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Developing Self-Compacting Steel Fibre Reinforced Concrete (SCSFRC) Mixes Based On Target Plastic Viscosity and Compressive Strength

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Abstract - Steel fibres increase inhomogeneity and alter rheological and hardened characteristics of self-compacting concrete. To investigate the rheological behaviour and hardened characteristics of self-compacting steel fibre reinforced concrete (SCSFRC), a wide range of normal strength self-compacting concrete (SCC) mixes containing steel fibres and coarse aggregates (10 mm, 20 mm) with target cube compressive strengths between 30 to 70 MPa were prepared in the laboratory. The plastic viscosity of theses mixes were estimated to be between 20–50 Pas [1][2][3][4], and the slump flow time t_{500} of each mix was recorded to ensure that the flow and passing ability for workability of the mixes satisfy the recommended standards (BS EN 206-9: 2010) [5]. This work mainly focuses on the properties of fibre reinforced self-compacting concrete containing 0.5% and 1% (by volume fraction) steel fibres and the effect of coarse aggregates on their rheological behaviour and flow characteristics. Further, the effect of steel fibre content on strength of the hardened concrete will also be investigated. In addition to the results presented in this paper, an investigation on the distribution of steel fibres within the hardened concrete beams will also be discussed at the conference.

***Keywords*:** Self-compacting steel fibre reinforced concrete, Steel fibre, Design mix, Plastic-viscosity.

1. Introduction

Self-compacting concrete (SCC) flows under its own weight, without vibration effort, bleeding or segregation, and it has ability to fill formworks evenly [6]. Hence, it is a suitable structural material for frames with highly congested reinforcement or complex geometries [7][8]. To attain satisfactory SCC mix, the concrete mix must be stable and to avoid segregation it should possess favourable rheological properties [9]. Therefore, viscosity-modifying agent (e.g. superplasticizer), additional cementitious materials (ACMs), natural pozzolans, and fly ash etc. are necessary elements to maintain suitable water/binder proportion for decreasing the production cost and increasing the viscosity of SCC [10]. The properties of SCC mix with steel fibres, both in its fresh and hardened states, substantially depend on the composition and characteristics of its components. The prediction of SCC flow including its passing behaviour is very challenging particularly in the presence of congested reinforcing steel bars and in formworks of complex shapes. Nevertheless, a comprehensive understanding of the rheological behaviour of SCC flow and its passing ability is crucial to achieve a high-quality Self-compacting steel fibre reinforced concrete (SCSFRC). The most pragmatic way to achieve such an understanding is by performing laboratory experiments, which will enable one to fully understand the flow, passing and filling ability behaviour of SCSFRC and to establish its characteristic strength.

The attractive properties of self-compacting concrete (SCC) are further enhanced by fibres which bridge cracks thus delaying their spread and hence improve the tensile strength, fracture toughness, and flexural strength of hardened SCC. Consequently, the utilization of fibres may expand the potential scope of application of SCC. SCSFRC has attracted wider interest because of the advantages of self-compacting behaviour in construction methods, and its hardened characteristics include being more ductile, with higher residual tensile strength compared to vibrated concrete [11]. The characteristics of steel fibre-reinforced compounds are largely established by the fibre aspect ratio, the fibre content, and the characteristic of fibre distribution within the matrix itself. The effectiveness of fibres on hardened properties of SCSFRC will depend on how the fibres are distributed within the structures cast. For this reason, it is important to investigate the distribution of steel fibre to ensure that mix design can yield evenly and favourably distributed fibres for obtaining optimum structural performance from SCSFRC.

The main aim of this paper is to analyse a wide range of normal strength SCSFRC mixes with coarse aggregates (sizes of 10 and 20 mm) and target cube compressive strength between 30 to 70 MPa. The target plastic viscosities of these mixes were estimated to be between 20 to 50 Pa s. The traditional slump cone, and J-ring tests were conducted to ensure that each mix met the flow, filling and passing ability criteria and, there was no segregation. First step in this investigation is to assess how the estimated plastic viscosity (PV) of the self-compacting concrete mixes with and without steel fibres relates to fresh and hardened states flow/mechanical properties of the developed mixes. Secondly, the effect of steel fibre volume fractions (i.e., 0.5%, 1.0%) and the size of coarse aggregates (i.e., 10 mm and 20 mm) on the properties of SCSFRC mixes were investigated. Thirdly, the influence of steel fibres on the fracture characteristics (e.g., fracture toughness) of the concrete beams cast from the developed SCSFRC mixes was explored. During these experiments, the correlation between concrete strength and fibre distribution/orientation was also analysed.

2. Development Of The Self-Compacting Steel Fibre Reinforced Concrete (SCSFRC) Mixes

An extensive laboratory study was conducted to develop various low and moderate strength SCC mix containing steel fibre (of 30 mm length, 0.55 mm diameter) with nominal 28-day cube compressive strengths of 30, 40, 50, 60 and 70 MPa. In these mixes coarse aggregates with size of 10 and 20 mm were used. All mixes were assessed for flow quality in their fresh state utilizing slump cone and J-ring tests. This procedure ensured that each mix was tested to satisfy the flowability, passing ability criteria and showed no visible signs of segregation as recommended by (BSI, 2010; EFNARC, 2005) [12] [13]. The development of these mixes followed a mix design procedure, which is based on the plastic viscosity and compressive strength of the SCSFRC mixes, in accordance with the rational mix design method proposed by Abo Dhaheer et al. (2016a, 2016b) [2] [14]. This mix design procedure rationalised and simplified the method suggested previously by Karihaloo and Ghanbari (2012) [15] and Deeb and Karihaloo (2013) [16].

The amounts and specification of the components used in the SCC mixes are shown in Table 1. Portland limestone cement (PLC) (CEM II/A-L/32.5R) conforming to [17] with a specific gravity of 2.95 and Ground granulated blast-furnace slag (GGBS) with a specific gravity of 2.40 were used as the main cement and cement replacement materials respectively. A new generation of polycarboxylic ether-based superplasticiser (SP) with specific gravity of 1.07 was used in all the test mixes. Crushed limestone coarse aggregate with maximum particle size of 20 mm and a specific gravity of 2.80 was used, while the fine aggregate was river sand (less than 2 mm) having a specific gravity of 2.65. Limestone powder (LP) as a filler with maximum particle size of 125 μm (specific gravity 2.40) was used. A part of the river sand was substituted by an equal amount of the coarser fraction of LP in the size range 125 μm – 2 mm.

Table 1: Constituents and proportions for SCSFRC mixes (kg/m^3).

Mix designation	cm[a]		Water	SP[c]	w/cm	SP/cm	LP[d]	SF[e] (0.5%) ratio	FA[f]		CA[g]
	Cement	ggbs[b]							FA**	FA***	
30 MPa	244	81	205	2.7	0.63	0.83	158	40	218	550	827
40 MPa	270	90	205	3	0.57	0.83	143	40	240	500	839
50 MPa	275	92	195	2.8	0.52	0.74	207	38	189	600	842
60 MPa	303	101	190	3.5	0.47	0.86	129	39	210	500	887
70 MPa	338	113	180	3.8	0.40	0.84	164	38	216	500	819

[a] Cementitious material, [b] Ground granulated blast-furnace slag, [c] Superplasticizer. [d] Limestone powder <125μm,
[e] Steel Fibre, [f] Fine aggregate<2mm (Note: a part of the fine aggregate is the coarser fraction of the limestone powder) FA**125 μm–2 mm, whereas FA*** refers to natural river sand < 2 mm), [g] Coarse aggregate < 20 mm and < 10 mm.

The plastic viscosity of each mixture was estimated using micro-mechanical theory based analytical method described by Ghanbari and Karihaloo (2009) [18] and the plastic viscosity of the homogeneous paste was obtained from

(Sun et al., 2006) [19]. Additional details of the developed SCSFRC test mixes are presented in Table 2. The results obtained from slump flow and J-ring tests are detailed in Table 3 which confirms that all the SCSFRC mixes with 0.5% volume fraction of steel fibres satisfy the flow criteria [12] [13].

Table 2 : Further details of test SCSFRC mixes.

Mix designation	Target Compressive strength at 28 days (MPa)	Estimate plastic viscosity (Pa s)	Paste vol. fraction	Solid vol. fraction	Paste/Solid (by vol.)
30 MPa	41.77	20	0.39	0.61	0.64
40 MPa	41.93	27	0.40	0.60	0.66
50 MPa	50.20	35	0.41	0.59	0.71
60 MPa	66.97	40	0.39	0.61	0.64
70 MPa	78.43	45	0.44	0.56	0.80

Table 3: Results of flow and pass-ability for SCSFRC mixes.

	Slump flow		J-ring flow test (12 Bars)			Difference between Slump flow and J-ring flow test
Mix designation	Spread (mm)	Time 500 mm (sec)	Spared (mm)	Time 500 mm (sec)	P_J (mm)	D_{FLOW} - D_J (mm)
30 MPa	632.5	2.16	630	2.50	9.50	2.5
40 MPa	635	2.27	615	2.54	7.75	20
50 MPa	635	2.47	625	3.47	7.75	10
60 MPa	645	2.50	625	3.37	7	20
70 MPa	750	2.67	745	3.50	7	5

3. Estimation of Mix Plastic Viscosity

The flow of SCC with or without steel fibre is best illustrated by a Bingham constitutive model. This model comprises two material characteristics, specifically the yield stress (τ_y) and the plastic viscosity (PV). It is recognised however that the yield stress of SCC mixtures is very low (around 200 Pa) in comparison with normal concretes (thousands of Pascal) and remains approximately constant for a large range of plastic viscosities [1]. The increase in plastic viscosity of the liquid phase (cement paste), as a consequence of adding solid components such as aggregates and fibres, can be estimated by means of a two-stage micro-mechanical model. It takes into account the shape and the volume fraction of the solid suspension particles [4].

The viscosity of a homogenous viscous fluid for example the paste of cement (liquid phase) can be measured accurately, which cannot be said regarding fluids of non-homogeneous viscous (solid phase) such as SCC and SCSFRC. Nevertheless, the plastic viscosity of SCC with or without steel fibres can be obtained by a micromechanical procedure from the knowledge of the plastic viscosity of cement paste alone or of the viscosity modifying admixture (VMA) and/or cement paste with SP. This process has been proven to predict the plastic viscosity of SCC mixes with and without fibres that agree very well with measured values [18].

This model involves treating SCSFRC as a two-phase suspension in which the solid phase is suspended in a viscous liquid phase. The plastic viscosity of the liquid phase can be measured accurately using a rheometer. The increase in the plastic viscosity of the paste resulted by the addition of the solid phase can be predicted in phases from the two-phase suspension model

The plastic viscosity of SCSFRC increases due to the inclusion of fibres, to a degree based on the structure of the reference mix [20]. The viscosity of SCC mixtures can be estimated using a micromechanical method, depending on the measured viscosity of the mix ratios and the cement paste. It was reported in [1] that the 30 mm long, 0.55 mm diameter with crimped ends considerably increased the viscosity of SCC with fibre mixes.

It is worth mentioning that the presence of steel fibres significantly increases the plastic viscosity of SCSFRC with various compressive strengths [30 MPa, 40MPa, 50MPa,60MPa and 70MPa]. Accordingly, the plastic viscosity of the viscous concrete comprising liquid and solid phases is additionally increased if SF are added to it. In the present work, amount of volume fraction of steel fibres is typically small, so that the dilute approximation is still applicable during the micro-mechanical theory based estimation of plastic viscosity [18].

4. Effect of Steel Fibres Content And Various Course Aggregate Size on SCSFRC Mixes

The steel fibre content (i.e., its volume fraction) and maximum size of coarse aggregate will have significant effect on self-compacting concrete mix, as well as on the distribution and orientation of steel fibres in terms of flow, passing, and filling ability in self-compacting concrete, which in turn influence both fresh and hardened properties of SCSFRC. The characteristics of steel fibre and maximum size of coarse aggregate (e.g., 20 mm) have considerable effect on SCSFRC properties. With increasing steel fibre content and size of coarse aggregate, the strength of SCSFRC increases while workability decreases, which may well fail to meet the EFNARC standard [13].

Table 4 presents constituents and proportions of various SCSFRC concrete mixes containing 1.0% (by volume) of steel fibres with target compressive strength 30 MPa. The results obtained during the fresh state tests of the mixes listed in Table 4 are shown in Table 5. The final spread diameter values are within the range of 600 mm to 750 mm for flow and passing ability tests in the case of all the SCSFRC mixes in Table 4.

Table 4: Constituents and proportions for SCSFRC (30 MPa) mixes with various coarse aggregate size (kg/m^3)

<table>
<tr><th rowspan="2">Mix designation</th><th colspan="3">cma</th><th rowspan="2">Water</th><th rowspan="2">SP[d]</th><th rowspan="2">w/cm</th><th rowspan="2">SP/cm</th><th rowspan="2">LP[e]</th><th rowspan="2">SF[f] (1.0%) ratio</th><th colspan="2">FA[g]</th><th rowspan="2">CA[h]</th></tr>
<tr><th>Cement</th><th>ggbs[b]</th><th>ms[c]</th><th>FA**</th><th>FA***</th></tr>
<tr><td rowspan="2">30 MPa (1)</td><td rowspan="2">247</td><td rowspan="2">82</td><td rowspan="2">--</td><td rowspan="2">207</td><td rowspan="2">2.8</td><td rowspan="2">0.63</td><td rowspan="2">0.86</td><td rowspan="2">278</td><td rowspan="2">76</td><td rowspan="2">205</td><td rowspan="2">500</td><td>364.5 (50%) 10 mm</td></tr>
<tr><td>364.5 (50%) 20 mm</td></tr>
<tr><td rowspan="2">30 MPa (2)</td><td rowspan="2">247</td><td rowspan="2">82</td><td rowspan="2">--</td><td rowspan="2">207</td><td rowspan="2">2.8</td><td rowspan="2">0.63</td><td rowspan="2">0.86</td><td rowspan="2">278</td><td rowspan="2">76</td><td rowspan="2">205</td><td rowspan="2">500</td><td>546.75 (75%) 10 mm</td></tr>
<tr><td>182.25 (25%) 20 mm</td></tr>
<tr><td rowspan="2">30 MPa (3)</td><td rowspan="2">247</td><td rowspan="2">82</td><td rowspan="2">--</td><td rowspan="2">207</td><td rowspan="2">2.8</td><td rowspan="2">0.63</td><td rowspan="2">0.86</td><td rowspan="2">278</td><td rowspan="2">76</td><td rowspan="2">205</td><td rowspan="2">500</td><td>729 (100%) 10 mm</td></tr>
<tr><td>0% 20mm</td></tr>
<tr><td rowspan="2">30 MPa (4)</td><td rowspan="2">328</td><td rowspan="2">--</td><td rowspan="2">58</td><td rowspan="2">243</td><td rowspan="2">4.75</td><td rowspan="2">0.63</td><td rowspan="2">1.23</td><td rowspan="2">366</td><td rowspan="2">103</td><td rowspan="2">446</td><td rowspan="2">700</td><td>0% 10mm</td></tr>
<tr><td>0% 20mm</td></tr>
</table>

[a] Cementitious material, [b] Ground granulated blast-furnace slag, [c] Micro-silica, [d] Superplasticizer, [e] Limestone powder <125 μm, [f] Steel Fibre. [g] Fine aggregate <2 mm (Note: a part of the fine aggregate is the coarser fraction of the limestone powder, FA**125 μm–2 mm, whereas FA*** refers to natural river sand < 2 mm), [h] Coarse aggregate < 20 mm and < 10 mm.

However, it can be noted that in the case of mix (1), the P_J value (i.e., blocking step height) is rather high indicating that there is a significant blocking and segregation of steel fibre and coarse aggregates. In addition, it can be also noted that for mix (2) and (3) the P_J value is greater than 10mm which again confirms that the flow is slightly blocked during the J-ring test. This fact is further established by L-box tests. Figure 1 illustrates the L-box test results for all the mixes in Table 4. As noted with J-ring tests, the L-box tests reveal that the flow of mix (1), (2) and (3) are subjected to blockage and segregation of fibres and coarse aggregates. As mix (4) does not contain any coarse aggregate, there is no visible blockage blockage in the case of mix (4). Further, the value of P_J in case of mix (4) is 6.25mm which is less than the maximum recommended value (i.e., 10mm) for self-compacting concrete.

Table 5 : Results of flow, passing and filling ability for SCSFRC mixes (30 MPa) for various size coarse aggregate content

	Slump flow		J-ring flow test (12 Bars)			Difference between Slump flow and J-ring flow test	L-box test		
Mix designation	Spread (mm)	Time 500 mm (sec)	Spared (mm)	Time 500 mm (sec)	P_J (mm)	D_{FLOW} - D_J (mm)	t_{200} (sec)	t_{400} (sec)	H_2/H_1
30 MPa (1)	630	1.97	615	3.50	24.5	15	1.17	2.33	0.88
30 MPa (2)	610	2.37	605	3.14	17	5	1.00	2.77	0.90
30 MPa (3)	605	1.99	600	3.05	12	5	1.01	2.50	0.89
30 MPa (4)	620	2.34	610	3.10	6.25	10	0.63	1.70	0.94

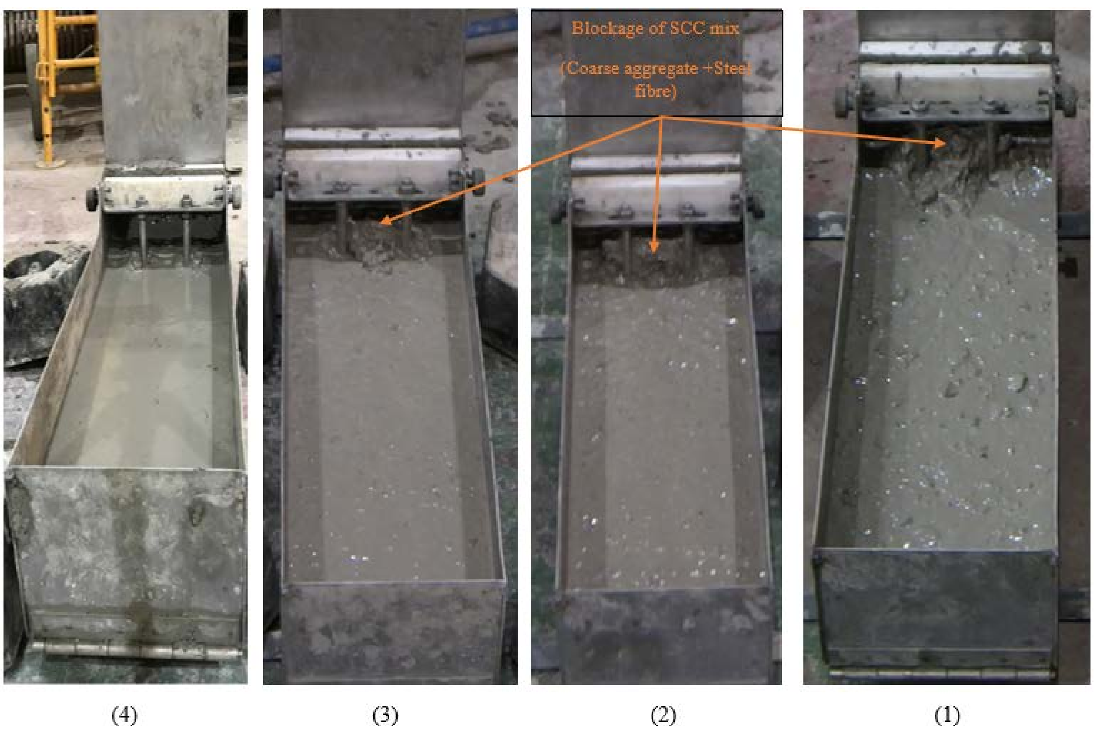

Figure 1:Passing and filling ability of SCSFRC mix with steel fibre (1%) volume (C30) (1-2-3-4).

To further investigate the properties of SCSFRC mix, an SCSFRC mix with target compressive strength of 40MPa was considered following the analysis of 30MPa mixes above. Table 6 presents constituents and proportions of the 40MPa mix. As can be noted from the Table 6, this mix contains 0.5% (by volume) steel fibres, 10mm and 20mm coarse aggregates of equal amounts. Table 7 details the results obtained during the fresh state slump flow and J-ring tests carried out with the mix in Table 6. The flow spread diameter values are within the range between 600 mm and 650 mm thus confirming satisfactory flowability of SCSFRC mix. This observation is consistent in the case of both 12 bar and 16 bar J-ring tests. However, it can be noted that P_J value for J-ring test with 16 bar is greater than 10mm. This indicates that the there is a possibility blockage and segregation during the flow of SCSFRC. This behaviour is further established by the observations illustrated in Figure 2. This figure clearly illustrates the flow blockage and the segregation of coarse aggregates. Therefore, it is suggested that by decreasing the amount of coarse aggregate, the passing ability can be further improved as in the case of 30MPa mixes presented above. However, it is important to ensure that the reduction is coarse aggregate does not affect the predicted compressive strength of hardened concrete.

Table 6 : Constituents and proportions for SCSFRC (40 MPa) mixes (kg/m^3).

Mix designation	cm[a]		Water	SP[c]	w/cm	SP/cm	LP[d]	SF[e] (0.5%) ratio	FA[f]		CA[g]
	Cement	ggbs[b]							FA**	FA***	
40 MPa	270	90	205	3	0.57	0.83	143	40	240	500	419.5 (50%) 10mm
											419.5 (50%) 20mm

[a] Cementitious material, [b] Ground granulated blast-furnace slag, [c] Superplasticizer. [d] Limestone powder <125 µm.
[e] Steel Fibre, [f] Fine aggregate <2 mm (Note: a part of the fine aggregate is the coarser fraction of the limestone powder, FA**125 µm–2 mm, whereas FA*** refers to natural river sand < 2 mm), [g] Coarse aggregate < 20 mm and < 10 mm.

Table 7: Results of flow and pass-ability for SCSFRC mixes (40 MPa).

	Slump flow		J-ring flow test			Difference between Slump flow and J-ring flow test
Mix designation	Spread (mm)	Time 500 mm (sec)	Spared (mm)	Time 500 mm (sec)	P_J (mm)	D_{FLOW} - D_J (mm)
40 MPa (16 Bars)	630	1.74	625	1.98	11	5
40 MPa (12 Bars)	635	2.27	615	2.54	7.75	20

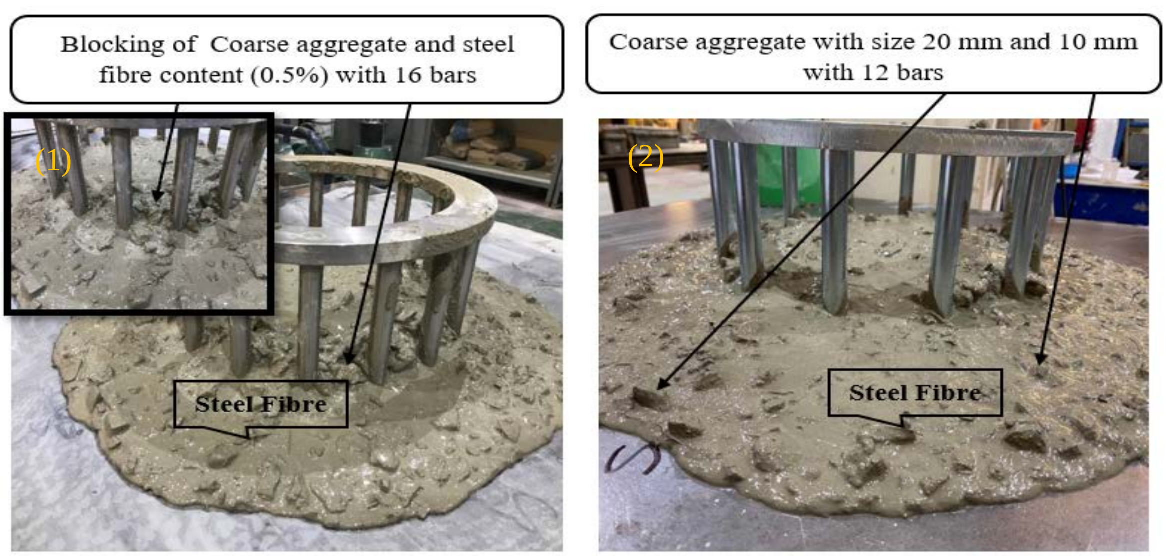

Figure 2: Flow and passing ability of SCSFRC mix: C40 (1) (Left) with 16 bars, C40 (2) with 12 bars (Right), (size of coarse aggregate with 50 % of 10mm and with 50 % of 20mm)

4. Conclusion

This paper has focused on developing self-compacting steel fibre reinforced concrete mixes and characterising their flow and mechanical properties. To understand the effect of steel fibres and coarse aggregates on SCC properties, mixes with 30MPa and 40MPa target compressive strengths were prepared and tested in the laboratory. The experimental results reveal that with the increase in the amount of 20mm aggregated, the blocking step height increases during the J-ring tests. This observation clearly indicates that the coarse aggregate (e.g., 20mm and 10mm) composition should be carefully optimised to obtain favourable self-compacting and mechanical properties of SCSFRC.

Due to page limitation, the results obtained for SCSFRC mixes with higher target compressive strengths (> 40MPa) could not be included in this paper. However, the whole set of experiments and the summary of experimental observations will be presented at the conference.

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