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Manuscript title: Plastic-viscosity based mix design and the effect of limestone powder on material performance of self-compacting concrete

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Abstract

The advantages of using self-compacting concrete (SCC) in comparison to traditional vibrated concrete are widely acknowledged. One of the key challenges in producing consistence SCC mix lies in the ability to control its performance both in fresh and hardened states. There are several methodologies currently used for mix proportion design of SCC to achieve better quality and strength. This paper investigates the consistency of a plastic-viscosity based mix proportioning method by exploring the fresh state flow properties and hardened state compressive strengths of SCC mix produced using Portland limestone cement (PLC). For this purpose, SCC design mixes with target compressive strengths between 30 MPa and 70 MPa are tested. It was revealed that while using the chosen PLC type, the mix proportioning method which is based on the estimation of plastic-viscosity failed to achieve the predicted compressive strength in the case of target mix strength 60MPa and above. This paper aims to propose a procedure to mitigate this discrepancy by demonstrating that the quality and performance of the self-compacting concrete produced using plastic-viscosity based mixed design can be influenced by the cement type used and this can also affect the target compressive strength achieved by the concrete mix.

Keywords: Self-compacting concrete (SCC); Limestone powder (LP); Paste Volume; Mix design; Plastic-viscosity

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1. Introduction

The use of SCC in construction industry has been increasing due to several advantages (Rich *et al.*, 2017) including economic benefits, excellent performance, less energy consumption and improved safety compared to normal vibrated concrete (Corinaldesi, Moriconi and Ash, 2011) . The main features of SCC properties are effective filling and passing ability under its own weight and the ability to maintain flow stability without segregation to achieve required material compaction (Goodier, 2003). To achieve desired performance, the SCC which behaves like a Non-Newtonian fluid in fresh state, should have appropriate plastic viscosity and yield stress (EFNARC, 2005) . Therefore, SCC normally requires a high volume of powder content (compared to vibrated concrete) to yield a cohesive and homogeneous mix (Topçu and Uygunoğlu, 2010). While an adequate amount of powder does provide sufficient deformability and smooth flow of fresh SCC, excess amount of powder can be counter-productive by increasing viscosity or yield strength of a mix (Girish, Ranganath and Vengala, 2010).

To achieve required level of flowability as per guidelines (EFNARC, 2005), SCC can be produced using a viscosity-modifying admixture (VMA) or, more generally, using large quantity of powder materials such as cement and mineral additions. In general, a super-plasticizer (SP) is effectively used to optimise the shear behaviour relating to plastic viscosity and yield stress (Nepomuceno, Oliveira and Lopes, 2012) of SCC mixes. To achieve these aims, besides employing a strong SP, a large amount of fine powder is required (Ho *et al.*, 2002). LP, fly ash and ground granulated blast furnace slag (GGBS) are commonly used in SCC mixtures to maintain consistency cohesion and segregation resistance (EFNARC, 2005).

The use of fly ash and LP filler increases the paste volume of SCC, which in turn improves workability (Collepardi *et al.*, 2003)(Okamura and Ouchi, 2007)(Bouzoubaâ and Lachemi, 2001). However, SCC requires higher fine aggregate content to attain stability in the fresh state, which often leads to high cement consumption (Vurst *et al.*, 2017)(Jiao *et al.*, 2017)(Thanh *et al.*, 2015). In this context, its cost is one of the disadvantages of SCC, due to the use of high volumes of Portland cement (PC) and chemical admixtures. One alternative to decrease the cost of SCC is the use of mineral additives such as natural pozzolans, LP, slag, and fly ash, which are finely divided materials supplementary to concrete as separate components, either during or before mixing (Şahmaran, Christianto and Yaman, 2006). The development of SCC normally involves the use of additional cementitious materials, such as LP. Due to its favourable physical and chemical properties, LP can be incorporated to improve the packing of the binder through the filler effect without significantly altering the particle packing of the solid matrix (Wang *et al.*, 2018).

Use of PLC for producing SCC has both economic and technological benefits (Tsivilis, Voglis and Photou, 1999). The British and European Standard (BS EN 197-1, 2011) has allowed up to 5% LP as a minor supplementary constituent and classified four types of PLC: types II/ A-L and II/A-LL, comprising (6–20%) limestone; and types II/B-L and II/B-LL, comprising (21–35%) limestone. In addition, it is possible to use LP in mixture with supplementary cementitious materials. The maximum allowable LP addition tends to vary according to international and national standards, ranging between 6–35%. The fresh properties of concrete are of great significance because of their influences on construction quality in the forming and casting processes, as well as the characteristics of hardened concrete (Jiao *et al.*, 2017). To reduce the artificial errors, it is important to characterize fresh and hardened properties of concrete using fundamental national standards. Although the performance of PLC has been explored commonly in the past in terms of workability (flow and passing ability) and strength of SCC mix design, the obtainable information has remained fragmented and often unhelpful in further improving the use of PLC in concrete construction.

The use of PLC as a blended SCC, incorporating powder content as a cementitious supplementary (filler), such as fly ash, limestone, and GGBS, is now widely promoted (Lim, Ling and Hussin, 2012) and a great deal of research relating to this has been published. For practical reasons, the impact of using PLC as a blended cement in SCC is not commonly understood, particularly in terms of the effects of incorporating LP on flowability, pass-ability, and compressive strength during the development of concrete. As SCC contains various materials with individual characteristics, its mix design procedures should be able to accurately predict the rheological and mechanical properties of resulting SCC mix. There are several procedures including artificial neural network-based methods (DeRousseau *et al.*, 2018) (Hocine *et al.*, 2018) (Ramkumar *et al.*, 2020) are used to investigate the effectiveness of various components in SCC mix. The plastic-viscosity based procedure (Abo Dhaheer *et al.*, 2016) is one of the simple and effective mix design methods used in proportioning materials for SCC mix. The design consistency of this method for a chosen PLC type would be assessed in this article.

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This paper explores the rheological and structural properties of SCC mix design with various compressive strengths. In this investigation, the SCC mixes were made from PLC of type CEM II (CEMII/A-L 32,5 R). The main emphasis here is to investigate how the chosen PLC type influences the compressive strength achieved by SCC mix which is designed based on the estimation of mix plastic-viscosity (Abo Dhaheer *et al.*, 2016). Next section of this paper provides a summary of materials used and their specifications. Section 3 highlights the mix design method used in the present work. Section 4 outlines the experimental procedures and the standards to be satisfied by SCC mixes. Validation of the designed SCC mixes from the experimental results are presented in section 5. After confirming that the mixes satisfy SCC standards, the compressive strengths of all mixes were tested and assessed in this section. Section 6 focuses on discrepancies observed in the resulted target compressive strengths. To investigate the source of these discrepancies, alternative mixes were developed and compared with originally developed mixes. Finally, concluding remarks are summarised in Section 7 based on the results and observations made.

2. Material specifications

PLC (CEM II/A-L/32.5R) conforming to (BS EN 197-1, 2011) with a specific gravity of 2.95 and 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. 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. The results of sieve analysis for these two types of aggregate are shown in Figure 1.

3. Mix design method

Better proportioning of design mixes in SCC are achieved through optimising the percentage of filler materials in the mix. The fundamental materials and secondary materials for the mix in SCC are produced following the European Federation of Specialist Construction Chemicals and Concrete Systems (EFNARC) guidelines (EFNARC, 2005), where the specified typical ranges of primary constituent materials include powder (cementitious materials + filler), water, and aggregate as shown in

Table 1. A rigorous process of proportioning materials for normal strength SCC is dependent on the plastic viscosity and compressive strength of the SCC mixes (Abo Dhaheer *et al.*, 2016).

The mix design selected raw materials in optimal proportions to provide concrete with the required characteristics in fresh and hardened states for specific applications. Densely compacted cementitious matrix with good workability and strength can be achieved by targeted SCC design. (Abo Dhaheer *et al.*, 2016) developed a mix design method for SCC based on the desired target plastic-viscosity and compressive strength of the mix. In the present work, proportioning of SCC mixes were undertaken using the procedures described in (Abo Dhaheer *et al.*, 2016). The mix proportions of SCC test mixes designed based on (Abo Dhaheer *et al.*, 2016) are shown in Table 2. For the convenience of readership, as an example of mix design calculation, SCC mix proportion for a mix with target compressive strength of 50 MPa is presented in Appendix.

Procedure described in the Appendix was followed for calculating mix proportions of all the mixes developed. Additional details of SCC test mixes in Table 2 are presented in Table 3. In these tables the 'Mix designation' indicates target compressive strength (in MPa) of the corresponding SCC mix. In Table 3, 'PV' denotes plastic-viscosity and for brevity, this notation is used in tables throughout this paper.

Testing procedures of the designed mixes and corresponding results achieved in this study are discussed in the following sections.

4. Experimental Methodologies

Fresh and hardened concrete characteristics were investigated to confirm whether the self-compacting ability and compressive strength of the suggested method met the mix design requirements. Several experiments were conducted to evaluate the performance of the designed SCC mixes. For example, the slump flow trial was performed to determine the flow and filling ability; this trial characterises the plastic viscosity of fresh SCC. The J-ring trial was performed to analyse the passing ability of SCC among reinforcement steel bars without producing segregation and blocking, according to (EFNARC, 2005). Table 4 illustrates the general acceptance criteria of SCC according to literature (BS EN 206-9, 2010). Additionally, visual inspection was performed on the SCC concrete mix to assess the characteristics with respect to bleeding and segregation. The compressive strength of SCC was achieved in accordance with (BS EN 12390-3, 2009), using concrete cube samples with size $100 \times 100 \times 100$ mm^3. Samples were demoulded and kept in water for curing until ages of 7, 14, and 28 days before each testing. Temperature of the water used for curing was maintained between 20-24°C. A schematic diagram describing testing procedure for mix design is summarised below in Figure 2.

5. Validation of mix design method

5.1. Tests on fresh SCC

Examinations were conducted to measure t_{500} of the slump flow of fresh mixes as shown in Table 5. The time taken by the fresh SCC mix to reach a 500 mm diameter spread in the slump cone flow test t_{500} was determined from time sequencing a video recording of the test, with an accuracy of a thousandth of a second. The chosen range of flow spread diameters of all tested SCC mixes were between 600 to 750 mm (SF_1/SF_2), with t_{500} varied between 1.13 - 1.87 s, and the correponding viscosity class was VS_1 (t_{500} < 2 s) according to (BS EN 206-9, 2010) . As a sample illustration, Figure 3 displays the horizontal spread of SCC mix with designation 30 MPa and 40 MPa. A thorough visual inspection indicated that the self-compacting mixtures showed no signs of bleeding or segregation as it can be noted from this figure.

Figure 4 illustrates the flow time for all the mixtures and the corresponding water to powder (i.e. cement + GGBS+ LP < 125 μm) ratio (w/p). It can be clearly observed that a higher t_{500} is associated with larger powder or lower water content. It has been reported that a water to powder (w/p) proportion has a significant effect on both the fresh and hardened characteristics of SCC, and its impact on flow characteristics often limits the amount that can be used (Dhaheer, Alyhya and Karihaloo, 2016). Moreover, the use of LP increases the fluidity of the SCC mix, but can also negatively influence its stability. The increase in the amount of LP reduces the plastic viscosity of the mix (Derabla and Benmalek, 2014). Meanwhile, the use of LP in SCC increases the SP requirement to maintain a steady slump flow diameter (Gesoğlu *et al.*, 2012). However, mixtures with low water content may require comparatively high dosages of SP, specifically at low cement contents, to realize acceptable requirement of SCC deformability (Okamura and Ouchi, 2007).

Figure 5 shows the relationship between w/cm ratio and corresponding SP volume used for all the mixes. It can be clearly observed that a higher SP dosage is used for lower water-to-cement ratio. When SP was added to increase the workability of the slump and flow, it was observed that a higher SP dosage was needed for lower water-to-cement ratio. It can be observed that the SP amount required for stable and smooth flow increased from 2.1 to 3.5 kg/m^3. Especially in the case of mix with target compressive strength 70 MPa, more than estimated amount of SP was needed to maintain stable and cohesive flow of the SCC mix.

Furthermore, the increase in SP dosage was proportionally greater than the increase in content of powder, as shown through the increase of SP dosage for each content of powder with the limestone fines. The increase in SP amount required may be attributed to decrease in workability due to the addition of limestone fines as a cementitious paste replacement (Chen, Kwan and Jiang, 2014).

The time needed to reach 500 mm diameter spread is compared against corresponding plastic viscosity of the mix as illustrated in Figure 6. It was also observed that the slump flow spread diameter of the mixes ranged between 600 – 750 mm which confirmed that they meet the recommended SCC standard. Assuming that the mixes had approximately the same yield stress, plastic viscosity was used as the monitoring parameter to relate with t_{500} as in Figure 6. It is described in (Nehdi, Mindess and Aïtcin, 2012) that the LP as a filler substitution of cement slightly increases the yield stress of cement paste and reduces its plastic viscosity, which in turn causes improved flow ability and stability in cement paste. However, increasing the LP content causes bleeding of cement paste with high water-to-binder ratios, although it does not have significant influence at low water-to-binder ratios. An appropriate volume of powder guarantees sufficient flow and deformability of fresh SCC, while additional powder can be counter-productive by increasing the viscosity or yield stress of a mix (Girish, Ranganath and Vengala, 2010).

All the above trial mixtures that fulfilled the flow-ability standard and presented no signs of segregation were subjected to the filling and passing ability trial using the J-ring to ensure that they were able to pass through narrow gaps that exist among reinforcing bars in structural elements of reinforced concrete. For this purpose, 300 mm diameter J-ring equipment with 16 steel rods (each of diameter 16 mm and 100 mm height) was used as recommended by (BS EN 12350-8, 2010). In these J-ring tests, final spread values of the slump ranged between 590 and 695 mm. In addition, the variation in viscosity class was demonstrated by t_{500J}, ranging from 1.59 to 2.59 s (VS_1 or VS_2). Table 6 presents the J-ring test results for the fresh SCC mixtures. All mixes passed the flow and passing ability standards and showed no blockage or signs of segregation. For example, the experimental observation of flow spread during J-ring test for mixes C40 and C50 are shown in Figure 7. The J-ring test results obtained here are in agreement with the results reported by (Dhaheer, Alyhya and Karihaloo, 2016).

The passing ability of SCC can also be judged by measuring height variation between the concrete mix outside and inside steel bars of the J-ring test. According to (BS EN 206-9, 2010), the blocking step (P_J) should be less than10 mm for an SCC mix to satisfy the passing ability. The blocking step height (P_J) obtained during the J-ring test is also presented in Table 6. It is clear from the results that all SCC mixes satisfy the passing ability criteria.

In accordance with (ASTM:C1621/C 1621M[1], 2017), the slump flow trial can be used together with J-ring trial to measure the passing ability of SCC. If the variation between spread diameters of these two trials ($D_{flow} - D_{J\text{-}ring}$) is minimal (i.e. less than 25 mm), there is no visual blockage. If it is between 25 and 50 mm, there is minimum to visible blockage. Table 6 displays the difference in spread diameter between slump flow and J-ring trial, clearly demonstrating that for all mixes there is minimum or no blockage.

5.2. Tests on hardened SCC

The measurement of compressive strength in this experimental study was performed on the $100 \times 100 \times 100$ mm cube specimens (three per mixture and age) cured in water at ambient temperature. The tests were carried out at 7, 14, and 28 days. The results obtained in these compressive strength tests are shown in Table 7 and Figure 8. It can be clearly noted that the growth of compressive strength is consistent with reducing water to powder content and corresponds to w/cm ratios as shown in Figure 9. These results are in agreement with observations made by (Rao, 2001) and (Fernandes *et al.*, 2005).

It can be noted from the above results, that the SCC mixes with target compressive strength 60 MPa and 70 MPa did not achieve the expected strength in 28 days. Although these mixes satisfied the SCC criteria for fresh state tests, they are not able to reach the predicted compressive strengths. To further investigate this behaviour, additional tests were carried out on SCC mix with target compressive strength of 60 MPa. The next section present the experiments and corresponding results obtained during this investigation.

6. Further analysis of SCC mix with target compressive strength 60 MPa

To further explore the characteristics of 60 MPa mix, two categories of experiments were performed. In the first category, the target plastic vicosity of the mixes were increased to check whether that influences the compressive strength attained by the mix. In the second category, the amount cement and LP was varied recognising the fact that PLC (CEM II/A-L/32.5R) already contains around 6 - 20% LP.

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6.1 Investigation based on target plastic viscosity of SCC mix

As described in section 3, 60 MPa (target 28-day compressive strength) SCC mixes with two different target plastic viscosities 9 Pa s and 10 Pa s (denoted respectively by C60† and C60‡) were developed. Table 8 below shows the mix proportions of these mixes and compares them with the originally developed mix C60. Additional details of these SCC test mixes are presented in Table 9.

Tables 10 and 11 present the experimental results obtained in slump flow and J-ring tests. As it can be noted from these tests, all the above mixes successfully pass both tests and satisfy recommended SCC properties in fresh state.

Table 12 summarises the experimental results obtained during cube compression tests. It is evident from these results that none of the mixes were able to reach target compressive strength in 28 days. This observation (from the above SCC mixes) demonstrates that the increase in target plastic visocity does not enable these mixes to reach the target 28-day compressive strength. One of the obvious reasons for not achieving the predicted strength may be attributed to insufficient cement in the mix. Though the chosen mix proportioning method was successful in predicting target compressive strength between 30 MPa to 50 MPa, it failed in the case of 60 MPa and above for the chosen PLC (CEM II/A-L/32.5R). It was noted that, according to the specification in the Standards (BS EN 197-1, 2011), CEM II/A-L/32.5R may contain 6-20% LP by weight. Therefore, when mix proportions were calculated based on (Abo Dhaheer *et al.*, 2016) the proportion of PLC used may not have sufficient amount of cement within to achieve the predicted compressive strength. This discrepancy was not encountered when the target compressive strength was 50 MPa or less. In other words, for lower target compressive strength the amount of cement within PLC was probably sufficient to achieve the predicted strength. To further investigate this, more SCC mixes with target compressive strength of 60 MPa were considered. Next section describes the additional experiments conducted, their results and corresponding observations made.

6.2 Investigation based on LP content in SCC mix proportion

From the observations made in section 6.1, it is clear that by simply increasing the amount of cement and adjusting the other constituents of a SCC mix according to the proposed technique (Abo Dhaheer *et al.*, 2016) will enable the SCC mix to achieve target compressive strength. However, instead of merely increasing the amount of cement, in the present work, an attempt was made to investigate the influence of LP already present in the PLC (CEM II/A-L/32.5R) used. For this purpose, four different

SCC mixes with same target plastic viscosity (8.5 Pa s) and target compressive strength (60 MPa) were considered.

According to the specification of PLC (CEM II/A-L/32.5R) cement used, this cement is likely to contain 6 – 20% of LP in a chosen weight. To investigate the influence of LP already contained in this cement, four different mixes were designed assuming that the cement already includes (i) 6% , (ii) 10%, (iii)15% or (iv) 20% LP and denoted respectively as C60$^{(i)}$, C60$^{(ii)}$, C60$^{(iii)}$ and C60$^{(iv)}$. For example, in mix C60$^{(i)}$, mix proportions of the constituents were estimated assuming that the PLC already contains 6% of LP by weight and accordingly adjustments were made in the amount of cement and LP used in the mix design. To be precise, compared to C60 mix in Table 2, 6% more PLC (CEM II/A-L/32.5R) was used in C60$^{(i)}$ and, accordingly corresponding amount of LP was reduced compared to C60. The same procedure was repeated in the case of other three mixes according to 10%, 15% and 20% LP content in the cement.

Table 13 below shows the mix proportions for all four mixes and compares them with the originally developed 60 MPa mix. Additional details of these SCC test mixes are presented in Table 14.

Tables 15 and 16 present the experimental results obtained in slump flow and J-ring tests. As it can be noted from these tests, all the above mixes successfully fulfill both flow tests and satisfy recommended SCC properties in fresh state. Further, it can be noticed that the flow properties (e.g., flow spread) of the mixtures are not significantly affected by the changes made in the amount of PLC and LP.

Table 17 summarises the experimental results obtained during cube compression tests. It can be seen from the Table 17 that the new mixes (i.e. C60$^{(i)}$, C60$^{(ii)}$, C60$^{(iii)}$ & C60$^{(iv)}$) were able to achieve compressive stregth very close to 60 MPa. Figure 10 provides additional information on the range of compressive strength reached at 28 days of age for these mixes and compares with original SCC mix with target compressive strength 60 MPa (i.e. C60). It can also be noted from the above results that the difference in compressive strength achieved by the new mixes at the end of 28 days was not significant.

To verify if the mix design with target compressive strength 70MPa (i.e. C70) also displays similar behaviour, the above experiment was repeated for mix designated as C70. The new mixes are denoted as C70$^{(i)}$, C70$^{(ii)}$, C70$^{(iii)}$ and C70$^{(iv)}$ in a manner similar to C60. Tables 18, 19, 20, 21 and 22 present the mix proportions for these mixes, fresh state (slump flow and J-ring) test results and compression test results respectively. All the new mixes satisfied recommended standard required in fresh state. Further, it can be seen clearly from Figure 11 that the new mixes were able to achieve compressive strength closer to the predicted value.

It can be observed from the above results that, amending the amount of PLC and accordingly adjusting the amount of LP as per the specification of CEM II/A-L/32.5R enable the recommended (Abo Dhaheer *et al.*, 2016) mix proportion to achieve target compressive strength of 60MPa or above. The investigations here demonstrate that, the mix proportions derived according to (Abo Dhaheer *et al.*, 2016) may not always produce desired compressive strength for SCC mix unless PLC with suitable specification is used. Therefore, while using the procedure described in (Abo Dhaheer *et al.*, 2016)**,** it is important to consider the choice of cement specifiction to be used when preparing the mix proportions especially for higher compressive strengths (i.e. for 60 MPa and above).

7. Concluding remarks

This study explored fresh state properties and hardened state compressive strength of SCC mix yielded by mix proportioning method based on the estimation of mix plasic-vicosity (Abo Dhaheer *et al.*, 2016) using PLC (PLC-CEM II/A-L 32,5 R). As predicted, all mixes produced by this mix proportioning method were able to satisfy the recommended SCC properties in the fresh state. However, the target 28-day compressive strengths were not achieved for the mixes with target strengths 60 MPa or higher. In order to explore this discrepancy, two sets of experimental investigations were carried out. In the first set, 60 MPa mixes were designed with higher target plastic viscosities (9 and 10 Pa s) compared to the original mix (8.5 Pa s). The results of this set of experiments proved that the mixes were still not able to reach the target compressive strength. It was realised that one of the reasons for this may lie in the fact that the amount of cement in the mix was not sufficient to reach the target compressive strength. This was further reinforced by the cement type used for the mixes. According to the specification (BS EN 197-1, 2011), the cement used PLC-CEM II/A-L, may contain around 6-20% of LP by weight. Noting this, in the second set of experiments, the amount of cement was slightly increased and at the same time the amount of LP was adjusted to maintain the mix proportion same as recommended by the plastic-viscosity based method (Abo Dhaheer *et al.*, 2016). This set of experiments demonstrated that the new SCC mixes were able to reach target compressive strength as predicted. Therefore, it has been demonstrated that, while using the mix proportioning method proposed by (Abo Dhaheer *et al.*, 2016), it is important to ensure that suitable cement type is used or other relevant steps are considered in order to achieve the target compressive strength.

Appendix

Following procedure describes (with the help of design chart in Figure 12) the steps involved in producing the mix design for a given SCC target compressive strength of 50 MPa (Figure 12) with cement replacement of 25% GGBS. Please note that the design chart in Figure 12 corresponds to target compressive strength of 50MPa. This chart displays, for a given compressive strength (i.e. 50MPa in the present case), mass of various ingredients with respect to plastic viscosity. Similar charts can be produced for other relevant target strengths as described in (Abo Dhaheer *et al.*, 2016).

Step1

- Assume the required target plastic viscosity (η_{mix}) of mixture is 7 Pa s.
- For the required target compressive strength of 50 MPa, the corresponding w/cm ratio is approximately 0.53 (Abo Dhaheer *et al.*, 2016);
- Suppose a trial super-plasticizer dose (SP) as a percentage of mass of cementitious materials (say 0.65%).

Step 2: Determine the cementitious material content (cm) using Figure 12;

$$For\ \eta_{mix} = 7\ Pa\ s\ \ \rightarrow\ \ \frac{cm}{\eta} = 57\ \ (bottom\ curve\ )\ \rightarrow cm = 57 \times 7 = 399\ \ kg/m^3$$

$$cement = 0.75\ \times 399\ = 299.25\ \ kg/m^3$$

$$ggbs = 0.25\ \times 399 = 99.75\ kg/m^3$$

As $\frac{W}{Cm} = 0.53\ \ \rightarrow w = 0.53 \times 399 =\ 211.47\ \ kg/m^3$

Step 3: Determine the solid stage component contents (LP, FA, and CA) using Figure 12;

$$For\ \ \eta_{mix} = 7\ Pa\ s\ \ \rightarrow\ \ \frac{cm + LP}{\eta} = 73.5\ \ (second\ curve\ from\ bottom)\ \rightarrow (cm + LP) = 73.5 \times 7$$

$$= 514.5\ \ kg/m^3\ \ \rightarrow\ \ LP = 514.5 - 399 = 115.5\ \ kg/m^3$$

$$\frac{cm + LP + FA}{\eta} = 186\ \ (second\ curve\ from\ top)\ \rightarrow (cm + LP + FA) = 186 \times 7 = 1302\ kg/m^3\ \ \rightarrow\ \ FA$$

$$= 1302 - 399 - 115.5\ \ = 787.5\ \ kg/m^3$$

$$\frac{cm+LP+FA+CA}{\eta} = 298\ \ (\,top\ curve\,)\ \rightarrow (cm+LP+FA+CA) = 298\times 7 = 2086\,kg/m^3\ \ \rightarrow\ \ FA$$

$$= 2086 - 787.5 - 399 - 115.5\ = 784\ \ kg/m^3$$

Step 4: Calculate the total volume of the mixture ;

Using the calculated mass above and corresponding densities (ρ), the total volume can be evaluated as below.

$$Total\ volume = \left(\frac{cm}{\rho_{Cm}} + \frac{ggbs}{\rho_{ggbs}} + \frac{w}{\rho_w} + \frac{SP}{\rho_{sp}} + \frac{LP}{\rho_{LP}} + \frac{FA}{\rho_{FA}} + \frac{CA}{\rho_{CA}} + 0.02\right)$$

Chosen densities:

cement (ρ_{Cm}) = 2950 kg/m^3 ; ggbs (ρ_{ggbs}) = 2400 kg/m^3; water (ρ_w) = 1000 kg/m^3; SP (ρ_{sp}) = 1070 kg/m^3; LP (ρ_{LP}) = 2400 kg/m^3; FA (ρ_{FA}) = 2650 kg/m^3; CA (ρ_{CA}) = 2800 kg/m^3

$$Total\ volume = \left(\frac{399\times 0.75}{2950} + \frac{399\times 0.25}{2400} + \frac{211.47}{1000} + \frac{3.00}{1070} + \frac{115.5}{2400} + \frac{787.5}{2650} + \frac{784}{2800}\ \ + 0.02\right)$$

$$= 1.0025\ \ \ m^3$$

As the yield volume does not equal 1 m^3, the volumes of material are adjusted, and the mixture plastic viscosity is determined using micromechanical procedure (Abo Dhaheer *et al.*, 2016).

$cm = \ 299.25/1.0025\ \ \ = 298.48\ \cong 300\,kg/m^3$

$ggbs = \ 99.75/1.0025\ \ \ = 99.49 \cong 100\,kg/m^3$

$w = \ 211.47/1.0025\ \ \ = 210.92 \cong 210\,kg/m^3$

$SP = \ 3.00/1.0025\ \ \ = 2.99\ \ kg/m^3$

$LP = \ 115.5/1.0025\ \ \ = 115.20\ \cong 115\ \ kg/m^3$

$FA = \ 787.5/1.0025\ \ \ = 785.98 \cong 785 kg/m^3$

$CA = \ 784/1.0025 = 781.98\ \cong 780\,kg/m^3$

$$Total\ volume = \left(\frac{300}{2950} + \frac{100}{2400} + \frac{210}{1000} + \frac{2.99}{1070} + \frac{115}{2400} + \frac{785}{2650} + \frac{780}{2800} + 0.02\right) = 1.00\ \ \ m^3$$

Step 5: Calculate the following amount fractions of solid stages ;

volume fraction of LP, $\emptyset_{LP} = \dfrac{\frac{LP}{\rho_{LP}}}{\left(\frac{c}{\rho_C} + \frac{ggbs}{\rho_{ggbs}} + \frac{w}{\rho_w} + \frac{SP}{\rho_{sp}} + 0.02\right) + \frac{LP}{\rho_{LP}}}\ \ \ = 0.113$

volume fraction of FA, $\emptyset_{FA} = \dfrac{\frac{FA}{\rho_{FA}}}{\left(\frac{c}{\rho_C} + \frac{ggbs}{\rho_{ggbs}} + \frac{w}{\rho_w} + \frac{SP}{\rho_{sp}} + \frac{LP}{\rho_{LP}} + 0.02\right) + \frac{FA}{\rho_{FA}}}\ = 0.411$

volume fraction of CA, $\emptyset_{CA} = \frac{\frac{CA}{\rho_{CA}}}{\left(\frac{c}{\rho_C}+\frac{ggbs}{\rho_{ggbs}}+\frac{w}{\rho_w}+\frac{SP}{\rho_{sp}}+\frac{LP}{\rho_{LP}}+\frac{FA}{\rho_{FA}}+0.02\right)+\frac{CA}{\rho_{CA}}} = 0.279$

Step 6: Check the plastic viscosity using micromechanical procedure described in (Abo Dhaheer *et al.*, 2016);

$$\eta_{mix} = \eta_{paste} \times \left(1 - \frac{\emptyset_{LP}}{\emptyset_m}\right)^{-1.9} \times \left(1 - \frac{\emptyset_{FA}}{\emptyset_m}\right)^{-1.9} \times \left(1 - \frac{\emptyset_{CA}}{\emptyset_m}\right)^{-1.9},$$

where, $\emptyset_m$ denote maximum packing geometry.

$$\eta_{mix} = 0.23 \times \left(1 - \frac{0.113}{0.524}\right)^{-1.9} \times \left(1 - \frac{0.411}{0.63}\right)^{-1.9} \times \left(1 - \frac{0.279}{0.74}\right)^{-1.9} = 6.76\ Pa.s,$$

$$Viscosity\ diff. = \frac{(Calulated\ \eta_{mix} - Target\ \ \eta_{mix})}{Target\ \ \eta_{mix}} \times 100$$

$$Viscosity\ diff. = \frac{(6.76 - 7)}{7} \times 100 = -3.3\ \%$$

The actual mixture plastic viscosity is within ±5%, thus the above mixture proportions are acceptable.

Symbols and abbreviations

ACMs	Additional Cementitious Materials
CA	Coarse aggregate
EFNARC	The European Federation of Specialist Construction Chemicals and Concrete Systems.
f_{cu}	The 28-day corresponding cube compressive strength (MPa)
FA	Fine aggregate
GGBS	Ground granulated blast-furnace slag
LP	Limestone powder
PLC	Portland limestone cement
PC	Portland cement
SCC	Self-compacting concrete
SP	Super-plasticiser
SP/cm	Super-plasticiser to cement ratio
VC	Vibrated Concrete
w/cm	Water to cement ratio
w/p	Water to powder ratio

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Table 1 Typical range of SCC mix compositions according to (EFNARC, 2005)

Ingredients	Typical range by mass (kg/m^3)	Typical range by volume (litres/m^3)
Powder (cementitious materials + filler)	380–600	-
Water	150–210	150–210
Coarse aggregate	750–1000	270–360
Water to powder ratio by volume	0.85–1.10	
Fine aggregate	Typically, 48–55% of the total aggregate	

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Table 2 Mix proportions of test SCC mixes (kg / m^3)

<table>
<tr><td rowspan="2">Mix designation</td><td colspan="2">cm[a]</td><td rowspan="2">Water</td><td rowspan="2">SP[b]</td><td rowspan="2">w/cm</td><td rowspan="2">SP/cm</td><td rowspan="2">LP[c]</td><td colspan="2">FA[d]</td><td rowspan="2">CA[e]</td></tr>
<tr><td>Cement</td><td>ggbs</td><td>FA**</td><td>FA***</td></tr>
<tr><td rowspan="2">C30</td><td rowspan="2">239</td><td rowspan="2">78</td><td rowspan="2">201</td><td rowspan="2">2.1</td><td rowspan="2">0.63</td><td rowspan="2">0.65</td><td rowspan="2">160</td><td>222</td><td>550</td><td rowspan="2">851</td></tr>
<tr><td colspan="2">772</td></tr>
<tr><td rowspan="2">C40</td><td rowspan="2">288</td><td rowspan="2">95</td><td rowspan="2">219</td><td rowspan="2">2.5</td><td rowspan="2">0.57</td><td rowspan="2">0.78</td><td rowspan="2">130</td><td>200</td><td>544</td><td rowspan="2">770</td></tr>
<tr><td colspan="2">744</td></tr>
<tr><td rowspan="2">C50</td><td rowspan="2">293</td><td rowspan="2">98</td><td rowspan="2">207</td><td rowspan="2">2.6</td><td rowspan="2">0.53</td><td rowspan="2">0.66</td><td rowspan="2">69</td><td>248</td><td>500</td><td rowspan="2">890</td></tr>
<tr><td colspan="2">748</td></tr>
<tr><td rowspan="2">C60</td><td rowspan="2">315</td><td rowspan="2">105</td><td rowspan="2">197.5</td><td rowspan="2">2.7</td><td rowspan="2">0.47</td><td rowspan="2">0.57</td><td rowspan="2">125</td><td>188</td><td>528</td><td rowspan="2">840</td></tr>
<tr><td colspan="2">716</td></tr>
<tr><td rowspan="2">C70</td><td rowspan="2">348</td><td rowspan="2">116</td><td rowspan="2">186</td><td rowspan="2">2.8
(3.5)[1]</td><td rowspan="2">0.40</td><td rowspan="2">0.60</td><td rowspan="2">117</td><td>230</td><td>501</td><td rowspan="2">843</td></tr>
<tr><td colspan="2">731</td></tr>
</table>

[a]Cementitious material.
[b]Super-plasticizer.
[c]Limestone powder <125 μm.
[d]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).
[e]Coarse aggregate < 20 mm.
(3.5)[1] Amount of SP required during the experiment instead of estimated value 2.8

Table 3 Further details of test SCC mixes

Mix designation	Target PV (Pa s)	Actual PV (Pa s)	% PV difference	Paste vol. fraction	Solid vol. fraction	Paste/Solid (by vol.)
C30	5	4.92	-1.69	0.38	0.61	0.62
C40	5	4.91	-1.76	0.39	0.61	0.64
C50	7	6.76	-3.42	0.38	0.62	0.61
C60	8.5	8.18	-3.76	0.41	0.59	0.69
C70	9.5	9.55	-0.53	0.40	0.60	0.68

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Table 4 General acceptance criteria for SCC mix (BS EN 206-9, 2010) and (ASTM:C1621/C 1621M[1], 2017).

Slump-flow classes		Viscosity classes (t_{500}: time taken for reaching 500 mm spread diameter)	
Class	Slump flow spread (mm)	class	t_{500} (s)
SF_1	550 to 650	VS_1	< 2.0
SF_2	660 to 750	VS_2	≥ 2.0
Passing ability classes – J-ring			
Class		J-ring step (mm)	
P_J (Height difference between the concrete inside and outside the steel bars of the J-ring test)		≤ 10 with 16 rebars	
Blocking assessment (mm)			
Difference between Slump flow and J-Ring flow		Blocking assessment (mm)	
≤ 25 mm		No visible blocking	
> 25 to 50 mm		Minimal to noticeable blocking	
> 50 mm		Noticeable to extreme blocking	

Table 5 Slump flow test for SCC mixes

Mix designation	Slump flow spread diameter, D_{FLOW} (mm)	t_{500} (sec)	Viscosity class t_{500} < 2 s or ≥ 2 s
C30	610	1.13	VS_1
C40	602.5	1.20	VS_1
C50	615	1.17	VS_1
C60	650	1.32	VS_1
C70	690	1.87	VS_1

Table 6 J-ring test results of the SCC mixes

Mix designation	J-ring spread diameter D_J (mm)	t_{500J} (sec)	Viscosity class t_{500}< 2 s or ≥ 2 s	P_J (mm)	D_{FLOW} - D_J (mm)
C30	600	1.97	VS_1	10	10
C40	600	2.02	VS_2	9.5	2.5
C50	610	1.73	VS_1	8	5
C60	645	1.43	VS_1	9	5
C70	685	2.24	VS_2	9.75	5

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Table 7 Compressive strength of samples water cured at 7, 14 and 28 days

Mix designation	Compressive strength (7 days) MPa	Compressive strength (14 days) MPa	Compressive strength (28 days) MPa
C30	26.21	32.18	39.51
C40	29.13	34.71	40.64
C50	29.33	45.68	50.74
C60	35.05	45.25	56.57
C70	45.35	55.01	63.05

Table 8 Mix proportions of test SCC mixes (kg / m^3).

<table>
<tr><th rowspan="2">Mix designation</th><th rowspan="2">PV (Pa s)</th><th colspan="2">cm[a]</th><th rowspan="2">Water</th><th rowspan="2">SP[b]</th><th rowspan="2">w/cm</th><th rowspan="2">SP/cm</th><th rowspan="2">LP[c]</th><th colspan="2">FA[d]</th><th rowspan="2">CA[e]</th></tr>
<tr><th>Cement</th><th>ggbs</th><th>FA**</th><th>FA***</th></tr>
<tr><td rowspan="2">C60‡</td><td rowspan="2">10</td><td rowspan="2">305</td><td rowspan="2">105</td><td rowspan="2">195</td><td rowspan="2">3</td><td rowspan="2">0.47</td><td rowspan="2">0.73</td><td rowspan="2">132</td><td>200</td><td>580</td><td rowspan="2">812</td></tr>
<tr><td colspan="2">780</td></tr>
<tr><td rowspan="2">C60†</td><td rowspan="2">9</td><td rowspan="2">308</td><td rowspan="2">102</td><td rowspan="2">194</td><td rowspan="2">3 (2.7)[1]</td><td rowspan="2">0.47</td><td rowspan="2">0.73</td><td rowspan="2">92</td><td>200</td><td>577</td><td rowspan="2">823</td></tr>
<tr><td colspan="2">777</td></tr>
<tr><td rowspan="2">C60</td><td rowspan="2">8.5</td><td rowspan="2">315</td><td rowspan="2">105</td><td rowspan="2">197.5</td><td rowspan="2">2.7</td><td rowspan="2">0.47</td><td rowspan="2">0.57</td><td rowspan="2">125</td><td>188</td><td>528</td><td rowspan="2">840</td></tr>
<tr><td colspan="2">716</td></tr>
</table>

[a]Cementitious material.
[b]Super-plasticizer.
[c]Limestone powder <125 μm.
[d]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).
[e]Coarse aggregate < 20 mm.
(2.7)[1] Amount of SP required during the experiment instead of estimated value 3

Table 9 Further details of test SCC mixes.

Mix designation	Target PV (Pa s)	Actual PV (Pa s)	% PV difference	Paste vol. fraction	Solid vol. fraction	Paste/Solid (by vol.)
C60‡	10	10.12	+1.19	0.39	0.61	0.65
C60†	9	9.23	+2.51	0.38	0.61	0.64
C60	8.5	8.18	-3.76	0.41	0.59	0.69

Table 10 Slump flow test for SCC mixes.

Mix designation	Slump flow spread diameter, D_{FLOW} (mm)	t_{500} (sec)	Viscosity class t_{500}< 2 s or ≥ 2 s
C60‡	697.5	2.00	VS_1
C60†	650	1.09	VS_1
C60	650	1.32	VS_1

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Table 11 J-ring test for SCC mixes.

Mix designation	J-ring spread diameter D_J (mm)	t_{500J} (sec)	Viscosity class t_{500} < 2 s or ≥ 2 s	P_J (mm)	D_{FLOW} -D_J (mm)
C60‡	715	2.35	VS_2	9.25	17.5
C60†	637.5	1.03	VS_1	8	12.5
C60	645	1.43	VS_1	9	5

Table 12 Compressive strength of samples water cured at 7, 14 and 28 days.

Mix designation	Compressive strength (7 days) MPa	Compressive strength (14 days) MPa	Compressive strength (28 days) MPa
C60‡	37.47	44.55	55.34
C60†	35.70	41.75	53.28
C60	35.05	45.25	56.57

Table 13 Mix proportions of test SCC mixes (kg / m^3).

Mix designation	cm[a]		Water	SP[b]	w/cm	SP/cm	LP[c]	FA[d]		CA[e]
	Cement	ggbs						FA**	FA***	
C60	315	105	197.5	2.7	0.47	0.57	125	188	528	840
								716		
C60(i)	315	105	198	2.9	0.47	0.69	151	284	410	856
								694		
C60(ii)	315	105	198	2.6	0.47	0.62	140	198	500	862
								698		
C60(iii)	315	105	198	2.3	0.47	0.55	125	206	500	871
								706		
C60(iv)	315	105	198	2	0.47	0.48	109	214	500	881
								714		

[a]Cementitious material.
[b]Super-plasticizer.
[c]Limestone powder <125 µm.
[d]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).
[e]Coarse aggregate < 20 mm.

Table 14 Further details of test SCC mixes.

Mix designation	Target PV (Pa s)	Actual PV (Pa s)	% PV difference	Paste vol. fraction	Solid vol. fraction	Paste/Solid (by vol.)
C60	8.5	8.18	-3.76	0.41	0.59	0.69
C60(i)	8.5	8.35	-1.82	0.41	0.58	0.70
C60(ii)	8.5	8.32	-2.07	0.41	0.59	0.69
C60(iii)	8.5	8.32	-2.06	0.40	0.59	0.67
C60(iv)	8.5	8.32	-2.07	0.39	0.60	0.65

Accepted manuscript doi: 10.1680/jcoma.21.00038

Table 15 Slump flow results for SCC mixes.

Mix designation	Slump flow spread diameter, D_{FLOW} (mm)	t_{500} (sec)	Viscosity class $t_{500}< 2$ s or ≥ 2 s
C60	650	1.32	VS_1
C60$^{(i)}$	675	1.67	VS_1
C60$^{(ii)}$	625	1.41	VS_1
C60$^{(iii)}$	645	1.29	VS_1
C60$^{(iv)}$	705	1.18	VS_1

Table 16 J-ring results for the SCC mixes.

Mix designation	J-ring spread diameter D_J (mm)	t_{500J} (sec)	Viscosity class $t_{500}<$ 2 s or $\geq$ 2 s	P_J (mm)	D_{FLOW}-D_J (mm)
C60	645	1.43	VS_1	9	5
C60$^{(i)}$	665	1.75	VS_1	7.5	10
C60$^{(ii)}$	620	1.73	VS_1	7.75	5
C60$^{(iii)}$	635	1.66	VS_1	9.25	5
C60$^{(iv)}$	690	1.59	VS_1	8	15

Table 17 Compressive strength of samples water cured at 7, 14 and 28 days.

Mix designation	Compressive strength (7 days) MPa	Compressive strength (14 days) MPa	Compressive strength (28 days) MPa
C60	35.05	45.25	56.57
C60$^{(i)}$	39.44	51.86	58.33
C60$^{(ii)}$	38.12	51.44	60.98
C60$^{(iii)}$	37.81	55.01	58.38
C60$^{(iv)}$	37.77	50.83	59.79

Accepted manuscript doi:
10.1680/jcoma.21.00038

Table 18 Mix proportions of test SCC mixes (kg / m^3).

<table>
<tr><th rowspan="2">Mix designation</th><th colspan="2">cm[a]</th><th rowspan="2">Water</th><th rowspan="2">SP[b]</th><th rowspan="2">w/cm</th><th rowspan="2">SP/cm</th><th rowspan="2">LP[c]</th><th colspan="2">FA[d]</th><th rowspan="2">CA[e]</th></tr>
<tr><th>Cement</th><th>ggbs</th><th>FA**</th><th>FA***</th></tr>
<tr><td rowspan="2">C70</td><td rowspan="2">348</td><td rowspan="2">116</td><td rowspan="2">186</td><td rowspan="2">2.8 (3.5)[1]</td><td rowspan="2">0.40</td><td rowspan="2">0.60</td><td rowspan="2">117</td><td>230</td><td>501</td><td rowspan="2">843</td></tr>
<tr><td colspan="2">731</td></tr>
<tr><td rowspan="2">C70$^{(i)}$</td><td rowspan="2">351</td><td rowspan="2">117</td><td rowspan="2">187</td><td rowspan="2">2.8 (3.8)[2]</td><td rowspan="2">0.40</td><td rowspan="2">0.59</td><td rowspan="2">96</td><td>238</td><td>500</td><td rowspan="2">851</td></tr>
<tr><td colspan="2">738</td></tr>
<tr><td rowspan="2">C70$^{(ii)}$</td><td rowspan="2">351</td><td rowspan="2">117</td><td rowspan="2">187</td><td rowspan="2">2.8 (3.8)[2]</td><td rowspan="2">0.40</td><td rowspan="2">0.59</td><td rowspan="2">85</td><td>224</td><td>520</td><td rowspan="2">858</td></tr>
<tr><td colspan="2">744</td></tr>
<tr><td rowspan="2">C70$^{(iii)}$</td><td rowspan="2">351</td><td rowspan="2">117</td><td rowspan="2">187</td><td rowspan="2">2.8 (3.9)[3]</td><td rowspan="2">0.40</td><td rowspan="2">0.59</td><td rowspan="2">68</td><td>252</td><td>500</td><td rowspan="2">868</td></tr>
<tr><td colspan="2">752</td></tr>
<tr><td rowspan="2">C70$^{(iv)}$</td><td rowspan="2">351</td><td rowspan="2">117</td><td rowspan="2">187</td><td rowspan="2">2.8 (3.9)[3]</td><td rowspan="2">0.40</td><td rowspan="2">0.59</td><td rowspan="2">49</td><td>261</td><td>500</td><td rowspan="2">879</td></tr>
<tr><td colspan="2">761</td></tr>
</table>

[a]Cementitious material.
[b]Super-plasticizer.
[c]Limestone powder <125 μm.
[d]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).
[e]Coarse aggregate < 20 mm.
(3.5)[1] Amount of SP required during the experiment instead of estimated value 2.8
(3.8)[2] Amount of SP required during the experiment instead of estimated value 2.8
(3.9)[3] Amount of SP required during the experiment instead of estimated value 2.8

Table 19 Further details of test SCC mixes.

Mix designation	Target PV (Pa s)	Actual PV (Pa s)	% PV difference	Paste vol. fraction	Solid vol. fraction	Paste/Solid (by vol.)
C70	9.5	9.55	-0.53%	0.40	0.60	0.68
C70$^{(i)}$	9.5	9.24	-2.73%	0.39	0.60	0.66
C70$^{(ii)}$	9.5	9.34	-1.72%	0.39	0.61	0.65
C70$^{(iii)}$	9.5	9.38	-1.27%	0.38	0.61	0.63
C70$^{(iv)}$	9.5	9.42	-0.79%	0.37	0.60	0.61

Table 20 Slump flow results for SCC mixes.

Mix designation	Slump flow spread diameter, D_{FLOW} (mm)	t_{500} (sec)	Viscosity class $t_{500} < 2$ s or ≥ 2 s
C70	690	1.87	VS_1
C70$^{(i)}$	625	2.36	VS_2
C70$^{(ii)}$	645	2.60	VS_2
C70$^{(iii)}$	725	2.58	VS_2
C70$^{(iv)}$	740	2.33	VS_2

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Table 21 J-ring results for the SCC mixes.

Mix designation	J-ring spread diameter D_J (mm)	t_{500J} (sec)	Viscosity class $t_{500}<$ 2 s or $\geq$ 2 s	NP_J (mm)	D_{FLOW}-D_J B (mm)
C70	685	2.24	VS_2	9.75	5
C70(i)	602.5	2.80	VS_2	8	22.5
C70(ii)	622.5	2.83	VS_2	7.5	22.5
C70(iii)	710	2.56	VS_2	9	15
C70(iv)	730	2.93	VS_2	9	10

Table 22 Compressive strength of samples water cured at 7, 14 and 28 days.

Mix designation	Compressive strength (7 days) MPa	Compressive strength (14 days) MPa	Compressive strength (28 days) MPa
C70	45.35	55.01	63.05
C70(i)	55.79	58.97	72.89
C70(ii)	55.36	60.61	66.57
C70(iii)	55.30	62.68	70.72
C70(iv)	56.06	63.32	65.81

Figure captions

Figure 1: Particle size distribution curves for FA and coarser fraction of LP.
Figure 2: Scheme of stages in experimental investigation.
Figure 3: Horizontal spread of SCC mix:C30 (Left), C40 (Right).
Figure 4: Flow time t_{500} vs water to powder ratio by volume of SCC mix.
Figure 5: Amount of super-plasticizer vs water to cement by volume of SCC mix.
Figure 6: Plastic viscosity, t500 and target flow spread 650 ± 50 mm [C30, C40, C50, C60 and C70].
Figure 7: Flow and passing ability of SCC mix 40 (Left) and 50 (Right).
Figure 8: Variation of compressive strengths with age.
Figure 9: w/cm ratios vs 28 days compressive strength
Figure 10: Comparison of compressive strength between new mixes and control mix C60.
Figure 11: Comparison of compressive strength between new mixes and control mix C70.
Figure 12: Ingredient mass (kg) normalized with respect to mixture plastic viscosity for 50 MPa.

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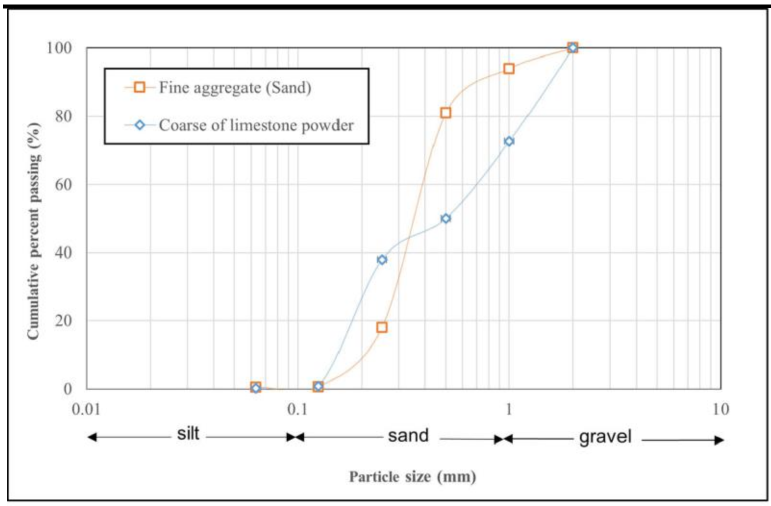

Figure 1

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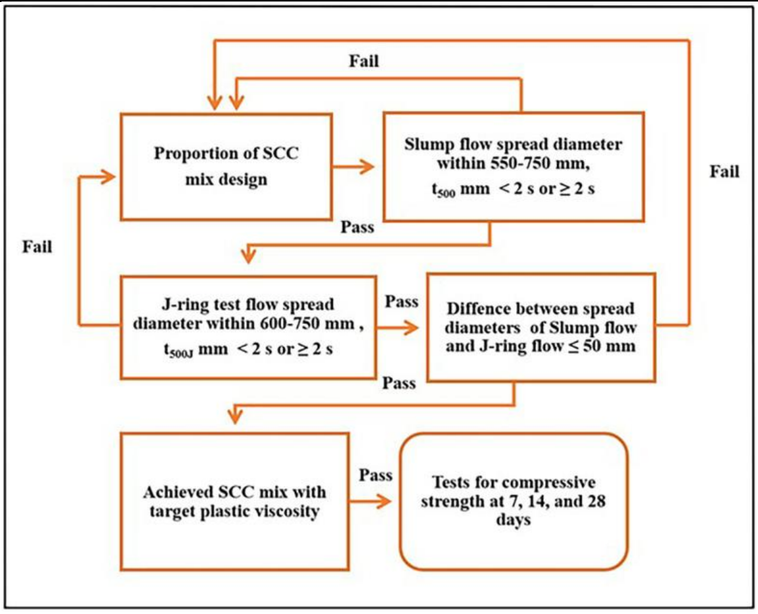

Figure 2

Figure 3

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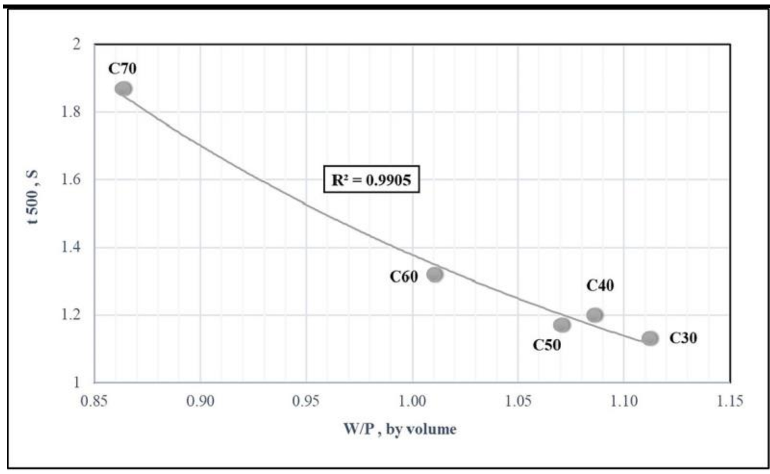

Figure 4

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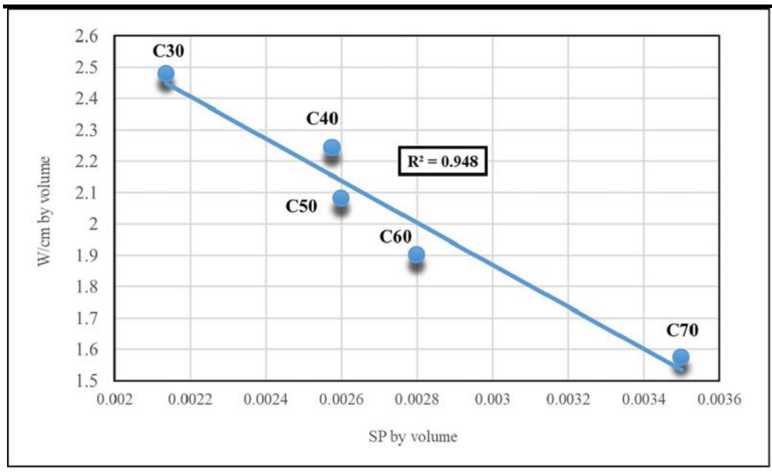

Figure 5

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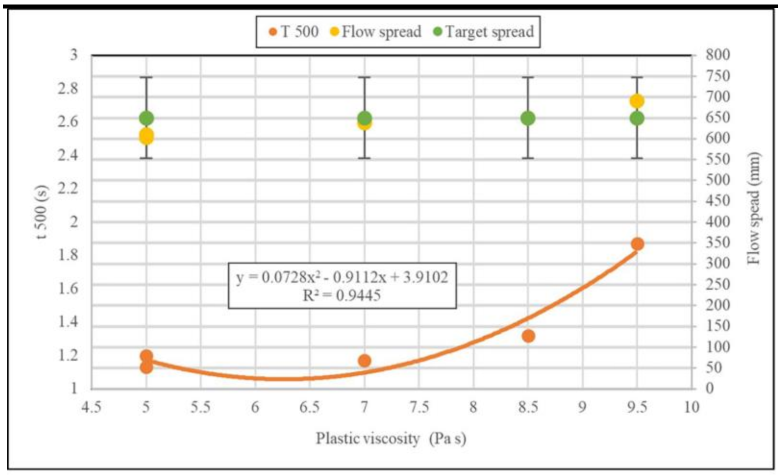

Figure 6

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Figure 7

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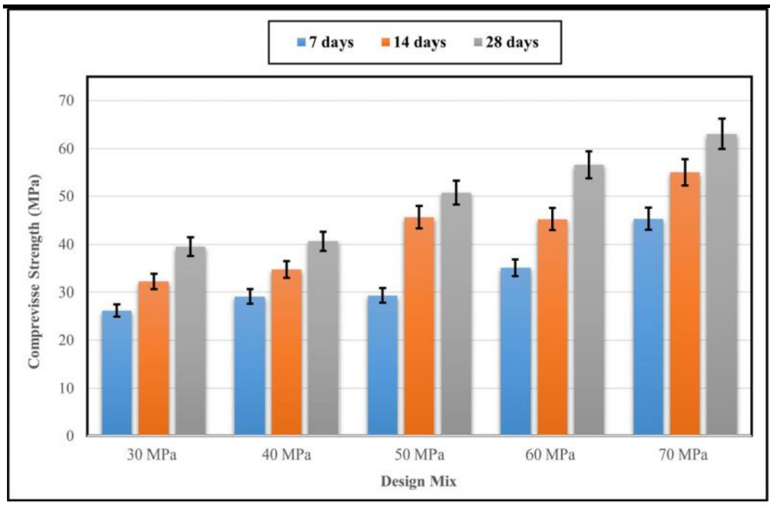

Figure 8

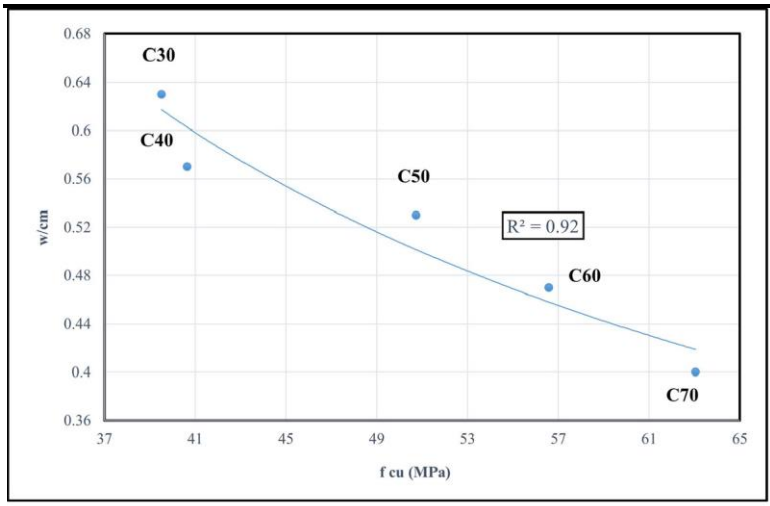
C30
C40
C50
C60
C70
R² = 0.92
w/cm
f cu (MPa)
0.68
0.64
0.6
0.56
0.52
0.48
0.44
0.4
0.36
37
41
45
49
53
57
61
65

Figure 9

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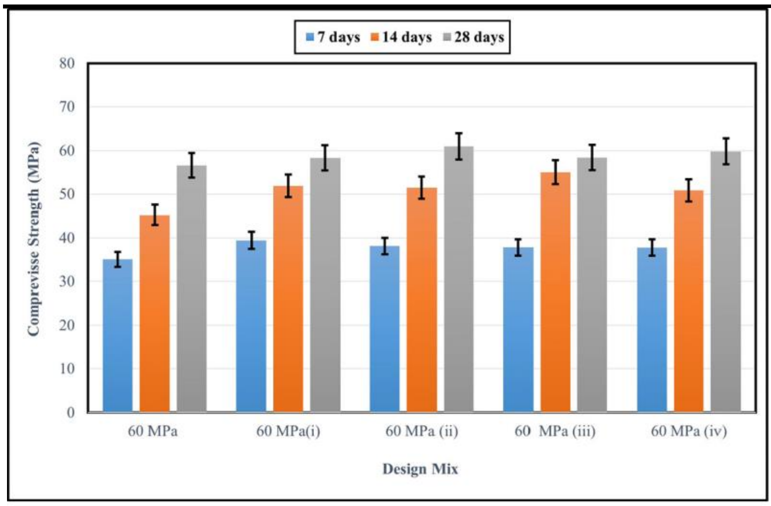

Figure 10

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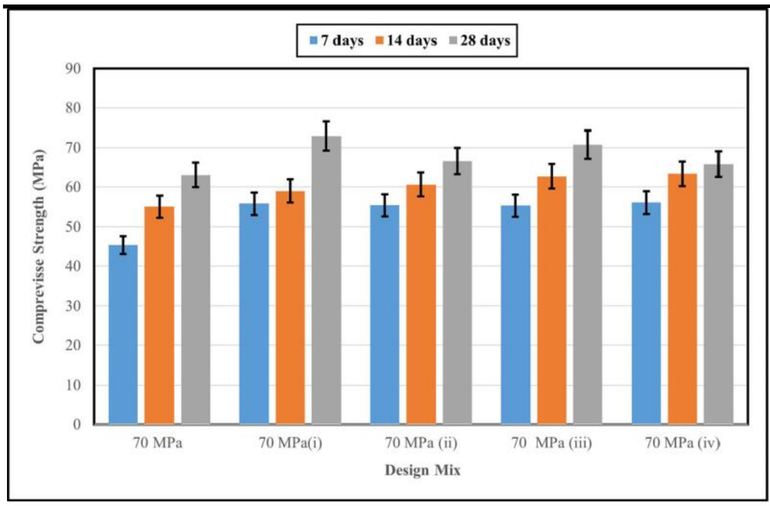

Figure 11

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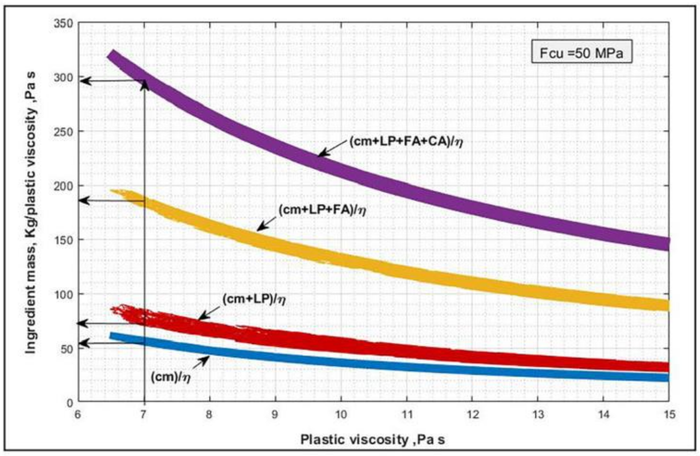

Figure 12