

**Modelling Flowable Engineered
Cementitious Composites and Its
Fibre Orientation and Distribution
for Tensile Performance Evaluation**

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the degree of

Doctor of Philosophy

under the supervision of Professor Jianchun Li,
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Certificate of Original Authorship

I, Hai Tran Thanh declare that this thesis is submitted in fulfilment of the requirements for the award of Doctor of Philosophy, in the 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.

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Table of Contents

Certificate of Original Authorship	i
Acknowledgements	ii
Publications from this Thesis	iii
Table of Contents	iv
List of Figures	ix
List of Tables	xiv
Abstract	xv
Chapter 1	1
Introduction	1
1.1 Engineered Cementitious Composites (ECC).....	2
1.1.1 Historical development of ECC	2
1.1.2 Micromechanics approach of ECC.....	6
1.2 The Role of Fibre Orientation and Distribution on Tensile Behaviour of ECC: A Multiscale Consideration	9
1.2.1 Pullout behaviour of an inclined fibre at the microscale level	9
1.2.2 Fibre-bridging consecutive law at the lower mesoscale level.....	11
1.2.3 Inhomogeneous fibre distribution at the macroscale level.....	13
1.3 Self-Consolidating (or Flowable) ECC	16
1.3.1 Development and application of self-consolidating (flowable) ECC	17
1.3.2 Workability and rheology of fresh self-consolidating ECC	19
1.3.2.1 Slump flow test	21
1.3.2.2 V-funnel test	21
1.3.2.3 U-box test.....	22
1.3.2.4 Beneficial and drawbacks of workability tests	23

1.4 Motivation and Objectives of this Research	24
1.4.1 Motivation of this research	24
1.4.2 Research objectives	27
1.5 Outline of the Thesis	28
Chapter 2	32
Numerical Modelling Flowable Fibre-Reinforced Cement-Based Materials	32
2.1 Introduction	33
2.2 Previous Efforts for Modelling the Flow Behaviour of Self-Compacting Fibre-Reinforced Cement-Based Materials	34
2.3 Scheme for Numerical Modelling the Flow of Self-Compacting Fibre-Reinforced Cement-Based Materials	38
2.4 The Governing Equations of Viscous Fluid	39
2.4.1 The continuity equation	40
2.4.2 The momentum equation	41
2.5 Rheology Models to Describe the Behaviour of a non-Newtonian Viscous Fluid ..	45
2.5.1 Bingham model	45
2.5.2 Herschel-Bulkley model	46
2.5.3 Cross model	47
2.6 SPH Method-Numerical Approximation	48
2.6.1 Integral and summation interpolants	49
2.6.2 The smoothing kernels in SPH	50
2.6.2.1 SPH kernel and genetic properties	50
2.6.2.2 Kernel Functions	51
2.6.3 Improvement of SPH approximation	54
2.6.3.1 Kernel correction	54
2.6.3.2 Kernel gradient correction	55

2.6.4 Equation of states and numerical schemes in SPH.....	56
2.6.4.1 Weakly compressible SPH (WCSPH).....	56
2.6.4.2 Truly incompressible SPH (ISPH).....	58
2.6.5 Boundary conditions.....	60
2.7 Conclusions.....	63
Chapter 3	64
Modelling of Self-Consolidating ECC Flow Using SPH.....	64
3.1 Introduction.....	65
3.2 Numerical Schemes.....	68
3.2.1 Governing equations.....	68
3.2.2 Smoothed particle hydrodynamics (SPH).....	69
3.2.2.1 Integral and summation interpolants	69
3.2.2.2 Artificial viscosity	71
3.2.2.3 Viscosity term.....	72
3.2.2.4 Weakly compressible SPH	73
3.2.2.5 Boundary conditions.....	74
3.3 Numerical Simulation Procedures.....	75
3.3.1 Fibre modelling	75
3.3.2 Rheology parameters	76
3.3.3 Time integration scheme	78
3.4 Simulation Results and Discussions	80
3.4.1 Slump flow test.....	81
3.4.2 Beam/slab moulding.....	85
3.5 Conclusions.....	89
Chapter 4	91
Flow of Self-Consolidating ECC with V-Funnel and U-Box.....	91

4.1 Introduction.....	92
4.2 Model Development.....	95
4.2.1 Constitutive rheology model	95
4.2.2 Modelling of SC-ECC flow with SPH	96
4.2.3 Flexible synthetic fibre modelling.....	98
4.2.4 Boundary particle condition	99
4.3 Initial Configuration for Computational Efficiency.....	101
4.4 Simulation Results	104
4.4.1 V-funnel test.....	104
4.4.2 U-box test	107
4.5 Influence of Steel Reinforcement on the Flow of SC-ECC and Fibre Distribution	110
4.6 Correlation between Plastic Viscosity, Flow Rate and Fibre Dispersion of SC-ECC	112
4.7 Conclusions.....	115
Chapter 5	117
Effect of Specimen Thickness on Fibre Orientation Distribution	117
5.1 Introduction.....	118
5.2 Simulation of the Moulding of Fresh SC-ECC	119
5.3 Initial Configuration.....	120
5.4 Results and Discussions	122
5.4.1 Simulation results and cutting specimens.....	122
5.4.2 Fibre orientation factor	123
5.4.3 Fibre ratio along depths of specimen	124
5.5 Conclusions.....	125
Chapter 6	127

Fibre Orientation and Distribution and Their Effects on Tensile Performance of ECC	127
6.1 Introduction	128
6.2 Methodology	132
6.2.1 Simulation of the moulding of fresh ECC at the fresh state.....	132
6.2.2 Stress-crack opening relationship for a single crack at the hardened state	132
6.3 A Benchmark Example	139
6.3.1 Moulding simulation of a beam specimen	139
6.3.2 Fibre orientation and distribution	142
6.3.2.1 Fibre orientation factor	145
6.3.2.2 Fibre distribution	147
6.3.3 Peak bridging strength at various sections	149
6.3.4 Stress-crack opening relationships of different fibre orientation distributions .	150
6.4 Conclusions	153
Chapter 7	154
Conclusions and Recommendations for Future Research	154
7.1 Summary and Conclusions.....	155
7.1.1 Modelling flowable ECC at the fresh state	155
7.1.2 Evaluation of fibre orientation and distribution and the tensile behaviour of ECC at the hardened state.....	158
7.2 Recommendations for Future Research	160
References	162

List of Figures

Figure 1.1	Tensile stress-strain behaviour of regular and high performance FRCC (Parra-Montesinos 2005).....	3
Figure 1.2	Typical tensile stress-strain crack width relationship of SC-ECC (Yang et al. 2008).....	4
Figure 1.3	Typical tensile strain-hardening $\sigma - \delta$ curve. Hatched zone signifies the complementary energy $\int \sigma d\epsilon$. Shaded zone signifies the crack tip toughness J_{tip} (Yang et al. 2008).....	7
Figure 1.4	(a) Snubbing effect; (b) Matrix spalling of an inclined fibre.	10
Figure 1.5	Lower mesoscale level of fibres bridging crack in ECC (Kabele 2007).	11
Figure 1.6	Model prediction and experimental data of $\sigma - \delta$ curve with different fibre volume fraction: (a) $V_f = 0.1\%$; (b) $V_f = 0.5\%$ (Huang et al. 2015).....	12
Figure 1.7	Schematic evaluation technique of PVA fibre dispersion (Lee et al. 2009).	15
Figure 1.8	Application of SC-ECC: (a) Link slabs of bridge deck in Michigan, USA (Lepech & Li 2009); (b) Coupling beams in the core region of multi-storey structures in Japan (Maruta et al. 2005).....	19
Figure 1.9	Measuring the diameter of flowability ECC of a slump flow test (Li 2008).....	21
Figure 1.10	Setup for V-funnel test (Okamura & Ouchi 2003).....	22
Figure 1.11	U-box device for testing self-placing ability of SC-ECC and measuring the results (Kong et al. 2003a).....	23
Figure 2.1	LBM for modelling slump flow test (Švec et al. 2012).....	34
Figure 2.2	3D simulation of SFR-SCC: (a) Slump flow test (Deeb, Kulasegaram, et al. 2014b); (b) L-box test (Deeb, Kulasegaram, et al. 2014a).....	36

Figure 2.3	Modelling of rigid fibre orientation distributions at time step t_n and t_{n+1} (Deeb, Kulasegaram, et al. 2014b).	36
Figure 2.4	(a) The moulding simulation of SCC flow; (b) corresponding steel fibres motion (Bi et al. 2017).	37
Figure 2.5	Flow chart of numerical strategy for modelling the flow of self-consolidating fibre-reinforced cement-based materials.	39
Figure 2.6	Surface forces in x-direction of a moving infinitesimal element of fluid: (a) two- dimensional space and (b) three-dimensional space.	42
Figure 2.7	The Bingham-Papanastasiou model with different m values. An approach to bi-linear Bingham fluid when $m = 5.10^4$ (Ghanbari & Karihaloo 2009).	46
Figure 2.8	Particles distribution inside and outside of support domain Ω of particle a (Violeau & Rogers 2016).	50
Figure 2.9	(a) Cubic spline and its derivative ($\kappa = 2$); (b) Comparison of the Cubic spline and Gaussian kernel functions (Li & Liu 2002).	53
Figure 2.10	Double cosine function and its derivatives ($\kappa = 2$) (Yang et al. 2014). ..	53
Figure 2.11	Flow chart showing the three steps of predictor-corrector algorithm in WCSPH.	58
Figure 2.12	Flow chart showing the predictor-corrector steps of projection method in ISPH.	59
Figure 2.13	Group methods of boundary particle conditions represent the rigid walls in SPH (Violeau & Rogers 2016).	60
Figure 2.14	Boundary particles at free-surface condition.	62
Figure 3.1	Truncated smoothing kernel at boundary.	70
Figure 3.2	Repulsive force from boundary particles to particle a.	75
Figure 3.3	Synthetic flexible fibre motion at different time steps t_{n-1} , t_n and t_{n+1}	76
Figure 3.4	Simulation results of mini cone slump flow test.	82
Figure 3.5	Simulation results of the conventional slump flow test.	83

Figure 3.6	Comparison of the flow of the conventional cone test with two plastic viscosity values as it spreads to 50cm: (a) $\mu_B = 17 \text{ Pa}\cdot\text{s}$; (b) $\mu_B = 30 \text{ Pa}\cdot\text{s}$	84
Figure 3.7	(a) Cast at the end of the mould, (b) Cast in the middle of the mould. .	85
Figure 3.8	Three parts of the completed casting specimen of case C1 shown on a large scale: (a) Part I (at the end), (b) Part II (in the middle), (c) Part III (at the other end).....	86
Figure 3.9	Three parts of the completed casting specimen of case C2 shown on a large scale: (a) Part I (at the end), (b) Part II (in the middle), (c) Part III (at the other end).....	87
Figure 3.10	Magnitude of the longitudinal velocity when the flow reached the vertical walls: (a) Case C1, (b) Case C2.....	88
Figure 4.1	Smoothing kernel W and its support domain for the approximation of a current particle a	97
Figure 4.2	Flow chart of three steps of predictor-corrector algorithm.	98
Figure 4.3	Repulsive force from boundary particles to particle a : (a) in 3D simulation; (b) in 2D simulation.....	100
Figure 4.4	Comparison of the repulsive force boundary at $t = 0.40 \text{ s}$: (a) before implementing αD ; (b) after implementing αD	101
Figure 4.5	(a) V-funnel configuration; (b) Repulsive force boundary particles, initial generated mortar and random fibre particles.....	103
Figure 4.6	(a) U-box vessel configuration; (b) Repulsive force boundary particles, initial generated mortar and random fibre particles.	103
Figure 4.7	Numerical simulation results of the V-funnel test at different time steps.	106
Figure 4.8	Numerical simulation results of the U-box test at different time steps.	109
Figure 4.9	Demonstration of the self-consolidation of SC-ECC: (a) Simulation result in this study; (b) Experimental result in (Kong et al. 2003a).....	110

Figure 4.10	Comparison of magnitude of horizontal velocity at 1.0 second: (a) ordinary U-box; (b) U-box without steel bars.	111
Figure 4.11	Fibre distribution in: (a) ordinary U-box; (b) U-box without steel bars.	112
Figure 4.12	Correlation between the viscosity and the flow rate of SC-ECC.	114
Figure 4.13	The dispersion of fibres in container box with three values of viscosity at $t = 12.5$ s after completing vacate the V-funnel.	114
Figure 5.1	Moulding of beam specimens.....	120
Figure 5.2	Initial mortar and synthetic fibre particles for beams thickness T: (a) $T = 30$ mm; (b) $T = 50$ mm; (c) $T = 100$ mm.....	121
Figure 5.3	Moulding results of three thickness beams: (a) $T = 30$ mm; (b) $T = 50$ mm; (c) $T = 100$ mm.	122
Figure 5.4	(a) Vertical and horizontal cutting planes; (b) Fibre particles intersection at multiple cutting planes.....	123
Figure 5.5	Distribution of fibre orientation factor along three beams of different thickness.	124
Figure 5.6	Fibre ratio along depths of three different thickness beams.....	125
Figure 6.1	Schematic diagram of an inclined fibre θ bridging at both sides of a crack δ	134
Figure 6.2	Comparison of model prediction and experimental data of $\sigma(\delta)$ curve: (a) $V_f = 0.1\%$; (b) $V_f = 0.5\%$	137
Figure 6.3	The $\sigma(\delta)$ relationship for a crack with different ranges of fibre inclination.	139
Figure 6.4	Initial configuration of contained funnel, fibre and mortar particles, and formwork of specimen for moulding.....	140
Figure 6.5	Flow patterns of mortar and fibre particles at four time steps during the moulding process.....	141
Figure 6.6	Bending of fibres at different times of flow.	142

Figure 6.7	Different 3D-view of fibre orientation and distribution in the specimen after completing flow.	144
Figure 6.8	Two 2D-views of fibre orientation and distribution from the top and front of the specimen and the numbered sections.	145
Figure 6.9	Schematic of two nearby fibre particles j and $j+1$ with section i	146
Figure 6.10	Variation of the average fibre orientation factor θ_i along the specimen.	147
Figure 6.11	Difference between the theoretical and simulated number of fibres... ..	148
Figure 6.12	Correlation between the number of inclined fibre and peak bridging stress at sections.	149
Figure 6.13	The variation of fibre inclination at four consecutive sections.	150
Figure 6.14	Histogram of fibre inclination at four consecutive sections.	151
Figure 6.15	Influence of fibre orientation and distribution on the $\sigma - \delta$ relationship at four consecutive sections from 102 to 105: (a) full span view; (b) magnified view of (a) with $\delta = 0 \sim 0.1$ mm.....	152

List of Tables

Table 1.1	Mix proportion by weight for SC-ECC (ECC-M45) (Lepech & Li 2008).	18
Table 1.2	Test devices for fresh SC-ECC.....	20
Table 3.1	Properties of the SC-ECC mix and polyvinyl alcohol (PVA) fibres.....	78
Table 3.2	Devices configuration and number of particles represented in the 2D simulations.....	81
Table 3.3	Comparison of slump flow tests of SC-ECC (PVA) in the simulation with experimental test data.	84
Table 4.1	The measured indices and the number of particles involve in simulations	104
Table 4.2	Comparison of the flow of SC-ECC (PVA) in the simulations with experimental test data in literature.	108
Table 5.1	The number of involved particles in simulations.	121
Table 6.1	Matrix and PVA fibre parameters (Yang et al. 2008)	134

Abstract

Fibres have been implemented in cement-based materials in an attempt to overcome their brittleness nature. This implementation has illustrated the ability to reduce or eliminate the brittleness of concrete, enhance the ductility and fracture toughness of structures using fibre-reinforced cement-based materials (FRCs). However, it has been revealed by numerous studies that there is a dissimilarity in the mechanical performance of FRCs at different parts of specimens, even casting within the same mixture. The variation of fibres/matrix interaction, which is largely influenced by the distribution and orientation of fibre in the matrix, has been identified as a main factor leading to such divergence in FRCs behaviour. This vital shortcoming has restrained the application of FRCs in large-scale on-site production and industrial construction. Previous investigations have indicated the rheology properties of the fresh mix, fibre properties, mixing and casting procedure, size of specimens and wall-effect contribute to the fibre distribution and orientation in FRCs. Nevertheless, most research on the distribution and orientation of fibres in FRCs so far is limited to rigid steel fibre.

Engineered Cementitious Composites (ECC) is a unique class of high-performance fibre-reinforced cementitious composites (HPFRCC), exhibiting high tensile ductility with the tensile strain capacity up to 5% with a moderately low synthetic fibre fraction (typically 2% or less by volume). Through micromechanics tools, ECC properties can be engineered based on applications, forming a range of ECC materials for disparate functionalities in addition to the common characteristics of high tensile ductility and multiple fine cracking. Different groups of ECC are named based on their dominant characteristics. For example, self-consolidating or flowable ECC was

developed for large-scale on-site construction applications and employed in real-scale structural members. ECC typically utilises short synthetic fibres, such as polyvinyl alcohol (PVA) or polyethylene (PE) fibres, which are tiny in diameter. These fibres are flexible, i.e., they can be bent or coiled in the matrix of ECC. Notably, the orientation of a bent or coiled fibre varies at different cross-sections of the specimen. Moreover, actual distribution of the fibre orientation can be affected by other factors such as casting techniques or the rheology of fresh mix. Hitherto, what has not been reported is a reliable approach that can provide a full understanding of the orientation and distribution of flexible synthetic fibres in the matrix of ECC and practical information regarding fibre orientation and distribution for estimating the tensile performance of ECC.

The aim of this PhD research is to model the flow behaviour of ECC and then investigate the distribution and orientation of flexible synthetic fibres and their effects on the tensile performance of ECC material. To achieve this aim, a numerical model was first developed to simulate the flow of fresh ECC, in order to gain insights into ECC flow as well as distribution and orientation of flexible synthetic fibres in the cementitious matrix of fresh ECC. The developed model particularly focused on the flow characteristics of self-consolidating or flowable ECC. The flow of self-consolidating ECC was described as a non-Newtonian viscous fluid. The Lagrangian form of the Navier-Stokes constitutive equations of fresh ECC was solved using a mesh-free, smoothed particle hydrodynamics method. The flexible synthetic fibre in ECC was modelled as separate particles in the computational domain, which possessed identical continuum properties as mortar particles except for the drag force between two adjacent fibre particles.

The developed models were then validated by several standard tests through simulating the flow of self-consolidating ECC, including the flow cone tests, V-funnel and U-box tests. Numerical results were found to be consistent with the experimental test data obtained from the literature. Through these validations, the proposed model has proved its capability of providing insight into the flow behaviour of self-consolidating ECC in terms of filling, passing abilities and the distribution/orientation of flexible synthetic fibres. A simple technique was then proposed for evaluating the orientation distribution of flexible synthetic fibres at various sections of a simulated specimen after the fresh ECC stopped flowing in the mould. The influence of specimen thickness on the orientation of synthetic fibres in ECC was also numerically investigated through the simulation the casting of fresh self-consolidating ECC into different thicknesses of moulds. The bending phenomenon of flexible synthetic fibres and its influence on the distribution of fibre orientations were also studied.

Over the years, since the stress-crack opening relationship of a single crack at the lower mesoscale of ECC crucially governs the stress strain-hardening at its macroscale composite structure, several fibre-bridging constitutive models have been developed. However, although the two-way pullout mechanism of fibre, micro-matrix spalling and Cook-Gordon effects were considered in these models, the prediction of the stress-crack opening relationship still showed a remarkable difference compared to the experimental test data. To take advantage on the understanding of the orientation distribution of flexible synthetic fibres from the developed model above, a novel fibre-bridging model was also developed in this thesis. In this innovative model, the relationship between fibre stress and its displacement when bearing the stress released from the cracked matrix was derived through considering the two-way pullout mechanisms of an arbitrary inclined

fibre. Consequently, the findings of the proposed fibre-bridging model reveal much better agreements with the experimental testing data in comparison with existing models, especially during the pullout stage of fibre. Finally, a novel approach was proposed for estimating the tensile performance of ECC through the developed models at two states of ECC above. The information of fibre orientation and distribution at different cross-sections of a moulding specimen were incorporated into the developed fibre-bridging model to estimate the tensile behaviour of ECC. With this strategy, the distinct effects of fibre orientation and distribution on the tensile behaviour of ECC were also exposed.

Although the flowable ECC has garnered much attention in this work, the developed models in this thesis have great engineering potential for applications of other ECC. Extrudable or printable ECC, for instance, exhibits self-reinforcing properties being emerged as an encouraging material for 3D printing concrete. In this regard, modelling the extrusion process can be valuable for observing and evaluating the orientation and distribution of flexible fibres at each print filament. Moreover, modelling of extrudable ECC at the fresh state is worthwhile, and help us to understand the influences of its rheology properties on the deformation of filaments and stability of printed structures. If successful, this can save a huge amount of materials and effort on 3D printing research using ECC.