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Permeability properties of self-consolidating concrete containing various supplementary cementitious materials

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HIGHLIGHTS

- Several amounts of SCM were used as binary, ternary and quaternary blends in SCC.
- Silica fume, Class C and F fly ash, metakaolin and slag were studied in one paper.
- Good correlation was established between permeable voids and water absorption rate.
- SCM reduced the permeability of almost all mixtures.
- Class C fly ash improved the permeability better than Class F fly ash.

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ABSTRACT

In this study, permeability properties of 17 self-consolidating concrete (SCC) mixtures containing various supplementary cementitious materials (SCM) were investigated by different experimental approaches. The effects of SCM type and content on the compressive strength, rapid chloride ion permeability (RCPT), water penetration depth, water absorption and sorptivity were studied. For these purposes, 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. Results showed that partial replacement of PC by SCM increased the compressive strength of control mixtures at 28 and 90 days (except for FAF at 28 days). Mixtures containing MK presented a better performance compared to other SCM at 7 days. The utilization of SCM reduced the RCPT results of almost all mixtures compared to the control mixtures and the reduction was more significant with an increase in the SCM content. All of the mixtures containing SCM had lower penetration depths when compared to reference mixtures at 28 and 90 days. Good correlations were established between the percentage of permeable voids and water absorption. Moreover, there was an inverse but almost linear relationship between permeable voids content and compressive strength of the mixtures.

1. Introduction

Self-consolidating concrete (SCC), one of the latest achievements of concrete technology, was first emerged by Japanese researchers in the second half of 1980s. It is considered as a concrete which can flow readily under its own weight to completely fill the formwork and self-consolidate without any mechanical vibration. This kind of concrete must achieve magnificent deformability and great stability to ensure high filling capacity of the formwork with complicated shapes, deep and narrow sections and congested structural members [1,2].

One of the most important differences between SCC and conventional vibrated concrete is the incorporation of supplementary cementitious materials (SCM), such as fly ash (FA), blast-furnace slag (BFS) and silica fume (SF) at higher volumes in SCC. Thus, a number of studies about the effects of SCM on the fresh and hardened properties of SCC have been conducted. It was reported that utilization of SCM in SCC not only improves the rheological properties and stability of the fresh concretes but also can decrease the cost of SCC and the amount of the CO_2 production related to the use of Portland cement (PC) in concrete. On the other hand, utilizing by-products or wastes as alternative cementitious materials in concrete provide a more sustainable concrete technology through the creation of a balance between development and environment.

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In addition, the use of SCM in SCC mixtures improves the mechanical, durability and long term properties of concrete [3–10].

FA is one of the most widely used SCM in SCC. The current annual worldwide production of coal ash is estimated about 700 million tones of which at least 70% is fly ash [11,12]. Many studies [13,14] reported that the use of FA in concrete reduces the dosage of HRWR to obtain similar workability compared to concrete made with only PC and improves the rheological and mechanical properties and durability of concrete. Moreover, FA utilization reduces the demand for cement, fine fillers and viscosity-enhancing chemical admixtures in SCC [15,16].

Another important SCM that has more application in production of SCC is BFS. Each year, in spite of 250 million tones production of BFS in the world, just 90 million tones of it has been utilized in the production of concrete [17]. Similar to FA, utilization of BFS in concrete may increase the workability, durability and long-term properties of concrete [17,18].

SF is considered one of the most effective SCM that greatly increases the strength and significantly reduces the permeability of concrete. In spite of its a few disadvantages such as its limited availability, difficulty to obtain the desired workability and the current high price (relative to PC and other SCM) of SF, it is being used increasingly as a property-enhancing material [19,20].

Metakaolin (MK) is a thermally activated aluminosilicate material processed by calcining kaolin clay within the temperature range of 650–800 °C. An important difference between MK and other SCM is that MK is a primary product, while FA, BFS and SF are secondary products or by-products. Thus, MK can be produced with a controlled process to achieve the desired properties [21,22]. In recent years, there has been a growing interest in the use of MK as a SCM to produce concretes with improved properties. However, only a limited number of studies are available about the properties of SCC containing MK. According to the previous studies [5,7,22] it has been reported that the concrete incorporating MK has a higher compressive strength with no detrimental effect on the long-term strength, higher resistance to the transportation of water and diffusion of harmful ions and higher durability aspects than the control PC concrete.

Despite the above-mentioned advantages of SCM in SCC, they may also weaken SCC properties compared to the plain mixture containing no SCM. For instance, SF and MK significantly increase the early strength and considerably reduce the permeability of SCC but may impair the required workability in fresh concrete [5,20–22]. On the contrary, FA and BFS generally decrease early strength but improve workability [5,8,13,16]. These negative effects may be hindered by combined use of the SCM in concrete by providing a synergistic effect [4,5,23]. However, there is only limited work on the use of ternary and quaternary blends of SCM in SCC. Such a lack of information has found significant importance in this investigation.

The current study focuses on the permeability properties of SCC containing various amounts of SF, FA, MK and BFS as a partial replacement of cement. These SCM were used in binary, ternary, and quaternary cementitious blends to investigate the variations of some rheological and hardened properties of SCC. The fresh concrete tests include slump flow, T_{50} time, V-funnel flow time and plastic viscosity while hardened concrete tests were compressive strength, chloride ion permeability, water penetration depth, water absorption rate, volume of permeable voids and sorptivity.

2. Experimental methods

2.1. Materials

In this study an ordinary Portland cement CEM I 42.5 R, was used. Five types of SCM, which are SF, FAC, FAF, MK, and BFS, were also used in the binary, ternary, and quaternary cementitious blends. Table 1 summarizes the physical and chemical properties, and Fig. 1 shows the particle-size distributions of the PC and SCM. As can be seen in Fig. 1, SF is obviously the finest of all SCM. The next finer material is MK which is considerably different from the other SCM. In addition, the particle size distribution of PC, BFS, FAC and FAF are similar to each other. 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 of the coarse and fine aggregates were 2.64 and 2.61, respectively, and their absorption capacities were 0.21% and 0.67%, respectively. A polycarboxylate ether-based HRWR conforming to ASTM C494 Type F [24] with a specific gravity of 1.06 and a solid content of 28% was employed to achieve the desired workability in all of the mixtures.

Table 1
Physical and chemical properties of PC and SCM.

	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_2O_3 (%)	4.76	0.4	13.5	18.5	39.1	10.2
Fe_2O_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_2O (%)	0.8	0.81	0.94	1.93	1.78	0.97
Na_2O (%)	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)	–	24520	–	–	15410	–
Residue on 45 μm sieve (%)	4.2	–	17.4	19.5	0.4	1.3

2.2. Mix proportions

As summarized in Table 2, one control mixture without any SCM and 16 SCC mixtures with SCM were designed to have a constant w/b ratio of 0.44 and a total binder content of 454.5 kg/m^3. For all SCC mixtures the fine aggregate-to-total aggregate ratio, by mass, was set at 0.53. These parameters were not altered in this research to eliminate their effects on the results and to inspect the effect of SCM merely. The HRWR dosages used in the mixtures were adjusted to secure an initial slump flow of 650 ± 10 mm. The control mixture contained only PC whereas other mixtures incorporated 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 in which a portion of PC was replaced with the SCM. The replacement levels for various SCM were different: it was 4%, 8% and 12% for SF, 4%, 8%, 18% and 36% for MK, 18% and 36% for FA and only 18% for BFS (36% BFS was not used since there was some bleeding on the surface when it was utilized by more than 18–25%). All substitutions of the cement by SCM were made on the total mass basis of the binder. In the production of SCC the mixing efficiency, mixer type, mixing sequence, etc. are very important factors affecting the properties of SCC [25,26]. Therefore, the same procedure for batching and mixing was followed to supply the same homogeneity and uniformity in all of the mixtures. The identification of the mixtures was made according to the type and amount of the SCM. For example, (8SF18FAC18BFS) denotes the quaternary mixture containing 8% SF, 18% FAC and 18% BFS.

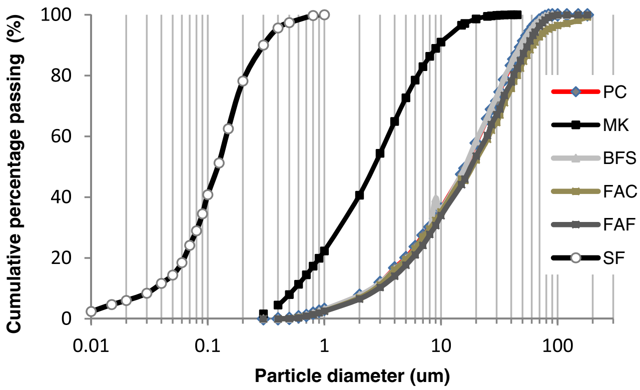

Fig. 1. Particle size distributions of PC and SCM.

Table 2
Mix proportions of SCC mixtures substituted with SCM (kg/m^3).

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	–	–	–	–	6.7	880	778
8SF	200	418.5	36	–	–	–	–	7.5	875	774
12SF	200	400	54.5	–	–	–	–	8	870	771
8SF18BFS	200	337	36	–	–	–	81.5	6.7	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	5.5	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	–	6.5	878	779
18MK	200	373	–	–	–	81.5	–	7.5	873	773
36MK	200	291	–	–	–	163.5	–	10	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	868	769

2.3. Testing procedure

2.3.1. Fresh and mechanical properties

The slump flow value of mixtures was measured immediately at the end of mixing (9 min after the initial contact of water with cement). 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. When the flow of the spread stopped, the concrete was inspected visually to check the presence of any segregation and bleeding. All of the mixtures prepared in the present study were homogeneous with no evidence of bleeding or segregation. Then plastic viscosity and V-funnel time tests were made in parallel. 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 V-funnel time test consisted of a V-shaped container with an opening of 65×65 mm at the bottom and 500×65 mm at the top. The plastic viscosity of mixtures was evaluated using a coaxial cylinder concrete rheometer (ConTec 4SCC). The viscosity was determined at 6 rotational speeds varying between 0.10 and 0.70 rps. For each rotational speed, the concrete mixture was sheared for 6 s, and the torque values related with the shear stress were noted. A linear regression was used to correlate the shear stress and shear rate values determined at the descending branch to calculate the plastic viscosity, assuming the Bingham flow model for the concrete mixture. The compressive strength of the concrete was determined using 100×200 mm cylinders according to ASTM C 39 [27]. The average compressive strength of three specimens are reported at 7, 28 and 90 days.

2.3.2. Permeability properties

The rapid chloride permeability test (RCPT) was conducted on 50 mm-thick specimens cut from the middle of each 100-mm diameter concrete cylinders as mentioned in ASTM C 1202 [28]. The results were evaluated by average Coulomb charge of three specimens. The water penetration depths under pressure were performed on 150 mm cubes as per TS EN 12390-8 [29]. In this procedure 150 mm cube specimens were exposed to 500 ± 50 kPa downward pressure for 72 h to penetrate drinkable water throughout the specimen (Fig. 2). After the end of 72 h, the test specimens were split exactly into halves and water penetration front was marked on the specimen as shown in Fig. 3. The maximum penetration depth of water under the test area was measured in mm. The results are reported in the average of three specimens. The sorptivity test was conducted in accordance with ASTM C 1585 [30]. This test method is based on determining the rate of absorption of water by concrete by measuring the increase in the mass of a cubic specimen with time when only one surface of the specimen is exposed to water. The exposed surface of the three cubic specimens was immersed in water and water ingress of unsaturated concrete was dominated by capillary suction during contact with water. In this test, the cumulative volume of water absorbed per unit surface area (mm^3/mm^2) was determined as a function of time. The water absorption rate and percentage of permeable voids test were determined according to the procedure given in ASTM 642 [31]. Three 100-mm cubic specimens were immersed in water and the weight gain was observed at regular periods until a constant weight gain was observed. The results of initial surface absorption were almost negligible and the final absorption of all specimens was observed after 96 h immersing in water. All of these permeability tests were conducted at 28 and 90 days.

Fig. 2. Permeability test set up for determining the water penetration depth.

Fig. 3. Water penetration depth after the test.

3. Results and discussion

3.1. Fresh and mechanical properties

3.1.1. T_{50} flow time

T_{50} flow time is a test to assess the flowability and the flow rate of SCC in the absence of obstructions. T_{50} flow times obtained from 17 SCC mixtures with various SCM are presented in Table 3 and Fig. 4. These values are in the range of 1.1–5.28 s. Such a wide range in flow time for the mixtures having same slump flow values and w/b ratio is due to the use of different SCM types with very diverse properties in these mixtures. As demonstrated in Fig. 4 the partial replacement of PC by FAC and MK increased T_{50} flow time of control mixtures. The binder containing 36% MK or 36% FAC increased T_{50} flow times up to 4.96 and 5.28 s, respectively. On the other hand, T_{50} flow time reduced when SF and BFS were incorporated in the binder system. The mixture containing 8% SF, 18% FAC and 18% BFS (quaternary system) led to the greatest reduction in T_{50} flow time. As can be seen in Fig. 4, higher flow times were obtained when replacement percentage of FAC and MK was increased while contrary behavior was observed when percentage of SF was increased. Also partial substitution of FAF with PC has no significant effect on T_{50} flow time values. Besides, in all ternary systems, with the use of 18% BFS with other SCM types a downward trend of T_{50} flow time was observed in comparison with binary systems without BFS. As shown in Fig. 4, among the 17 mixtures prepared in this study, eight of them have T_{50} flow time under 2 s, while the remaining mixtures showed flow times greater than 2 s. It can be noted that according to classification of European Guidelines [32], these mixtures can be classified as VS1 and VS2, respectively.

3.1.2. V-funnel flow time

V-funnel flow times obtained from 17 SCC mixtures with various SCM are presented in Table 3 and Fig. 4. As seen in Fig. 4 these values ranged from 8 to 25 s. SF had a significant influence on V-funnel time. As the amount of SF was increased, reduction in flow time values was visible. 12% replacement of SF resulted in the greatest reduction (2 times less) in V-funnel flow time. Also reduction in flow time values was observed with the use of FAF and BFS in SCC mixtures. On the other hand, adding MK and FAC increased flow time values in all of the mixtures. The binder containing 36% MK or 36% FAC increased V-funnel times up to 24 and 25 s, respectively, while that of control mixture was only 16 s. As shown in Fig. 4 the mixture containing 8% SF, 18% FAC and 18% BFS (quaternary system) led to a decrease in V-funnel flow time relative to the mixture containing only PC. In addition, in all ternary systems, use of 18% BFS with other SCM resulted in a considerable decrease in V-funnel flow time compared to those of the binary systems without BFS (Fig. 4). European Guidelines [32] provides a classification

Table 3
Rheological and mechanical properties of the SCC mixtures made with various SCM.

Mixture ID	T_{50} time (s)	V-funnel time (s)	Plastic viscosity (Pa s)	Compressive strength (MPa)		
				7 days	28 days	90 days
Control	2	16	174	39	43.8	51.5
4SF	1.6	15	150.8	40.6	53.7	58.8
8SF	1.8	13	107.7	34.5	64	64.6
12SF	1.1	8	74.3	35.5	64	66.8
8SF18BFS	1.7	12	87.6	36.7	66.5	71
18FAC	3.5	21	228.3	39.7	50.1	54.2
36FAC	5.3	25	328.3	41.1	56.5	63
36FAC18BFS	3.8	22	277.5	38.9	50	56.3
18FAF	1.9	14	184.5	37.6	41	50.6
36FAF	2.2	14	206.1	25.6	37.6	54.1
36FAF18BFS	2	12	189	18.8	35.8	45.6
8MK	2.9	20	184.9	44.2	45.2	52.9
18MK	3.4	19	203.3	56	63.4	67.7
36MK	4.9	24	302.2	46.3	64.5	65
36MK18BFS	4.1	21	270.5	39	47.1	59.6
18BFS	1.9	15	131.6	41.7	54.6	65.6
8SF18FAC18BFS	1.5	14	124.3	37.3	56.8	66.8

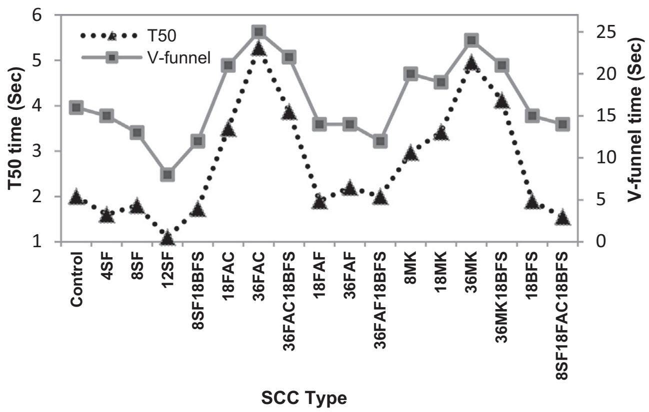

Fig. 4. T_{50} and V-funnel flow times for SCC mixtures made with various SCM.

of SCC viscosity according to V-funnel times. The mixtures having a V-funnel time between 9 and 25 s are classified as VF2. According to this classification all of the mixtures prepared in this study are classified as VF2.

3.1.3. Plastic viscosity

Plastic viscosity values for the binary, ternary and quaternary mixtures containing various SCM are presented in Table 3 and Fig. 5. These values are between 74 and 328 Pa s. As can be seen in Fig. 5, the partial replacement of PC by FAC, FAF and MK have increased plastic viscosity of the control mixtures. The highest increase was observed in 36FAC mixture whose plastic viscosity was approximately 88% greater than the viscosity of the control mixture. On the other hand, plastic viscosity was reduced when SF and BFS were incorporated in the binder systems. This reduction was more pronounced when 12% SF was incorporated with PC in control mixtures. As demonstrated in Fig. 5 the amount of reduction became lower as the replacement level of SF was decreased. This behavior was contrary to the behaviors of MK and FAC: as the percentage of MK and FAC was increased, plastic viscosity also increased. As shown in Fig. 5 8SF18FAC18BFS mixtures (quaternary system) led to a decrease in plastic viscosity relative to the control mixture and mixtures containing 18% FAC. Besides, similar to T_{50} and V-funnel flow times, in all ternary systems use of 18% BFS with other SCM resulted in a decrease in plastic viscosity values compared to those of the binary systems without BFS.

SF particles due to their spherical shape can pack better than PC particles [33]. Increasing the packing density can reduce shear stress to enhance the flow by filling the voids and providing additional lubrication [34] thus reduction in plastic viscosity values. Morphology is an important factor that affected the plastic viscosity of the mixtures with MK: contrary to the lubrication effect of spherical shape and smooth surface (as was the case in SF), open pores at the surface, elongated shape, irregular surface texture of the MK particles can increase the plastic viscosity values.

3.1.4. Relationship between rheological parameters

One of the aims of the present study is to establish correlations between workability test results (T_{50} flow time, V-funnel flow time) and plastic viscosity values. The relationship between T_{50} flow time and V-funnel flow time is plotted in Fig. 6. It was observed that there is a strong positive relationship between the results of these two tests. This result is consistent with the previous results [32,35]. As shown in Fig. 7, T_{50} flow time values are well correlated with plastic viscosity values. In addition a positive exponential relationship was observed between V-funnel flow time and plastic viscosity values (Fig. 8). The correlation coefficients of these relationships were calculated as 0.868 and 0.813 respectively.

As shown in Figs. 7 and 8, there is a gradual increase in the plastic viscosity values by increasing the T_{50} and V-funnel flow time values. However, when the correlation coefficients of these relationships are compared, it can be concluded that T_{50} test results reveal a better correlation with plastic viscosity values than the V-funnel test results. From the results above it can be concluded that it is possible to have an idea about the plastic viscosity of SCC mixtures by measuring the T_{50} and V-funnel flow times of them.

3.1.5. Compressive strength

The compressive strength test results of the 17 SCC mixtures are presented in Table 3 and Fig. 9. As can clearly be seen in this figure, the 90-day compressive strengths of the mixtures were slightly increased in comparison with 28-day compressive strengths. However, the increase in strength of the mixtures was significant within the time interval of 7–28 days. The highest compressive strength was observed in 8SF18BFS mixture whose compressive strength was approximately 38% greater than of the control mixture at 90 days. The lowest compressive strength belonged to 36FAF18BFS mixtures at 7 days. As shown in Fig. 9, except for the mixture containing 4% SF, the partial replacement of PC by SF and FAF decreased the compressive strength of control mixtures at 7 days. This reduction was more pronounced when FAF incorporated in higher levels. In addition, mixtures containing MK present a better performance compared to the other SCM at 7 days. This behavior is due to high pozzolanic activity of MK particles at early age. Güneyisi et al. [36] reported that addition of MK into the

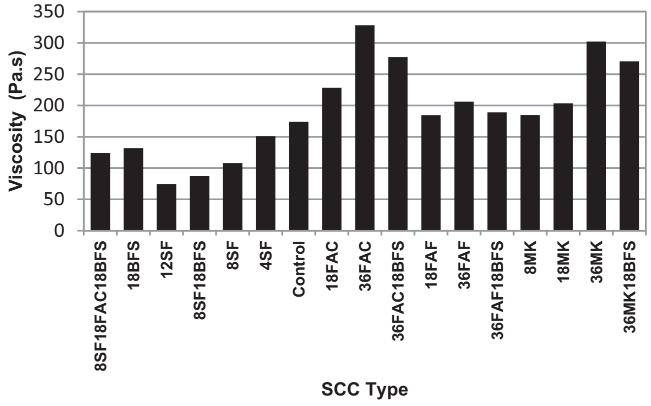

Fig. 5. Variation of plastic viscosity in SCC mixtures made with various SCM.

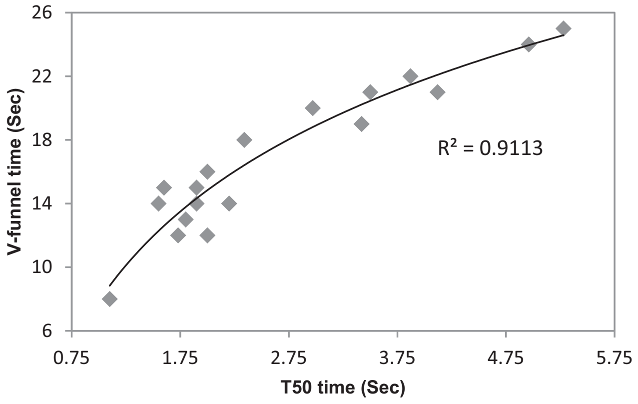

Fig. 6. Relationship between T_{50} and V-funnel flow time.

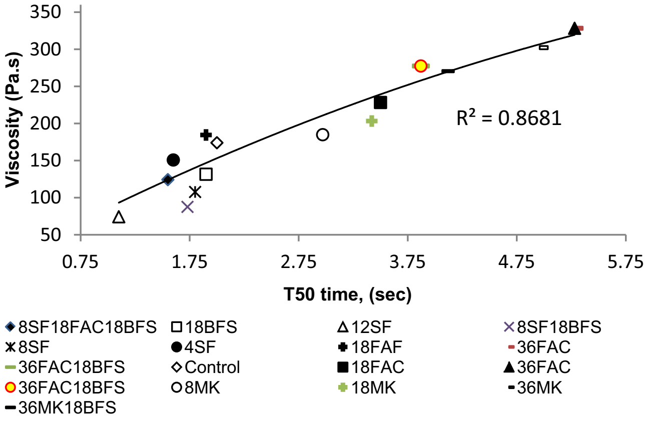

Fig. 7. Relationship between T_{50} flow time and plastic viscosity.

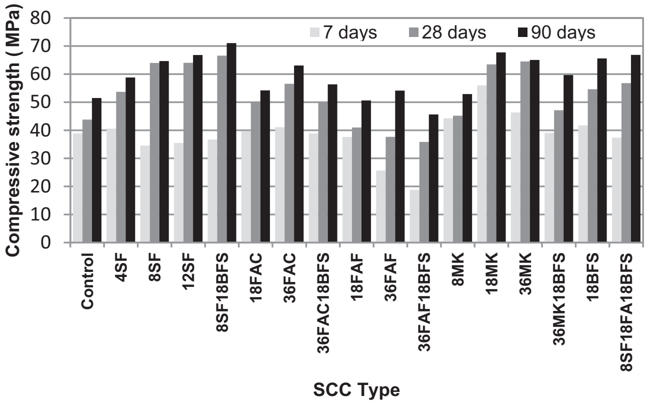

Fig. 9. Variation of compressive strength in SCC mixtures made with various SCM.

matrix improved the bond between the cement paste and aggregate particles, which in turn significantly modified the strength of concrete. Also Poon et al. [37] showed that at early ages, the higher pozzolanic activity of MK resulted in a higher rate of strength development and pore refinement when compared to SF or FA blended cement paste. The results of the present study showed that the contribution of MK to concrete strength was noticeable up to 18% replacement of cement by MK. Accordingly, regardless of the age of concrete, increasing the percentage of MK from 18% to 36% did not show a significant effect on compressive strength. These results are in agreement with the findings of the other researchers [7,37–40].

As demonstrated in Fig. 9 the binary and ternary use of FAF reduced the compressive strength of the control mixtures irrespective of the testing age. In contrast, the compressive strength development of FAC included mixtures was found to have higher strength values than the control mixtures at all ages. The reason for this fact can be explained as follows: FA is a pozzolanic by-product containing glassy material which can be broken down only when the pH value of the pore solution is at least 13.2. Since the increase in the alkalinity of the pore solution requires a certain amount of hydration of the PC in the mix to take place, the pozzolanic reaction of FAF could not begin until a couple of months [41].

As can be seen in Fig. 9 there is a considerable increase in the compressive strength of mixtures containing SF between the ages of 7 and 28 days. On the other hand, compressive strength development of SF incorporated mixtures was found to be insignificant beyond 28 days. For example, the increase in strength of 12SF mixture was 80% between 7 and 28 days while it was only 0.04% between 28 and 90 days. According to ACI 234R guideline [19] the main contribution of SF to concrete strength development at normal curing temperatures takes place from about 3 to 28 days, and after 28 days it is minimal.

As shown in Fig. 9 except for the mixtures containing FAF and BFS, there was not any significant development of compressive strength after 28 days. It should be noted that when BFS was blended with PC and SF in binary and ternary systems, compressive strength of the mixtures was increased, while the opposite tendency was observed when it was blended with other SCM in ternary systems, irrespective of the age of the mixture. The reason for behavior can be explained as follows: in the ternary mixtures containing BFS, the volume of other SCM is more than the binary mixtures containing BFS and ternary mixtures containing BFS and SF. On the other hand, the strength development of concretes containing these SCM and BFS was impaired, indicating the absence of sufficient CH for BFS pozzolanic activity. In spite of this, Bickley et al. [42] reported that high strength development of concrete could be obtained with addition of BFS to mixtures containing SF. This explanation is in agreement with the result obtained for the highest compressive strength of the mixture containing 8% SF and 18% BFS among the mixtures prepared in the present study.

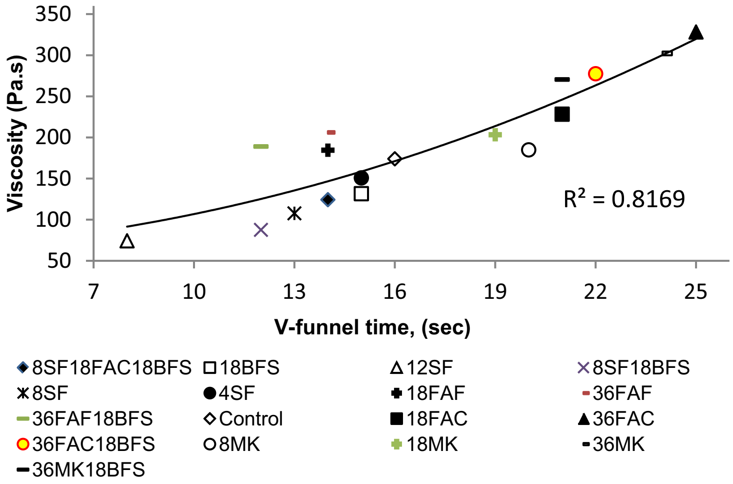

Fig. 8. Relationship between V-funnel flow time and plastic viscosity.

3.2. Permeability properties

3.2.1. Chloride ion permeability

The effect of using single, binary and ternary blends of SCM on the rapid chloride ion permeability test (RCPT) results is shown in Table 4 and Fig. 10. As can be seen, the utilization of SCM reduced the RCPT results of all mixtures (except for the 28-day age mixtures containing FAF) compared to the control mixtures. The reduction became more significant with an increase in the SCM content. The chloride ion penetrability limits, suggested by ASTM C1202 [28], were compared with the test results and according to this classification, the SCC mixtures of this study (except for the 28-day age concretes containing FA) can be classified as concretes with low (1000–2000 Coulomb) and very low (100–1000 Coulomb) permeability.

As can be seen in Fig. 10, chloride ion permeability of MK blended mixtures was lower than that of the other mixtures. This is more significant at 28-day results. While the chloride permeability of the reference mixture was 6535 Coulomb, that of the SCC mixture with 18% MK decreased to only 259 Coulomb (Fig. 10). Similar results were obtained for 90-day results as well. Moreover, chloride ion permeability of the mixtures containing SF and MK were observed to be similar to each other (Fig. 10). 28- and 90-day results of the mixture with 12% SF were only 10% and 8% of the reference mixture, respectively.

The 28-day permeability of the FAF mixtures was comparable to that of the reference mixture as can be seen in Fig. 10. However, a significant improvement was observed in these mixtures at the end of 90 days, which can be explained by the pozzolanic activity of FAF that became significant at later ages. For example, while the 28-day permeability of the mixture containing 18% FAF was 86% of the reference mixture, it was only 23% of the reference at 90 days. In addition, the chloride ion permeability of the mixtures containing FAC and BFS were higher than that of the SF and MK mixtures at 28 days. However, the difference decreased at 90 days. In spite of this, the decrease in the permeability of FAF mixtures beyond 28 days was not seen in the mixtures containing FAC and BFS.

The main effect of the SCM on the pore structure of concrete is the reduction of large pores via blocking them with hydration products. The transformation of continuous pores into discontinuous pores has a profound effect on the permeability of concrete [19]. Sellevold and Nilsen [43] reported that SF is more effective in reducing permeability than it is in enhancing strength and suggested that it is the improved quality of the cement paste aggregate transition zone which is largely responsible for this behavior. In another investigation Kostuch et al. [44] concluded that reduction in diffusion properties of mortars containing MK is related to the significant decrease in the average pore size of mortar matrix. They reported that MK can be effective in reducing the rate of diffusion of Cl^- and Na^+ ions in mortar.

Byfors [45] reported that addition of SF up to 20% by mass of cement considerably reduced the diffusion rate of chloride ion compared to the performance of ordinary PC paste.

In a study presented by Poon et al. [21], it was stated that, compared to that of the control mixture, incorporation of 20% MK and 15% SF decreased chloride ion permeability by 79% and 62%, respectively. In a more resent study Hassan et al. [7] investigated the chloride ion permeability of SCC incorporating MK and SF. They reported that chloride ion permeability of mixtures containing 11% SF and 20% MK decreased by 54% and 88%, respectively compared to that of the control mixture. Also Güneyisi et al. [5] reported that MK was the most effective SCM that had significant effect in reducing the chloride ion diffusivity of SCC in comparison with mixtures containing FA and BFS.

Bouikni et al. [46] stated that the pore size of cement matrices containing 50–65% BFS was considerably reduced when compared with PC paste without BFS. Moreover, Güneyisi and Gesoglu [47] reported that the decrease in the chloride ion permeability of concrete containing BFS was due to change in the pore structure of the hydrated cementitious system.

Similar to the present study, Uysal et al. [12] studied the effects of FAC and FAF on chloride ion permeability of SCC. They reported that chloride ion permeability of the concretes containing FAC and FAF decreased at 90 days when the FA content, regardless of its type, was increased. Moreover, it was noticed that mixtures containing FAC performed better than FAF mixtures. Improvement in chloride ion penetration of SCC mixtures containing FA could be related to the capability of transformation of large pores in the cementitious matrix into small pores and reduction in micro cracking in the transition zone [10,48]. The results obtained in present study upon utilization of FA in SCC were similarly observed by other researchers [16,23,48].

3.2.2. Water penetration depth

The water penetration depth describes the ease with which a fluid may flow through a porous body on a pressure differential. The variations of water penetration depth values for binary, ternary and quaternary mixtures containing SCM are demonstrated in Fig. 11. As can be seen, the 90-day results were lower than the

Table 4
Permeability properties of the SCC mixtures made with various SCM.

Mixture ID	Chloride ion permeability (coulombs)		Water penetration (mm)		Water absorption (%)		Permeable voids (%)		Sorptivity index (mm/min$^{1/2}$)	
	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days	28 days	90 days
Control	5635	5058	24.4	18.0	2.96	2.09	7.0	5.0	0.068	0.039
4SF	5183	1403	23.6	16.3	2.72	1.9	6.4	4.5	0.057	0.020
8SF	966	685	14.3	6.8	1.97	1.98	4.6	4.8	0.049	0.012
12SF	560	408	12.1	7.6	1.69	1.27	3.9	2.9	0.031	0.017
8SF18BFS	614	529	13.7	5.3	1.90	1.26	4.4	3.0	0.051	0.019
18FAC	3810	1386	18.0	11.0	2.83	2.08	6.6	4.8	0.053	0.035
36FAC	3240	2286	19.0	5.5	2.72	2.0	6.3	4.8	0.056	0.028
36FAC18BFS	1326	942	20.1	8.3	2.26	1.48	5.2	3.4	0.073	0.014
18FAF	4901	1171	21.0	12.0	3.90	2.0	8.9	4.6	0.055	0.033
36FAF	4159	624	24.0	16.8	3.20	2.02	7.3	4.6	0.104	0.020
36FAF18BFS	4204	660	23.1	13.2	2.67	1.96	6.1	4.5	0.074	0.019
8MK	871	618	20.8	14.8	2.0	1.85	4.8	4.4	0.062	0.027
18MK	259	158	15.8	9.8	1.91	1.27	4.4	3.0	0.037	0.015
36MK	268	140	17.0	9.1	2.29	1.39	5.2	3.2	0.050	0.029
36MK18BFS	307	256	17.3	5.6	1.91	1.62	4.3	3.7	0.061	0.024
18BFS	2520	1834	19.4	12.6	2.65	1.5	6.0	3.5	0.071	0.023
8SF18FAC18BFS	511	359	8.7	5.3	1.34	1.28	3.1	3.0	0.051	0.013

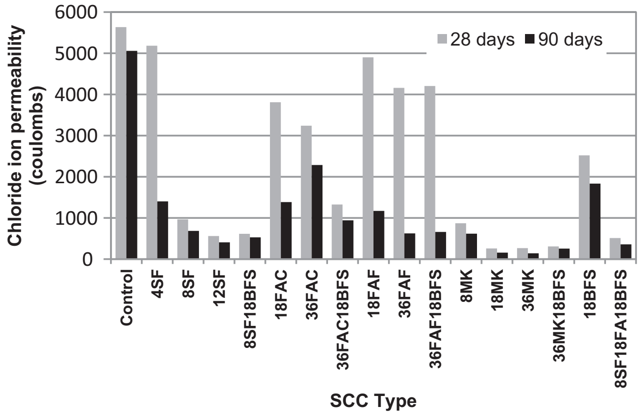

Fig. 10. Variation of chloride ion permeability in SCC mixtures made with various SCM.

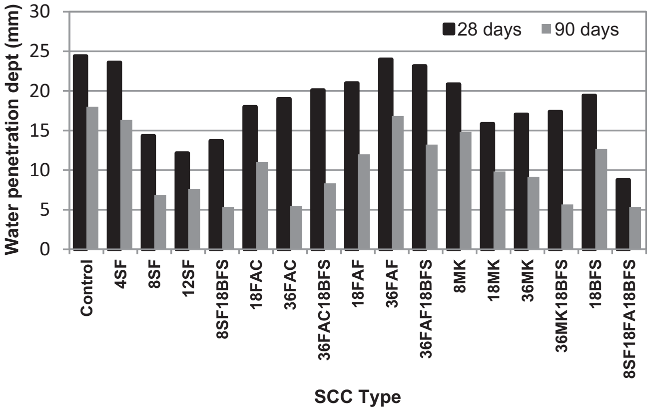

Fig. 11. Variation of water penetration depth in SCC mixtures made with various SCM.

28-day results. Moreover, all of the mixtures had lower penetration depths when compared to the reference mixtures at both ages. The lowest penetration depth (which was only 29% of that of control mixture) was obtained at 90 days for the 8SF18BFS and 8SF18FAC18BFS mixtures. The mixture with 36% FAF showed the highest depth at 28 days, which was still 98% of the reference mixture.

It is clear from Fig. 11 that similar to the results of RCPT, SF and MK were the two significant SCM in the reduction of water penetration depths at 28 and 90 days. The decrease was more significant at 90 days. An increase in replacement level of SF and MK decreased the penetration depths further. Such a decrease was greater when BFS was used with SF and MK. Although it is certain that FAF and FAC can decrease the water penetration depths of the reference mixture at 28 and 90 days, the behavior of these admixtures was inconsistent when their contents were increased in the binary binders. However, in the ternary blends containing FAF and BFS, the decrease in penetration depth was more significant. Besides, when used in the binary systems, BFS decreased the penetration depth compared to that of the reference mixture; however, it showed a more efficient performance when used together with SF and FAC.

Although the use of SCM reduced both water penetration depth and chloride ion permeability, the reductions in the former test results were not so significant as the reductions in the RCPT results. This can be explained as follows: water permeability test is based on measuring the ingress of water to the capillary pores of an unsaturated concrete, whereas RCPT test is based on the electrical conductivity of the concrete specimen through its connected capillary pores. The difference between the results of these two permeability tests can be related to the ability of these SCM to combine the Cl^- and Na^+ ions of the pore solution. Besides, the RCPT result depends on the electrical conductivity of the pore solution, which is determined by the composition of the pore solution. The electrical conductivity or RCPT value of a concrete can be reduced by lowering the alkalinity of concrete pore solution. Accordingly significant reduction in concentration of alkali ions and associated hydroxyl ions in the pore solution with utilization of SCM can be an expected phenomenon [49].

Gesoglu et al. [23] studied the single and combined effects of SF, FA and BFS on the permeation properties of SCC. Similar to our observation they indicated that both the binary cements containing SF and quaternary blend containing SF, FA and BFS, had the lowest water penetration depth compared to the control mixture. Moreover, the SCC mixtures incorporating SF led to a better water permeability owing to their less porous interfacial zone and the refined pore structure of the paste matrix. In another investigation [5] on the permeability properties of SCC containing MK, FAF and BFS, it was reported that MK was the most efficient mineral admixture to reduce the water penetration depth of the SCC mixtures. In addition, reduction in water penetration depth was observed when FA and BFS were incorporated with PC in binary, ternary and quaternary SCC mixtures. These results are in agreement with the observations of present study.

Dinakar et al. [50] studied the water penetration rate of SCC containing 10–70% FAF. They reported that mixtures containing 10–30% FAF performed a better water penetration depth compared to those containing higher replacement percentages. Moreover, in an investigation on the effect of mineral admixture replacement level on SCC properties, Uysal et al. [8] presented that mixtures containing15% FAC and 20% BFS were the two mixtures that had the lowest water penetration depths when compared to other mixtures including the control one.

3.2.3. Water absorption and permeable voids

28- and 90-day water absorption values of the mixtures having a w/b ratio of 0.44 and containing various SCM are presented in Table 4 and Fig. 12. Similar to the previous sections, significant improvements in water tightness and permeable voids content of the SCM-bearing mixtures were observed at later (90-day) age. The lowest absorption values were seen in the quaternary system at both 28- and 90-day ages. The highest absorption, which was 133% of the reference mixture, belonged to the mixture with 36%

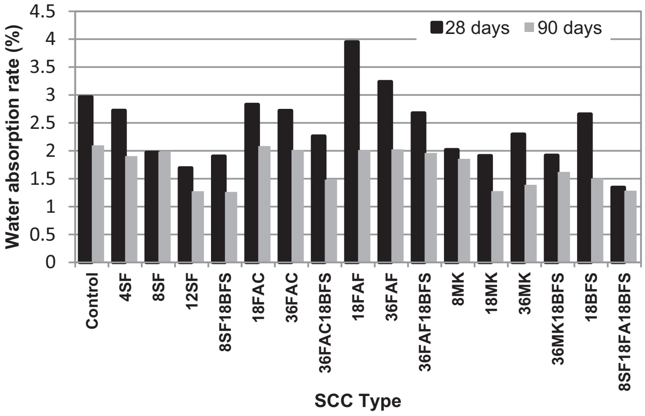

Fig. 12. Variation of water absorption in SCC mixtures made with various SCM.

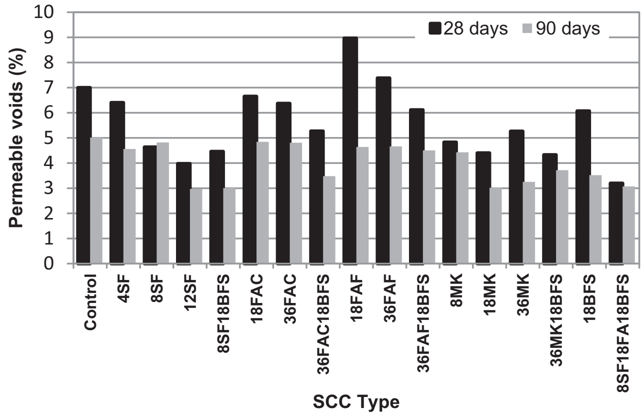

Fig. 13. Variation of permeable voids in SCC mixtures made with various SCM.

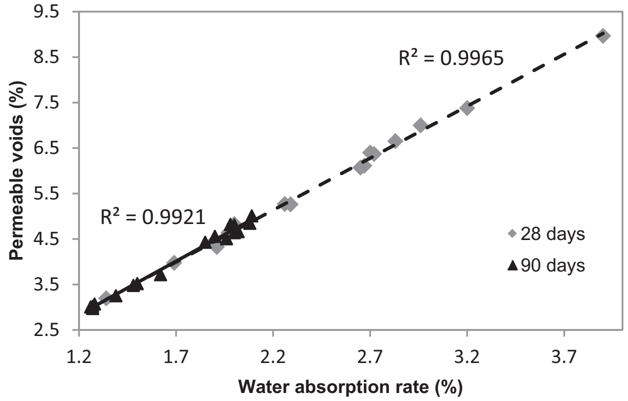

Fig. 14. Relationship between water absorption rate and permeable voids.

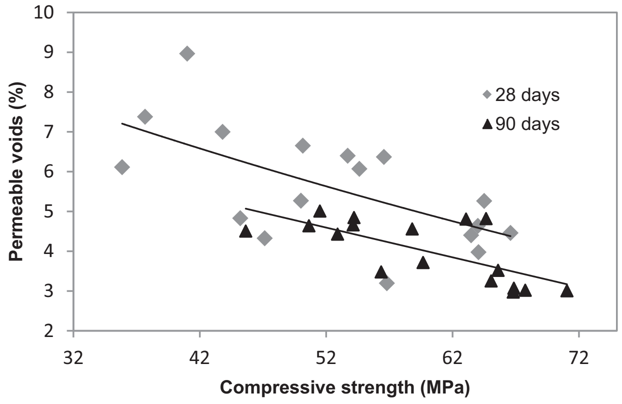

Fig. 15. Relationship between compressive strength and permeable voids.

FAF at 28 days. The 90-day absorption of this mixture was very close to that of the reference mixture.

As can be seen from Fig. 12, the 28- and 90-day absorptions of the MK and SF mixtures were lower than those of the reference mixtures. Generally, the absorption decreased with an increase in the MK and SF replacement levels. The beneficial effect of SF and MK in reducing the water absorption of mixtures can be due to the filling effect of ultrafine SF and MK particles as well as their pozzolanic reaction. The reduction in the size of capillary pores increases the probability of transforming the continuous pores into discontinuous ones. The absorption values of the mixtures with FAF were higher than those of the reference mixture at 28 days. However, at 90 days, the results of FAF mixtures became close to the reference mixture (Fig. 12). Also the absorption values of FAC and BFS mixtures were similar and lower than the reference mixture at 28 and 90 days, respectively. As cited by Sabet et al. [51], Shetty [52] reported that a high quality concrete should have a final absorption of less than 5%. According to this classification, all of the SCC mixtures prepared in this study could be classified as high-quality from absorption point of view.

Sabet et al. [51] studied the effects of SF, FA and natural zeolite on water absorption properties of SCC. Similar to our results, they reported that among the SCM types investigated in their study, SF was the most effective SCM in reducing the water absorption of SCC. It was also noticed that incorporation of natural zeolite and FA decreased water absorption, however these SCM were not as effective as SF. In another investigation Madandoust et al. [53] observed that the water absorption of SCC containing MK was much lower than that of a reference concrete. Moreover, Shekarchi et al. [54] reported that water absorption in normal concrete was decreased by 28% for a mixture containing 15% MK.

Fig. 13 presents the volume of permeable voids for SCC mixtures containing various SCM. Similar to water absorption, the volume of permeable voids was also lower for SCC containing various SCM. As shown in this figure SF and MK have a significant effect on the volume of permeable voids in SCC. Fig. 14 shows that the correlation ratio between the percentage of permeable voids and water absorption for 90 days and 28 days were respectively 0.996 and 0.992 (Note that there are two trendlines in Fig. 14 for 28 and 90 days and they almost coincide). From this figure it can be concluded that there is a good correlation between these two parameters. The permeable voids content increases as water absorption increases. The relationship between the permeable voids content and compressive strength is presented in Fig. 15, indicating that there is an inverse but almost linear relationship between these two sets of results.

3.2.4. Sorptivity index

The variations of 28- and 90-day sorptivity indices of binary, ternary and quaternary mixtures containing SCM are presented in Fig. 16. Similar to water absorption test results, the sorptivity values at 90 days were lower than those at 28 days. However, except 36FAC18BFS, 36FAF, 36FAF18BFS and 18BFS mixtures, the 28-day sorptivity values of all of the mixtures were lower compared to the reference mixture. On the other hand, all of the mixtures presented a sorptivity index lower than that of the reference mixture at 90 days. The lowest sorptivity, which was 31% of the reference mixture, was observed for the 8SF mixture at

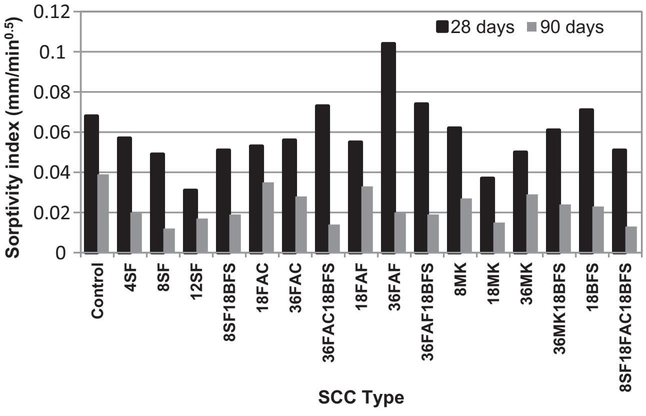

Fig. 16. Variation of sorptivity index in SCC mixtures made with various SCM.

90 days. The highest value (153% of the reference mixture) belonged to the 28-day result of the 36FAF mixture. Similar to other permeability test results, the sorptivity index of SF and MK bearing mixtures is much lower than that of the reference mixture. This behavior was based on the filler effect and high pozzolanic activity of SF and MK particles at early ages. As shown in Fig. 16, FAC bearing mixtures had a sorptivity index close to reference mixture while the use of FAF generally increased the sorptivity index at 28 days. On the other hand, sorptivity was observed to decrease at 90 days for the FAC and FAF bearing mixtures that can be related to pozzolanic activity of FAF at later ages.

4. Conclusion

The main conclusions derived from this study can be summarized as follows:

(1) Plastic viscosity values were found to be well correlated with both T_{50} and V-funnel values. However, the correlation was better with the former one.
(2) The increase in strength for most of the mixtures (except 18FAF, 36FAF and 18BFS mixtures) was more significant between 7 and 28 days than the increase between 28 and 90 days. The highest compressive strength was observed in 8SF18BFS mixture at 90 days and the lowest strength belonged to 36FAF18BFS mixture at 7 days.
(3) The partial replacement of PC by SF (when its amount is higher than 4%) and FAF decreased the compressive strength of control mixture at 7 days while mixtures containing MK presented a better performance compared to the other SCM at the same age. The development of strength in FAC bearing mixtures was higher than the control mixtures at all ages.
(4) The compressive strength of mixtures containing SCM except FAF were higher than the control mixtures at 28 days and there was not any significant development of strength after 28 days except in the FAF and BFS mixtures.
(5) The utilization of SCM reduced the RCPT results of all of the mixtures (except the 28-day mixtures containing FAF) compared to that of the control mixtures and the reduction was more significant with an increase in the SCM content. The permeability of MK and SF blended mixtures was lower than that of the other mixtures.
(6) The chloride ion permeability of the mixtures containing FAC and BFS were higher than that of the SF and MK mixtures at 28 days. However, the difference decreased at 90 days and the mixtures containing FAC performed better than FAF mixtures.
(7) All of the mixtures containing SCM had lower penetration depths when compared to the reference mixtures at both ages. The lowest depth was obtained at 90 days for the 8SF18BFS and 8SF18FAC18BFS mixtures and the highest depth belonged to 36FAF at 28 days.
(8) Similar to the RCPT results, SF and MK were the two significant SCM in reducing the water penetration depths at 28 and 90 days but the reductions were more apparent in the RCPT results.
(9) FAF and FAC decreased the water penetration depths of the reference mixture at 28 and 90 days. BFS decreased the penetration depth of the reference mixture, too; however, it showed a more efficient performance when used together with SF and FAC.
(10) The lowest absorption values were seen for the quaternary system at both ages. The highest absorption, which was 133% of the reference mixture, belonged to the mixture with 36% FAF at 28 days. In addition SF and MK were, again, the two SCM that had the most significant effect on the water absorption of control mixture.
(11) Similar to water absorption, the volume of permeable voids was also lower in the mixtures containing SCM. There was a good correlation between the percentage of permeable voids and water absorption. Moreover, there was an inverse but almost linear relation between permeable voids and compressive strength.
(12) Except 36FAC18BFS, 36FAF, 36FAF18BFS and 18BFS mixtures, the 28-day sorptivity values of all of the mixtures were lower compared to the reference mixture. There was a progressive reduction in sorptivity indices with prolonged curing.

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References

[1] Saleh Ahari R. Effect of mineral admixtures on rheological, thixotropic and permeability characteristics of self-consolidating concrete (SCC) [Ph.D. thesis]. İzmir: Ege University; 2014. 215 p.
[2] Erdem TK, Khayat K, Yahia A. Correlating rheology of self-consolidating concrete to corresponding concrete-equivalent mortar. ACI Mater J 2009;106:154–60.
[3] Yuksel C, Saleh Ahari R, Abbaspoursani Ahari B, Ramyar K. Evaluation of three test methods for determining the alkali–silica reactivity of glass aggregate. Cem Concr Compos 2013;38:57–64.
[4] Erdem TK, Kirca Ö. Use of binary and ternary blends in high strength concrete. Constr Build Mater 2008;22:1477–83.
[5] Güneyisi E, Gesoglu M, Ozbay E. Permeation properties of self-consolidating concretes with mineral admixtures. ACI Mater J 2011;108:150–8.
[6] Habert G, Roussel N. Study of two concrete mix-design strategies to reach carbon mitigation objectives. Cem Concr Compos 2009;31. 397-2.
[7] Hassan AA, Lachemi M, Hossain K. Effect of metakaolin and silica fume on the durability of self-consolidating concrete. Cem Concr Compos 2012;34:801–7.
[8] Uysal M, Yilmaz K, Ipek M. The effect of mineral admixtures on mechanical properties, chloride ion permeability and impermeability of self-compacting concrete. Constr Build Mater 2012;27:263–70.
[9] Chung CW, Shon CS, Kim YS. Chloride ion diffusivity of fly ash and silica fume concretes exposed to freeze-thaw cycles. Constr Build Mater 2010;24:1739–45.
[10] Sahmaram M, Yaman IO, Tokyay M. Transport and mechanical properties of self consolidating concrete with high volume fly ash. Cem Concr Compos 2009;31:99–106.
[11] Sahmaran M, Yaman O, Tokyay M. Development of high-volume low-lime and high-lime fly-ash-incorporated self-consolidating concrete. Mag Concr Res 2007;59:97–106.
[12] Uysal M, Akyuncu V. Durability performance of concrete incorporating Class F and Class C fly ashes. Constr Build Mater 2010;34:170–8.
[13] Bouzoubaa N, Lachemi M. Self compacting concrete incorporating high volumes of class f fly ash preliminary results. Cem Concr Res 2001;31:413–20.
[14] Yahia A, Tanimura M, Shimabukuro A, Shimoyama Y. Effect of rheological parameters on self compactability of concrete containing various mineral admixtures. In: Proceedings of the first RILEM international symposium on self-compacting concrete, Stockholm; 1999. p. 523–35.
[15] Khurana R, Saccone R. Fly ash in self-compacting concrete. In: Proc of fly ash, silica fume, slag and natural pozzolans in concrete, ACI SP-199; 2001. p. 259–74.
[16] Siddique R. Properties of self-compacting concrete containing class F fly ash. Mater Des 2011;32:1501–7.
[17] Boukendakdji O, Kenai S, Kadri EH, Rouis F. Effect of slag on the rheology of fresh self-compacted concrete. Constr Build Mater 2009;23:2593–8.
[18] Oner M, Erdogdu K, Gunlu A. Effect of components fineness on strength of blast furnace slag cement. Cem Concr Res 2003;33:463–9.
[19] ACI 234R-96. Guide for the use of silica fume in concrete. American Concrete Institute; 1996.
[20] Hassan A, Lachemi M, Hossain K. Effect of metakaolin and silica fume on rheology of self-consolidating concrete. ACI Mater J 2012;109:657–64.
[21] Poon CS, Kou SC, Lam L. Compressive strength, chloride diffusivity and pore structure of high performance metakaolin and silica fume concrete. Constr Build Mater 2006;20:858–65.
[22] Sabir BB, Wild S, Bai J. Metakaolin and calcined clay as pozzolans for concrete: a review. Cem Concr Compos 2001;16:441–54.

[23] Gesoglu M, Güneyisi E, Ozbay E. Properties of self-compacting concretes made with binary, ternary, and quaternary cementitious blends of fly ash, blast furnace slag. Constr Build Mater 2009;23:1847–54.

[24] ASTM C494-08. Standard specification for chemical admixtures for concrete. ASTM International; 2008.

[25] Skarendahl A, Peterson SO. Self-compacting concrete. State of the art report of RILEM TC174-SCC, France; 2000. p. 47–55.

[26] Khayat KH, Bickley J, Lessard M. Performance of air-entrained, self consolidating concrete for casting basement and foundation walls. ACI Mater J 2000;97:374–80.

[27] ASTM C39/C39M-12a. Standard test method for compressive strength of cylindrical concrete specimens. ASTM International; 2012.

[28] ASTM C1202-12. Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. ASTM International; 2012.

[29] TS EN 12390-8. Testing hardened concrete-part 8: depth of penetration of water under pressure. Ankara, Turkey: Institute of Turkish Standards; 2010.

[30] ASTM C1585-13. Standard test method for measurement of rate of absorption of water by hydraulic-cement concretes. ASTM International; 2013.

[31] ASTM C642-13. Standard test method for density, absorption, and voids in hardened concrete. ASTM International; 2013.

[32] EFNARC. Self compacting concrete, European project group. The European guidelines for self-compacting concrete: specification, production and use; 2005.

[33] Bentz DP, Ferraris CF, Galler MA, Hansen AS, Guynn JM. Influence of particle size distributions on yield stress and viscosity of cement-fly ash pastes. Cem Concr Res 2012;42:404–9.

[34] Tattersall GH, Banfill PFG. The rheology of fresh concrete. London: Pitman Advanced Publishing Program; 1983.

[35] Khayat KH. Workability, testing, and performance of self-consolidating concrete. ACI Mater J 1999;96:346–53.

[36] Güneyisi E, Mermerdas K. Comparative study on strength sorptivity and chloride ingress characteristics of air-cured and water cured concretes modified with metakaolin. Mater Struct 2007;40:1161–71.

[37] Poon CS, Lam L, Kou SC, Wong YL, Wong R. Rate of puzzolanic reaction of metakaolin in high-performance cement pastes. Cem Concr Res 2001;31:1301–6.

[38] Wild S, Khatip JM, Jones A. Relative strength, pozzolanic activity and cement hydration in superplasticized metakaolin concrete. Cem Concr Res 1996;26:1537–44.

[39] Dinkar P, Manu SN. Concrete mix design for high strength self-compacting concrete using metakaolin. Mater Des 2014;60:661–8.

[40] Cassagnabere F, Escadeillas G, Mouret M. Study of the reactivity of cement/metakaolin binders at early age for specific use in steam cured precast concrete. Constr Build Mater 2009;23:775–84.

[41] Fraay ALA, Bijen JM, De Haan YM. The reaction of fly ash in concrete: a critical examination. Cem Concr Res 1989;19:235–46.

[42] Bickley JA, Ryell J, Rogers CA, Hooton RD. Some characteristics of high strength concrete. Can J Civ Eng 1991;18:885–9.

[43] Sellevold EJ, Nilsen T. Condensed silica fume in concrete: a world review. In: Malhotra VM, editor. Supplementary cementing materials for concrete. Ottawa, Canada: CANMET; 1987. p. 165–243.

[44] Kostuch JA, Walters GV, Jones TR. High performance concrete incorporating metakaolin a review concrete 2000. Dundee, Scotland, UK: University of Dundee; 1993. p. 1799–811.

[45] Byfors K. Influence of silica fume and fly ash on chloride diffusion and pH values in cement paste. Cem Concr Res 1987;17:115–30.

[46] Bouikni A, Swamy RN, Bali A. Durability properties of concrete containing 50% and 65% slag. Constr Build Mater 2009;23:2836–45.

[47] Güneyisi E, Gesoglu M. A study on durability properties of high performance concretes incorporating high replacement levels of slag. Mater Struct 2008;41:479–93.

[48] Patel R, Hossain KMA, Shehata M, Bouzoubaa N, Lachemi M. Development of statistical models for mixture design of high-volume fly ash self-consolidation concrete. ACI Mater J 2004;101:294–302.

[49] Shi C. Effect of mixing proportions of concrete on its electrical conductivity and rapid chloride permeability test results. Cem Concr Res 2004;34:537–45.

[50] Dinkar P, Kartik Reddy M, Sharma M. Behaviour of self compacting concrete using Portland pozzolana cement with different levels of fly ash. Mater Des 2013;46:609–16.

[51] Sabet FA, Libre NA, Shekarchi M. Mechanical and durability properties of self consolidating high performance concrete incorporating natural zeolite, silica fume and fly ash. Constr Build Mater 2013;44:175–84.

[52] Shetty MS. Concrete technology: theory and practice. New Delhi, India: S. Chand and Company Ltd.; 2001.

[53] Madandoust R, Mousavi SY. Fresh and hardened properties of self-compacting concrete containing metakaolin. Constr Build Mater 2012;35:752–60.

[54] Shekarchi M, Bonakdar A, Bakhshi M, Mirdamadi A, Mobasher B. Transport properties in metakaolin blended concrete. Constr Build Mater 2010;24:2217–23.