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

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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

Published Research Papers:

- Shakor, P., Sanjayan, J., Nazari, A. & Nejadi, S. 2017, 'Modified 3D printed powder to cement-based material and mechanical properties of cement scaffold used in 3D printing', Construction and Building Materials, vol. 138, pp. 398-409.
- Shakor, P., Nejadi, S., Paul, G. & Malek, S. 2019, 'Review of emerging additive manufacturing technologies in 3D printing of cementitious materials in the construction industry', Frontiers in Built Environment, vol. 4, pp. 85.
- Shakor, P., Nejadi, S., Paul, G., Sanjayan, J. & Nazari, A. 2019, Mechanical Properties of Cement-Based Materials and Effect of Elevated Temperature on Three-Dimensional (3-D) Printed Mortar Specimens in Inkjet 3-D Printing', ACI Materials Journal, vol. 116, pp. 55-67.
- Shakor, P., Nejadi, S. & Paul, G. 2019, 'A study into the effect of different nozzles shapes and fibre-reinforcement in 3D printed mortar', Materials, vol. 12, pp. 1708.
- Shakor, P., Nejadi S., Paul, G., Sanjayan, J. & Aslani, F. 2019 'Heat Curing as a Means of Post-processing Influence on 3D Printed Mortar Specimens in Powder-based 3D Printing', vol. 93, pp. 65-74.

Submitted Research Papers:

- Shakor, P., Nejadi, S., Paul, G. 'Effects of Different Orientation Angle on the Mechanical Behaviours of the Cementitious Powder and Gypsum Powder in Inkjet 3DP ', Cement and Concrete Composites Journal.

- Shakor, P., Nejadi, S., Paul, G. 'Investigation into the effect of delays between printed layers on the mechanical strength of inkjet 3DP mortar ', Manufacturing Letters. (Accepted)
- Shakor, P., Nejadi, S., Paul, G.& Sanjayan J., 'Dimensional accuracy, wettability, flowability and porosity in the inkjet 3DP for the gypsum and cement mortar materials', Automation in Construction. (Accepted)

Conference Papers:

- Shakor, P., Renneberg, J., Nejadi, S. & Paul, G. 2017, 'Optimisation of Different Concrete Mix Designs for 3D Printing by Utilising 6DOF Industrial Robot', ISARC. 34^{th} Proceedings of the International Symposium on Automation and Robotics in Construction, Taipei, Taiwan.
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- Shakor, P., Nejadi, S., Paul, G. & Sanjayan, J. 2018, 'A Novel Methodology of Powder-based Cementitious Materials in 3D Inkjet Printing for Construction Applications ', 6^{th} International Conference on the Durability of Concrete Structures, Leeds, UK.
- Shakor, P., Nejadi, S. & Paul, G. 2018, 'An investigation into the behaviour of cementitious mortar in the construction of 3D printed members by the means of extrusion printing', 3DcP. 1^{st} international conference on 3D Construction Printing, Melbourne, Australia.

- Shakor, P., Nejadi, S. & Paul, G. 2018, 'Wettability, flowability and porosity in the inkjet 3DP for the gypsum and cement mortar materials.', 6th conference of the combined Australian Materials Societies; incorporating materials Australia and the Australian Ceramic Society, Wollongong, Australia.
- Shakor, P., Nejadi, S., and Paul, G. 2019, 'An Investigation into the Effects of Deposition Orientation of Material on the Mechanical Behaviours of the Cementitious Powder and Gypsum Powder in Inkjet 3D Printing' 36th International Symposium on Automation and Robotics in Construction Alberta, Canada.
- Shakor, P., Nejadi, S., and Paul, G. 2019, 'Effect of Elevated Temperatures as a means of Curing in Inkjet 3D Printed Mortar Specimens', 29th Biennial National Conference, Concrete Institute of Australia, Sydney, Australia.

The author has received an award for excellence in concrete 2017 at the Concrete Institute of Australia-VIC for an innovative study for construction applications.

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