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Superfine cement for improving packing density, rheology and strength of cement paste

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ABSTRACT

Superfine cement is a cement ground to a much higher fineness than ordinary cement. The addition of a small quantity of superfine cement to fill into the voids of ordinary cement can improve the packing density of the cement and thereby reduce the amount of mixing water needed to fill the voids. In this study, the effects of superfine cement on the packing density of cement (directly measured by a wet packing test), the water film thickness of cement paste (taken as the excess water to solid surface area ratio), and the flowability, rheology and strength of cement paste were investigated. The results showed that the addition of 10% to 20% superfine cement can significantly increase the packing density of the cement and the water film thickness of the cement paste. Such increases in packing density and water film thickness would then improve the flowability, rheology and strength of the cement paste. Hence, superfine cement is an effective cementitious filler for improving cement performance.

1. Introduction

In a cement paste, the water added must first of all be sufficient to fill the voids between the solid particles because any unfilled voids would become air voids that might significantly reduce the strength of the cement paste. The excess water (the water in excess of that needed to fill the voids) would then form water films coating the solid particles to lubricate the solid surfaces and give the cement paste the desired flowability. Hence, the packing density of the cementitious materials, which determines the amount of voids to be filled with water, is an important property governing the rheological and strength performance of the cement paste. Basically, a higher packing density would demand less water to fill the voids and, at the same water/cementitious materials (W/CM) ratio, release more excess water for increasing the flowability of the cement paste. Furthermore, at the same flowability requirement, it would allow the W/CM ratio to be reduced to increase the strength of the cement paste.

Ordinary Portland cement (OPC) usually has a packing density of about 0.60. With this packing density, the minimum W/CM ratio for filling the voids with water may be evaluated as 0.67 by volume or 0.22 by mass. Hence, if the W/CM ratio by mass is lower than 0.22, the cement paste will have air voids entrapped no matter how hard it is compacted and no excess water for lubrication. As a result, a cement paste with such low W/CM ratio will not produce a high-strength concrete with reasonable flowability. To further reduce the W/CM ratio so as to produce a higher strength concrete, fillers are often added to increase the packing density. One commonly used filler is condensed silica fume (CSF), which generally has a mean particle size smaller than 1 μm. Due to its high fineness, it has been proven to be a very effective filler [1,2]. Its addition would allow the reduction of the W/CM ratio to 0.20 or even lower to increase strength [3]. Alternatively, its addition without reducing the W/CM ratio would release more excess water to increase workability [4]. However, the high fineness of CSF is a two-edge sword; whilst the small particle size enables the CSF to fill into very small voids, the large specific surface imposes a high demand of superplasticizer (SP) to disperse the CSF particles and a high demand of water to form water films coating the CSF particles [5]. Moreover, CSF is still a relatively high cost material.

There are several other fillers that may also be used. High fineness powders made of pulverised fuel ash (also called fly ash), ground granulated blastfurnace slag (also called slag), cement, metakaolin, rice husk ash, ground silica and limestone fine have been tried and some of these are already commercially available. A brief literature review is presented below (note that in the literature, the terms ultrafine and superfine are used interchangeably and any powder finer than ordinary cement is regarded as ultrafine or superfine; however, the authors are of the view that only powders as fine as CSF or finer than 1 μm should be regarded as ultrafine).

Early in 1998, Nedhi et al. [6] compared the effectiveness of limestone filler, ground silica and CSF, and found that whilst partial replacement of cement by CSF increases the SP demand, partial replacement of cement by limestone filler or ground silica reduces the SP demand. In 1999, Collins and Sanjayan [7] studied the effects of adding ultrafine fly ash or slag, and found that unlike the addition of CSF which causes significant loss of workability, the addition of ultrafine fly ash increases the workability while

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the addition of ultrafine slag causes only minimal loss of workability. In 2000, Zhang and Han [8] evaluated the effects of ultrafine fly ash, ultrafine slag, limestone filler and CSF on the rheology of cement paste. They concluded that the addition of all these fillers can decrease the yield stress and viscosity of cement paste.

In 2001, Gao et al. [9] studied the possible use of a superfine slag and found that replacement of cement by superfine slag up to 20% can improve the workability as well as the strength of concrete. In 2002, Long et al. [10] conducted similar studies on the uses of ultrafine fly ash and slag. They showed that the addition of ultrafine fly ash or slag can improve the fluidity of low water content cement paste and, by adopting a very low W/CM ratio and adding ultrafine fly ash or slag together with CSF, produced mortar strengths higher than 200 MPa. In 2004, Kaufmann et al. [11] tested cement pastes containing CSF, metakaolin, ultrafine cement or limestone filler and found that the rheological properties of cement paste can be improved by blending normal cement with ultrafine cement or limestone filler. In 2006, Jones et al. [12] applied air-cyclonic separation to produce ultrafine fly ash and showed that the addition of such cycloned fly ash up to 30% can significantly increase both the flow and strength of mortar.

In 2009, Cordeiro et al. [13] studied the use of rice husk ash and found that the effect of adding ultrafine rice husk ash is dependent on the SP dosage and that if the SP dosage is increased to allow for the increase in solid surface area, the addition of ultrafine rice husk ash can reduce the yield stress and plastic viscosity of concrete. In 2010, Givi et al. [14] tried two types of rice husk ash with different fineness. Their results showed that partial replacement of cement by either type of rice husk ash improves both the workability and strength of concrete. Relatively, the coarser ash gives better workability whereas the finer ash gives higher strength.

Theoretical and experimental studies on the packing density of cementitious materials have also been carried out. In 2002, Niu et al. [15] conducted theoretical analysis of how fine particles can be packed into voids and suggested that the particle size distribution and range are the main factors governing packing density. In same year, Jones et al. [16] evaluated the applicability of existing packing models to cement-sized particles and found that some of the models do not always agree with the experimental results. One year later, Jones et al. [17] studied theoretically and experimentally the optimum filler content for maximum packing density. The results indicated that the packing effect of a filler is dependent on its fineness and the presence of SP.

However, there have been many problems with packing density measurement. The traditional dry packing methods are not really suitable for cement-sized particles, which tend to form agglomerates under dry condition. Moreover, the packing density so measured is very sensitive to the compaction applied. To resolve these problems, the authors' research group has developed a new wet packing method for measuring the packing density of cement-sized particles [18,19]. This wet packing method is capable of simulating the actual wet condition in cement paste and allowing for the presence of any SP, which may have significant effects on the packing density.

In this study, the new wet packing method was employed to directly measure the change in packing density due to the addition of a superfine cement. The consequential effects of such change in packing density on the water film thickness, flowability, rheology and strength of cement paste were then investigated, as presented herein.

2. Materials

Two types of cementitious materials, namely, ordinary Portland cement (OPC) and superfine cement (SFC), were used. The OPC was of strength grade 52.5 N obtained locally and had been tested to verify its compliance with BS 12: 1996, whereas the SFC was imported from France and according to the supplier it was a slag cement containing 80% slag and was 100% finer than 6 μm. The solid densities of the OPC and SFC had been measured in accordance with BS 812: Part 2: 1995 as 3112 kg/m^3 and 2940 kg/m^3, respectively. Their particle size distributions were measured by a laser diffraction particle size analyser and the results so obtained are plotted in Fig. 1. Based on these particle size distributions, the mean particle sizes of the OPC and SFC were calculated as 12.4 μm and 3.1 μm, respectively, whereas the specific surface areas of the OPC and SFC were calculated as 1.014×10^6 m^2/m^3 (equivalent to 326 m^2/kg) and 2.293×10^6 m^2/m^3 (equivalent to 780 m^2/kg), respectively.

To disperse the cement grains and reduce agglomeration, a superplasticizer (SP) was added to each cement paste sample. The SP used was a polycarboxylate ether-based polymer having a molecular structure characterised by a main chain attached with side chains. It was an aqueous solution with a solid mass content and a relative density of 20% and 1.03, respectively. According to the supplier, the normal dosage of this SP, measured in terms of liquid mass, should be 0.5–3.0% by mass of cement. As it is the dosage of SP per solid surface area of the cementitious materials that actually governs the effectiveness of the SP (note that SP is a surface reactant), the SP dosage should have been expressed in terms of the liquid mass of SP per solid surface area of the cementitious materials [5]. Before setting the SP dosage to be used, trial cement paste mixing using different SP dosages was carried out and it was found that the saturation dosage of the SP (the dosage beyond which further addition of the SP yields little further increase in flowability) was 26×10^{-6} kg/m^2 (this corresponds to 0.84% by mass of cement when only OPC is used). Hence, the SP dosage in terms of liquid mass of SP per solid surface area of cementitious materials was set as 26×10^{-6} kg/m^2 for all the cement paste samples. Because of the higher fineness of the SFC, the SP dosage per mass of cementitious materials was higher at a higher SFC content.

3. Experimental program

The experimental program consisted of two parts. The first part was to measure the wet packing densities of cementitious materials containing different amounts of SFC in order to study the effectiveness of the SFC in reducing the voids content and increasing the packing density of cementitious materials. In this part, the SFC content was varied from 0% to 30% in increments of 10%.

The second part was to measure the flow spread, flow rate, rheological properties, cohesiveness and cube strength of cement

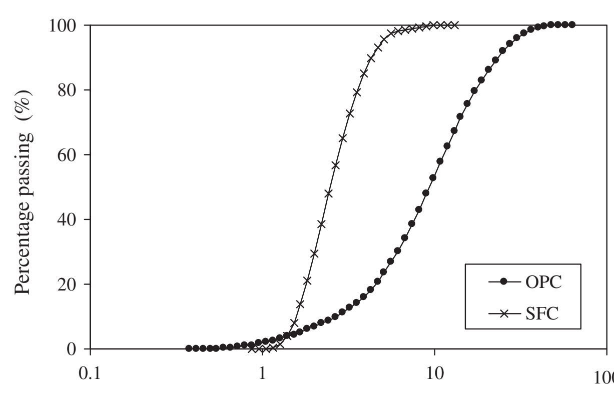

Fig. 1. Particle size distributions of OPC and SFC.

paste samples containing different amounts of SFC and water in order to study the effects of adding SFC on the rheological and strength performance of cement paste at different W/CM ratios. In this part, the SFC content was varied from 0% to 20% in increments of 10% (the SFC content was increased only up to 20% because test results in the first part showed that further addition of SFC to higher than 20% would decrease instead of increase the packing density). The mix proportions of the cement paste samples tested are summarised in Table 1. Each cement paste sample so produced for testing was assigned an identification code of RS-*X*-*Y*, in which RS means rheology and strength measurement, *X* denotes the SFC content expressed as a percentage of the total cementitious materials by mass and *Y* denotes the W/CM ratio by mass.

Each cement paste sample was of 2550 ml size. It was produced by mixing the designed mix proportions of OPC, SFC and water together, as per Table 1, using a standard mixer in compliance with BS EN 196: Parts 1–3. To ensure thorough mixing of the cementitious materials with water, a special mixing procedure of adding the cementitious materials in several small increments to the water was adopted. The authors' research group has been using this method of mixing for cement paste samples containing ultrafine fillers [18,19] because the conventional method of mixing all the cementitious materials and water in one go would encounter difficulties when the filler content is high and/or the water content is low due to the apparent dryness of the cement paste formed. The whole sample preparation and testing procedures were carried out in a laboratory maintained at a temperature of 24 ± 2 °C.

4. Test methods

4.1. Measurement of packing density

The wet packing method developed by the authors' research group [18,19] was used to measure the packing density of the cementitious materials. Since the details of the method have been given before, only the main features are presented here. Basically, this method determines the packing density of the cementitious materials as the maximum solid concentration achieved by the cementitious materials when they are mixed with water at varying W/CM ratios. To perform the test, six to eight cement paste samples having the same mix proportions of solid particles and the same SP dosage but different water contents (ranging from insufficient to more than sufficient to fill the voids between the particles) were produced and their respective bulk densities were measured to determine the corresponding solid concentrations. In general, as the water content varied, the solid concentration first increased with the water content to a maximum value and then decreased. The maximum solid concentration so obtained was taken as the packing density of the cementitious materials.

4.2. Measurement of flow spread and flow rate

The mini slump cone test and Marsh cone test were used to measure the flow spread and flow rate, respectively, of the cement paste samples, as suggested by Aïtcin [20]. However, there are many different versions of mini slump cone and Marsh cone. In this study, the mini slump cone adopted was the same as that used by Okamura and Ouchi [21] while the Marsh cone adopted was the same as that specified in BS EN 445: 1997, as in previous studies by the authors' research group [22,23]. To perform the mini slump cone test, the slump cone was placed at the centre of a levelled steel plate, the cement paste was poured slowly into the slump cone until it was full, the slump cone was gently lifted and finally the flow spread was determined as the average diameter of the cement paste patty formed minus the base diameter of the slump cone. To perform the Marsh cone test, the orifice of the Marsh cone was first closed, the cement paste was poured slowly into the Marsh cone until it was full, the orifice was opened to allow the cement paste to flow out, the flow time was recorded and finally the flow rate was determined as the volume of cement paste divided by the flow time.

4.3. Measurement of rheological properties

The rheometer and test method used were the same as those used in previous studies [23]. Since the details have been given before, only the basic features are presented here. The shearing sequence applied to each cement paste sample consisted of two shearing cycles. The first shearing cycle (pre-shearing cycle) was to ensure that each cement paste sample had undergone the same shearing history before measurement. The second shearing cycle (data-logging cycle) was the cycle in which actual measurement was carried out by a data-logger. During each shearing cycle, the shear rate was increased from 0 to 50 s^{-1} in 75 s and then decreased

Table 1
Mix proportions and water film thickness.

Mix no.	Dosage of each ingredient in the paste (kg/m^3)				Water film thickness (μm)
	OPC	SFC	Water	SP	
RS-0-0.18	1994.7	0.0	342.3	16.7	−0.014
RS-0-0.20	1918.1	0.0	367.5	16.1	0.047
RS-0-0.22	1847.3	0.0	390.9	15.5	0.108
RS-0-0.24	1781.5	0.0	412.6	14.9	0.170
RS-0-0.26	1720.2	0.0	432.8	14.4	0.231
RS-0-0.28	1663.0	0.0	451.7	14.0	0.292
RS-0-0.30	1609.4	0.0	469.3	13.5	0.354
RS-10-0.18	1788.5	198.7	338.7	19.0	0.029
RS-10-0.20	1720.1	191.1	364.0	18.3	0.083
RS-10-0.22	1656.8	184.1	387.4	17.6	0.137
RS-10-0.24	1598.0	177.6	409.1	17.0	0.191
RS-10-0.26	1543.2	171.5	429.4	16.4	0.245
RS-10-0.28	1492.0	165.8	448.3	15.8	0.299
RS-10-0.30	1444.1	160.5	466.0	15.3	0.352
RS-20-0.18	1583.9	396.0	335.1	21.2	0.058
RS-20-0.20	1523.5	380.9	360.4	20.4	0.106
RS-20-0.22	1467.6	366.9	383.9	19.7	0.154
RS-20-0.24	1415.7	353.9	405.7	19.0	0.202
RS-20-0.26	1367.3	341.8	426.0	18.3	0.250
RS-20-0.28	1322.1	330.5	445.0	17.7	0.298
RS-20-0.30	1279.8	320.0	462.8	17.2	0.346

to 0 s^{-1} in another 75 s. Two shear stress–shear rate curves were obtained, one at increasing shear rate and the other at decreasing shear rate. The shear stress–shear rate curve at decreasing shear rate, which is generally more consistent and repeatable, was used for evaluating the rheological properties of the cement paste sample.

The shear stress–shear strain curve may be described in terms of either the Bingham model or the Herschel–Bulkley model. Herein, the Herschel–Bulkley model, which generally agrees better with the experimental results, was adopted. Its shear stress–shear rate equation is given by the following equation.

$$\tau = \tau_y + K\gamma^n \quad (1)$$

where τ (Pa) is shear stress, γ (s^{-1}) is shear rate, τ_y (Pa) is yield stress, and K (Pa-s^n) and n (dimensionless) are empirical coefficients. For each cement paste sample, the best-fit curve based on this equation was obtained by regression analysis. From the best-fit curve so obtained, the shear stress at a shear rate of 0 s^{-1} and the ratio of shear stress to shear rate at a shear rate of 50 s^{-1} were taken as the yield stress and the apparent viscosity, respectively. Furthermore, the n-value of the best-fit curve was taken as a measure of the degree of shear thickening of the cement paste sample ($n > 1.0$ implies shear thickening whereas $n < 1.0$ implies shear thinning).

4.4. Measurement of cohesiveness

There is, up to now, no established test method for measuring the cohesiveness of cement paste. In this study, a mini version of the sieve segregation test was used to measure the cohesiveness of cement paste. Two sieves, one of 0.6 mm aperture size and the other of 1.18 mm aperture size, were employed for the sieve segregation tests. These two sieves are just those normally used for sieve analysis of fine aggregate. Apart from the aperture size, they are similar to each other and both have an overall diameter of 200 mm. To perform the test, an approximately 0.1 l cement paste sample was poured onto the sieve from a height of 300 mm and then allowed to drip through the sieve. After 2 min, when the dripping should have finished, the cement paste dripped through the sieve and collected by a base receiver was weighed and the sieve segregation index (SSI) was determined as the proportion of cement paste dripped through the sieve and collected by the base receiver, expressed as a percentage by mass. For a cement paste with low cohesiveness, nearly all the cement paste poured onto the sieve would drip through the sieve. On the contrary, for a cement paste with high cohesiveness, only a small proportion of cement paste or even no cement paste would drip through the sieve. Hence, a low SSI indicates high cohesiveness whereas a high SSI indicates low cohesiveness.

4.5. Measurement of cube strength

Six 70.7 mm cubes were made from each cement paste sample. The cubes were each made by placing the cement paste into a cube mould, tamping the cement paste by a steel rod, mounting the mould on a vibration table for compaction and covering the top surface of the mould with a plastic sheet. The cubes were then stored at a temperature of 24 ± 2 °C. At 1 day after casting, the moulds were removed and the cubes were water cured at a temperature of 27 ± 2 °C. Three of the cubes were tested at an age of 7-day while the other three cubes were tested at an age of 28-day.

5. Test results

5.1. Packing density and water film thickness

With no SFC added, the cement was measured to have a packing density of 0.637 and a voids ratio of 0.570. With 10% SFC added, the packing density was increased to 0.659 whereas the voids ratio was decreased to 0.517. With 20% SFC added, the packing density was further increased to 0.679 and the voids ratio was further decreased to 0.473. However, when the SFC content was increased from 20% to 30%, the packing density became 0.678 (there was no further increase) and voids ratio became 0.475 (there was no further decrease). For easier interpretation, the variations of the packing density and voids ratio with the SFC content are presented graphically in Fig. 2. Although the maximum increase in packing density was only 6.6%, the corresponding maximum decrease in voids ratio was as much as 17.0%.

The reduction in voids ratio due to the addition of SFC would significantly decrease the amount of water needed to fill the voids and increase the amount of excess water for forming water films coating the particles in the cement paste. Such effect on the water films is dependent on the total solid surface area of the particles in the paste and the water content of the paste. It can be evaluated in terms of the water film thickness (WFT), which may be determined simply as the excess water to solid surface area ratio, as the authors have been advocating in recent years [22–24]. The WFT so determined for the cement paste samples are tabulated in the last column of Table 1 and plotted against the W/CM ratio for different SFC contents in Fig. 3. From the curves plotted, it can be seen that at W/CM ratio lower than 0.30, the addition of SFC would significantly increase the WFT. In general, the increase in WFT is larger at a lower W/CM ratio.

5.2. Flow spread and flow rate

The flow spread results are tabulated in the second column of Table 2 and plotted against the W/CM ratio and WFT in Fig. 4. From

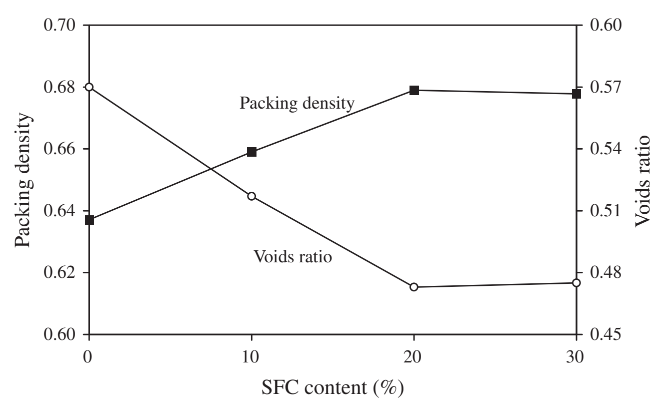

Fig. 2. Variation of packing density and voids ratio with SFC content.

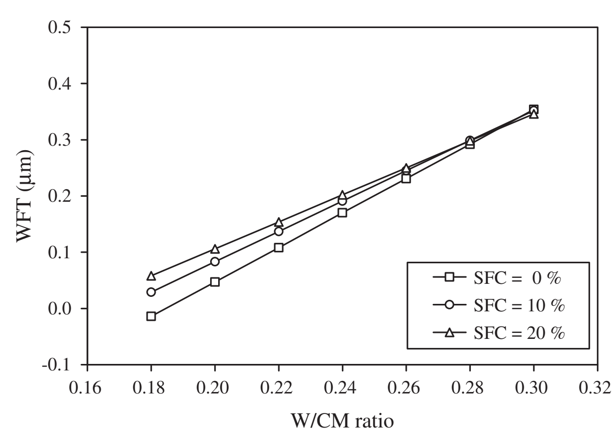

Fig. 3. Variation of WFT with W/CM ratio at different SFC contents.

Table 2
Flowability and rheological properties.

Mix no.	Flow spread (mm)	Flow rate (ml/s)	Yield stress (Pa)	Apparent viscosity (Pa s)	*n*-Value
RS-0-0.18	0.0	0.0	–	–	–
RS-0-0.20	0.0	0.0	–	–	–
RS-0-0.22	113.5	2.1	17.53	3.23	1.16
RS-0-0.24	167.0	7.4	6.66	1.98	1.23
RS-0-0.26	205.0	9.9	3.89	1.47	1.32
RS-0-0.28	233.3	13.2	2.01	1.05	1.34
RS-0-0.30	248.5	15.5	0.96	0.79	1.39
RS-10-0.18	0.0	0.0	–	–	–
RS-10-0.20	90.8	1.1	29.86	4.39	1.07
RS-10-0.22	148.3	4.1	10.62	2.73	1.12
RS-10-0.24	183.0	8.1	8.23	1.86	1.21
RS-10-0.26	217.0	10.8	3.12	1.41	1.29
RS-10-0.28	234.5	13.6	2.02	1.08	1.35
RS-10-0.30	252.0	17.0	1.05	0.71	1.41
RS-20-0.18	51.0	0.0	–	–	–
RS-20-0.20	112.8	2.0	33.43	5.03	1.01
RS-20-0.22	163.0	5.7	16.81	3.10	1.05
RS-20-0.24	186.8	9.3	12.73	2.06	1.16
RS-20-0.26	204.0	11.1	6.37	1.71	1.22
RS-20-0.28	233.8	13.8	2.97	1.46	1.31
RS-20-0.30	250.3	16.2	2.63	0.90	1.38

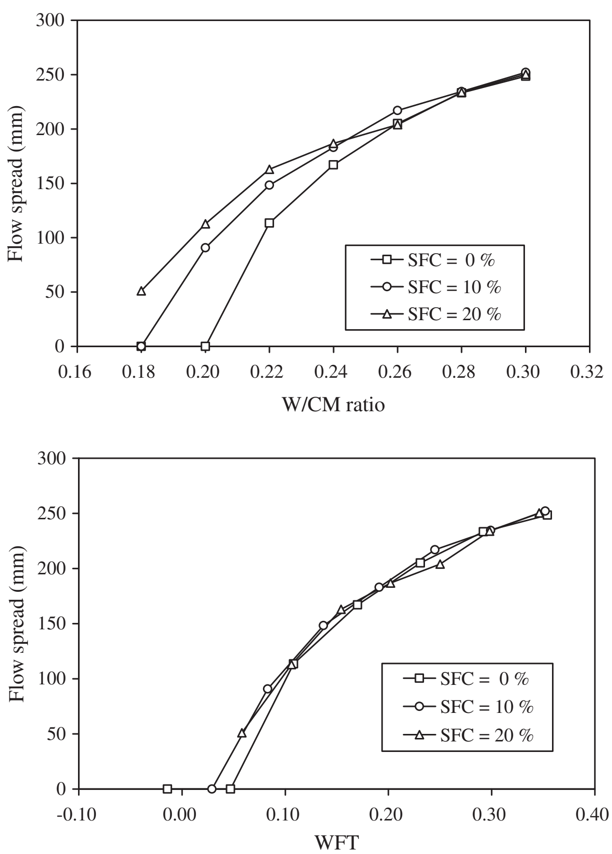

Fig. 4. Flow spread versus W/CM ratio and WFT.

the flow spread-W/CM ratio curves, it is evident that the addition of SFC up to 20% had significantly increased the flow spread of the cement paste. Such increase in flow spread was proportionally larger at lower W/CM ratio. For instance, the addition of 20% SFC increased the flow spread from 113.5 to 163.0 mm at a W/CM ratio of 0.22 and increased the flow spread from 0 to 112.8 mm at a W/CM ratio of 0.20. On the other hand, from the flow spread-WFT curves, it can be seen that at the same WFT, the flow spread was more or less the same regardless of the SFC content. Hence, it may be inferred that the SFC exerted its effect on the flow spread mainly through the WFT. It was the increase in WFT due to the addition of SFC that caused the increase in flow spread.

The flow rate results are tabulated in the third column of Table 2 and plotted against the W/CM ratio and WFT in Fig. 5. From the flow rate-W/CM ratio curves, it is evident that the addition of SFC up to 20% had significantly increased the flow rate of the cement paste. Such increase in flow rate was proportionally larger at lower W/CM ratio. For instance, the addition of 20% SFC increased the flow rate from 2.1 to 5.7 ml/s at a W/CM ratio of 0.22 and increased the flow rate from 0 to 2.0 ml/s at a W/CM ratio of 0.20. On the other hand, from the flow rate-WFT curves, it can be seen that at the same WFT, the flow rate was more or less the same regardless of the SFC content. Hence, it may be inferred that the SFC exerted its effect on the flow rate mainly through the WFT. It was the increase in WFT due to the addition of SFC that caused the increase in flow rate.

5.3. Rheological properties

The rheological properties were measured using a rheometer, which applies torque through a spindle to shear the cement paste sample for testing. However, during the tests of RS-0-0.18, RS-0-0.20, RS-10-0.18 and RS-20-0.18, the torque required to shear the cement paste sample had exceeded the capacity of the rheometer and for this reason the rheological properties of these samples were not obtained.

The yield stress results are tabulated in the fourth column of Table 2 and plotted against the W/CM ratio and WFT in Fig. 6. Although the yield stress results of the samples RS-0-0.18, RS-0-0.20, RS-10-0.18 and RS-20-0.18 were not obtained, it may be assumed that the yield stress of each of these samples was higher than 35 Pa (the upper limit of yield stress that the rheometer can cope with). Comparing the yield stress-W/CM ratio curves, it is seen that at W/CM ratio $\geqslant 0.24$, the addition of SFC increased the yield stress while at W/CM ratio $\leqslant 0.22$, the addition of SFC decreased the yield stress. Comparing the yield stress-WFT curves, it is also seen that at the same WFT, the addition of SFC generally increased the yield stress, apart from slight variations due to experimental errors.

The apparent viscosity results are tabulated in the fifth column of Table 2 and plotted against the W/CM ratio and WFT in Fig. 7. Although the apparent viscosity results of the samples RS-0-0.18,

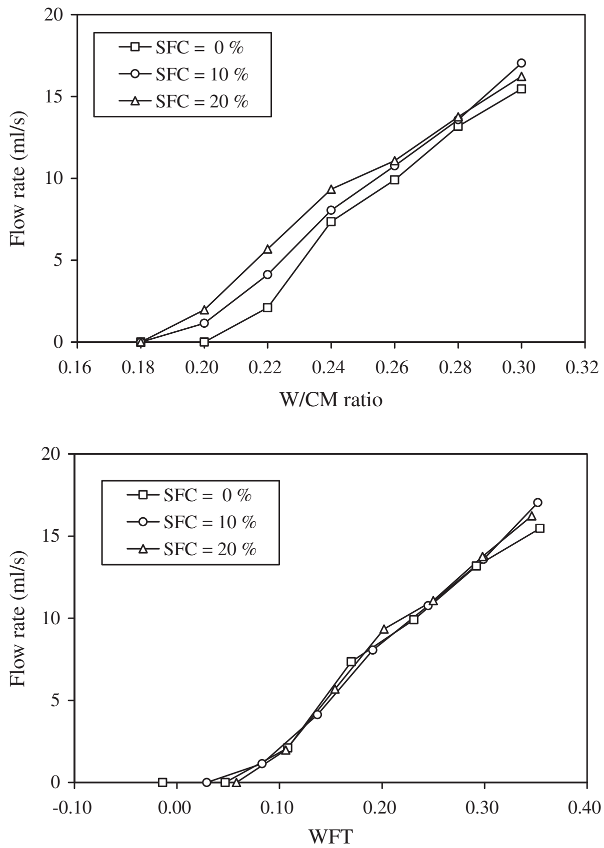

Fig. 5. Flow rate versus W/CM ratio and WFT.

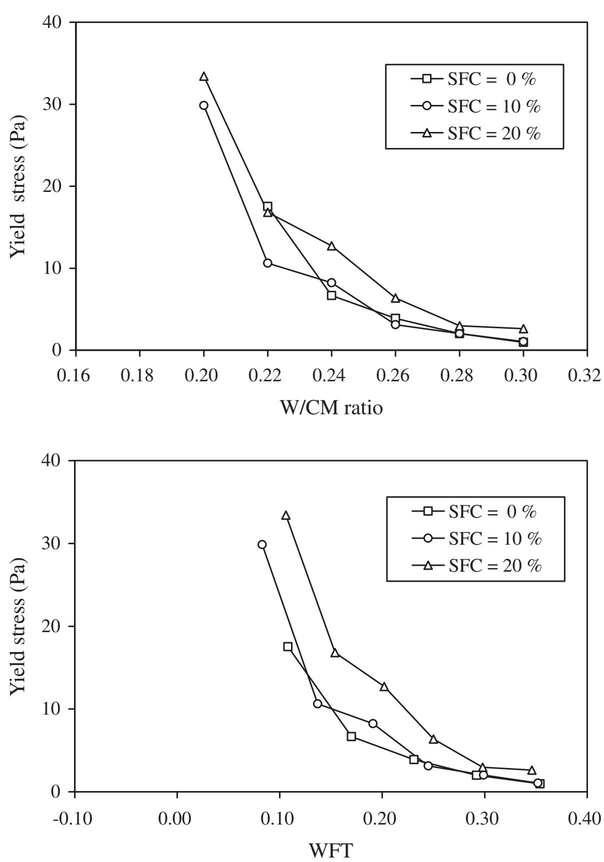

Fig. 6. Yield stress versus W/CM ratio and WFT.

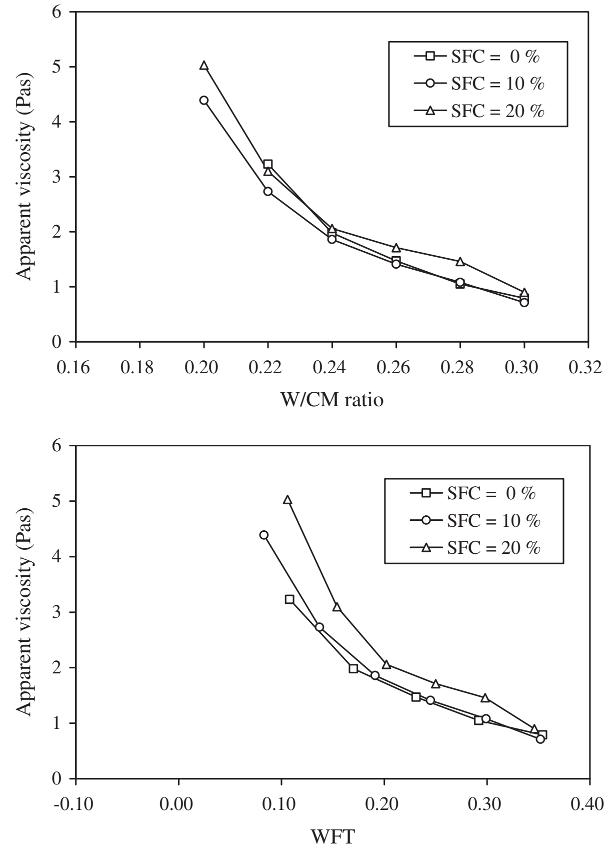

Fig. 7. Apparent viscosity versus W/CM ratio and WFT.

RS-0-0.20, RS-10-0.18 and RS-20-0.18 were not obtained, it may be assumed that the apparent viscosity of each of these cement paste samples was higher than 5.5 Pa s (the rheometer has been able to measure apparent viscosity up to this value). Comparing the apparent viscosity-W/CM ratio curves, it is seen that at W/CM ratio $\geqslant$ 0.24, the addition of SFC increased the apparent viscosity while at W/CM ratio $\leqslant$ 0.22, the addition of SFC decreased the apparent viscosity. Comparing the apparent viscosity-WFT curves, it is also seen that at the same WFT, the addition of SFC generally increased the apparent viscosity.

The *n*-value results are tabulated in the sixth column of Table 2 and plotted against the W/CM ratio and WFT in Fig. 8. From the *n*-value versus W/CM ratio curves, it can be seen that at W/CM ratio $\geqslant$ 0.28, the addition of SFC had little effect on the *n*-value while at W/CM ratio $\leqslant$ 0.26, the addition of SFC decreased the *n*-value. From the *n*-value versus WFT curves, it can also be seen that at WFT > 0.30 μm, the addition of SFC had little effect on the *n*-value while at WFT < 0.30 μm, the addition of SFC decreased the *n*-value. On the whole, when the water content was high, the addition of SFC had insignificant effect on the degree of shear thickening of the cement paste but when the water content was low, the addition of SFC significantly reduced the degree of shear thickening of the cement paste. This was because at WFT < 0.30 μm, the addition of SFC produced a proportionally larger increase in yield stress than apparent viscosity, as can be seen from Figs. 6 and 7.

5.4. Cohesiveness

The 0.6 mm SSI results (SSI values determined using the 0.6 mm sieve) are tabulated in the second column of Table 3 and plotted against the W/CM ratio and WFT in Fig. 9. Likewise, the 1.18 mm SSI results (SSI values determined using the 1.18 mm sieve) are tabulated in the third column of Table 3 and plotted against the

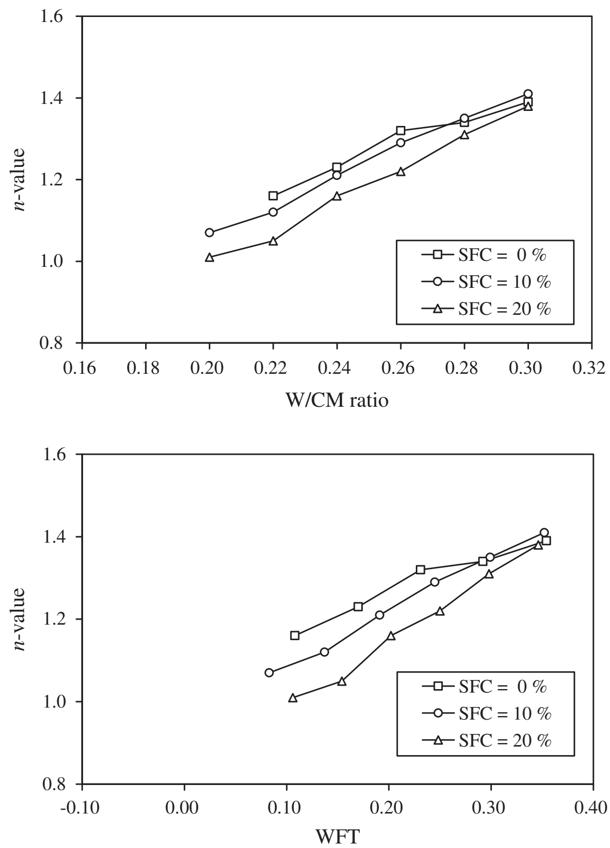

Fig. 8. *n*-Value versus W/CM ratio and WFT.

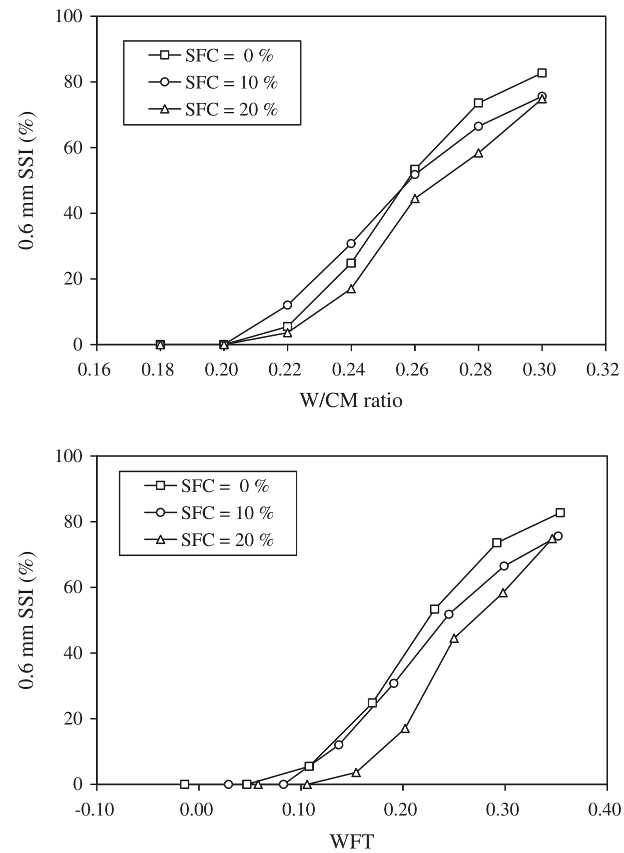

Fig. 9. 0.6 mm SSI versus W/CM ratio and WFT.

Table 3
Sieve segregation indices and strength.

Mix no.	0.6 mm SSI	1.18 mm SSI	7-Day strength (MPa)	28-Day strength (MPa)
RS-0-0.18	0.0	0.0	93.7	97.7
RS-0-0.20	0.0	0.0	95.4	105.7
RS-0-0.22	5.5	18.6	108.1	119.4
RS-0-0.24	24.8	50.8	105.5	119.1
RS-0-0.26	53.3	82.5	101.5	116.4
RS-0-0.28	73.6	87.8	94.7	104.7
RS-0-0.30	82.7	91.7	87.1	98.6
RS-10-0.18	0.0	0.0	108.5	113.7
RS-10-0.20	0.0	0.0	116.9	119.8
RS-10-0.22	12.0	34.7	115.4	124.8
RS-10-0.24	30.7	63.7	112.8	122.9
RS-10-0.26	51.8	71.6	104.6	117.1
RS-10-0.28	66.4	84.0	101.7	110.9
RS-10-0.30	75.6	89.0	94.5	102.3
RS-20-0.18	0.0	0.0	126.2	130.3
RS-20-0.20	0.0	0.0	136.7	137.7
RS-20-0.22	3.6	9.0	131.0	132.1
RS-20-0.24	17.1	43.5	123.1	129.5
RS-20-0.26	44.5	64.9	113.4	121.9
RS-20-0.28	58.4	78.5	105.7	116.4
RS-20-0.30	74.9	85.8	99.8	104.2

W/CM ratio and WFT in Fig. 10. From the 0.6 mm SSI-W/CM ratio and 1.18 mm SSI-W/CM ratio curves, it can be seen that at a constant W/CM ratio, the addition of SFC could increase or decrease the SSI. Hence, at a constant W/CM ratio, the addition of SFC had not exerted any definite effect on the SSI or cohesiveness of cement paste. However, from the 0.6 mm SSI-WFT and 1.18 mm SSI-WFT curves, it can also be seen that at a constant WFT, the addition of SFC always decreased the SSI or, in other words, increased the cohesiveness of cement paste.

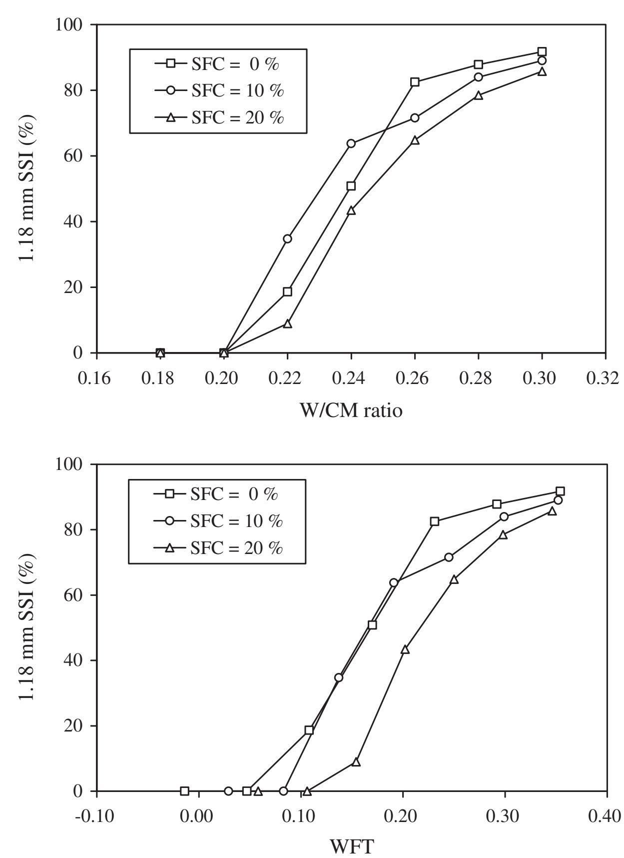

Fig. 10. 1.18 mm SSI versus W/CM ratio and WFT.

The SSI-WFT curves reveal clearly that as the WFT increased, the SSI also increased. Based on this observation, it may be inferred that the addition of SFC has two opposite effects on SSI. At the same WFT, the addition of SFC would decrease the SSI. However, at the same W/CM ratio, the addition of SFC would increase the WFT and such increase in WFT would increase the SSI. The decrease in SSI due to addition of SFC at same WFT and the increase in SSI due to increase in WFT tend to counteract each other and that is why at a constant W/CM ratio, the addition of SFC has no definite effect on the SSI or cohesiveness of cement paste.

5.5. Cube strength

The 7-day cube strength results are tabulated in the fourth column of Table 3 and plotted against the W/CM ratio and WFT in Fig. 11. Likewise, the 28-day cube strength results are tabulated in the fifth column of Table 3 and plotted against the W/CM ratio and WFT in Fig. 12. Each cube strength result presented is the average of the three cubes tested at the same time. The variations of the 7-day and 28-day cube strengths with the W/CM ratio reveal that regardless of age, the cube strength increased as the W/CM ratio decreased and then decreased as the W/CM ratio decreased to beyond a certain optimum value. Furthermore, the optimum W/CM ratio for maximum cube strength was lower at a higher SFC content while the maximum cube strength was higher at a higher SFC content. Hence, the addition of SFC would allow a lower W/CM ratio to be adopted to achieve a higher strength.

On the other hand, the variations of the 7-day and 28-day cube strengths with the WFT reveal that regardless of age, the maximum cube strength generally occurred at a WFT of around 0.1 μm. When the WFT is relatively large, the W/CM ratio is on the high side and as a result the cube strength would be relatively low. But when the

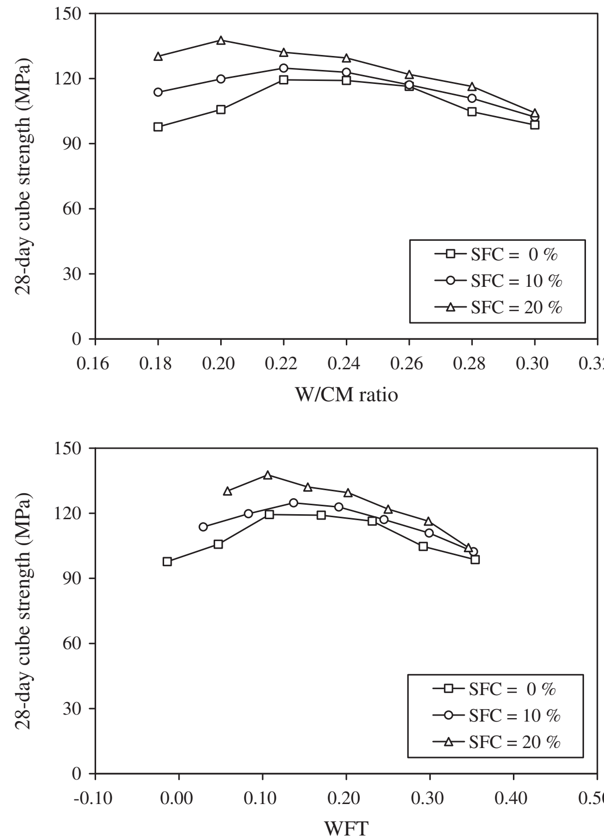

Fig. 12. 28-day cube strength versus W/CM ratio and WFT.

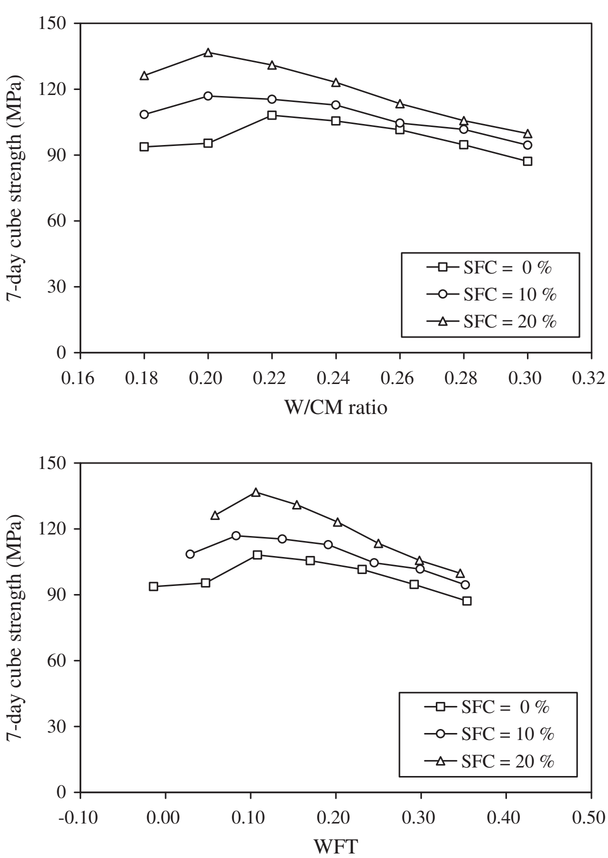

Fig. 11. 7-day cube strength versus W/CM ratio and WFT.

WFT is relatively small and close to zero, the mixing water is marginally sufficient to fill the voids between the cement grains. In such case, if there is any non-uniform distribution of water in the cement paste (in practice unavoidable due to difficulties in ensuring thorough mixing), then there would be a high probability that some of the voids between cement grains might not be completely filled with water leaving behind air voids entrapped no matter how hard the cement paste is compacted. To avoid such entrapment of air voids, which could lower the strength of cement paste or concrete, the WFT should not be too close to zero.

In this particular case, when no SFC was added, the maximum 7-day and 28-day cube strengths achieved were 108.1 and 119.4 MPa, respectively. With 10% SFC added, the maximum 7-day and 28-day cube strengths were increased to 116.9 and 124.8 MPa, respectively. With 20% SFC added, the maximum 7-day and 28-day cube strengths were further increased to 136.7 and 137.7 MPa, respectively. Hence, the addition of up to 20% SFC can increase the 7-day strength by 26.5% and the 28-day strength by 15.3%. Relatively, the increase in early strength is larger.

6. Concurrent strength-flowability performance

The effects of SFC content on the concurrent strength-flowability performance of cement paste are illustrated by plotting the 7-day and 28-day cube strengths against the flow spread in Fig. 13 and plotting the 7-day and 28-day cube strengths against the flow rate in Fig. 14. Each strength-flowability performance curve in these two figures is a plot of the cube strength (7-day cube strength or 28-day cube strength) and flowability (flow spread or flow rate) that could be concurrently achieved by the cement paste at a certain SFC content. Comparing the performance curves for different SFC contents, it is evident that as the SFC content increases

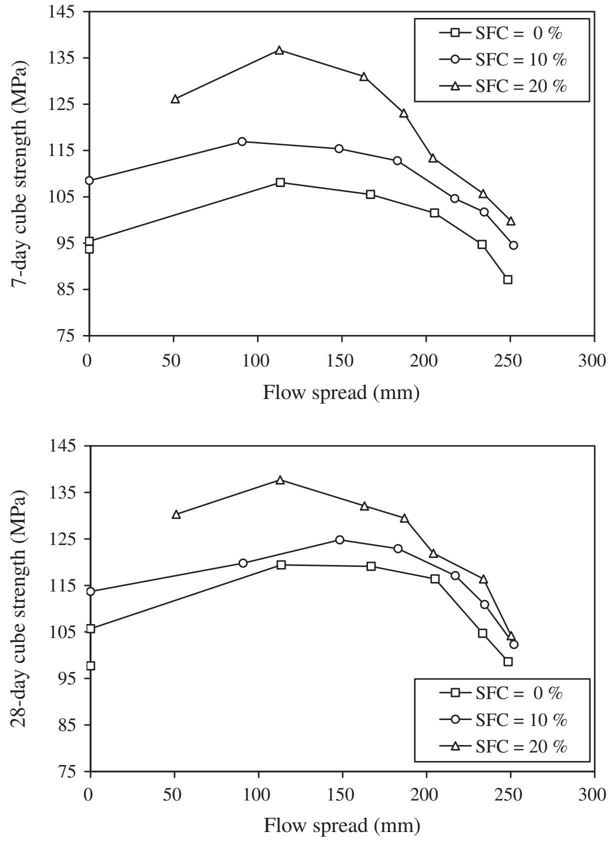

Fig. 13. Concurrent cube strength and flow spread performance.

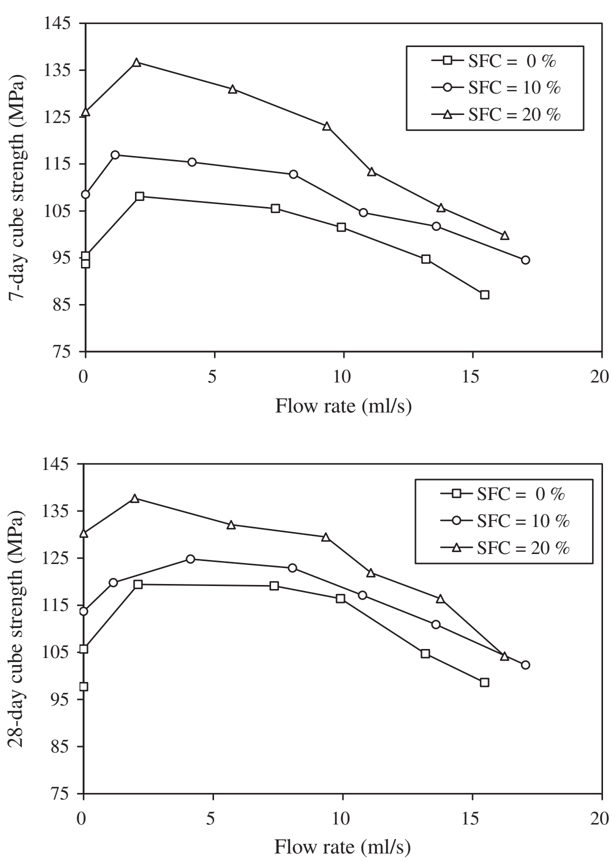

Fig. 14. Concurrent cube strength and flow rate performance.

from 0% to 10% and then to 20%, the performance curve is always shifted upwards and to the right. Since shifting of the curve upwards would lead to a higher strength at the same flowability and shifting of the curve to the right would lead to a higher flowability at the same strength, this indicates that the addition of SFC up to 20% can increase the strength at the same flowability, increase the flowability at the same strength, or increase both the strength and flowability at the same time.

7. Conclusions

An experimental program aiming to evaluate the effectiveness of a superfine cement (SFC) as a filler for increasing the packing density of cementitious materials and to investigate the consequential effects of any such increase in packing density on the rheological and strength performance of cement paste has been completed. The wet packing method developed by the authors' research group was successfully applied to evaluate the change in packing density with the SFC content and the results showed that the addition of 10% to 20% SFC can significantly increase the packing density of cementitious materials. With the packing density so increased, the water film thickness (WFT) of the cement paste formed would be increased. Generally, the increase in WFT is larger at a lower water/cementitious materials (W/CM) ratio.

The flowability test results revealed that at the same W/CM ratio, the addition of SFC up to 20% can significantly increase the flow spread and flow rate, especially at low W/CM ratio. However, at the same WFT, the flow spread and flow rate are unchanged by the SFC content. Hence, it may be inferred that the SFC exerts its effect mainly through the WFT; it is the increase in WFT due to the addition of SFC that causes the flow spread and flow rate to increase.

The rheometer test results revealed that at W/CM ratio $\geqslant 0.24$, the addition of SFC would increase the yield stress and apparent viscosity while at W/CM ratio $\leqslant 0.22$, the addition of SFC would decrease the yield stress and apparent viscosity. However, at the same WFT, the addition of SFC would always increase the yield stress and apparent viscosity. Due to proportionally larger increase in yield stress than apparent viscosity, the addition of SFC would reduce the degree of shear thickening at WFT < 0.30 μm.

The sieve segregation index (SSI) results revealed that the addition of SFC has two opposite effects on SSI. At the same WFT, the addition of SFC would decrease the SSI. However, at the same W/CM ratio, the addition of SFC would increase the WFT and such increase in WFT would increase the SSI. These two effects tend to counteract each other and consequently at a constant W/CM ratio, the addition of SFC has no definite effect on the SSI or cohesiveness of cement paste.

From the cube strength results, it was found that the strength would increase as the W/CM ratio decreases and then decrease as the W/CM ratio decreases to beyond a certain optimum value. The optimum W/CM ratio is lower and the maximum strength is higher at a higher SFC content. Hence, the addition of SFC would allow the W/CM ratio to be reduced to increase the strength. However, study on the effect of WFT revealed that to achieve maximum strength, a minimum WFT of 0.1 μm is needed to avoid having voids remaining unfilled with water. Finally, study on the concurrent strength-flowability performance proved that the addition of SFC can increase the strength at same flowability, increase the flowability at same strength, or increase both the strength and flowability at the same time.

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