UNIVERSITY OF TECHNOLOGY SYDNEY

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

**by Hai Tran Thanh**

Thesis submitted in fulfilment of the requirements for the degree of

**Doctor of Philosophy**

under the supervision of Professor Jianchun Li, A/Professor Yixia Zhang and Dr. Jianguo Wang

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January 2021

# 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.

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

This research is supported by the Australian Government Research Training Program.

Signature of Candidate

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Date: January 4, 2021

# Acknowledgements

First of all, I would like to express my sincere gratefulness to my principal supervisor, Professor Jianchun Li, for his great supervision, tremendous support and constant inspiration during my PhD study at the Centre for Built Infrastructure Research, University of Technology Sydney (UTS). I would also wish to thank my external supervisor, Associate Professor Yixia Zhang from Western University of Sydney for her helpful discussions and papers revision, and my co-supervisor Dr. Jack Wang at UTS for his helpful suggestions.

I would like to acknowledge the joint scholarship between VIED 911 scheme of Vietnamese Government and UTS, Australia, for sponsoring this research.

I would also like to thank all my friends and colleagues at UTS for making my time here enjoyable and memorable.

And finally, I want to dedicate all the works in this thesis to my beloved family for their endless encouragement and unconditional love. An exceptional and heartfelt thanks to my wife, Hang Duong, and my two sons, Ben and Bao, for their love and sacrifices throughout stages of my study.

# Publications from this Thesis

In this thesis, the research contents of Chapter III, IV, and V have been published, and Chapter VI has been submitted for publication.

**Journal Papers**

1. Thanh, H.T., Li, J. & Zhang, Y. 2019, 'Numerical modelling of the flow of self-consolidating engineered cementitious composites using smoothed particle hydrodynamics', *Construction and Building Materials*, vol. 211, pp. 109-19, (Chapter III).

2. Thanh, H.T., Li, J. & Zhang, Y.X. 2020, 'Numerical simulation of self-consolidating engineered cementitious composite flow with the V-funnel and U-box', *Construction and Building Materials*, vol. 236, p. 117467, (Chapter IV).

3. Thanh, H.T., Li, J. & Zhang, Y.X. 2021, 'A novel approach for evaluating the orientation and distribution of fibre and their effects on the tensile performance of ECC', submitted to Cement and Concrete Composites and under review (Chapter VI).

**Conference Paper**

1. Thanh, H.T., Li, J. & Zhang, Y.X. 2020, 'Numerical evaluation the effect of specimen thickness on fibre orientation in self-consolidating engineered cementitious composites', RILEM-fib International Symposium on Fibre Reinforced Concrete, Springer, pp. 661-9, (Chapter V).

**Book Chapter**

1. Thanh, H.T., Li, J. & Zhang, Y. 2022, 'Numerical modelling of the flow of self-consolidating engineered cementitious composites using smoothed particle hydrodynamics', Advances in Engineered Cementitious Composites: Materials, Structures and Numerical Modelling. To be published in January 2022.

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# 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.