
*Investigation of Cementitious Materials and
Fibre Reinforced Mortar in 3D Printing*

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A thesis in fulfilment of the requirement for the award of the degree

DOCTOR OF PHILOSOPHY

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Certificate of Original Authorship

I, **Pshtiwan Shakor**, declare that this thesis, submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the School of Civil and Environmental Engineering, Faculty of Engineering and Information Technology 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. This research is supported by the Australian Government Research Training Program.

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To my family

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List of Research Papers

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Abstract

At present, Three-Dimensional Printing (3DP) is one of the most promising developments in modern technology. This technology innovation has shown its potential in a wide range of applications, varying from medical to food industry and from aerospace engineering to household applications. Obviously, the building industry has aimed to adopt this technique to apply it on a larger scale. 3D concrete printing technology results in low cost and faster construction methods, which allows for greater freedom in both architectural design and construction techniques. Despite these clear benefits shown by a few pioneering companies and institutes in the world, the building industry is still far behind in the development of practical 3D printing machines. This is mainly attributed to the lack of fundamental research on the materials and structural behaviour of the to-be-printed objects. This research examines the two types of Additive Manufacturing (AM) techniques for cementitious materials and fibre reinforced mortar. Mortar and Concrete are new materials in the field of additive manufacturing. Since these types of materials are hardened by chemical reactions, considerable attention needs to be applied to the workability in the AM process.

It should be emphasised that different manufacturing processes require suitable material processing modifications. This is highly applicable to the cementitious material, which has adaptability in handling, comprising ordinary mixing and cast-in-situ for the construction production; shotcrete spraying for stabilising soil in the mining industry; extrusion-based in precasting factories for the construction industry; and spinning procedures for concrete pipes. However, 3D printing for construction also faces the challenge of alteration of the mix design and the manufacturing procedure. This study shows the formulation of the cement mortar powder for a powder-based Three-

Dimensional Printer. It shows the new approach of powder preparation and mix proportions for printing cement mortar. This investigation presents an extrusion-based printing technique, including (i) an outline of the required adjustments to mix ingredients and the mixing method; (ii) a machine to provide suitable rheology in the fresh state; (iii) design and fabrication of the nozzle; (iv) temporal considerations ensuring a satisfactory time-gap between interlayer bonds; and (v) mechanical strength results of the hardened printed mortar.

The innovative achievements are finding the water/cement ratio in the powder-based 3DP and optimising the slurry materials for extrusion-based printing. Using these techniques would be cost-effective, easy-to-apply and environmentally-friendly since it drastically reduces the need and use of different types of formworks.

Abbreviations list

Acronym	Meaning
<i>3DCP</i>	Three Dimensional Concrete Printing
<i>3DP</i>	Three Dimensional Printing
<i>6DOF</i>	Six Degree Of Freedom
<i>AM</i>	Additive Manufacturing
<i>CAC</i>	Calcium Aluminate Cement
<i>CAD</i>	Computer-Aided Design
<i>CIJ</i>	Continues Ink-Jet
<i>CNC</i>	Computer Numerical Control
<i>CP</i>	Cement Mortar Powder
<i>C-S-H</i>	Calcium Silicate Hydrate
<i>DLS</i>	Damp Least Squares
<i>DOD</i>	Drop On Demand
<i>FDM</i>	Fused Deposition Modelling
<i>G</i>	Glass fibre
<i>LCA</i>	Life Cycle Assessment
<i>LENS</i>	Laser Engineered Net Shaping
<i>LOM</i>	Laminated-Object Manufacturing
<i>OPC</i>	Ordinary Portland Cement
<i>PLA</i>	Polylactic Acid
<i>PP</i>	Polypropylene fibre
<i>Ra</i>	Surface Roughness
<i>RMRC</i>	Resolved Motion Rate Control
<i>RP</i>	Rapid Prototyping
<i>RPM</i>	Revolutions Per Minute
<i>SEM</i>	Scanning Electronic Microscope
<i>SLA</i>	Stereolithography
<i>SLS</i>	Selective Laser Sintering
<i>SMA</i>	Shape Memory Alloy
<i>Ssk</i>	Value of Skewness
<i>w/c</i>	Water to Cement Ratio
<i>Zb63</i>	Clear binder solution
<i>ZP, ZP 150, ZP151</i>	Calcium Sulfate Hemihydrate

Notations list

Annotation	Meaning
$\Delta\theta$	Angular displacement
μ	Plastic viscosity
a	Air content by volume
A_{thix}	Rate of the flocculation
b	Width of specimen
d	Diameters as an average value of the spreading mortar
d_0	Base diameter of the mini cone
D_{CAD}	CAD dimension
DDR	Dimensional deviation ratio
D_e	Dimensional error
D_p	Actual printed dimension
f	Friction coefficient between the shear case and the shear load platform
F	Normal force
f	Force between the particles
f	Maximum force applied on sample
F_{cubes}	Force between cube particles
$F_{spheres}$	Force between sphere particles
G	Specific gravity of cement
h	Total height
h	Height of the pile
H	Hausner ratio
I	Carr's index
l	Length of specimen
L_{CAD}	CAD length value designed model
L_p	Real (printed) measured length value of the sample
m_1	Dry weight
m_2	Weight of the samples in soaked water
m_3	Weight of rolling the four side samples on the damp cloth
M_b	Mass of binder
M_p	Mass of powder
N_c	Number of chains
N_{pc}	Number of particles in a chain
\emptyset	Angle of repose
P	Axial force on the specimen

P_a	Apparent porosity
P_{bed}	Powder bed apparent porosity
Q	Normal shear force
R	Half-width of the line
r	Roughness ratio
r	Radius of the base
r_p	A relative slump
S	Shear area
T	Torque
V	Velocity on the centre line
V_b	Volume of binder
V_b	Bulk density
V_p	Volume of powder
V_t	Tapped density
w	Measure of manipulability
β	Shear angle
γ	Shear rate
δ	Indentation depth
ηf	Viscosity of the fluid as a newtonian
θ_m	Contact angle
θ_R	Solid-water declining contact angle
θ_w	Apparent receding contact angle for the porous surface
θ_Y	Young contact angle
λ	Damping constant
ρ_b	Density of binder
ρ_{bed}	In-process bed density
ρ_p	Density of powder
ρ_{true}	True density
σ	Compressive stress
τ	Shear stress
τ	Shear stress
τ_0	Yield stress
p	Total porosity for the fresh cement
α	Radius of the particle