



Simulating the mechanics of ultra-high performance fibre reinforced concrete for rapid low cost material development and analysis

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Abstract

The addition of randomly distributed fibres significantly alters the performance of reinforced concrete elements. Fibres that bridge flexural cracks provide a concrete tensile force in addition to that of conventional reinforcement. These enhance member flexural capacity, and reduce member deflection and crack width. Fibres that bridge sliding planes in the compression region allow for stable sliding during the formation of concrete softening wedges, leading to an increase in member ductility during overload scenarios. Together, these improvements in performance make fibre reinforced concrete an ideal construction material for structures of high importance.

A significant amount of testing has quantified the improvement in concrete material properties (compressive and tensile stress strain behaviour) arising due to the addition of fibres. It is however difficult to incorporate these directly into existing strain based member analysis approaches as they cannot directly accommodate the rigid body deformations which occur as during crack formation and widening and wedge sliding. That is traditional approaches cannot model the behaviours most strongly influenced by fibres. This project seeks to address this shortcoming by quantifying the fundamental mechanics that govern the flexural behaviour of fibre reinforced concrete.

Having quantified the fundamental mechanics of fibre reinforced concrete, it is shown how these can be applied to reduce the cost and increase the speed of developing new types of fibre reinforced concrete. This is important as the almost infinite combination of fibre type and dosage rates make empirically based design approaches unfeasible.

The remainder of the report is presented through a series of published and submitted manuscripts as follows.

Chapter 1 contains the paper ‘Fundamental mechanics that govern the flexural behaviour of reinforced concrete beams with fibre-reinforced concrete’. This paper describes the influence of fibres on the fundamental mechanisms of crack formation, tension stiffening and concrete

to concrete sliding. It is shown how the influence of fibres on these fundamental mechanics can be incorporated into numerical analyses, an example is provided in terms of predicting the strength, ductility and crack width behaviour of normal strength concrete beams and columns with a small quantity of steel fibres.

Chapter 2 contains the submitted manuscript titled: ‘Time dependent tension stiffening mechanics of fibre reinforced and ultra-high performance fibre reinforced concrete’. This work takes the tension stiffening mechanics formulated and solved numerically in chapter 1 and shows how it can be solved analytically with closed form solutions. This forms a significant first step towards developing design procedures for UHPFRC. Importantly, the solutions developed are generic enough to take any form of material tensile response, and unlike the current state-of-the-art do not require calibration from experimental testing.

Chapter 3 contains the 3 submitted manuscripts and 1 departmental report: ‘Blending Macro and micro fibres to enhance the serviceability behaviour of UHPFRC’, ‘Shear friction behaviour of ultra-high performance fibre reinforced concrete’, ‘Local bond slip behaviour of steel reinforcing bars embedded in UHPFRC’ and the report ‘Compressive stress-strain behaviour of UHPFRC.’ These manuscripts describe suggested experimental procedures required to extract the fundamental material properties required for the generic analysis approaches developed in chapter 2 and 3. In each paper, after presenting an experimental procedure an example of application is carried out on UHPFRC with blended fibres.

Chapter 4 rounds out the project by showing how each of the approaches and experimental procedures in chapters 1-3 can be applied to simulate the full load deflection response of a series of UHPFRC beams and slabs. Significantly, the manuscript ‘Mechanics of the flexural behaviour of UHPFRC beams under instantaneous and sustained loading’ shows how only a small quantity of cheap, small scale tests are required to extract the relevant information required to predict the load deflection and load crack width behaviour of UHPFRC at all load levels.

This research has: (i) identified the fundamental mechanisms influenced by the presence of fibre reinforcement; (ii) shown how each of these mechanisms can be modelled numerically; (iii) developed simple and cheap experimental procedures for extracting each of the material models required for analysis and; (iv) shown how the analysis techniques and material tests can be applied to predict the full range behaviour of UHPFRC flexural members. Significantly, this should reduce the need for undertaking large scale member tests thereby increasing the speed and reducing the cost of material development.

Future research is suggested to further develop analytical solutions for mechanisms influenced by fibre reinforcement (similar to those developed in Chapter 2 for tension stiffening). This research could then be applied: (i) directly as a design approach for consulting engineers; (ii) as the basis of fast running numerical models, or; (iii) as the basis for desktop studies into how specific material behaviour influences member behaviour, without the need for empirical testing.

List of Publications and Significant Collaborations that resulted from your AOARD supported project:

a) Papers published in peer reviewed journals:

- Visintin, P. and Oehlers, D.J., 2017. Fundamental mechanics that govern the flexural behaviour of reinforced concrete beams with fibre-reinforced concrete. *Advances in Structural Engineering*, p.1369433217739705.

b) Manuscripts submitted but not yet published:

- Sturm, A.B., Visintin, P. Oehlers, D.J., Seracino, R. (2017). Time dependent tension stiffening mechanics of fibre reinforced and ultra-high performance fibre reinforced concrete. *Submitted to ASCE Journal of Structural Engineering*.
- Visintin, P., Sturm, A.B., Mohamed Ali, M.S., Oehlers, D.J. (2017). Blending Macro and micro fibres to enhance the serviceability behaviour of UHPFRC. *Submitted to Cement and Concrete Composites*
- Sturm, A.B., Visintin, P. Farries, K., Oehlers, D.J. (2017). Shear friction behaviour of ultra-high performance fibre reinforced concrete. *Submitted to ASCE Journal of Materials in Civil Engineering*.
- Sturm, A.B., Visintin, P. (2017). Local bond slip behaviour of steel reinforcing bars embedded in UHPFRC. *Submitted to Structural Concrete*.
- Sturm, A.B., Visintin, P., Oehlers, D.J. (2017). Mechanics of the flexural behaviour of UHPFFRC beams under instantaneous and sustained loading. *Submitted to Engineering Structures*.

c) Manuscripts published as departmental reports:

- Sturm, A.B., Visintin P. (2017). Compressive stress-strain behaviour of UHPFRC. *Departmental Report, No. R198*, School of Civil, Environmental & Mining Engineering, University of Adelaide, Adelaide, South Australia, Australia.

Attachments: Publications in categories a), b) and c) listed above.

Chapter 1

- Visintin, P. and Oehlers, D.J., 2017. Fundamental mechanics that govern the flexural behaviour of reinforced concrete beams with fibre-reinforced concrete. *Advances in Structural Engineering*, p.1369433217739705.

Chapter 2

- Sturm, A.B., Visintin, P. Oehlers, D.J., Seracino, R. (2017). Time dependent tension stiffening mechanics of fibre reinforced and ultra-high performance fibre reinforced concrete. *Submitted to ASCE Journal of Structural Engineering*.

Chapter 3

- Visintin, P., Sturm, A.B., Mohamed Ali, M.S., Oehlers, D.J. (2017). Blending Macro and micro fibres to enhance the serviceability behaviour of UHPFRC. *Submitted to Cement and Concrete Composites*
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Compressive stress-strain behaviour of UHPFRC

Sturm, A.B. and Visintin, P.

ABSTRACT

In this paper the compressive behaviour of UHPFRC manufactured from conventional materials and reinforced with a blend of short straight and long hooked steel fibres is experimentally characterised. To achieve this 18 tests were performed on 210 mm x 100 mm x 50 mm prisms to determine the stress-strain relationship and 43 tests were performed on cylinders to determine the compressive strength, elastic modulus and Poisson's ratio. Shrinkage prisms were also monitored for 5 of the 6 mix designs. From this, the blending of fibres was found to effect the residual compressive stress-strain behaviour however other parameters were unaffected.

INTRODUCTION

UHPFRC is an advanced concrete technology first developed in Denmark in 1986 by Aalborg Portland (Buitelaar 2004). This material is characterised by the very low water to binder ratios (<0.2) as well as the removal of coarse aggregates and the introduction of steel fibres. The low water contents serve to cause a reduction in porosity resulting in a dense concrete matrix. The removal of coarse aggregates removes defects that can be a source of microcracks under compressive loads. Finally, the introduction of fibres results in strain hardening and ductile behaviour under tension. The introduction of fibres however complicates the development of mix designs due to the variety of different fibres that are available, particularly as previous research (Markovic 2006) has indicated that blends of fibres can have synergistic effects.

In this paper a number of key design material properties will be evaluated. These include the compressive stress-strain relationship, concrete strength, elastic modulus and the Poisson's ratio. The last parameter is important as it relates the axial and lateral stress-strain relationships within the elastic regime. It also allows the determination of the shear modulus from the elastic modulus. The development of shrinkage was also monitored.

MIX DESIGN

The mix design is based on that proposed by Sobuz et al. (2017) and is shown in Table 1.

Table 1. Mix design for experimental programme

Mix designation	Cement (kg/m ³)	Sand (kg/m ³)	Silica fume (kg/m ³)	Water (kg/m ³)	Superplasticiser (kg/m ³)	Macro fibres (kg/m ³)	Micro fibres (kg/m ³)
No fibres	978	973	260	171	44	0	0
1 Macro: 0 Micro	950	951	253	161	43	222	0
0.6 Macro: 0.4 Micro	950	945	253	166	43	88	133

0.5 Macro: 0.5 Micro	950	944	253	167	43	111	111
0.4 Macro: 0.6 Micro	950	944	253	167	43	133	88
0 Macro: 1 Micro	950	943	253	168	43	0	222

The macrofibres were 35 mm long and 0.55 mm diameter hooked end steel fibres with a yield strength of 1100 MPa and the microfibres were 13 mm long and 0.5 mm diameter straight steel fibres with a yield strength of 2850 MPa. The sulphate resisting cement had a fineness modulus of 365m²/kg, a 28 day compressive strength as determined in accordance with AS 2350.11-2006 (Standards Australia 2006a) of 60MPa and a 28 day mortar shrinkage strain determined in accordance with AS 2350.13-2006 (Standards Australia 2006b) of 650x10⁻⁶/mm was used along with an undensified silica fume that had a bulk density of 625 kg/m³. The sand was a washed river sand and had a fineness modulus of 2.34. A third generation high range water reducer with an added retarder was used to improve the workability

The mixing procedure consisted of first mixing all the dry components for 1 minute in the pan mixer until well combined. The water and superplasticiser were then added and the concrete mixed until visibly flowable. After the concrete started to flow, the fibres were added and mixed for a further 5 minutes.

TEST SETUPS

Compressive stress-strain relationship

The compressive stress-strain relationship was obtained from prisms with the dimensions highlighted in Fig. 1(a-b). The prisms were loaded at 0.07 mm/min until the peak load was reached, then 1 mm/min till a displacement of 5 mm was reached and finally at 2 mm/min until a displacement of 20 mm was reached. The deformation was measured by four LVDTs situated platen to platen. A failed specimen demonstrating a sliding wedge type failure is illustrated in Fig. 1(c).

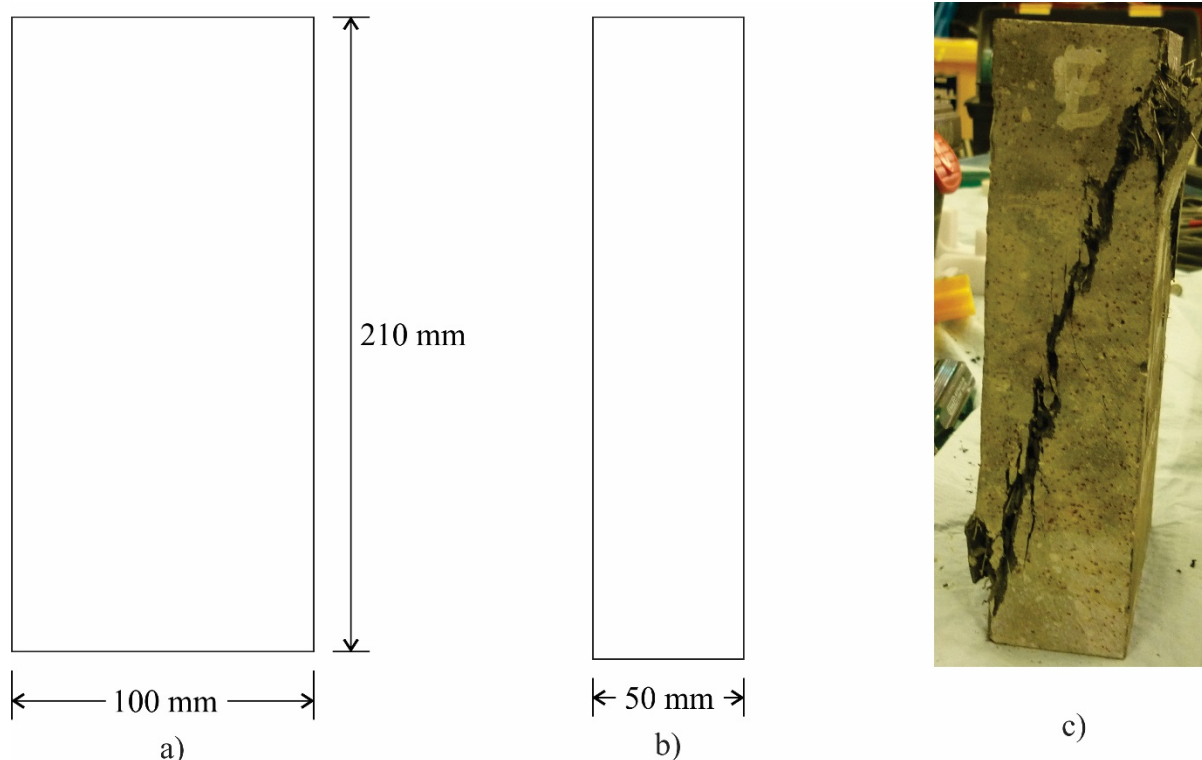


Figure 1. Compression prism

Compressive Strength, Density, Elastic Modulus and Poisson's Ratio

The density, compressive strength, elastic modulus and Poisson's ratio was estimated from cylinders with dimensions illustrated in Fig. 2(a-b). For each specimen the density was determined by weighing the specimens and measuring the dimensions. For specimens without strain gauges the compressive strength was simply obtained in accordance with AS1012.9-1997 (Standards Australia 1997a). This involved loading the specimen in uniaxial compression at a rate of 20 MPa/min until the peak load was reached. A failed specimen is indicated in Fig. 2(c). For the specimens with strain gauges the elastic modulus, Poisson's ratio and compressive strength was obtained. First the elastic modulus and Poisson's ratio were determined according to AS1012.17-1997 (Standards Australia 1997b). This involved loading and unloading the specimen up to 40% of the peak compressive load for five cycles of which the last two were recorded to determine the elastic modulus and Poisson's ratio. A load rate of 15 MPa/mm was utilised at this stage of the test. Following this the cylinder was then loaded up to failure at 20 MPa/mm as was done for the specimens without strain gauges. Note that the specimens without strain gauges were tested first to determine the appropriate peak load for determining the elastic modulus and Poisson's ratio. For the strain gauged specimens two vertical strain gauges were provided on each side to determine the elastic modulus and two horizontal strain gauges were provided on each side to determine the Poisson's ratio.

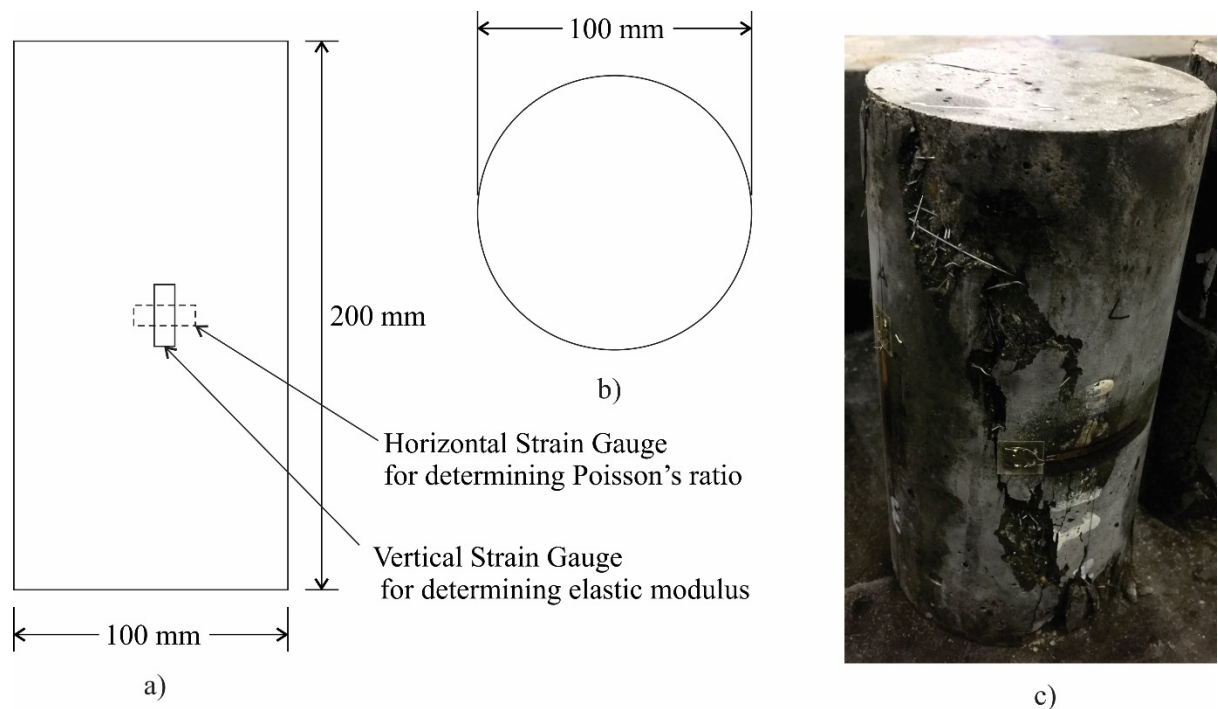


Figure 2. Compression cylinder

Shrinkage

For five of the six mixes (excluding 1 Macro: 0 Micro) the total shrinkage was monitored on 75 mm x 75 mm x 275 mm concrete prisms in accordance with AS1012.8.4:2015 (Standards Australia 2015).

TEST RESULTS

Compressive stress-strain relationship

The average compressive stress-strain relationships for each mix are shown in Fig. 3 while the individual results are shown in Appendix A. From this it can be seen that for the mix without fibres due to the very high brittleness of this specimen failed immediately at the peak load without a post-peak response. For the specimens with fibres it can be seen that the stress-strain relationship is approximately tri-linear with an elastic ascending phase followed by a steep descending phase followed by a residual branch. 0 Macro: 1 Micro had the highest residual strength followed by 0.4 Macro: 0.6 Micro. The lowest residual strength was for 0.5 Macro: 0.5 Micro.

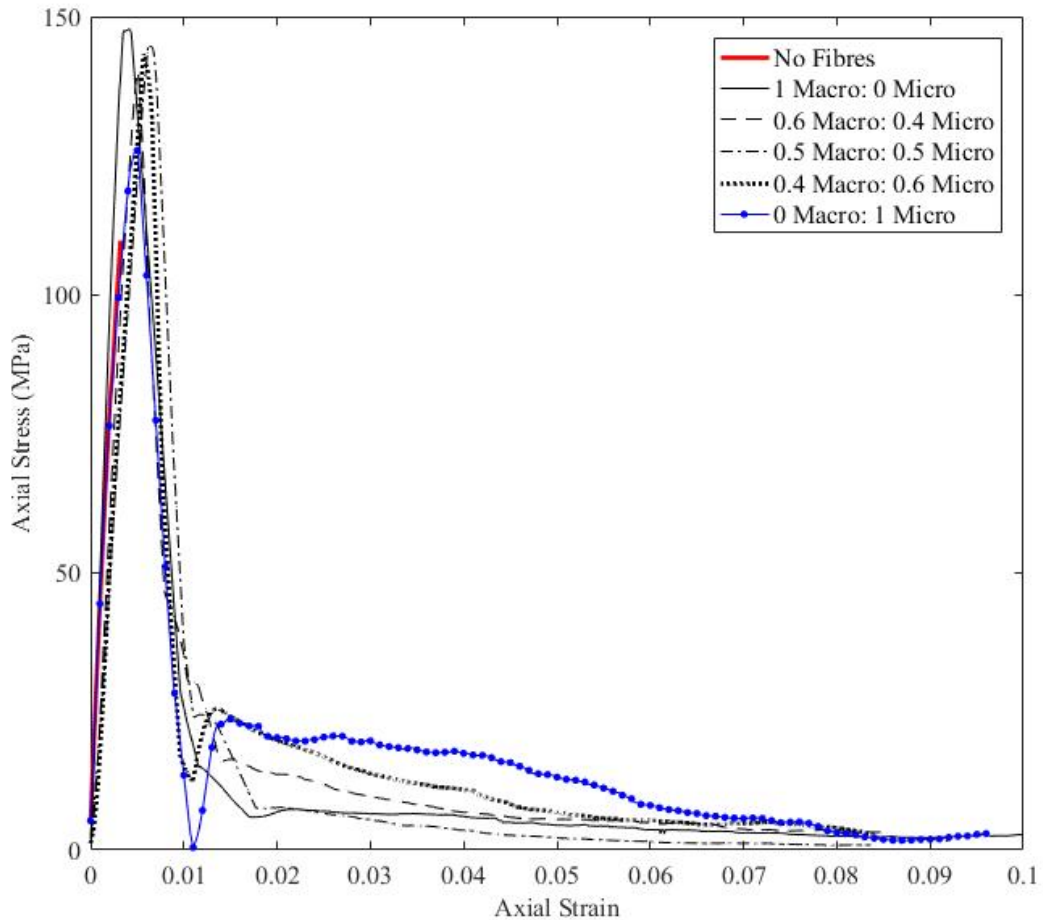


Figure 3. Average compressive-stress strain behaviour for each mix

Compressive Strength and Density

For 1 Macro: 0 Micro 5 specimens were tested at 27 days and 3 specimens were tested at 40 days with one specimen tested at 219 days. For all the other mixes for the first two testing times 3 specimens were tested and one specimen was tested at the final test time. The results are contained in Table 2 and plotted versus time in Fig. 4. From Fig. 4 it can be seen that there is negligible strength development after 20 days and that there appears to be negligible effect due to the presence of fibres as well. Considering all the results together the mean compressive strength is 158.6 MPa and the characteristic strength is 146.0 MPa.

The density was also measured for each specimen. It was noted that due to the higher density of steel (7850 kg/m^3) the density of the concrete with 2% fibres was 8% higher than that without fibres. The average density of UHPC without fibres was 2328 kg/m^3 and the upper characteristic value of the density is 2340 kg/m^3 . The average density of the UHPFRC was 2517 kg/m^3 and the upper characteristic value of the density is 2549 kg/m^3 .

Table 2. Compressive strength and density

Mix	Age at Testing (days)	f_c (MPa)	ρ (kg/m ³)	Age at Testing (days)	f_c (MPa)	ρ (kg/m ³)	Age at Testing (days)	f_c (MPa)	ρ (kg/m ³)
No Fibres	29	150	2330	54	169	2325	166	172	
1 Macro: 0 Micro	27	160	2535	40	171	2542	219	167	2546
0.6 Macro: 0.4 Micro	27	157	2513	48	157	2513	99	162	2522
0.5 Macro: 0.5 Micro	63	151	2506	84	157	2522	142	150	2527
0.4 Macro: 0.6 Micro	44	156	2509	65	157	2511			
0 Macro: 1 Micro	24	154	2500	48	156	2489	157	164	2517

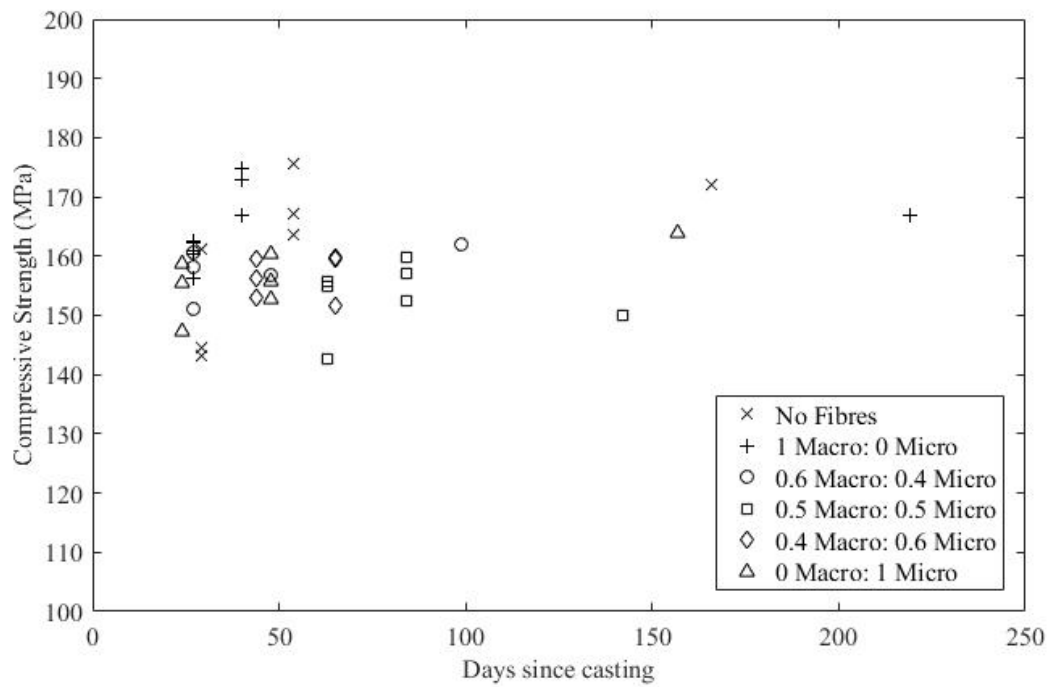
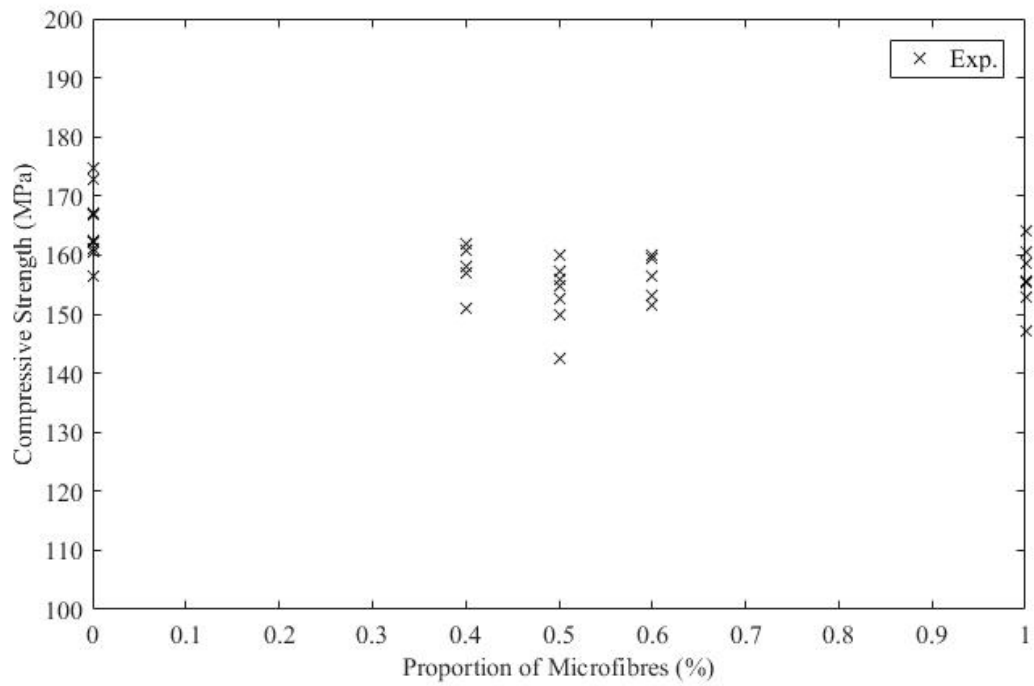


Figure 4. Compressive strength versus proportion of microfibres and age

Elastic Modulus and Poisson's Ratio

In Table 3 the elastic modulus and Poisson's Ratio is recorded for each testing period. For 1 Macro: 0 Micro three specimens were tested at each testing period and for the first testing period for No Fibres and 0 Macro: 1 Micro. For the remaining testing periods only one specimen was tested. The average elastic modulus is 49900 MPa and the lower characteristic value is 46000 MPa. The average Poisson's ratio is 0.226 and the characteristic value is 0.208. The values of the elastic modulus and Poisson's ratio do not appear to be effected by age of testing or fibres.

Table 3. Density, Elastic modulus and Poisson's ratio

Mix	Age at Testing (days)	E_c (MPa)	ν	Age at Testing (days)	E_c (MPa)	ν
No Fibres	29	48158	0.231	54	47864	0.227
1 Macro: 0 Micro	27	51061	0.224	40	48453	0.227
0.6 Macro: 0.4 Micro	27	49073	0.217	48	52013	0.229
0.5 Macro: 0.5 Micro	63	49314	0.204	84	58202	0.259
0.4 Macro: 0.6 Micro	44	50060	0.230	65	51521	0.226
0 Macro: 1 Micro	24	50402	0.227	48	49538	0.229

Note: E_c is the elastic modulus and ν is the Poisson's Ratio

Shrinkage

In Fig. 5 the smoothed shrinkage results are shown, with the individual results shown in Appendix B. From the plots it can be seen that the shrinkage strain develops quickly till about 40 days followed by a long plateau. There is considerable variation in the shrinkage strains developed but this appears to be a function of the time at which the concrete was cast and cured as opposed to fibre type. It should be seen that higher shrinkage values were obtained for the concrete cast during the summer while lower shrinkage values were obtained for concrete cast later during the autumn. This indicates that the environment effects the shrinkage behaviour of this material.

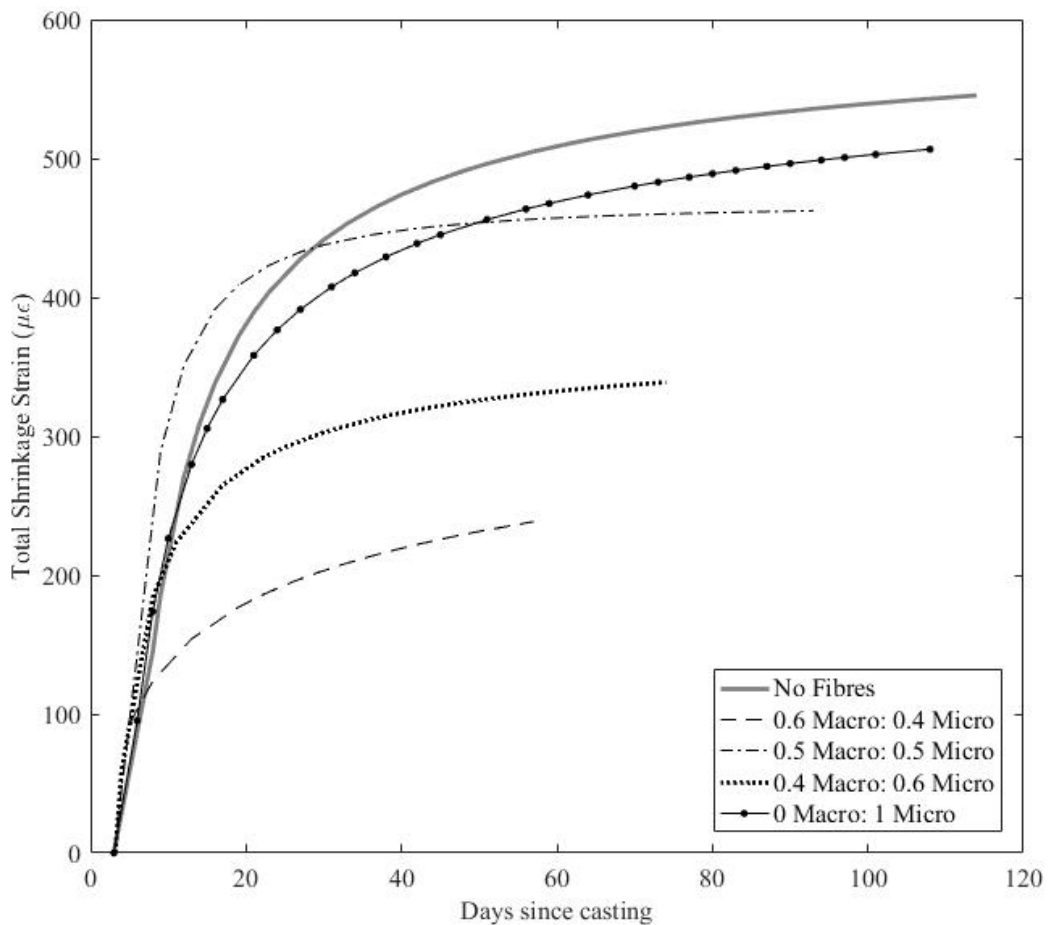


Figure 5. Variation of shrinkage with time

CONCLUSION

For a UHPFRC manufactured from conventional materials a series of key parameters for design have been characterised including: the axial stress strain relationship, compressive strength, elastic modulus, density, Poisson's ratio and shrinkage. It was found that the fibre type has some effect on the residual compressive behaviour however the other parameters were unaffected. However, the quantity of shrinkage appears to be effected by the environmental effects.

APPENDIX A RAW STRESS-STRAIN RESULTS

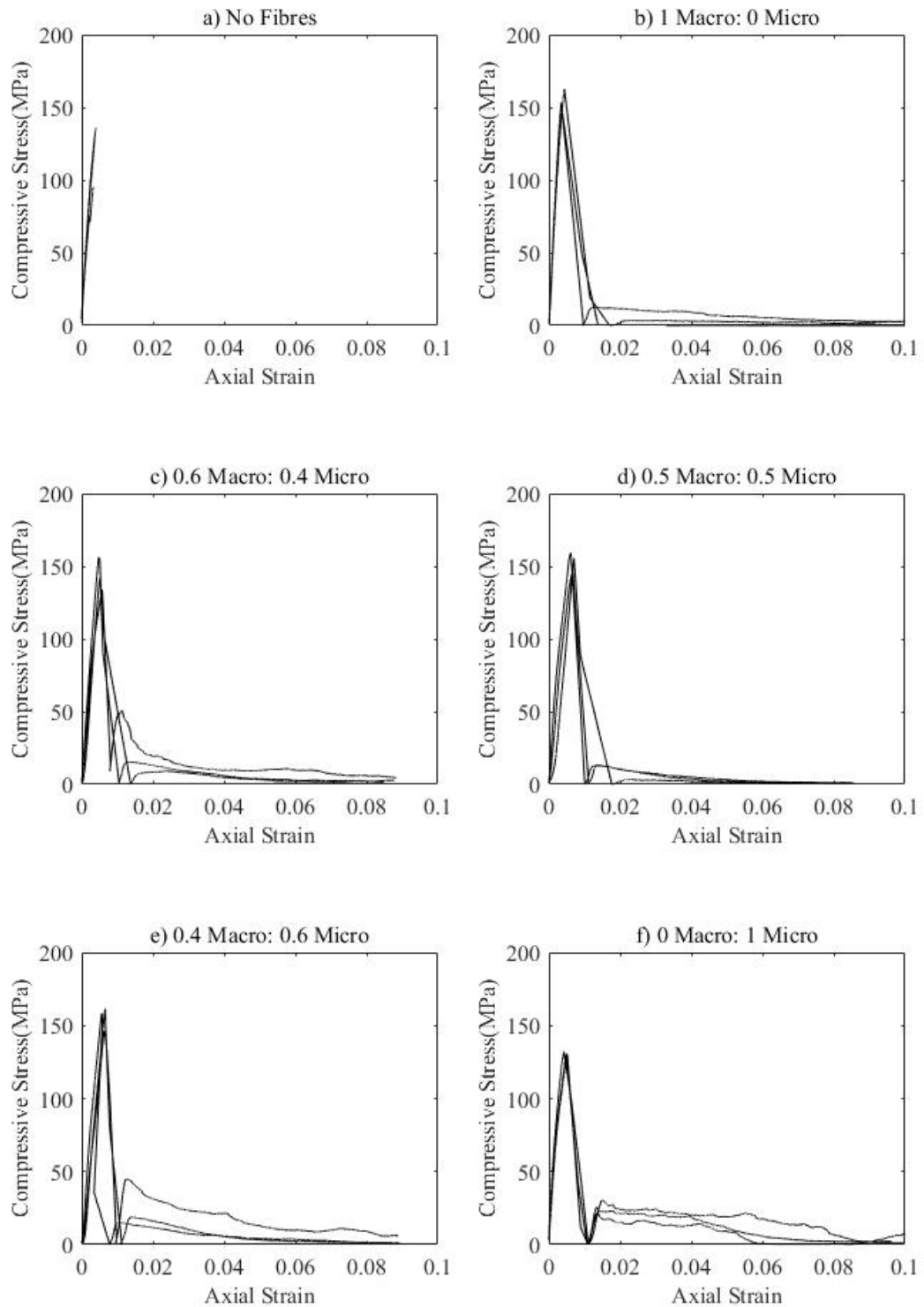


Figure A1. Compressive stress-strain relationship

APPENDIX B RAW SHRINKAGE RESULTS

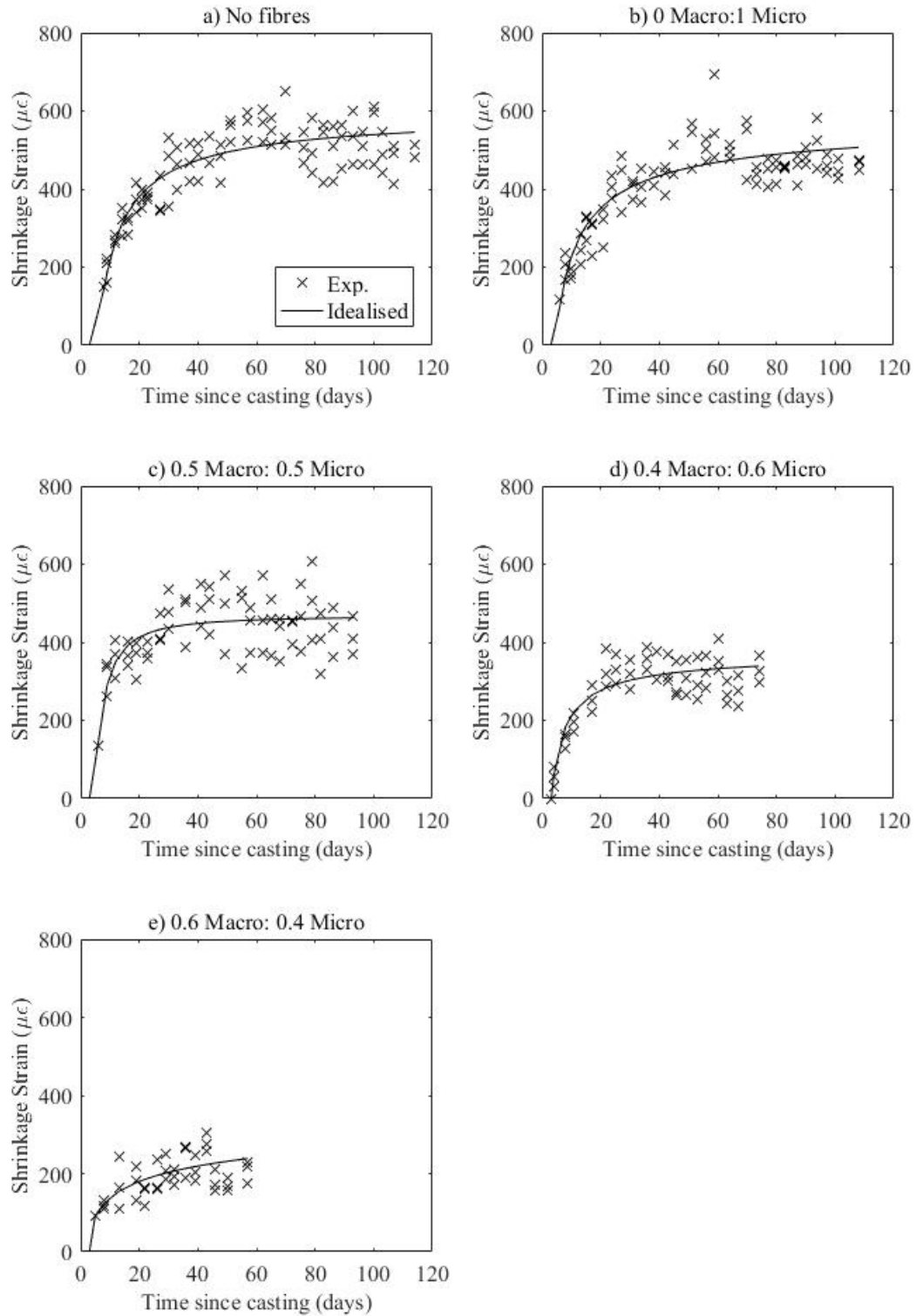


Figure B1: Variation of shrinkage with time

ACKNOWLEDGEMENTS

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Chapter 4

- Sturm, A.B., Visintin, P., Oehlers, D.J. (2017). Mechanics of the flexural behaviour of UHPFFRC beams under instantaneous and sustained loading. *Submitted to Engineering Structures*.