Experimental Study of UHPC with High Fire Resistance and Meso-Scale Modelling

by

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CERTIFICATE OF ORIGINAL AUTHORSHIP

I certify that the work in this thesis has not previously been submitted for any degree nor has it been submitted as part of requirements for a degree except as fully acknowledged within the text.

I also certify that the thesis has been written by me. And help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

Xiangwei Liang

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LIST OF NOTATIONS

ΔU	change of system internal energy
ΔKE	change of system kinetic energy
ΔPE	change of system potential energy
λ	thermal conductivity
λ_0	thermal conductivity of plain concrete
λ_c	thermal conductivity of concrete
λ_s	thermal conductivity of steel fibre
ϕ_q	heat flux
1D	one-dimensional
2D	two-dimensional
3D	three-dimensional
σ	stress
σ_s	compressive stress in sample
ε	strain
ε_u	ultimate strain

ε_{uT}	ultimate strain under high temperature
ε_r	strain measured on reflection bar
ε_s	strain in sample
$\dot{\varepsilon}_s$	strain rate in sample
ε_t	strain measured on transmission bar
A	cross-section area or contacting area
A_b	bond area
A_s	cross-section area of sample
c	specific heat
c_0	wave velocity
c_c	specific heat of concrete
c_s	specific heat of steel fibre
D	diameter
DA	damage parameter
E	modulus of elasticity
E_0	initial modulus of elasticity

E_{0T}	initial modulus of elasticity under high temperature
E_s	modulus of elasticity of steel fibre
EXP	exponent in damage curve
f	force
f_c	compressive strength
$f_{c20°C}$	compressive strength under 20 °C or room temperature
f_{cT}	compressive strength under high temperature
f_y	yield strength
GB	bond shear modulus
h	convection or film coefficient
l_s	length of sample
q	rate of heat transfer
Q	heat
Q-0	UHPC sample with quartz sand as aggregate but without any fibre
Q-P	UHPC sample with quartz sand as aggregate and with PP fibre
Q-S	UHPC sample with quartz sand as aggregate and with steel fibre

Q-SP	UHPC sample with quartz sand as aggregate and with hybrid PP fibre and steel fibre
R_e	outer radius
S-0	UHPC sample with steel slag as aggregate but without any fibre
S-SP	UHPC sample with steel slag as aggregate and with hybrid PP fibre and steel fibre
$S_{\max}$	the maximum elastic slip
t	time
T	temperature
T_b	temperature of contacting fluid
T_s	temperature of solid surface
u	slip strain per unit length
$u_{\max}$	the maximum slip strain
v	velocity
V	volume
V_f	fibre content by volume
vol.	volume

U	internal energy
W	work

LIST OF ACRONYMS

BFS	Boundary Face Subdivide
CH	calcium hydroxide
C-S-H	calcium silicate hydrate
CFS	constraining facet set
CPS	constraining point set
CSS	constraining segment set
DOF	degree of freedom
DTeS	Delaunay tetrahedron set
DTS(CF)	Delaunay triangle set of constraining facets
FEA	finite element analysis
FRC	fibre reinforced concrete
FSI	Facet Subdivide Iterative
GGBFS	ground granulated blast furnace slag
HPC	high performance concrete
HSC	high strength concrete
K&C	Karagozian & Case

LDPM	lattice discrete particle model
NSC	normal strength concrete
PP	polypropylene
RC	reinforced concrete
RHT	Riedel, Hiermayer and Thoma
SCC	self-consolidating concrete
SCC-S	self-consolidating concrete reinforced with steel fibre
SHPB	split Hopkinson pressure bar
SFRC	steel fibre reinforced concrete
SSI	Segment Subdivide Iterative
UHPC	ultra-high performance concrete
UHPFRCC	ultra-high performance fibre-reinforced cementitious composites

TABLE OF CONTENTS

CERTIFICATE OF ORIGINAL AUTHORSHIP i

ACKNOWLEDGEMENT ii

LIST OF PUBLICATIONS iii

LIST OF NOTATIONS v

LIST OF ACRONYMS x

TABLE OF CONTENTS xii

LIST OF FIGURES xviii

LIST OF TABLES xxv

ABSTRACT xxviii

1 INTRODUCTION 2

- 1.1 Background 2
- 1.2 Research objectives and scope 5
- 1.3 Research methodology 6
  - 1.3.1 Development of UHPC with high fire resistance 6
  - 1.3.2 Quasi-static tests of UHPC exposed to high temperatures 6
  - 1.3.3 SHPB tests of UHPC under high temperatures 7
  - 1.3.4 Numerical simulation of thermal conductivity of UHPC 7
  - 1.3.5 Numerical simulation of mechanical properties of UHPC 8
- 1.4 Research significance and contribution to knowledge 8
- 1.5 Layout of the thesis 9

2 LITERATURE REVIEW 12

2.1 Concretes under impact loading 12

2.2 Concretes exposed to elevated temperature 13

2.3 Concretes under combined effect of elevated temperature and impact loading 18

2.4 HPC & UHPC under elevated temperature or combined effect of elevated temperature and impact loading 27

2.5 Effect of steel fibre on thermal conductivity of SFRC/UHPC 31

2.6 Meso-scale modelling of SFRC/UHPC on thermal properties 32

2.7 Meso-scale modelling of SFRC/UHPC on mechanical properties 33

2.8 Bond-slip behaviour of steel fibre in UHPC under elevated temperature 36

2.9 Gap in knowledge 38

3 DEVELOPMENT OF UHPC WITH HIGH FIRE RESISTANCE 41

3.1 Materials 41

3.2 Mixture proportioning 43

3.3 Specimen preparation and tests 45

3.4 Mass loss 48

3.5 Control of explosive spalling 49

3.5.1 Effect of heating rate on explosive spalling 49

3.5.2 Explosive spalling of specimens without PP fibres 51

3.5.3 Explosive spalling of specimens with PP fibres 54

3.6 Quasi-static compression tests 56

3.6.1 Specimens without PP fibres 56

3.6.2 Specimens with PP fibres 59

3.7 Summary 67

4 COMPRESSIVE STRENGTH OF UHPC SUBJECTED TO COMBINED EFFECT OF ELEVATED TEMPERATURE AND IMPACT LOADING 70

4.1 Experimental details.. 70

4.1.1 Specimen preparation.. 70

4.1.2 Experimental setup and methodology.. 71

4.2 Results and discussion 75

4.2.1 Explosive spalling and colour changes 75

4.2.2 SHPB tests under high temperatures.. 77

4.2.2.1 Effect of temperature on strain rate.. 77

4.2.2.2 Damage appearances of specimens subjected to combined loading....... 79

4.2.2.3 Dynamic compressive strength under combined loading 80

4.2.2.4 Modulus of elasticity under combined loading...................................... 84

4.3 Summary 86

5 TENSILE STRENGTH OF UHPC SUBJECTED TO COMBINED EFFECT OF ELEVATED TEMPERATURE AND IMPACT LOADING 89

5.1 Experimental details.. 89

5.2 Results and discussion 91

5.2.1 Static splitting tensile tests at high temperatures 93

5.2.1.1 Failure appearances under static tests 93

5.2.1.2 Static splitting tensile strength 93

5.2.1.3 Comparison between static tensile strength and compressive strength at high temperatures.. 95

5.2.2 Dynamic splitting tensile tests at high temperatures..................................... 96

5.2.2.1 Failure appearances under dynamic tests 96

5.2.2.2 Dynamic splitting tensile strength under combined loading 97

5.2.2.3 Comparison between tensile strength and compressive strength under combined loading 99

5.2.2.4 Comparison between strengths obtained in hot state and cooled down state 101

5.3 Summary 102

6 NUMERICAL STUDY OF THERMAL PROPERTIES OF SFRC/UHPC USING MESO-SCALE MODELLING 105

6.1 Model preparation 105

6.1.1 Generation of geometric model 105

6.1.2 Mesh generation with Delaunay triangulation 106

6.2 Thermal parameters and material models 109

6.3 Model validation 112

6.4 Simulation results and discussion 116

6.4.1 Effect of model thicknesses on simulation outcomes of thermal conductivity 117

6.4.2 Effect of fibre content on thermal conductivity 119

6.4.3 Effect of fibre diameter on thermal conductivity 122

6.4.4 Difference of thermal conductivity between edge and middle sections 125

6.5 Summary 126

7 NUMERICAL STUDY OF MECHANICAL PROPERTIES OF SFRC/UHPC USING MESO-SCALE MODELLING 129

7.1 Model validation 129

7.1.1 Material model, contact algorism and material properties 129

7.1.2 Single fibre pull-out 132

7.1.3 Quasi-static uniaxial compression 133

7.1.4 Flexural tension simulation 134

7.1.5 Splitting tension simulation 136

7.2 Effect of steel fibre on properties of SFRCs 141

7.2.1 Study on effect of fibre content on properties of SFRCs 141

7.2.1.1 Compressive strength 141

7.2.1.2 Splitting tensile strength 143

7.2.2 Study on effect of fibre length (aspect ratio) on properties of SFRCs 145

7.2.2.1 Compressive strength 145

7.2.2.2 Splitting tensile strength 146

7.3 Summary 147

8 CONCLUSIONS AND RECOMMENDATIONS 150

8.1 Summary and conclusions 150

8.1.1 Development of UHPC with high fire resistance 150

8.1.2 Dynamic properties of the UHPC with high fire resistance 151

8.1.3 Meso-scale modelling of SFRCs/UHPCs 152

8.2 Recommendations and future works 154

REFERENCES 156

Appendix A (Chapter 3) 167

Appendix B (Chapter 4 & 5) 177

LIST OF FIGURES

Figure 2.1. stress-strain curves under different strain rate (Grote et al. 2001). 13

Figure 2.2. strain rate versus normalized compressive strength (Grote et al. 2001).......13

Figure 2.3. Normalized compressive strength vs temperature (Jia 2011).......................14

Figure 2.4. Normalized ultimate strain vs temperature (Jia 2011)..................................14

Figure 2.5. Normalized modulus of elasticity vs temperature (Jia 2011). 15

Figure 2.6. Stress-strain curve at various temperatures (Jia 2011). 15

Figure 2.7. Comparison of compressive strength between specimens tested hot and cooled-down (Hager 2013). 16

Figure 2.8. Damage characteristics under ambient (left) and 400°C (right) temperature (Jia 2011)...17

Figure 2.9. Two types of damage under 400°C (Jia 2011)...18

Figure 2.10 SHPB test setup (Huo et al. 2012)...19

Figure 2.11. SHPB schematic diagram (Huo et al. 2012)...19

Figure 2.12. Typical incident, reflected and transmission wave (Huo et al. 2012).........20

Figure 2.13. Heat insulation (Jia 2011)...20

Figure 2.14. Strain rate vs projectile velocity at different temperatures (Su et al. 2014). 21

Figure 2.15. Dynamic compressive strength vs strain rate under different temperatures (Su et al. 2014)...22

Figure 2.16. Normalized strength vs logarithm of strain rate under different temperatures (Liu et al. 2011)...22

Figure 2.17. Effect of strain rate on stress-strain relation (Huo et al. 2012)..................23

Figure 2.18. Normalized strength vs logarithm of normalized temperature for concrete

under strain rate of 100/s (Liu et al. 2011)...24

Figure 2.19. Effect of high temperature on stress versus strain relations (Huo et al. 2012). 25

Figure 2.20. Damage forms of concrete under various temperatures and strain rates (Su et al. 2014)..26

Figure 2.21. Models cut from an SFRC block. 33

Figure 2.22. The three stages of pull-out process (Aslani and Nejadi 2012)...................38

Figure 3.1. Sieve analysis of quartz sand and steel slag. 42

Figure 3.2. Steel fibre and PP fibre...43

Figure 3.3. Comparison of temperature time-history between furnace chamber and specimen centre under target temperature 1000 °C. 47

Figure 3.4. Sketch of testing setup...47

Figure 3.5. Mass loss under different temperatures..49

Figure 3.6. Sieving results of debris of mixtures without PP fibres.................................54

Figure 3.7. Stress versus strain curves. 58

Figure 3.8. Normalised compressive strength versus temperature. 62

Figure 3.9. SEM analysis of S-SP concrete after exposure to different temperatures. ...64

Figure 3.10. Stress versus strain curves of Q-P concrete...65

Figure 3.11. Stress versus strain curves of Q-SP concrete...65

Figure 3.12. Stress versus strain curves of S-SP concrete. 66

Figure 3.13. Normalised modulus of elasticity versus temperature..................................67

Figure 4.1. Specimens for SHPB tests. 70

Figure 4.2. Pot clay cushions. 71

Figure 4.3. SHPB setup..72

Figure 4.4. Schematic diagram of electric furnace. 72

Figure 4.5. Heating test. 73

Figure 4.6. Temperature time-history curves of specimen centre under different target temperatures. 73

Figure 4.7. Time history of temperature difference between chamber and specimen centre 75

Figure 4.8. Debris of specimen suffering explosive spalling at 370 °C......................... 76

Figure 4.9. Colour changes after exposure to different temperatures. 76

Figure 4.10. Relationship between strain rate and temperature under different projectile velocity. 78

Figure 4.11. Relationship between strain rate and projectile velocity under different temperatures. 78

Figure 4.12. Comparison between tested hot and cooled down under 10.1 m/s projectile velocity. 79

Figure 4.13. Stress versus strain curves with different strain rates under 400 °C. 81

Figure 4.14. Stress versus strain curves with different temperatures under projectile velocity of 10.1 m/s. 82

Figure 4.15. Relationship between peak stress and strain rate under different temperatures. 83

Figure 4.16. Dynamic compressive strength increase ratio versus strain rate under different temperatures. 83

Figure 4.17. Comparison of strength versus temperature curves between tested hot and cooled down under projectile velocity of 10.1 m/s. 84

Figure 4.18. Relationship between modulus of elasticity and strain rate under different temperatures. 85

Figure 4.19. Modulus of elasticity increase ratio versus strain rate under different

temperatures. 85

Figure 4.20. Comparison of modulus of elasticity versus temperature curves between tested hot and cooled down under projectile velocity of 10.1 m/s. 86

Figure 5.1. A specimen with a mat for dynamic splitting tensile tests. 90

Figure 5.2. Setup of static splitting tensile tests. 90

Figure 5.3. Normalised splitting tensile strength versus temperature. 94

Figure 5.4. Comparison of normalized static strength between splitting tension and compression. 95

Figure 5.5. Relationships between peak tensile stress and temperature 97

Figure 5.6. Relationships between DIF and projectile velocity at different temperatures. 98

Figure 5.7. Dynamic strength increase ratio versus projectile velocity under different temperatures. 99

Figure 5.8. Comparison of normalised dynamic strength between splitting tension and compression under projectile velocity of 7.2 m/s. 100

Figure 5.9. Ratio of compressive strength to splitting tensile strength under static loading and projectile velocity of 7.2 m/s. 101

Figure 5.10. Comparison of normalised dynamic strength between hot state and cooled-down state. 102

Figure 6.1. A meso-scale model of SFRCs. 106

Figure 6.2. Illustration of constraining facets and segments. 107

Figure 6.3. Flowchart of BFS process 108

Figure 6.4. Demonstration of Delaunay triangulation of SFRC models. 109

Figure 6.5. Model for calculating thermal conductivity. 113

Figure 6.6. Test setup for measuring thermal conductivity (Khaliq and Kodur 2011). 113

Figure 6.7. Geometric and analytic models. ... 114

Figure 6.8. Temperature distribution at 800 °C... 115

Figure 6.9. Distribution of heat flux vector at 800 °C (bottom view). ... 115

Figure 6.10. Comparison of thermal conductivity between test and simulation... 116

Figure 6.11. Curves of thermal conductivity versus model thickness. ... 118

Figure 6.12. Temperature distribution of models with different fibre contents. ... 119

Figure 6.13. Heat flux vector distribution of models with different fibre contents (bottom view)... 120

Figure 6.14. Thermal conductivity versus fibre content. ... 121

Figure 6.15. Temperature distribution of models with different fibre diameters. ... 123

Figure 6.16. Heat flux vector distribution of models with different fibre diameters (bottom view)... 124

Figure 6.17. Thermal conductivity versus fibre diameter. ... 124

Figure 6.18. Comparison between thermal conductivity of middle-section and edge-section model. ... 125

Figure 6.19. Difference of thermal conductivity versus fibre content. ... 126

Figure 7.1. Bond shear stress versus slip. ... 130

Figure 7.2. Simulation of single fibre pull-out... 132

Figure 7.3. Pull-out force versus slip. ... 133

Figure 7.4. Analytical model of 1.0% fibre SFRC. ... 134

Figure 7.5. Compressive stress versus strain. ... 135

Figure 7.6. Geometric model for flexural tension simulation. ... 135

Figure 7.7. Analytical model for flexural tension simulation. ... 136

Figure 7.8. Load versus mid-span deflection. ... 136

Figure 7.9. Geometric model for splitting tension simulation. 137

Figure 7.10. Analytical model for splitting tension simulation. 138

Figure 7.11. Split stress versus deformation. 138

Figure 7.12. Damage development along loading axis. 140

Figure 7.13. Comparison of damage mode between simulation and test. 140

Figure 7.14. Geometric models with different fibre contents. 142

Figure 7.15. Compressive strength versus strain under different fibre contents. 143

Figure 7.16. Relationship between compressive strength and fibre content. 143

Figure 7.17. Split stress versus deformation under different fibre contents. 144

Figure 7.18. Relationship between splitting tensile strength and fibre content. 144

Figure 7.19. Compressive strength versus strain under different fibre lengths. 145

Figure 7.20. Relationship between compressive strength and fibre aspect ratio. 146

Figure 7.21. Split stress versus deformation under different fibre lengths. 147

Figure 7.22. Relationship between splitting tensile strength and fibre aspect ratio. 147

Figure A.1. Compression test setup. 167

Figure A.2. 1000 kN capacity electrohydraulic servo pressure testing machine. 167

Figure A.3. Water tank with thermostatic control. 168

Figure A.4. Mixer. 168

Figure A.5. Mixing agitator. 168

Figure A.6. Sieves. 169

Figure A.7. Electric furnace. 169

Figure A.8. Steel mould. 170

Figure B.1. DSO7014B oscilloscope 177

Figure B.2. Constant-temperature drying oven..177

LIST OF TABLES

Table 3.1. Chemical compositions of cement, silica fume, fly ash and steel slag (%) ... 42

Table 3.2. Properties of steel fibre and PP fibre ... 43

Table 3.3. Mixture proportions of UHPCs (unit: kg/m^3) ... 44

Table 3.4. Fresh state properties of UHPC mixtures ... 45

Table 3.5. Specimens ... 46

Table 3.6. Details of explosive spalling of Q-S concrete at different heating rates ... 50

Table 3.7. Explosive spalling of Q-S concrete at different heating rates ... 50

Table 3.8. Details of explosive spalling of mixtures without PP fibres at heating rate of 4 °C/min ... 52

Table 3.9. Explosive spalling of mixtures without PP fibres at heating rate of 4 °C/min ... 53

Table 3.10. Details of explosive spalling of mixtures with PP fibres under different target temperatures ... 54

Table 3.11. Explosive spalling of mixtures with PP fibres under different temperatures 55

Table 3.12. Compressive strength under various temperatures ... 57

Table 3.13. Failure forms of mixtures with PP fibres under different temperatures ... 58

Table 3.14. Compressive failure forms of mixtures with PP fibres under different temperatures ... 61

Table 4.1. Test results ... 74

Table 4.2. Damage appearances ... 80

Table 5.1. Specimen sizes (unit: mm) ... 89

Table 5.2. Results of splitting tensile tests ... 92

Table 5.3. Failure appearances under static tests 93

Table 5.4. Failure appearances under dynamic tests 96

Table 6.1. Thermal conductivity under various temperatures (unit: W/(mK)) 116

Table 6.2. Thermal conductivity under different model thicknesses and fibre lengths (unit: W/(mK)) 118

Table 7.1. Properties of steel fibre 131

Table 7.2. Constituents of SFRC 131

Table 7.3 Parameters of bond-slip contact 131

Table 7.4. Properties of plywood 137

Table 7.5. Parameters of bond-slip contact for splitting tension 137

Table 7.6. Peak compressive stress and peak strain under various fibre contents 142

Table 7.7. Peak split stress and peak deformation under various fibre contents 143

Table 7.8. Peak compressive strength and peak strain under various fibre lengths 146

Table A.1. Mass record during drying 171

Table A.2. Effect of duration of curing in hot water on compression strength 171

Table A.3. Data of compression test for admixture Q-0 172

Table A.4. Data of compression test for admixture Q-S 172

Table A.5. Data of compression test for admixture Q-P 173

Table A.6. Data of compression test for admixture Q-SP 174

Table A.7. Data of compression test for admixture S-0 175

Table A.8. Data of compression test for admixture S-SP 176

Table B.1. Record of SHPB waves for 20 °C compressive tests 178

Table B.2. Record of SHPB waves for 200 °C compressive tests 179

Table B.3. Record of SHPB waves for 400 °C compressive tests 180

Table B.4. Record of SHPB waves for 600 °C compressive tests 181

Table B.5. Record of SHPB waves for 800 °C compressive tests 182

Table B.6. Record of SHPB waves for 20 °C splitting tensile tests 183

Table B.7. Record of SHPB waves for 200 °C splitting tensile tests 184

Table B.8. Record of SHPB waves for 400 °C splitting tensile tests 185

Table B.9. Record of SHPB waves for 600 °C splitting tensile tests 186

Table B.10. Record of SHPB waves for 800 °C splitting tensile tests 187

ABSTRACT

Despite the use of state-of-the-art technology and materials, modern buildings are still vulnerable to fire. Damage made to ultra-high performance concrete (UHPC) by fire or high temperature is usually severer than normal strength concrete (NSC) or high performance concrete (HPC) due to its compact internal structure. For example, strength loss of UHPCs can reach up to 80% after exposure to 800 °C and explosive spalling is a common disaster to UHPCs. To develop a UHPC with high fire resistance, a total of six UHPC mixtures were designed and tested after subjected to elevated temperatures up to 1000 °C in this study. The effects of aggregate type, fibre type and heating rate were investigated. Residual compressive strengths and stress-strain relationships were studied. Besides, attention was paid to explosive spalling. Scanning electron microscope (SEM) analysis was conducted to help understand the mechanism of variation of internal micro-structure under different temperatures. It was found the mixture containing steel slag and hybrid fibre, i.e. steel fibre and polypropylene (PP) fibre, had excellent fire resistance. After being subjected to 1000 °C, this mixture retained a residual compressive strength of 112.8 MPa or a relative value of 69%.

Furthermore, to study the behaviour of the newly developed UHPC under simultaneous effect of fire and blast, both compressive and splitting tensile split Hopkinson pressure bar (SHPB) tests were carried out under combined action of high temperatures up to 800 °C and impact loading. The dynamic tests were done both under high temperatures (hot test) and after cooling down (cool test) and comparisons were made between the two scenarios. Based on the tests on this UHPC, mechanic and physical characteristics under the combined effect were studied. Besides, explosive spalling was observed in the tests and analysed in this work. It was interesting to find PP fibre could play a negative role in preventing explosive spalling between 320 and 380 °C.

To investigate the effect of steel fibre on thermal conductivity of steel fibre reinforced concrete (SFRC) (including UHPC), a meso-scale model for heat analysis was developed. Delaunay triangulation was employed to generate the unstructured mesh for SFRC materials. The model was validated using existing experimental data. Then, it was used

to study how model thickness affected simulation outcomes of thermal conductivity of models with different fibre lengths, by which an appropriate thickness was determined for the later analyses. The validated and optimised model was applied to study of relationships between thermal conductivity and factors such as fibre content, fibre aspect ratio and different parts of an SFRC block by conducting steady-state heat analyses with the finite element analysis (FEA) software ANSYS. The simulation results reveal that presence of steel fibres has an obvious impact on the distribution of temperature and heat flux vector of the SFRC blocks. Besides, fibre content improves thermal conductivity considerably, while fibre aspect ratio only has an insignificant effect.

Based on the Delaunay triangulation meshing method applied above for thermal analysis, a 3D meso-scale model for mechanical analysis of SFRCs is also successfully developed and verified, which has the potential to more accurately simulate behaviour of SFRCs under elevated temperatures in the future. This approach modelling fibre and concrete separately and linking them with slide line contact has the capability to truly reflect the interfacial behaviour of fibre and mortar, and thus achieve high fidelity of numerical simulations. However, meso-scale modelling usually means tremendous complexity and long computational time. This study proposes a model to achieve relatively high computation efficiency, as well as accuracy. Besides, the model has the ability to deal with small specimens cut from SFRC blocks.