Time-dependent rheological characteristics of self-consolidating concrete containing various mineral admixtures

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H I G H L I G H T S

- Time-dependent rheology of SCC with various mineral admixtures was investigated.
- Apparent yield stress and thixotropy of SCC increased significantly with time.
- Time-dependent torque plastic viscosity values changed only in a limited range.
- Viscosity and yield stress were affected mostly by metakaolin and Class C fly ash.
- Metakaolin and silica fume, had more influence on thixotropy as time was elapsed.

A R T I C L E   I N F O

A B S T R A C T

The study herein was intended to evaluate the influence of elapsing time on rheological properties and thixotropy of self-consolidating concrete (SCC) mixtures containing various mineral admixtures. For this purpose, variation of T_{50} flow time, torque plastic viscosity, apparent yield stress and thixotropy were investigated as a function of time in a standstill condition. Various amounts of silica fume (SF), metakaolin (MK), Class F fly ash (FAF), Class C fly ash (FAC) and granulated blast-furnace slag (BFS) were utilized in binary, ternary and quaternary cementitious blends in 17 different SCC mixtures having a constant slump flow value. The results showed that SCC mixtures containing various mineral admixtures were highly stable or moderately stable (VSI between 0 and 1) at 0 min according to ASTM C 1611. However, mixtures containing FAC, FAF and BFS exhibited some bleeding and segregation at 50 min. In a standstill condition, apparent yield stress and thixotropy increased significantly with time while torque plastic viscosity values changed only in a limited range. In addition, with elapsing time, MK and FAC were found to have more influence on torque plastic viscosity and yield stress values in comparison with the other admixtures. However, increase in the yield values were more pronounced in comparison with the torque plastic viscosity values. Increase in thixotropy with time for the SF and MK blended mixtures were higher when compared to the control mixtures and mixtures containing the other mineral admixtures.

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1. Introduction

Rheology and thixotropy of self-consolidating concrete (SCC) have been recognized as important tools to be tailored to achieve a multifold set of engineering properties required for successful accomplishment and performance of the intended application. Static stability, flowability, segregation resistance, formwork pressure and its decay after casting, air entrapment, surface quality and interlayer bond strength between consecutive concrete layers strongly depend on rheology and thixotropy of SCC [1–9].

In general, immediately after or during its mixing, concrete is transported from its mixing location to the final destination. Loss of consistency in fresh concrete with elapsing time due to chemical and physical processes (evaporation of water or hydration of cement), segregation and bleeding owing to prolong mixing time, distinct concrete layers arisen from delayed casting between consecutive layers are important problems that are related with rheological properties of flowable concrete. Such problems are

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mostly confronted in the ready-mixed concrete production due to the long travel distances, traffic jamming and delays associated with placement and subsequent operations at the job site. In spite of these difficulties, rheological properties of SCC should remain within acceptable tolerances to achieve a given apparent viscosity and thixotropy for various requirements including pumping pressure and distance, freefall of concrete into formwork, formwork pressure, required stability level after placement and consolidation during the dormant period as well as bond strength between consecutive concrete layers [10–12].

A few studies in the literature investigated the rheological properties of cement pastes and concrete having high consistency as a function of time [12–19]. Martini et al. [13] investigated the effect of time on rheological properties of cement pastes with various superplasticizers. It was reported that, regardless of the type of admixture, the thixotropy of mixtures increased with time below the admixture saturation dosage. Li et al. [14] concluded that the increase in apparent plastic viscosity and yield stress with the elapsed time was more significant when the concrete mixture was under the standstill condition than under continuous agitation. In another investigation Ferron et al. [15] determined the structural buildup of cement pastes of SCC containing silica fume (SF) and fly ash (FA) at a rest time up to 90 min. It was reported that in a standstill condition structural buildup of SF and FA blended mixtures increased with time. The enhancement was more significant in the mixtures having lower slump flow values compared to the mixtures with high flow properties. Assaad et al. [16] showed that in a standstill condition, thixotropy of SCC mixtures containing SF and FA increased as time was elapsed. They reported that increase in thixotropy was more significant when both SF and FA were incorporated with PC in SCC mixtures in comparison with the mixtures containing only PC. In a more recent study, Lomboy et al. [18] studied the rheological behavior of SCC and normal concrete as a function of time in a standstill condition. It was found that in SCC mixtures yield stress values increased with time while plastic viscosity and thixotropy values did not show a significant change with time.

Utilization of mineral admixtures as cementitious materials in concrete has a tendency to increase in future in order to provide greater sustainability in construction industry. In addition to the enhancement of mechanical properties and durability, the use of mineral admixtures can improve rheological properties and stability of the fresh concretes. Moreover, the use of by-product mineral admixtures can decrease the cost of SCC and the amount of the CO_2 emitted during the production of PC. Besides, incorporation of different mineral admixtures in ternary and quaternary binders can have a considerable synergistic effect on both fresh and hardened properties of the concrete. Moreover, utilizing by-products or wastes as alternative cementitious materials in concrete provides a more sustainable concrete technology through the creation of a balance between development and environment [20–27].

As a part of a more extensive study [2], this paper presents the time-dependent variation of rheological properties of SCC containing various mineral admixtures. It is aimed to develop a better understanding of time-dependent variation of rheology on the performance of SCC in a standstill condition, and to formulate more realistic recommendations for using mineral admixtures in SCC. For this purpose SCC mixtures with a w/b = 0.44 were prepared with various amounts of Class C fly ash (FAC), Class F fly ash (FAF), SF, BFS and MK at a constant slump by adjusting the superplasticizer dosage. The rheological properties of mixtures were evaluated with a coaxial cylinder concrete rheometer after 0 and 50 min of mixing.

2. Experimental methods

2.1. Materials

In this study an ordinary portland cement (CEM I 42.5 R) and five types of mineral admixtures, i.e., SF, FAC, FAF, MK, and BFS were used as binary, ternary and quaternary cementitious blends in SCC mixtures. Table 1 and Fig. 1 summarizes the physical and chemical properties and particle-size distributions of the PC and mineral admixtures. In addition, the micrographs of the mineral admixtures and PC demonstrating their shape and texture are shown in Fig. 2. Crushed limestone with a maximum particle size of 15 mm and 4 mm were used as coarse and fine aggregate, respectively. The bulk specific gravity and absorption capacity of the coarse and fine aggregates were 2.64 and 2.61, as well as 0.21% and 0.67%, respectively. A polycarboxylate ether-based high-range water-reducer (HRWR), conforming to ASTM C494 Type F [28] with a specific gravity of 1.06 and solid content of 28% was employed to achieve the desired workability.

2.2. Mix proportions and mixing

As summarized in Table 2, in addition to the control mixture without any mineral admixture, 16 SCC mixtures containing various types and amounts of mineral admixtures were designed to have a constant w/b ratio of 0.44 and a total binder content of 454.5 kg/m^3. In all of the SCC mixtures the fine aggregate-to-total aggregate ratio, by mass, was set at 0.53. The HRWR dosages used in the mixtures were adjusted to secure an initial slump flow of 650 ± 10 mm. By the partial replacement of cement with the mineral admixtures, binary (PC + SF, PC + FAC, PC + FAF, PC + MK and PC + BFS), ternary (PC + SF + BFS, PC + FAC + BFS, PC + FAF + BFS and PC + MK + BFS) and quaternary (PC + SF + FAC + BFS) cementitious blends were. The mix proportion of ternary and quaternary mixtures was selected according to the conducting trial tests and those applied by the other researchers. The replacement levels of the various mineral admixtures were different: i.e., 4%, 8% and 12% for SF, 4%, 8%, 18% and 36% for MK, 18% and 36% for FA and only 18% for BFS. All substitutions of the cement by mineral admixtures were made on the total mass basis of the binder. The factors such as mixing efficiency, mixer type, mixing sequence, etc. that affect the properties of SCC during its production [29,30] were kept constant throughout the study. The mixing procedure consisted of homogenizing the aggregate with 35% of the mixing water for 1 min in a batch of 20 L using a rotary planetary mixer. Then, the cementitious materials with 40% of the mixing water were added and mixed for further 2 min. Afterwards, the HRWR, diluted with the remaining water, was introduced gradually over 2 min. Following 2 min of rest, the concrete was mixed for 3 additional min. The ambient temperature during mixing and testing was maintained constant at 20 ± 2 °C. The mixtures are designated according to the type and amount of the cementitious materials. For example, 8SF18FAC18BFS shows the quaternary mixture containing 8% SF, 18% FAC and 18% BFS by mass of the cement.

2.3. Testing procedure

The measurement of fresh SCC properties was started immediately after mixing (9 min after the initial contact of water with cement). The slump flow values were represented by the mean diameter (measured from two perpendicular directions) of the concrete spread after lifting the standard slump cone. The final diameter was determined in the slump flow test, and the time required for the concrete to spread to a diameter of 500 mm (T$_{50}$) was recorded. Once a slump flow of 650 mm was ensured, the visual stability index (VSI) of the mixtures was determined according to ASTM C 1611 [31]. Then, the rheological parameters (torque plastic viscosity and apparent yield stress) were evaluated using a coaxial cylinder concrete rheometer (ConTec 4SCC). A four-bladed vane rotating coaxially was used

Table 1
Physical and chemical properties of PC and mineral admixtures.

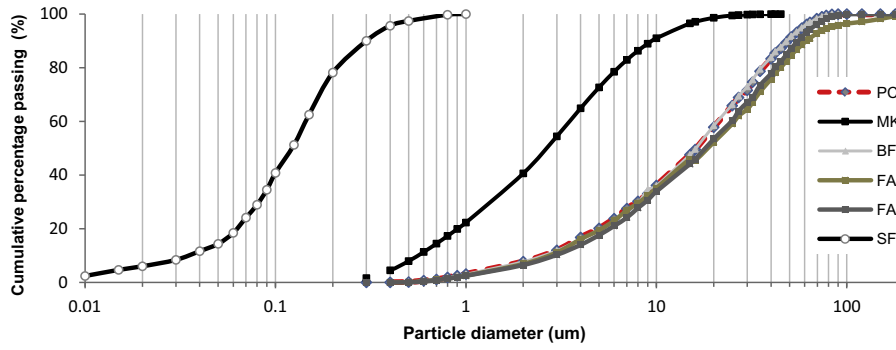|	PC	SF	FAC	FAF	MK	BFS
CaO, %	64.06	0.25	36.56	3.24	0.3	35.2
SiO$_2$, %	17.74	87.92	31.94	59.5	51.1	40.3
Al$_2$O$_3$, %	4.76	0.4	13.5	18.5	39.1	10.2
Fe$_2$O$_3$, %	3.17	0.35	4.09	6.96	2.15	0.67
MgO, %	1.28	3.97	1.42	2.03	0.7	6.9
SO$_3$, %	2.94	0.21	3.86	0.47	0.08	1.4
K$_2$O, %	0.8	0.81	0.94	1.93	1.78	0.97
Na$_2$O, %	0.45	1.79	1.1	1.27	0.11	1.12
Free lime, %	2.21	–	2.69	0.42	–	–
Other minor oxides, %	0.64	1.43	0.91	1.26	0.88	1.34
Loss on ignition, %	1.95	2.87	2.99	4.32	3.8	1.9
Specific gravity	3.13	2.29	2.73	2.38	2.54	2.97
Blaine fineness, cm^2/g	3310	–	3470	3220	–	3650
Surface area B.E.T., m^2/kg	–	24,520	–	–	15,410	–
Residue on 45 μm sieve, %	4.2	–	17.4	19.5	0.4	1.3

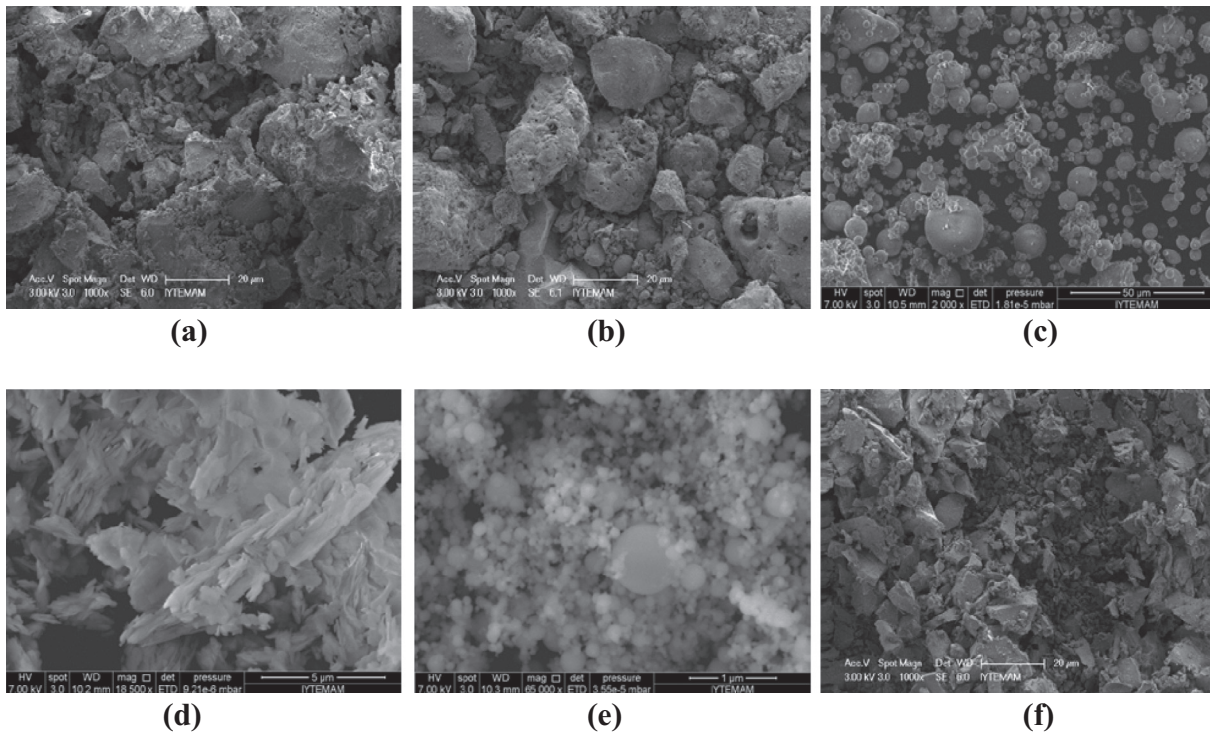**Fig. 1.** Particle size distributions of PC and mineral admixtures.

Fig. 2. SEM images of (a) PC, (b) FAC, (c) FAF, (d) MK, (e) SF and (f) BFS particles.

Table 2
Mix proportions of SCC mixtures substituted with mineral admixtures (kg/m³).

Mixture ID	Water	PC	SF	FAC	FAF	MK	BFS	HRWR	Aggregates (SSD)	
									Fine	Coarse
Control	200	454.5	–	–	–	–	–	5.75	883	783
4SF	200	436.5	18	–	–	–	–	6.70	880	778
8SF	200	418.5	36	–	–	–	–	7.50	875	774
12SF	200	400	54.5	–	–	–	–	8.0	870	771
8SF18BFS	200	337	36	–	–	–	81.5	6.70	874	774
18FAC	200	373	–	81.5	–	–	–	5.82	878	778
36FAC	200	291	–	163.5	–	–	–	6.35	872	773
36FAC18BFS	200	209.5	–	163.5	–	–	81.5	5.50	871	772
18FAF	200	373	–	–	81.5	–	–	4.67	872	772
36FAF	200	291	–	–	163.5	–	–	4.36	859	762
36FAF18BFS	200	209.5	–	–	163.5	–	81.5	4.31	858	761
8MK	200	418.5	–	–	–	36	–	6.50	878	779
18MK	200	373	–	–	–	81.5	–	7.50	873	773
36MK	200	291	–	–	–	163.5	–	10.0	861	762
36MK18BFS	200	209.5	–	–	–	163.5	81.5	9.35	860	761
18BFS	200	373	–	–	–	–	81.5	5.35	881	781
8SF18FAC18BFS	200	255.5	36	81.5	–	–	81.5	7.0	868	769

for the impeller. The container of the rheometer had an internal diameter of 240 mm and a depth of 240 mm, allowing a concrete sample volume of approximately 8 L. Following the rheology tests, thixotropy tests were performed. In order to determine the effect of elapsing time, the rheological parameters were measured at 0 and 50 min after mixing. To prevent the effect of evaporation, the fresh mixtures was covered by plastic sheets during standstill time interval. At the end of 50 min rest, the concrete was remixed for 2 min and the measurements of the fresh properties were repeated. The 28-day compressive strength of the mixtures was also determined according to ASTM C 39 [32]. The average compressive strength of three specimens was recorded for each mixture.

2.3.1. Evaluating torque plastic viscosity and apparent yield stress

Torque plastic viscosity of the mixtures was measured at five different revolution speeds of 0.70, 0.55, 0.40, 0.25 and 0.10 rps. The selected speed values were determined by conducting trial tests and are similar to those applied by the other researchers [16,33]. The measuring sequence started from the highest speed to the slowest speed (down-curve). Each speed was applied for a period of 8 s. However, the torque values obtained only during the last 6 s of the test were used in calculating the average torque value corresponding to that speed. Since it was possible to take 4 torque readings per second from the rheometer, $6 \times 4 = 24$ torque values were averaged for each speed. In this way, torque-rotation speed chart was generated for each concrete mixture. Bingham model was constructed by fitting the best line to the data. The intersection point of the trendline with the torque axis (apparent yield stress, g) and the slope of the trendline (torque plastic viscosity, h) were determined.

2.3.2. Evaluating thixotropy by breakdown area

Structural breakdown values of the mixtures were evaluated by the approach recommended by Lapasin et al. [34]. In this method, after five minutes of rest in the bowl of the rheometer, the mixture was subjected to a constant rotational speed of 0.2 rps for 10 s. Then, after another five-minute rest period, the mixture was subjected to a constant rotational speed of 0.4 rps for 10 s. The same procedure was repeated for speeds of 0.6 and 0.8 rps. For each speed, the time-dependent change in torque was recorded to obtain the initial torque (T_i) and equilibrium torque (T_e) values (Fig. 3a). Then, the initial and equilibrium torque values were plotted on torque-rotational speed graphs (Fig. 3b). The best curves, i.e., second order polynomial functions were fitted to the data (Fig. 3b). The area between the initial torque curve and the equilibrium curve, called "structural breakdown area", was calculated by integration and used to quantify the thixotropic behavior of the mixture.

3. Results and discussion

3.1. Visual stability index (VSI)

The VSI is a method for determining the segregation resistance of the mixture and to evaluate the relative stability of batches of the same SCC mixture. The VSI is determined through visual rating of the concrete appearance just after the slump flow test. The SCC mixture is considered stable and suitable for the intended use when the VSI rating is 0 or 1, and a VSI rating of 2 or 3 gives an indication of segregation potential [35]. ASTM C1611 [32] defines the VSI value as follows: VSI (0) = concrete mass is homogeneous and no evidence of bleeding, VSI (1) = concrete shows slight bleeding observed as a sheen on the surface, VSI (2) = evidence of a mortar halo and water sheen, VSI (3) = concentration of coarse aggregate at the center of concrete mass and presence of a mortar halo. The VSI values of the 17 SCC mixtures immediately after

mixing and when subjected to 50 min. rest are presented in Table 3. The instability of mixtures were judged by the evidence of mortar halo or bleed water at the edge of the mixture subjected to flow test. At 0 min. the VSI values of most of the mixtures were 0 or 1 indicating their high or moderate stability, respectively. Among the mixtures those containing SF, MK, 18% FAF, 18% FAC and the quaternary mixture showed no evidence of segregation or bleeding (VSI = 0). On the other hand, there was a slight bleeding in 36FAC, 18BFS, 8SF18BFS, 36FAC18BFS and 36 FAF mixtures (VS = 1). Besides, some bleeding and segregation was observed in the ternary systems containing BFS and FAF. On the other hand, after 50 min. rest except for 36 FAF18BFS mixture, some reduction in the stability of mixtures was occured. As a result VSI values of the mixtures varied between 0 and 2. In general, it was found that the presence of BFS in the binder of the mixture increased its liability to the bleeding or segregation.

As shown in Table 3, the VSI values of mixtures containing FAC, FAF and BFS increased after 50 min. of rest. These mixtures exhibited slight bleeding or segregation in slump flow test conducted after a standstill condition of 50 min. The fact was more pronounced in the 36FAF18BFS mixture. The spherical shape and (relatively) smooth texture of FAF particles (Fig. 2c) encouraged their ball-bearing effect to reduce the internal friction between the solid particles in the mixture. This facilitated the settling down of the coarse aggregate particles as well as rising some of the mixing water to the surface of the mixture [19]. The high stability of FAC bearing mixtures was attributed to the angular shape and rough texture of this mineral admixture (Fig. 2b). In addition to increasing the internal friction such particles may absorb some of the mixing water leaving less free water for bleeding. However, the absorption of some of the mixing water and HRWR admixture during the rest period increased the segregation liability of FAC bearing mixtures slightly. Moreover, the low absorption potential of BFS particles arisen from their glassy nature and smooth surface texture (Fig. 2f) seems to be responsible for the high bleeding capacity of the BFS-containing mixtures [2]. The effect was more pronounced after 50 min. rest. Besides, high cohesiveness of the binders containing either SF or MK caused an excellent stability in these mixtures even after 50 min. Rest. This is due to the extremely high surface area of these admixtures [1,19,36].

3.2. T_{50} flow time

The T_{50} flow time of the mixtures after 0 and 50 min. of mixing are presented in Table 3 and Fig. 4. Once again, the high cohesiveness of MK bearing mixtures seems to be the reason for the high T_{50} flow time of these mixtures at 0 and 50 min. rest times. Owing to the rough texture and high microporosity of FAC particles (Fig. 2b), similar T_{50} flow time results were obtained in FAC containing mixtures. On the other hand, short T_{50} flow times were recorded in SF and BFS incorporated mixtures irrespective of the
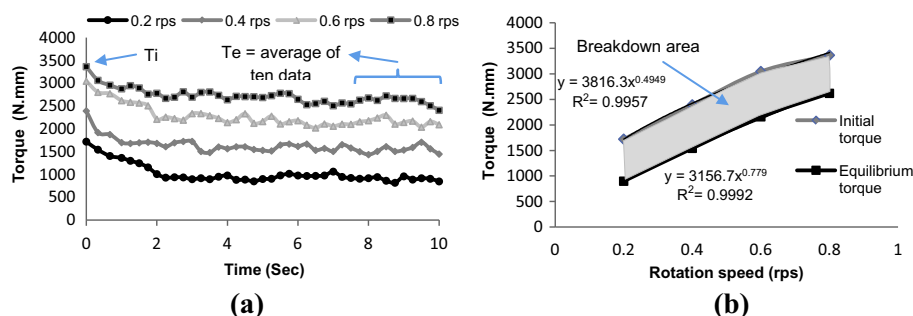

Fig. 3. Determination of thixotropy by breakdown area method for the 36FAF mixture (a) breakdown curves, (b) structural break-down area calculation.

Table 3
Properties of the SCC mixtures made with various mineral admixtures.

| Mixture ID	Compressive strength (MPa)	VSI		T_{50} time (s)		Torque plastic viscosity, (h) N.mm.s		Apparent yield stress, (g) N.mm		Thixotropy N.mm/s	
	28 days	0 min	50 min	0 min	50 min	0 min	50 min	0 min	50 min	0–30 min	50–80 min
Control	43.8	0	0	2	4.6	1392	1522	80.0	128	377	463
4SF	53.7	0	0	1.6	4.1	1206	1278	209	307	357	432
8SF	64	0	0	1.8	3.8	861	957	212	328	391	500
12SF	64	0	0	1.1	2.8	594	646	280	402	360	471
8SF18BFS	66.5	1	1	1.7	3	700	706	257	330	365	441
18FAC	50.1	0	1	3.5	7.4	1826	1925	88.8	190	510	596
36FAC	56.5	1	2	5.3	NA	2626	3117	116	236	830	962
36FAC18BFS	50	1	2	3.8	8.1	2220	2520	140	287	711	789
18FAF	41	0	0	1.9	4.1	1476	1495	129	202	422	493
36FAF	37.6	1	1	2.2	4.6	1648	1662	171	255	508	559
36FAF18BFS	35.8	2	3	2	4.1	1512	1499	216	352	486	524
8MK	45.2	0	0	2.9	5	1479	1553	165	301	449	543
18MK	63.4	0	0	3.4	6.9	1626	2000	187	346	487	637
36MK	64.5	0	0	4.9	NA	2417	2663	116	252	837	1104
36MK18BFS	47.1	0	1	4.1	NA	2164	2229	122	243	670	851
18BFS	54.6	1	1	1.9	3.1	1052	1028	74.0	110	337	367
8SF18FAC18BFS	56.8	0	0	1.5	2	994	982	230	310	472	509

Notes: NA: not available.
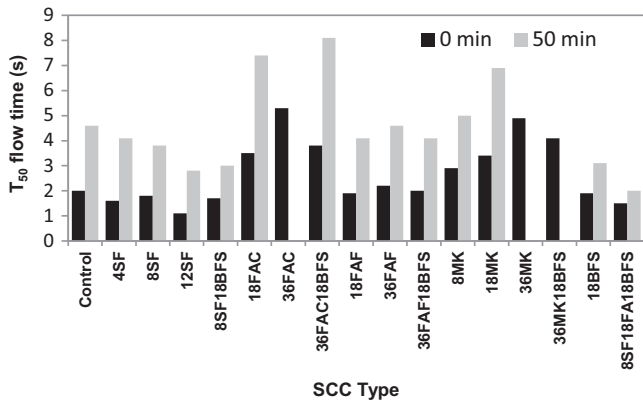
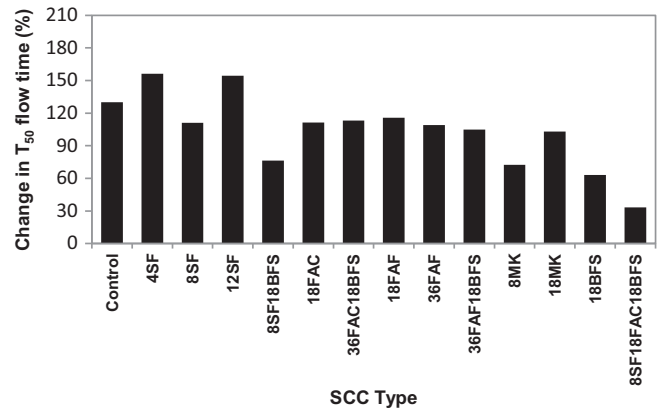**Fig. 4.** T_{50} flow times for SCC mixtures for different elapsing times.

Fig. 5. Change in T_{50} flow time with time.

rest time duration. Perhaps the ball bearing effect and additional lubrication provided by spherical and smooth-textured SF particles as well as glassy texture of BFS particles are the reasons for this behavior. Besides, partial substitution of PC with either FAF or BFS had a negligible effect on T_{50} flow time values. Similarly, the mixtures containing ternary binders showed very close T_{50} flow times to those of the counterpart mixtures containing binary binders (without BFS). It should be noted that after 50 min. rest the lowest increase in T_{50} time was recorded in mixture containing quaternary binder (Fig. 5). On the other hand, the flow values of 35FAC, 36MK and 36MK18BFS mixtures were lower than 500 mm after 50 min. rest. In short it is possible to claim that the absorption of some of the mixing water and HRWR admixture, controlled by the shape, fineness, surface texture and microporosity of the mineral admixture as well as the rate of hydration of the binder play an important role on the T_{50} flow time of the concrete mixture, particularly after a given rest period.

3.3. Torque plastic viscosity

The torque plastic viscosities of the mixtures measured at 0 min. and 50 min. rest times are given in Table 3. The effects of various mineral admixtures on the torque plastic viscosity of freshly mixed SCC immediately after mixing (0 min) were

discussed elsewhere [2]. The changes in torque plastic viscosity of SCC mixtures upon 50 min. rest were in the range of −2.3% to +23% as presented in Fig. 6. By elapsing time a significant increase in the plastic viscosity of MK- and FAC-containing mixtures was found. The highest increase (23%) was observed in 18MK mixture.
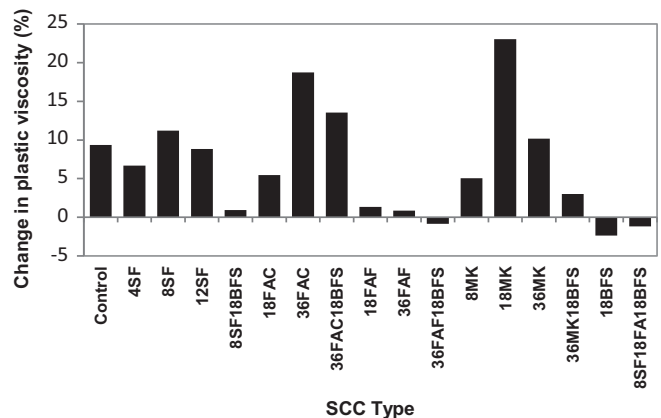

Fig. 6. Change in torque plastic viscosity with time.

The corresponding value was 18.7% in 36 FAC mixtures. The cellular structure and high microporosity of MK particles (Fig. 2d) coupled with their high fineness as well as the high microporosity of FAC particles (Fig. 2b) seem to be responsible for the huge change of plastic viscosity in the mixtures containing these admixtures. During the rest period, a considerable amount of mixing water and HRWR are expected to be absorbed by these mineral admixtures. It is well known the absorption of water and HRWR lead to a reduction in inter-particle distance and an increase in the level of attractive forces between solid particles. Both of which may increase the torque plastic viscosity significantly.

As shown in Fig. 6, the change in plastic viscosity of the mixtures incorporating SF (7–11%), are very close to that of the control mixtures (9%) containing only PC. The increase in torque plastic viscosity with time in control mixtures can be due to the rapid and progressive hydration of cement resulting in an increase in the solid volume concentration [37]. On the other hand, very fine particles of SF may provide better dispersion of the cement particles and promote their hydration resulting in a slight increase of the plastic viscosity. The effect seems to be masked to some extent by the ball-bearing effect of the SF particles which reduce the viscosity through reducing the solid (particularly cement) particles interaction.

On the other hand, except for 36FAC18BFS mixture, those mixtures containing ternary or quaternary binder as well as 18BFS mixture, the common feature of all of these is the presence of BFS, showed a slight increase or even decrease in torque plastic viscosity after 50 min. rest. Similar results were obtained in FAF bearing mixtures. The fact may be arisen, in part, from lower microporosity and lower absorption and in part, from lower chemical activity of the mineral admixtures during the rest period.

The relationship between T_{50} flow time and torque plastic viscosity for different rest times is plotted in Fig. 7. As can be seen from the figure good correlations ($R^2 = 0.865$ and $R^2 = 0.849$) was found between torque plastic viscosity and T_{50} flow time, irrespective of the duration of rest period. Besides, the slope of the line best fitted to the 0 min. data is somewhat greater than that of the best fitted line to the 50 min. data. This means that at early stages following the mixing, a definite change in the flow time value is an indication of a greater change in torque plastic viscosity, however, the same change in T_{50} flow time after 50 min. rest corresponds to a smaller change in plastic viscosity. Thus, it may be concluded that any simple empirical value such as T_{50} flow time is not adequate to fully characterize the fresh concrete under a stand still condition. For this reason it is recommended to use multiple-point based test results for the design and control of the concrete mixtures under standstill conditions.
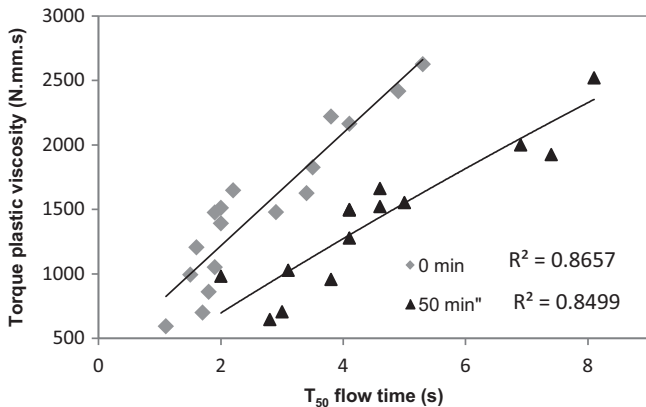
3.4. Apparent yield stress

The apparent yield stress values for 0 min and 50 min are given in Table 3. The effects of mineral admixtures on the apparent yield stress of freshly mixed SCC with a constant slump flow value were discussed previously [2]. Fig. 8 presents the change in apparent yield stress with time. As it can be seen from the figure, these values range from 28% to 115%. Similar to the discussions made for torque plastic viscosity, with elapsing time the change (increase) in the yield stress becomes significantly large in MK and FAC blended mixtures. Upon elapsing time, the increase in yield stress values are more pronounced compared to the changes of torque plastic viscosity values. After 50 min. rest, the highest increase in the yield stress (115%) was observed in 36MK. The corresponding value for 18FAC mixture was 114%. High surface area and porosity of MK as well as high porosity of FAC particles leave less free water and HRWR with elapsing time. This may lead to a higher degree of friction and provides a greater resistance to the beginning of flow, thereby resulting in an increase of shear stress necessary to maintain a steady-state condition.

In contrast to torque plastic viscosity values (as some reductions were observed in plastic viscosity values), yield stress values increased with time for all SCC mixtures; however, no clear trend were depicted with the replacement level of the mineral admixtures. For instance, apparent yield stress values of 18BFS mixtures was increased 48% in time while the torque plastic viscosity values for this mixture was decreased by −2.3%. Similarly, when 36FAF mixtures had an increase of 49% in yield values, enhancement of plastic viscosity for this mixture was approximately only 1% after 50 min of elapsing time. Similar results were observed also by a research of Lomboy et al. [18] where it was found that in a stand-still condition, passing of time had significant influence on increase of yield values while similar behavior was not obtained in plastic viscosity values of SCC mixtures. Moreover, similar to our observations, it was observed that yield stress values increased with time while torque plastic viscosity values changed only in a very limited range.

The reason behind this behavior can be summarized as follow: After 50 min of rest, due to use of free mixing water during the hydration reactions, absorption of water by mineral admixtures, and the decrease in the effect of the HRWR, mixtures become cohesive. When concrete stiffens, the torque values required for initiating the flow (corresponding to yield stress) become higher. But after flow has started, (after the yield stress has been overcome) the flow behavior of concrete is governed by the viscosity. Loss of concrete workability is directly reflected by the increase in yield stress; however, plastic viscosity could show different behavior [38–40].
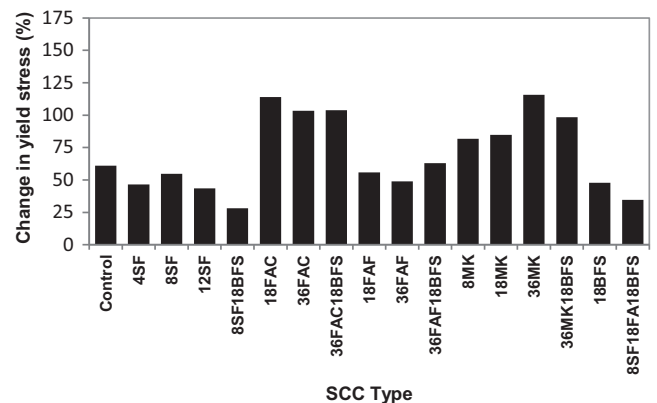

Fig. 7. Relationship between T_{50} flow time and torque plastic viscosity for different elapsing times.

Fig. 8. Change in apparent yield stress with time.

3.5. Thixotropy

Thixotropy is a reversible macroscopic phenomenon and is therefore often associated to reversible physico-chemical phenomena such as flocculation and de-flocculation under shear of colloidal suspensions [41]. It can define the time-dependent behavior of the fluids. In cement-based systems it depends strongly on mixture composition and processing parameters. Utilization of mineral admixtures in concrete increases the internal friction and hence attractive forces among solid particles, which in turn, increase the degree of physical and chemical bonds during cement hydration due to development of structural build-up in the cement based system with time [42–44]. In this study, two rest periods of 0–30 and 50–80 min were selected for determining the thixotropy by calculating the structure breakdown area values according to the procedure described in Section 2.3.2. The results are shown in Table 3 and the change in thixotropy with time is presented in Fig. 9. As shown in this figure, these values approximately ranged from 8% to 32%. Mixtures containing SF and MK had significant influence in enhancement of thixotropy with elapsing time. The highest increase was observed in 36MK mixture whose thixotropy at 50–80 min time period was approximately 32% greater than the thixotropy of the same mixture at 0–30 min. Similarly, 31% enhancement in thixotropy was observed in mixture containing 12% SF. On the other hand, the mixtures containing FAC, FAF and BFS had lower rates in enhancement of thixotropy with elapsing time. The lowest rate was observed in 36FAF18BFS mixture that increase was only 7.8%. While the increase in thixotropy of the reference mixture was 23%, it was only 8% for the quaternary mixture containing 8% SF, 18% BFS and 18% FAC.

A relatively high (23%) enhancement in thixotropy of the control mixture is related to hydration of PC with time. As a result of PC hydration, concentration of solid particles and interparticle links responsible for flocculation increases with time, causing an increase in thixotropy values. On the other hand, lower rates of enhancement of thixotropy with time for the mixtures containing FAC, FAF and BFS in comparison with control mixtures can be related to the lower degree of hydration of these mixtures. When these mineral admixtures are used with PC, solid volume concentration obtained from hydration of PC and magnitude of restructuring and strength of interparticle links, which have significant effect in thixotropy, can decrease owing to the lower reactivity of these mineral admixtures than PC.

As stated earlier, the increase in thixotropy with time for the SF and MK blended mixtures are higher when compared to the mixtures containing other mineral admixtures and control mixtures. This can be related to the high fineness (Fig. 1 and Table 1) and nucleating effect of these mineral admixtures with time. In a cement-based system, thixotropy is due to colloidal flocculation or CSH bridges between particles. Colloidal flocculation only affects thixotropy on a few seconds time scale and indeed CSH nucleation governs thixotropy behavior. High thixotropy values in the mixtures containing fine mineral admixtures is related to intercalated grains of these fine mineral admixtures with strong nucleating effect [41].

The behavior of the mixtures when left at rest and sheared again can be described as follows: The longer the material is maintained at rest, the more the structural build-up becomes significant, thus requiring higher initial shear stress to break down the structure. This is attributed to the stiffening effect, which enables the material to re-gain its shear strength when left at rest without any shearing action. Once shearing occurs, the particle spatial distribution and alignment become parallel to the flow direction, and the number of entanglements or associations decreases to the minimum. This leads to similar values of shear stress at equilibrium during shearing, thus resulting in higher thixotropy values with time [33,45].

Ferron et al. [15] determined the degree of thixotropy of cement pastes of SCC containing SF at a rest time up to 90 min. Similar to our observation they reported that in a standstill condition structural buildup of SF blended mixtures significantly increased with time. In an another investigation Assaad et al. [16,33] showed that in a standstill condition, thixotropy of SCC mixtures containing SF and FA increased as time was elapsed. They reported that increase in thixotropy was more significant when both SF and FA were incorporated with PC in SCC mixtures in comparison with the mixtures containing only PC.

3.6. Compressive strength

Table 3 and Fig. 10 present the 28-day compressive strength of SCC mixtures. Each result is the average of three strength values obtained on 100×200 mm cylinder specimens. It is clear from Fig. 10 that SF and MK significantly increased the compressive strength. This behavior was due to the high contribution of MK and SF to the strength due to the high pozzolanic activity of their particles at the tested age. As shown in Fig. 10, the highest compressive strength was observed in 8SF18BFS mixture, the compressive strength of which was approximately 52% greater than of the control mixture. Meanwhile, the lowest compressive strength was found in the 36FAF18BFS mixture. The reduction in the
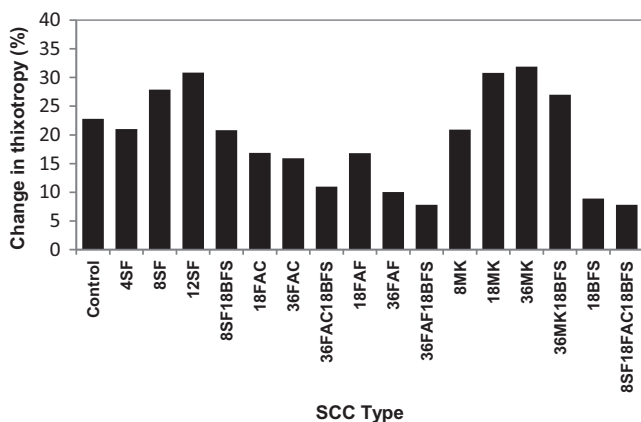

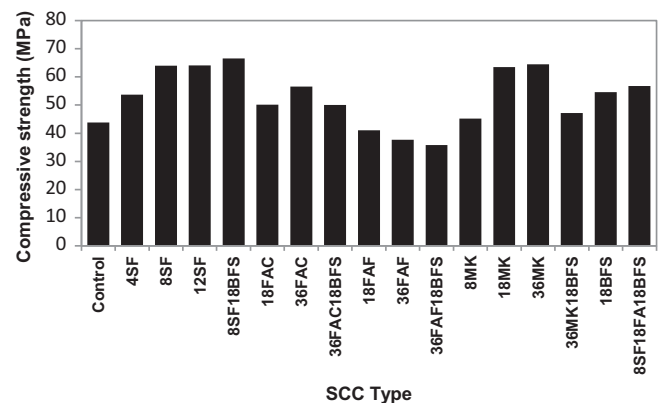**Fig. 9.** Change in thixotropy with time.

Fig. 10. Variation of compressive strength of SCC mixtures made with various mineral admixtures.

compressive strength of the concrete upon partial replacement of cement with FAF was more pronounced at higher replacement levels. In contrast to FAF, the compressive strength of FAC mixtures was found to be higher than that of the control mixture. The higher contribution of FAC (than FAF) to the 28-day strength of concrete seems to be arisen from its self cementitious property. As demonstrated in Fig. 10, when BFS was blended with PC and/or SF in the binary or ternary systems, it caused an increase in the compressive strength compared to those of control mixtures. However, when BFS was blended with the other mineral admixtures (i.e., FAF, FAC and MK) it resulted in an opposite effect on the strength of the ternary mixtures. This behavior seems to be due to the amount of the mineral admixture in these mixtures. The mineral admixture content of the ternary binders is 54% whereas it is 36% in the counterpart binary binder. On the other hand, the strength development of concretes containing these mineral admixtures and BFS was impaired, indicating the absence of sufficient CH for BFS pozzolanic activity.

4. Conclusion

The rheological properties of an SCC mixture containing a certain type and amount of SCC can be affected by the test methods (such as rheometer type) and material characteristics. Therefore, it should be kept in mind that the following conclusions were derived for the materials used and tests applied in this study:

(1) SCC mixtures containing various mineral admixtures were highly stable and moderately stable (VSI between 0 and 1) at 0 min according to ASTM C 1611. However, mixtures containing FAC, FAF and BFS exhibited some bleeding and segregation at 50 min while there was no significant change in the stability of SF and MK blended mixtures after 50 min of rest.
(2) T_{50} flow time of almost all mixtures after 50 min of rest (except 18BFS and 8SF18FAC18BFS mixtures) increased approximately 2 times compared to 0 min. MK and FAC were the two mineral admixtures that had most significant effect on T_{50} with time especially when they were incorporated at high replacement levels.
(3) Mixtures containing MK and FAC, showed significant increase in torque plastic viscosity with time. Torque plastic viscosity of the mixtures incorporating SF displayed comparable behavior to that of the control mixtures with time. Moreover, torque plastic viscosity was reduced in time when BFS was incorporated in binary and quaternary systems. In addition, FAF did not show significant effect on plastic viscosity values as function of time.
(4) Good correlations were established between T_{50} flow time and torque plastic viscosity values, irrespective of the duration of rest period.
(5) In contrast to torque plastic viscosity values, apparent yield stress values increased with time for all SCC mixtures; however, no clear trend was depicted with the replacement level of the mineral admixtures. Similar to torque plastic viscosity values, MK and FAC blended mixtures had significant influence on yield stress with elapsing time. Increase in yield values were more pronounced in comparison with torque plastic viscosity values after 50 min of elapsing time.
(6) Increase in thixotropy with time for the SF and MK blended mixtures were higher when compared to the control mixtures and the mixtures containing other mineral admixtures (FAC, FAF and BFS). The highest increase was observed in 36MK mixture whose thixotropy at 50–80 min time period was approximately 32% greater than the thixotropy of the same mixture at 0–30 min.

(7) SF and MK significantly increased the compressive strength of the mixtures. The highest compressive strength was observed in 8SF18BFS mixture whose compressive strength was approximately 52% greater than of the control mixture. The partial replacement of PC by FAF decreased compressive strength of control mixtures while the compressive strength of FAC mixtures was found to be higher than control mixtures.

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