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Development of self-compacting high and ultra high performance concretes with and without steel fibres

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ABSTRACT

This paper describes the steps taken to develop self-compacting high and ultra high-performance concretes with and without steel fibres. For the self-compacting concrete mixes without steel fibres the fulfilment of flow and cohesiveness criteria are sufficient for the mix design. However, for the design of self-compacting concrete mixes with steel fibres it is found, as expected, that they must additionally meet the passing ability criterion. The plastic viscosity of the mixes with and without steel fibres has been estimated from the known plastic viscosity of the cement paste using simple micromechanical relations.

1. Introduction

The ideal design of a self-compacting concrete (SCC) mix is a compromise between two conflicting objectives. On the one hand, the SCC has to be as fluid as possible to ensure that it will fill the formwork under its own weight, but on the other, it has to be a stable mixture to prevent segregation of solids during the flow [1–3]. The former is ensured by using super-plasticiser and/or viscosity modifying admixtures, while the latter is achieved through the selection of an appropriate amount and type of powders, i.e., cement and cement replacement materials (CRMs), and by striking a proper balance between the solids and liquids in the mix.

The addition of steel fibres improves the mechanical properties and the ductility of SCC in much the same manner as in vibrated concrete. However, the fibres greatly impair the workability of SCC because of their elongated shape and large surface area. The amount of fibre that can be added to a SCC mix is therefore limited and depends on the fibre type used and the composition of the SCC mix. The maximum amount of fibre needs to be determined in such a way as to cause the least decrease in the workability, whilst maintaining good flow and passing ability. In order to make the best use of the fibres, they need to be homogeneously distributed in the mix without clustering [4].

This paper reports on the development of self-compacting high and ultra high performance concrete mixes with and without steel fibres. The aim is to investigate how the proportions of solids and liquids and the type of super-plasticiser need to be selected for a particular type of steel fibre in order to produce SCC mixes with the right flow and passing ability. The plastic viscosity of the SCC mixes so developed will then be estimated by the micromechanical procedure described by Ghanbari and Karihaloo [5]. This plastic viscosity, together with the yield stress of the mix, is needed in the numerical simulation of SCC flow in moulds of different shapes and sizes [6].

2. Development of self-compacting high-performance fibre-reinforced concrete (SCHPFRC)

The aim of this part of the investigation was to develop a self-compacting counterpart of a high-performance vibrated concrete (with a nominal 28-day characteristic compressive strength of 100 MPa) that had been produced regularly in the same laboratory over many years using naphthalene sulphonate-based super-plasticiser. The mix proportions of this reference vibrated mix are shown in Table 1. The binder refers to cement plus micro-silica. To achieve this goal several trial mixes were made and tested as follows:

- The coarse aggregate (crushed limestone without dust, particle size range 4–10 mm) content was decreased by between 18% and 28% in order to reduce the inter-particle friction.
- Limestone dust (particle size range 0.05–4 mm) was added to increase the paste volume to lubricate the aggregate particles.
- Micro-silica (mean particle size 0.5 μm) content was increased by up to 30%.

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Table 1
Constituents and proportions for high-performance concrete mixes (kg/m^3).

Constituents	Reference mix	Mix 1[a]	Mix 2 [b]	Mix 3 [c]	Mix 4 [d]	Mix 5[e]	Mix 6[e]
Cement	500	500	500	500	500	500	500
Micro-silica	55	72	72	75	75	75	75
Coarse aggregates (crushed limestone) < 10 mm	1105	797	797	850	850	833	833
Sand < 2 mm	660	648	648	680	680	700	700
Water	161	166	166	127	127	138	138
Limestone	0	232	232	243	243	200	200
Fibres (30 mm long with crimped ends, volume fraction)	–	–	0.5%	0	0.5%	–	0.5%
Super-plasticiser/cement	1.8%	3.7%	3.7%	3.7%	3.7%	4%	4%
Water/binder	0.29	0.29	0.29	0.22	0.22	0.24	0.24
Flow spread (mm)	–	600	560	780	770	805	760
T_{500} (s)	–	3	3	3	3	3	3

[a] Mix 1 is the self-compacting version of reference mix.
[b] Mix 2 contains 0.5% by volume Dramix steel fibres.
[c] Mix 3 is SCHPC using polycarboxylate ether-based super-plasticiser.
[d] Mix 4 is SCHPFRC using polycarboxylate ether-based super-plasticiser and contains 0.5% by volume Dramix steel fibres.
[e] Mix 5 and mix 6 are final SCHPC and SCHPFRC mixes that achieve both workability and passing ability.

- Super-plasticiser was increased from 1.8% to 3.7% by weight of cement.
- The sand (particle size range 0.15–2 mm) content was decreased modestly by 1.87%.
- The water to binder ratio was held unchanged at 0.29 when the naphthalene sulphonate-based super-plasticiser was used.

The trial mixes were prepared in a planetary mixer by mixing the coarsest constituent (coarse aggregate) and the finest one (micro-silica), followed by the next coarsest (sand) and next finest constituent (cement), and so on. Before each addition, the constituents were mixed for 2 min. To fluidize the dry mix, two-thirds of the super-plasticiser (SP) was added to the water. One-half of this water–SP mixture was added to the dry constituents and mixed for 2 min. One-half of the remaining water–SP mixture was then added and mixed for 2 min. This process was continued until all water–SP mixture was added in about 10 min. The remaining one-third of the SP was added and mixed for 2 min just before transferring the SCC mix into the slump cone. The horizontal spread up to 500 mm was timed. If it was different from 3 s, or any segregation was visible, the mix proportions were judiciously altered. This trial process was continued until the mix met the flow-ability criterion (horizontal spread T_{500} of 500 mm in 3 s) and was homogeneous with no visible segregation. In this manner, the self-compacting high-performance concrete (SCHPC) mix 1 shown in Table 1 was developed (Fig. 1). Tests on specimens at the age of 28 days reached a compressive strength of 80 MPa. That this mix fell short of the 28-day target compressive strength of 100 MPa is not surprising in view of the fact that the coarse aggregate content was reduced by nearly 28% in order to achieve the desired flow-ability and resistance against segregation.

A small amount of steel fibres (0.5% by volume of 30 mm long Z560 Dramix fibres with crimped ends) was added to the above SCHPC mix without altering any other mix proportions to examine whether it will still satisfy the flow-ability criterion. The fibres, which are supplied by the manufacturer as small flat packs containing more than 40 fibres temporarily held together by water-solvable glue, were added progressively to the wet SCHPC mix (i.e. after all the water–SP mixture had been added and mixed; see above) and mixed until the glue had dissolved and the fibres had dispersed uniformly in the mix. The remaining one-third of the SP was added and mixed for 2 min just before transferring the fibre-reinforced mix into the slump cone. The horizontal spread up to 500 mm was timed at 3 s, as required, although the final spread was slightly less than that of the SCHPC without fibres (560 mm against 600 mm). This self-compacting high-performance fibre-reinforced concrete (SCHPFRC) is designated mix 2 in Table 1. Just as the SCHPC, it meets the flow-ability criterion and is very homogeneous with no visible segregation (Fig. 2).

2.1. Influence of the type of super-plasticiser

It has been reported [7] that polycarboxylate ether-based super-plasticisers, e.g. Glenium ACE 333, which disperse particles

Fig. 1. Horizontal spread of SCHPC mix 1.

Fig. 2. Horizontal spread of SCHPFRC mix 2.

by steric stabilization result in better workability than do the naphthalene sulphonate-based super-plasticisers, which disperse particles by electrostatic repulsion. For this reason, the naphthalene sulphonate-based super-plasticiser in mixes 1 and 2 of Table 1 was replaced by an equal amount of Glenium ACE 333. The resulting mixes were found to have very low viscosity with a horizontal spread in excess of 850 mm but with clear bleeding.

This meant that the solid content could be increased while that of the paste could be decreased. Accordingly, the water to binder ratio was reduced significantly from 0.29 to 0.22 while keeping the super-plasticiser content unchanged, and the coarse aggregate content was increased and that of the limestone dust decreased. The mixes so produced are designated 3 and 4 in Table 1. They both satisfied the flow-ability criterion and showed no visible signs of segregation.

2.2. Passing ability test

Mixes 3 and 4 that satisfied the flow-ability criterion and showed no signs of segregation were subjected to the passing ability test to ensure that they were able to pass through narrow gaps that exist between reinforcing bars in a real reinforced concrete structural element. For this test, a 300 mm diameter J-ring apparatus with 16 steel rods (each of diameter 16 mm) was used, as recommended by The European Federation of National Trade Associations (EFNRC) [8] (Fig. 3).

This test showed that there was some blocking in the SCHPFRC mix 4 with the bulk of the fibres and coarse aggregates lumped in the centre of flow spread. It was therefore necessary to adjust the mix proportions. To meet the passing ability requirement, the coarse aggregate was decreased slightly, with a corresponding increase in the fine aggregate (sand), as well as in water and super-plasticiser contents in both mixes 3 and 4, although mix 3 had satisfied the passing ability test. The aim was to ensure that the SCHPFRC had as its base the same SCHPC mix. The mixes designated mix 5 and mix 6 in Table 1 meet the passing ability criterion based on both EFNRC [8] and PCI [9] recommendations (Figs. 4 and 5). The SCHPFRC mix 6 was flow-able, resistant to segregation, and reached the target 28-day compressive strength of 100 MPa.

In the development of mixes 5 and 6 we found no need to add a viscosity modifying admixture (VMA) to reduce bleeding and blocking or to increase the resistance to segregation.

It should be mentioned that slump and J-ring tests can be performed by using an upright or inverted cone. We have used both orientations and observed that in the inverted orientation the flow time T_{500j} is slightly increased when large coarse aggregates are present. There was no discernible difference when such aggregates were absent, as in the mixes described below.

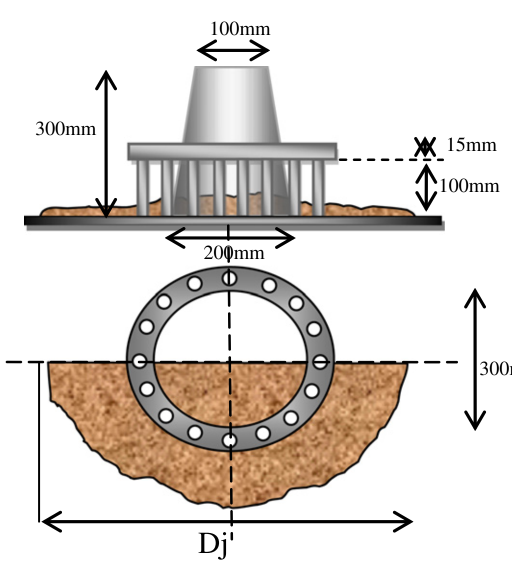

Fig. 3. J-ring apparatus.

3. Development of self-compacting ultra high-performance fibre-reinforced concrete (SCUHPFRC)

In this section, we describe the development of a SCUHPFRC. The base mix is CARDIFRC mix I [10–12]. This mix contains a total of 6% by volume of two types of fibre: 6 mm (5% by volume) and 13 mm (1% by volume) long steel fibres (diameter 0.15 mm). It is a very dense and highly viscous mix and is meant for vibratory compaction. However, the mix without the fibres is highly flow-able and thus has the potential for self-compaction. In the present development for cost and health and safety reasons, the 6% by volume brass-coated thin fibres (0.16 mm diameter) of the original CARDIFRC mix I, which could pose a health and safety hazard, will be replaced by 2.5% by volume of the cheaper 30 mm long steel Z560 Dramix fibres with 0.55 mm diameter.

Trial mixes were prepared from the original CARDIFRC mix I without fibres (for mix proportions, see Table 2) by replacing a part of the cement by granulated ground blast furnace slag (GGBS) (33–37%) and using Glenium ACE333 super-plasticiser instead of the naphthalene sulphonate-based one. Various water to binder ratios (0.18–0.20) and SP to water ratios (0.15–0.22) were tried to obtain highly flow-able trial mixes. Based on the experience with the SCHPFRC mix 6 reported above which contained only 0.5% by volume of the same type of fibres as envisaged in the present SCUHPFRC, it was reasonable to assume that the mix without fibres should have a larger horizontal spread than that of SCHPC,

Fig. 4. Flow and passing ability of SCHPC mix 5.

Fig. 5. Flow and passing ability of SCHPFRC mix 6.

Table 2
Constituents and proportions for ultra high performance mixes (kg/m^3).

Constituents	Reference mix[a]	SCUHPC mix 7[b]	SCUHPFRC mix 8[b]	SCUHPC mix 9[c]	SCUHPFRC mix 10[c]
Cement	855	543.5	543.5	543.5	543.5
Micro-silica	214	214	214	214	214
Ground granulated blast furnace slag (GGBS)		311.5	311.5	311.5	311.5
Quartz sand					
9–300 μm	470	470	470	470	470
250–600 μm	470	470	470	470	470
Water	188	188	188	188	188
Super-plasticiser	28	41.33	41.33	52.64	52.64
Water/binder	0.18	0.18	0.18	0.18	0.18
SP/water	0.15	0.22	0.22	0.28	0.28
Fibres 6 mm (diameter 0.16 mm)	390	–	–	–	–
Fibres 13 mm (diameter 0.16 mm)	78	–	–	–	–
Fibres (30 mm long with crimped ends, volume fraction)	–	–	2.5%	–	2.5%
Slump flow (mm)		905	780	910	830
T_{500} (s)		3	3	3	3

[a] Original CARDIFRC mix I.
[b] Mix 7 and mix 8 are the composition of the trial SCUHPC and SCUHPFRC, respectively.
[c] Mix 9 and mix 10 are mix proportions of SCUHPC and SCUHPFRC mixes, respectively, meeting the flow-ability, passing ability and resistance to segregation criteria.

so that by the time 2.5% by volume of 30 mm long Z560 Dramix fibres with crimped ends were added to this mix, it would satisfy the target flow time T_{500} of 3 s.

The following observations were made during the slump testing of trial mixes without fibres:

- When the SP/water ratio was increased from 0.15 to 0.20 the horizontal spread was 768 mm.
- When 36.5% of cement was replaced by GGBS to increase the volume of the powder binder, the spread was 772 mm.
- When the SP/water ratio was further increased to 0.22, the spread was 905 mm.

The composition of this mix with SP/water ratio of 0.22, designated mix 7 is given in Table 2. The horizontal spread in the cone test is shown in Fig. 6. 2.5% by volume of steel fibres were added to this mix. The fibres were evenly distributed in the mixer, as described above, and the resulting SCUHPFRC, designated mix 8 in Table 2, was found to satisfy the flow-ability and resistance to segregation criteria (Fig. 7), albeit with a reduced final flow spread (780 mm). Visual inspection showed that the fibres were distributed throughout the slump spread.

As before, the mixes 7 and 8 were subjected to the passing ability test in the J-ring apparatus, with the cone in the inverted orientation. The mix 7 without fibres easily and smoothly flowed through the gaps between the steel rods reaching a spread of 900 mm, with the spread T_{500j} timed at 3 s (Fig. 8). The mix 8 with fibres, on the other hand, did not satisfy the passing ability test. Some fibres nested around the steel bars, preventing the remaining fibres to pass through the gaps (Fig. 9). It was therefore necessary to improve the flow-ability of this mix by increasing the super-plasticiser

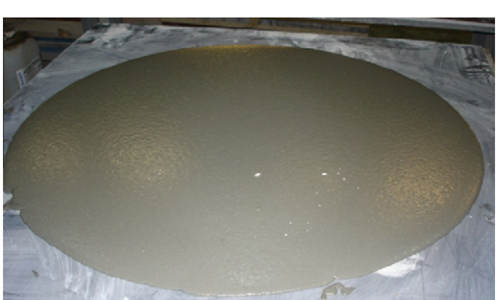

Fig. 6. Horizontal spread of SCUHPC mix 7.

Fig. 7. Horizontal spread of SCUHPFRC mix 8.

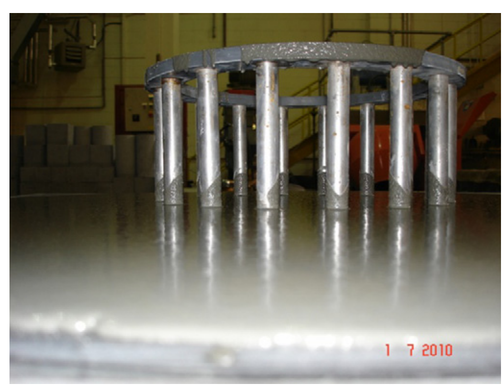

Fig. 8. SCUHPC mix 7 flows smoothly through the gaps between the steel rods.

content. However, the super-plasticiser content was also increased by the same amount in the base mix 7 without fibres in order to maintain commonality between the SCUHPC mixes with and without fibres. The SP to water ratio had to be increased from 0.22 of mixes 7 and 8 to 0.28 in order to satisfy the passing ability test (Figs. 10 and 11). The mix proportions of these mixes, designated SCUHPC mix 9 and SCUHPFRC mix 10 are given in Table 2. The compressive strength of SCUHPFRC mix 10 was measured at 162 MPa.

4. Estimation of the plastic viscosity

The flow of SCC with or without fibres is best described by the Bingham constitutive model. This model contains two material

Fig. 9. SCUHPFRC mix 8 did not satisfy the passing ability test. The fibres are nested around the steel rods as seen clearly in the right photo.

properties, namely the yield stress τ_y and the plastic viscosity, η. It is known however that the yield stress of SCC mixes is very low (around 200 Pa) in comparison with normal concretes (thousands of Pascal) and remains nearly constant over a large range of plastic viscosities [13]. The viscosity of a homogenous viscous fluid such as the cement paste can be measured accurately, which cannot be said about non-homogeneous viscous fluids such as SCHPFRC and SCUHPFRC. However, Ghanbari and Karihaloo [5] have developed a micromechanical procedure for estimating the plastic viscosity of SCC with or without steel fibres from the knowledge of the plastic viscosity of cement paste alone or of the cement paste with SP and/or VMA. This procedure has been shown to predict the plastic viscosity of SCC mixes with and without fibres that agree very well with measured values [5].

Based on the water to cement and the super-plasticiser to water ratios, the plastic viscosities of the cement pastes used in the SCHPFRC and SCUHPFRC (Table 2) developed above are estimated to be 0.4 Pa s and 0.3 Pa s, respectively [14–16]. In the procedure proposed by Ghanbari and Karihaloo [5], a concrete mix is regarded as a succession of two-phase suspensions. At each stage, the suspension consists of a liquid phase in which is suspended a discrete solid phase. Fig. 12 shows the hierarchy of these two-phase liquid–solid suspensions used in the estimation of the plastic viscosity of SCHPFRC and SCUHPFRC based on the viscosity of the cement paste used in them.

The plastic viscosity of the *i*th liquid–solid suspension can be estimated from the plastic viscosity of the preceding phase as follows:

$$\eta_{Ci} = \eta_{Ci-1} f_i(\phi_i) \tag{1}$$

where the function $f_i(\phi_i)$ will be defined below, and $\eta_{C0} = \eta_{Paste}$ is the known plastic viscosity of the cement paste. For instance, cement replacement materials form the solid phase in the viscous

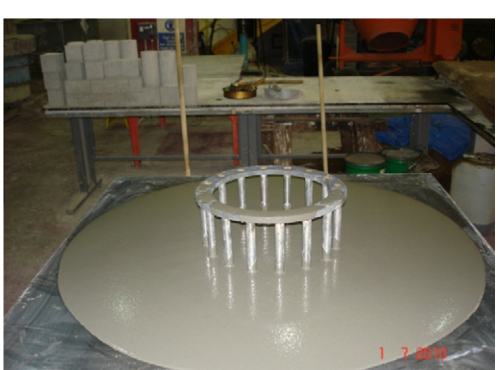

Fig. 10. Flow and passing ability of SCUHPC mix 9.

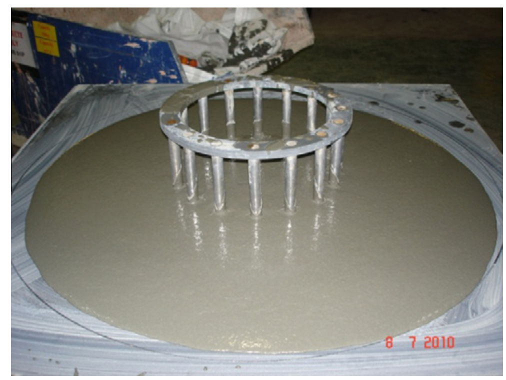

Fig. 11. Flow and passing ability of SCUHPFRC mix 10.

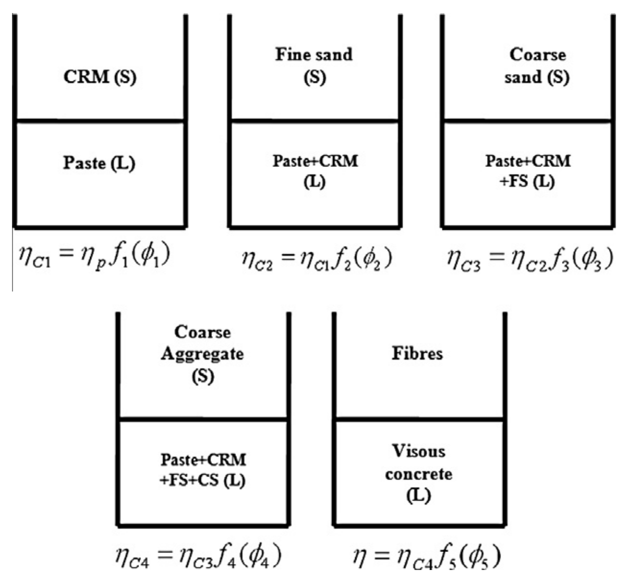

Fig. 12. Hierarchy of two-phase liquid–solid suspensions constituting an SCC mix with fibres, showing the liquid (L) and solid (S) phases in each suspension. CRM stands for cement replacement material (e.g. GGBS).

cement paste in the first liquid–solid suspension. The viscosity of this suspension is calculated from the known viscosity of the cement paste. This process is repeated until all the ingredients of SCC have been accounted for.

The function $f_i(\phi_i)$ depends only on the volume fraction of solid phase ϕ_i if the volume fraction is less than 10%. It can be expressed by the Einstein equation (or many of its later modifications) in the following form

Table 3
Plastic viscosities of SCHPC and SCUHPC mixes with and without fibres.

Plastic viscosity (Pa s)	Without fibres	With fibres
SCHPC (mixes 5 and 6)	9.9	42.7
SCUHPC (mixes 9 and 10)	3.1	54.4

$$f_i(\phi_i) = 1 + [\eta]\phi_i \tag{2}$$

where $[\eta]$ is the so-called non-dimensional intrinsic viscosity which is a measure of the effect of individual particles on the viscosity [17]. A value of $[\eta]$ = 2.5 is adopted when the particles are rigid spheres and the distance between them is large compared to the mean particle diameter.

However, when the volume fraction of solid phase exceeds 10% but is less than the maximum possible volume fraction ϕ_m then $f_i(\phi_i)$ depends not only on the volume fraction of the solid phase but also on how they are dispersed in the fluid and on their shape. ϕ_m represents the situation in which the particles have the minimum possible separation i.e. the void fraction (porosity) is the least and the viscosity is infinite. The value is 0.74 for hexagonal closed packing, 0.637 for random hexagonal packing, and 0.524 for cubic packing.

This is captured in the formula proposed by Krieger and Dougherty [18] given below:

$$f_i(\phi_i) = \left(1 - \frac{\phi_i}{\phi_m}\right)^{-[\eta]\phi_m} \tag{3}$$

The intrinsic viscosity $[\eta]$ and ϕ_m depend upon the shear rate; the former tends to decrease with increasing shear rate whereas the latter shows the opposite trend. However $[\eta]$ and ϕ_m change in such a way that an increase in the one leads to a decrease in the other, but the product of the two changes remains practically the same and equal on average to 1.9 for rigid spheres.

In the final fluid–solid suspension, the increase in the viscosity induced by a dilute concentration of long steel fibres is estimated. For this the fibres are regarded as rigid slender bodies whose free translation and rotation are restrained by the viscous concrete mix [5]. The plastic viscosity of SCC with fibres, designated η is given by

$$\eta = \eta_{NF}\left\{(1 - \phi_f) + \frac{\pi\phi_f l_d^2}{3\ln(2l_d)}\right\} \tag{4}$$

where η_{NF} is the plastic viscosity of the viscous concrete mix without fibres given by Eq. (1) above, ϕ_f is the fibre volume fraction, and l_d is the length to diameter ratio of the fibre.

The plastic viscosities of the SCHPC and SCUHPC mixes with and without steel fibres reported above (see Table 2) estimated using the procedure just described are given in Table 3. Judging by the excellent predictive capability of this procedure [5], it is reasonable to assume that the plastic viscosities given in Table 3 are accurate. The plastic viscosity, together with the yield stress of the self-compacting mix is needed in the simulation of its flow in formwork [6].

5. Discussion and conclusions

The development of self-compacting high-performance and ultra high-performance concrete mixes is a complex process requiring the resolution of conflicting demands of flow-ability and non-segregation. These demands can be reconciled by increasing the paste content and decreasing the large aggregate volume. The addition of long steel fibres with crimped ends can however compromise the ability of the mix to flow smoothly through gaps in the reinforcement and to cause segregation of the fibres. Our extensive investigations lead us to the following major conclusions.

For the self-compacting high- and ultra high-performance concrete mixes without steel fibres the fulfilment of the flow and cohesiveness criteria, as measured by the slump cone flow test, are sufficient for the mix design. The resistance to segregation was checked visually. In the mixes with fibres, it was noticed that the fibres were uniformly distributed in the slump spread right up to the edge. However, this does not ensure that the fibres will pass through narrow openings. It is additionally necessary to check that the mixes meet the passing ability criterion using the J-ring apparatus. Our investigations show that although the mixes with fibres meet the flow-ability criterion and are resistant to segregation, as judged by the slump flow test, they may not meet the passing ability criterion. These mixes need to be more flow-able than required by the slump flow test, in order to satisfy the passing ability test. The viscosity of SCC mixes can be accurately estimated using a micromechanical procedure based on the measured viscosity of the cement paste and the mix proportions. The 30 mm long, 0.55 mm diameter steel fibres with crimped ends significantly increase the viscosity of SCC mixes with fibres. The viscosity is required for the simulation of the flow of self-compacting mixes into formwork.

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