au/sutton-tools-170-x-8mm-short-auger-bit_p6370319

Swann, C. (2002). Action Research and the Practice of Design. *Design Issues*, *18*(1), 49-61. http://www.jstor.org/stable/1512029

Takano, T. (2020). Nataša Perković makes textured furniture from palm oil byproducts: A chair 3D printed using a mix of PLA and oil palm tree fibre micro powder. In. dezeen.com: Dezeen.

Tapangnoi, P., Sae-Oui, P., Naebpetch, W., & Siriwong, C. (2022). Preparation of purified spent coffee ground and its reinforcement in natural rubber composite. *Arabian Journal of Chemistry*, *15*(7), 103917. https://doi.org/https://doi.org/10.1016/j.arabjc.2022.103917

Tavares, K. M., Campos, A. d., Luchesi, B. R., Resende, A. A., Oliveira, J. E. d., & Marconcini, J. M. (2020). Effect of carboxymethyl cellulose concentration on mechanical and water vapor barrier properties of corn starch films. *Carbohydrate Polymers*, *246*, 116521. https://doi.org/https://doi.org/10.1016/j.carbpol.2020.116521

Tayeb, A. H., Amini, E., Ghasemi, S., & Tajvidi, M. (2018). Cellulose Nanomaterials—Binding Properties and Applications: A Review. *Molecules*, *23*(10), 2684. https://www.mdpi.com/1420-3049/23/10/2684

Tenhunen, T.-M., Moslemian, O., Kammiovirta, K., Harlin, A., Kääriäinen, P., Österberg, M., Tammelin, T., & Orelma, H. (2018). Surface tailoring and design-driven prototyping of fabrics

with 3D-printing: An all-cellulose approach. *Materials & Design*, *140*, 409-419. https://doi.org/https://doi.org/10.1016/j.matdes.2017.12.012

The Australian Bureau of Agricultural and Resource Economics and Sciences. (2019). *Area for crop production in Australia in financial years 2019 and 2020, by crop (in 1,000 hectares)*. Statista. Retrieved 26 October from https://www.statista.com/statistics/1093773/australia-agriculture-crop-area-by-crop/

Thomas, B., Ilpo, K., Johan, R., Stephan, W., & John, Z. (2011). *Design Research Through Practice*. Morgan Kaufmann. https://doi.org/10.1016/C2010-0-65896-2

Thomas, J., & Harden, A. (2008). Methods for the thematic synthesis of qualitative research in systematic reviews. *BMC Medical Research Methodology*, *8*(1), 45. https://doi.org/10.1186/1471-2288-8-45

Thomas, S., Rane, A. V., Kanny, K., Abitha, V., & Thomas, M. G. (Eds.). (2018). *Recycling of polyurethane foams*. Elsivier inc.

Thonet, M. (2023). *No.14 Vienna*. Thonet.com.au. https://thonet.com.au/products/no-14-vienna/

Tjalve, E. (2015). *A short course in industrial design*. Elsevier.

Torrence, A. (2006). Martin Newell's original teapot. In *ACM SIGGRAPH 2006 Teapot Copyright restrictions prevent ACM from providing the full text for the Teapot exhibits* (pp. 29-es). https://dl.acm.org/doi/10.1145/1180098.1180128

Tran, T. N., Bayer, I. S., Heredia-Guerrero, J. A., Frugone, M., Lagomarsino, M., Maggio, F., & Athanassiou, A. (2017). Cocoa Shell Waste Biofilaments for 3D Printing Applications. *Macromolecular Materials and Engineering*, *302*(11), 1700219. https://doi.org/10.1002/mame.201700219

Tri-Dung, N. (2020). Introduction to Composite Materials. In N. Tri-Dung (Ed.), *Composite and Nanocomposite Materials* (pp. Ch. 1). IntechOpen. https://doi.org/10.5772/intechopen.91285

Trudeau, N. (1995). *Professional modelmaking : a handbook of techniques and materials for architects and designers*. Whitney Library of Design.

Ulrich, K. T., & Eppinger, S. D. (2008). *Product design and development* (4th ed.). McGraw-Hill Higher Education.

Unruh, G. (2018). Circular Economy, 3D Printing, and the Biosphere Rules. *California Management Review*, *60*. https://doi.org/10.1177/0008125618759684

US Department of Agriculture. (2020). *Leading 10 wheat producers worldwide from 2016/2017 to 2019/20 (in 1,000 metric tons)*. Statista. Retrieved 2 November from https://www.statista.com/statistics/237908/global-top-wheat-producing-countries/

US Department of Agriculture. (2020). *Principal exporting countries of wheat, flour and wheat products from 2014/2015 to 2019/2020 (in 1,000 metric tons)*. Statista. Retrieved 2 November from https://www.statista.com/statistics/190429/principal-exporting-countries-of-wheat-flour-and-products/

US Department of Agriculture. (2020). *Sugar production worldwide in 2019/2020, by leading country (in million metric tons)**. Statista. Retrieved 27 October from https://www.statista.com/statistics/495973/sugar-production-worldwide/

US Department of Agriculture. (2024). *Leading 10 wheat producers worldwide in 2023/2024 (in 1,000 metric tons)* [Graph].* Statista. Retrieved 06 May from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/237912/global-top-wheat-producing-countries/

Valtonen, A. (2005). Six decades–and six different roles for the industrial designer. *Nordes*(1).

Varvara, R. A., Szabo, K., & Vodnar, D. C. (2021). 3D Food Printing: Principles of Obtaining Digitally-Designed Nourishment. *Nutrients*, *13*(10). https://doi.org/10.3390/nu13103617

Vasquez, E. S. L., Wang, H.-C., & Vega, K. (2020). The Environmental Impact of Physical Prototyping: a Five-Year CHI Review. Self-Sustainable CHI Workshop,

von Fraunhofer, J. A. (2012). Adhesion and cohesion. *International Journal Of Dentistry*, 951324. https://doi.org/10.1155/2012/951324

von Hasseln, K. (2017). Crystalline Tectonics: An Architect's Guide to 3D-Printing Sugar or Anything Else. *Architectural Design*, *87*(6), 98-105. https://doi.org/10.1002/ad.2244

Walden, R., Lie, S., Pandolfo, B., & Nemme, A. (2018). To Get There: Designing Together. Cumulus Conference, Paris.

Wang, M., Li, D., Zang, Z., Sun, X., Tan, H., Si, X., Tian, J., Teng, W., Wang, J., Liang, Q., Bao, Y., Li, B., & Liu, R. (2022). 3D food printing: Applications of plant-based materials in extrusion-based food printing. *Critical Reviews in Food Science and Nutrition*, *62*(26), 7184-7198. https://doi.org/10.1080/10408398.2021.1911929

Wang, Y.-L., Lee, Y.-H., Chiu, I.-J., Lin , Y.-F., & Chiu, H.-W. (2020). Potent Impact of Plastic Nanomaterials and Micromaterials on the Food Chain and Human Health. *International Journal of Molecular Sciences*, *21*(5), 1727. https://www.mdpi.com/1422-0067/21/5/1727

WASP. (2023). *Delta WASP 2040 Clay*. Retrieved 04 December from https://www.3dwasp.shop/en/prodotto/clay-3d-printer-delta-wasp-2040-clay/

WASP. (2023). *DeltaWASP 40100 CLAY*. Retrieved 29 December from https://deltawasp.com.au/shop/deltawasp-40100-clay/

WASP. (2023). *LDM WASP Extruder XL 3.0*. Retrieved 25 December from https://www.3dwasp.shop/en/prodotto/extruder-for-ceramics-ldm-wasp-extruder-xl/

Weng, Y.-X., Wang, L., Zhang, M., Wang, X.-L., & Wang, Y.-Z. (2013). Biodegradation behavior of P(3HB,4HB)/PLA blends in real soil environments. *Polymer Testing*, *32*(1), 60-70. https://doi.org/https://doi.org/10.1016/j.polymertesting.2012.09.014

Wensveen, S., & Matthews, B. (2014). Prototypes and prototyping in design research. In *The Routledge Companion to Design Research*. Routledge. https://doi.org/10.4324/9781315758466.ch21

Williams, C., & Hillmyer, M. (2008). Polymers from Renewable Resources: A Perspective for a Special Issue of Polymer Reviews. *Polymer Reviews*, *48*, 1-10. https://doi.org/10.1080/15583720701834133

Wilson, C. (2018). *Could sugarcane waste provide a value-add for growers and alternative to hay or feed?* ABC News. Retrieved 24 November from https://www.abc.net.au/news/2018-07-28/bagasse-can-be-used-as-animal-feed-for-livestock-and-energy/10034466

Wine Australia. (2020). *Total amount of wine grapes crushed in Australia for wine production in 2019, by wine area (in thousand metric tons)*. Statista. Retrieved 26 October from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/963563/australia-wine-grape-crush-by-area/

Wohlers Associates. (2020). *Global 3D printing products and services market size from 2020 to 2024 (in billion U.S. dollars)*. Statista. Retrieved 5 February from https://www-statista-com.ezproxy.lib.uts.edu.au/statistics/315386/global-market-for-3d-printers/

Wohlers, T. T. (2022). History of additive manufacturing. https://wohlersassociates.com/wohlers-report-2022-downloads/

Wohlers, T. T., Associates, W., Campbell, R. I., Diegel, O., Kowen, J., Huff, R., Mostow, N., Fidan, I., Bourell, D. L., & Van Rensburg, J. (2022). *Wohlers Report 2022: 3D Printing and Additive Manufacturing Global State of the Industry*. Wohlers Associates. https://books.google.com.au/books?id=CyUGzwEACAAJ

Wu, P., Wang, J., & Wang, X. (2016). A critical review of the use of 3-D printing in the construction industry. *Automation in Construction*, *68*, 21-31. https://doi.org/https://doi.org/10.1016/j.autcon.2016.04.005

Wu, Y., Zhu, Q., & Zhu, B. (2018). Decoupling analysis of world economic growth and CO2 emissions: A study comparing developed and developing countries. *Journal of Cleaner Production*, *190*, 94-103. https://doi.org/https://doi.org/10.1016/j.jclepro.2018.04.139

WWF. (2021). *The lifecycle of plastics*. Retrieved 21 September from https://www.wwf.org.au/news/blogs/the-lifecycle-of-plastics#gs.nnb4te

Xiao, Y., & Watson, M. (2019). Guidance on conducting a systematic literature review. *Journal of planning education and research*, *39*(1), 93-112.

Xiros, C., Katapodis, P., & Christakopoulos, P. (2011). Factors affecting cellulose and hemicellulose hydrolysis of alkali treated brewers spent grain by Fusarium oxysporum enzyme extract. *Bioresource Technology*, *102*(2), 1688-1696. https://doi.org/https://doi.org/10.1016/j.biortech.2010.09.108

Yablon, S. (2020). Columbia University's School of Engineering Makerspace @ Columbia is an innovative hub for interdisciplinary invention. In: syarchitecture.com.

Zeko-Pivač, A., Tišma, M., Žnidaršič-Plazl, P., Kulisic, B., Sakellaris, G., Hao, J., & Planinić, M. (2022). The Potential of Brewer's Spent Grain in the Circular Bioeconomy: State of the Art and Future Perspectives [Review]. *Frontiers in Bioengineering and Biotechnology*, *10*. https://doi.org/10.3389/fbioe.2022.870744

Zhang, D. (2022). Environmental regulation and firm product quality improvement: How does the greenwashing response? *International Review of Financial Analysis*, *80*, 102058. https://doi.org/https://doi.org/10.1016/j.irfa.2022.102058

Zhao, D. X., Cai, X., Shou, G. Z., Gu, Y. Q., & Wang, P. X. (2016). Study on the Preparation of Bamboo Plastic Composite Intend for Additive Manufacturing. *Key Engineering Materials*, *667*, 250-258. https://doi.org/10.4028/www.scientific.net/KEM.667.250