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Permeation Properties of Self-Consolidating Concretes with Mineral Admixtures

by Erhan Güneyisi, Mehmet Gesoglu, and Erdogan Özbay

This paper addresses the permeation properties of self-consolidating concretes (SCCs) with different types and amounts of mineral admixtures. Portland cement (PC), metakaolin (MK), fly ash (FA), and ground-granulated blast-furnace slag (GGBFS) were used in binary, ternary, and quaternary cementitious blends to improve the durability characteristics of SCCs. For this, a total of 22 SCCs were designed that have a constant water-binder ratio (w/b) of 0.32 and a cementitious materials content of 926.75 lb/yd³ (550 kg/m³). In addition to compressive strength and ultrasonic pulse velocity, the permeation resistance of SCCs was determined by means of chloride ion permeability, water permeability, and sorptivity tests. The test results indicated that the permeation properties of SCCs appeared to be very dependent on the type and amount of the mineral admixture used; the SCC mixtures containing MK were found to have considerably higher permeability resistance than the control mixture.

Keywords: chloride ingress; durability; mineral admixture; permeability; self-consolidating concrete.

INTRODUCTION

Self-consolidating concrete (SCC) emerged in Japan in the late 1980s as a material that can flow under its own weight so that it can be placed in formwork with dense reinforcement and complicated shapes without the need for additional mechanical compaction. The critical aspects of this technology involve attaining a highly fluid mixture while preventing segregation among constituents, especially segregation between the aggregate and the cement paste.[1,2] The advantages of SCC include high performance in its fresh and hardened states; economic efficiency (shortened construction time, reduced labor, and lower equipment costs); an improved working and living environment (high consumption of industrial by-products, reduced noise, and reduced health hazards); and enhancement toward the automation of the construction process.[3,4]

In the production of SCC, it is common practice to limit coarse aggregate content associated with its maximum size and to use a lower water-binder ratio (*w/b*), along with an appropriate high-range water-reducing admixture (HRWRA).[5] To achieve an SCC of high fluidity and to prevent segregation and bleeding during transportation and placing, the formulators have employed a high binder content and used an HRWRA and viscosity-modifying admixtures.[6-9] The cost of such concretes associated with the use of a high volume of portland cement (PC) and chemical admixtures, however, was remarkably higher. In some cases, the savings in labor cost might offset the increased cost. The use of mineral admixtures, such as fly ash (FA), blast-furnace slag, and/or limestone filler, however, reduced the material cost of the SCCs and also improved the fresh and hardened properties of the concretes.[10,11] A number of studies have been reported in the literature[6,12-15] concerning the use of mineral admixtures to enhance the self-compactibility characteristics of SCCs while reducing the material cost. It has been reported that economically competitive SCC can be produced by replacing up to 50% of PC with mineral admixtures.[1,16]

In recent years, there has been a growing interest in the use of metakaolin (MK) as a mineral admixture to produce concrete with high strength and durability properties. MK is a thermally activated aluminosilicate material obtained by calcining kaolin clay within the temperature range of 923 to 1073°K (650 to 800°C).[17] An important difference between MK and natural pozzolans or other types of artificial pozzolans is that MK is a primary product, whereas FA, ground-granulated blast-furnace slag (GGBFS), and silica fume (SF) are secondary products or by-products. Thus, MK can be produced with a controlled process to achieve the desired properties. A comprehensive review of the studies on the use of MK in conventional concrete has recently been presented by Sabir et al.[18] It was reported that the concrete incorporating 10% MK had a higher compressive strength than the control plain concrete.[19,20] With respect to the durability aspects, the resistance of MK concrete to chloride ion penetration was significantly higher than the control concrete.[20] In the literature, however, the use of MK in the production of SCC has not found adequate attention.

Using mineral admixtures, especially in SCC, necessitates further attention. With the incorporation of such materials, certain properties of the concrete may be enhanced, whereas others may worsen relative to the plain PC concrete. SF, for example, substantially increases early concrete strength but imparts a sharp fall in workability to fresh concrete,[21] whereas FA decreases early strength but improves workability.[22] These negative effects may be remedied by the combined use of the mineral admixtures. To date, only limited work has been carried out on the binary, ternary, and quaternary blends of mineral admixtures. Some examples involve the combined use of SF-FA-PC blends[23] and MK-FA-PC blends[18] in conventional concrete.

RESEARCH SIGNIFICANCE

The use of mineral admixtures will inevitably increase over the next few decades to provide greater sustainability in construction, and there will therefore be pressures to maximize their effectiveness with regard to cost, environmental impact, durability, and performance. The objective of this study is to investigate the effects of using mineral admixtures as a partial replacement for PC on the permeation properties of SCCs. Mineral admixtures, namely MK, FA, and GGBFS

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Erhan Güneyisi *is an Associate Professor at Gaziantep University, Gaziantep, Turkey. He received his MSc and PhD in civil engineering from Bogaziçi University, Istanbul, Turkey. His research interests include the durability of composite and blended cement concretes, the use of mineral admixtures in concrete, concrete anchors, self-consolidating concrete, and high-performance concrete.*

Mehmet Gesoglu *is an Associate Professor at Gaziantep University. He received his MSc and PhD in civil engineering from Bogaziçi University. His research interests include concrete anchors, lightweight-aggregate concretes, self-consolidating concrete, and high-performance concrete.*

Erdogan Özbay *is an Assistant Professor in the Construction Materials Division of the Faculty of Engineering of Mustafa Kemal University, Hatay, Turkey. He received his MSc and PhD from Gaziantep University. His research interests include the durability of concrete, the usage of waste materials in concrete, and self-consolidating concretes.*

were used in binary (two-component), ternary (three-component), and quaternary (four-component) cementitious blends to improve the characteristics of SCCs.

EXPERIMENTAL INVESTIGATIONS

Materials

The SCC mixtures investigated in this study were prepared with CEM-I 42.5 R PC, a Class F FA, a GGBFS, and MK. The chemical and physical properties of the cement and mineral admixtures used are summarized in Table 1. The coarse aggregate used was river gravel with a nominal particle size of 0.629 in. (16 mm). As fine aggregate, the mixture of natural river sand and crushed limestone was used with a nominal particle size of 0.196 in. (5 mm). They had fineness moduli of 2.87 and 2.57, respectively. The particle size gradation obtained through the sieve analysis and physical properties of the fine and coarse aggregates are presented in Table 2. A polycarboxylic-ether type HRWRA with a specific gravity of 1.07 and solid content of 40% by weight was employed to achieve the desired workability in all concrete mixtures.

Table 1—Chemical composition and physical properties of cement and mineral admixtures

Chemical analysis, %	PC	FA	GGBFS	MK
CaO	62.58	4.24	34.12	0.78
SiO_2	20.25	56.2	36.41	52.68
Al_2O_3	5.31	20.17	10.39	36.34
Fe_2O_3	4.04	6.69	0.69	2.14
MgO	2.82	1.92	10.26	0.16
SO_3	2.73	0.49	—	—
K_2O	0.92	1.89	0.97	0.62
Na_2O	0.22	0.58	0.35	0.26
Loss on ignition	3.02	1.78	1.64	0.98
Specific gravity	3.15	2.25	2.79	2.5
Fineness, cm^2/g	3260	2870	4180	120,000

Note: 1 cm^2/g = 0.48843 ft^2/lb.

Table 2—Sieve analysis and physical properties of fine and coarse aggregates

	Fine aggregate		
Sieve size, mm	River sand	Crushed sand	Coarse aggregate
16	100	100	100
8	100	100	31.5
4	86.6	95.4	1.0
2	56.7	63.3	0.5
1	37.7	39.1	0.5
0.5	25.7	28.4	0.5
0.25	6.7	16.4	0.4
Fineness modulus	2.87	2.57	5.66
Specific gravity	2.66	2.45	2.72
Absorption, %	0.55	0.92	0.45

Note: 1 mm = 0.0393 in.

Concrete mixture proportioning and casting

To cover a range of different mixture variations, a total of 22 concrete mixtures were designed having a constant *w/b* of 0.32 and a total binder content of 926.75 lb/yd^3 (550 kg/m^3). The control concrete was made of only PC as the binder, whereas the remaining mixtures incorporated binary (PC + FA, PC + GGBFS, and PC + MK); ternary (PC + FA + GGBFS, PC + FA + MK, and PC + GGBFS + MK); and quaternary (PC + FA + GGBFS + MK) cementitious blends in which a proportion of PC was replaced with the mineral admixtures. The replacement ratios for both FA and GGBFS were 20, 40, and 60%, whereas the replacement ratios of MK were 5, 10, and 15% by weight of total binder content. The mixture proportions are summarized in Table 3. The mixtures were designated according to the type and the amount of cementitious materials included. Mixture M22 (22.5FA22.5GGBFS15MK), for example, includes 22.5% FA, 22.5% GGBFS, and 15% MK.

In the production of SCCs, the mixing sequence and duration are very important.[15] Thus, the procedure for batching and mixing proposed by Sonebi[12] was employed to supply the same homogeneity and uniformity in all mixtures. The batching sequence consisted of homogenizing the fine and coarse aggregates for 30 seconds in a rotary planetary mixer, then adding approximately half of the mixing water into the mixer and continuing to mix for 1 more minute. Thereafter, the aggregates were left to absorb the water in the mixer for 1 minute. After the cement and mineral admixtures were added, the mixing was resumed for another minute. Finally, the HRWRA with remaining water was introduced, and the concrete was mixed for 3 minutes and then left for a 2-minute rest. Eventually, the concrete was mixed for an additional 2 minutes to complete the mixing sequence.

The workability of the SCCs was controlled through the slump flow test. The slump flow diameters of all the mixtures were designed to be in the range of 27.60 ± 1.18 in. (700 ± 30 mm) to satisfy the EFNARC limitation.[24] For this, trial batches were produced for each mixture until the desired slump flow was obtained by adjusting the dosage of the HRWRA. The measured slump flow diameters of the SCCs are given in Table 3.

From each concrete mixture, six 5.90 in. (150 mm) cubes and four Ø3.937 x 7.874 in. (Ø100 x 200 mm) cylinders were also cast full without any vibration or compaction. After 24 hours of casting, they were demolded and stored in lime-saturated water for 28 days and then stored in a controlled room of 73.4 ± 3.6°F (23 ± 2°C) temperature and 70 ± 5% relative humidity until the time of testing at 90 days.

Concrete test specimens and testing procedure

The rapid chloride permeability test (RCPT) was conducted to determine the resistance of the concrete to the penetration of chloride ions according to AASHTO T277-89.[25] Two specimens with dimensions of Ø3.937 x 7.874 in. (Ø100 x 200 mm) were simultaneously tested for each concrete at the end of the 90-day curing period. After curing, two 1.968 in.

Table 3—Concrete mixture proportioning

Mixture no.	Mixture ID	w/b	Water, kg/m³	PC, kg/m³	FA, kg/m³	GGBFS, kg/m³	MK, kg/m³	Natural sand, kg/m³	Crushed sand, kg/m³	Coarse aggregate, kg/m³	HRWRA, kg/m³	Slump flow, mm
M1	Control-PC	0.32	176	550	0	0	0	522	206	935	8.43	670
M2	20FA	0.32	176	440	110	0	0	512	202	917	7.43	730
M3	40FA	0.32	176	330	220	0	0	502	198	899	7.43	730
M4	60FA	0.32	176	220	330	0	0	492	194	881	6.67	730
M5	20GGBFS	0.32	176	440	0	110	0	520	205	931	10.43	700
M6	40GGBFS	0.32	176	330	0	220	0	518	204	928	10.00	700
M7	60GGBFS	0.32	176	220	0	330	0	516	204	924	8.89	730
M8	5MK	0.32	176	522.5	0	0	27.5	520	205	932	11.00	725
M9	10MK	0.32	176	495	0	0	55	519	205	929	11.00	730
M10	15MK	0.32	176	467.5	0	0	82.5	517	204	927	11.00	690
M11	15FA5MK	0.32	176	440	82.5	0	27.5	513	202	919	8.00	730
M12	30FA10MK	0.32	176	330	165	0	55	504	199	903	6.00	710
M13	45FA15MK	0.32	176	220	247.5	0	82.5	495	195	887	6.80	695
M14	15GGBFS5MK	0.32	176	440	0	82.5	27.5	519	205	929	8.00	730
M15	30GGBFS10MK	0.32	176	330	0	165	55	516	204	924	8.00	725
M16	45GGBFS15MK	0.32	176	220	0	247.5	82.5	513	202	919	8.00	705
M17	10FA10GGBFS	0.32	176	440	55	55	0	516	204	924	8.00	730
M18	20FA20GGBFS	0.32	176	330	110	110	0	510	201	913	7.50	730
M19	30FA30GGBFS	0.32	176	220	165	165	0	504	199	903	4.44	730
M20	7.5FA7.5GGBFS5MK	0.32	176	440	41.25	41.25	27.5	516	204	924	8.00	730
M21	15FA15GGBFS10MK	0.32	176	330	82.5	82.5	55	510	201	913	7.00	700
M22	22.5FA22.5GGBFS15MK	0.32	176	220	123.75	123.75	82.5	504	199	903	7.00	730

Notes: 1 kg/m³ = 1.6842 lb/yd³; 1 mm = 0.0393 in.

Fig. 1—Testing device for water permeability.

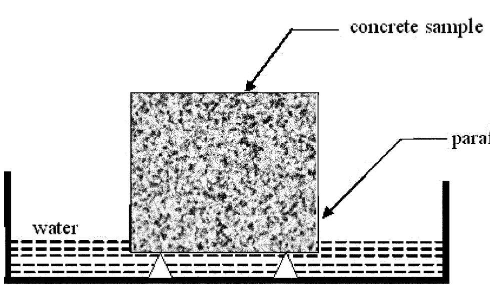

Fig. 2—Sorptivity measurement of SCCs.

(50 mm) thick disc samples were cut from the middle of each cylinder and conditioned, as mentioned in AASHTO T277-89.[25] Then, the disc specimens were transferred to the test cell, in which one face of the specimen was in touch with 0.30 N NaOH solution and the other was in touch with 3% NaCl solution. A direct voltage of 60.0 ± 0.1 V was applied across the faces. A data logger registered the current passing through the concrete over a 6-hour period. Terminating the test after 6 hours, current (in amperes) versus time (in seconds) was plotted for each concrete specimen, and the area underneath the curve was integrated to obtain the charge passed (in coulombs). AASHTO T277-89[25] classifies the chloride permeability in concrete into five classes, from "high" to "negligible" on the basis of the coulombs.

TS EN 12390-8[26] was followed to determine the water permeability of the concretes. For this, a 72.52 ± 7.25 psi (500 ± 50 kPa) downward pressure was applied on the 5.90 in. (150 mm) cube specimen for 72 hours to penetrate drinkable water throughout the specimen, as seen in Fig. 1. At the end of the 72-hour period, the test specimens were split in the middle and the greatest penetration depth of pressurized water was measured in millimeters. The test was conducted at 90 days, and the average of the two test specimens is presented in this study.

A sorptivity test measures the rate at which water is drawn into the pores of concrete. For this, two test specimens with dimensions of Ø3.937 x 1.968 in. (Ø100 x 50 mm) cut from Ø3.937 x 7.874 in. (Ø100 x 200 mm) cylinder specimens were employed. The specimens were dried in an oven at approximately 212 ± 9°F (100 ± 5°C) until the constant mass was obtained, and then the specimens were allowed to cool to the ambient temperature in a sealed container. Afterward, the sides of the specimens were coated with paraffin wax; the sorptivity test was carried out by placing the specimens on glass rods in a tray so that their bottom surfaces up to a height of 0.118 in. (3 mm) were in contact with water, as seen in Fig. 2. This procedure was considered to allow free water movement through the bottom surface. The specimens were removed from the tray and weighed at different time intervals up to 1 hour to evaluate mass gain. The volume of water absorbed was calculated by dividing the mass gained by the nominal surface area of the specimen and the density of water. These values were plotted against the square root of time. The slope of the line of the best fit was defined as the sorptivity coefficient of concrete. The test was carried out at 90 days.

The hardened concretes were also tested for compressive strength and ultrasonic pulse velocity at 28 and 90 days, as per the relevant ASTM standard. The average of the two test specimens was computed for the aforementioned concrete properties.

EXPERIMENTAL RESULTS AND DISCUSSION

Compressive strength and ultrasonic pulse velocity (UPV)

The variation in the compressive strength of the concretes measured at 28 and 90 days is shown in Fig. 3. Moreover, Fig. 4 shows the normalized compressive strength of the concretes with respect to the control specimen. It was observed that the control concrete had 28- and 90-day compressive strengths of approximately 11,602.96 and 13,053.33 psi (80 and 90 MPa), respectively. Replacing PC with FA within the binary blends, however, reduced the former and the latter to as low as 6816.74 and 9282.36 psi (47 and 64 MPa), respectively. In contrast to FA, the concretes with GGBFS had comparable strength values to those of the control concrete, irrespective of the testing age. As shown in Fig. 3, however, the compressive strength of the concretes incorporated with binary blends of MK was approximately 9 to 22% greater than that of the control concrete, mainly depending on the replacement level of MK and the testing age. The highest strengths of as high as 16,099.1 psi (111 MPa) were measured at 90 days and at 15% MK content. The addition of MK into the matrix improves the bond between the cement paste and the aggregate particles and increases the density of the cement paste, which in turn significantly improves the compressive strength of the concretes.[27] According to the literature,[28] the main factors that affect the contribution of MK to strength are: 1) the filling effect; 2) the dilution effect; and 3) the pozzolanic reaction of MK with $Ca(OH)_2$.

Even though the use of FA decreased the compressive strength, the ternary use of FA and MK mostly improved the compressive strength of the concretes so that Mixtures M11 and M12 had comparable strength values to those of the control concrete. Similarly, the combined use of GGBFS and MK gives the concretes a higher compressive strength than those containing binary blends of GGBFS, especially at 90 days. For example, the concrete containing 15% GGBFS and 5% MK had an approximately 20% higher compressive strength than the concrete with 20% GGBFS. In a similar way, the quaternary use of the mineral admixture resulted in higher strength values. Depending mainly on the replacement level, the concretes with quaternary blends had comparable or slightly higher compressive strengths than the control concrete in spite of the reducing effect of FA.

An ultrasonic pulse velocity (UPV) test is conducted to assess the quality and integrity of concrete by passing ultrasound waves through the specimen being tested. This test can also be used to determine the presence of honeycombs, voids, and cracks. The variation in the UPV of the concretes determined at 28 and 90 days is presented in Fig. 5. Moreover, Fig. 6 shows the normalized UPV values of the concretes with

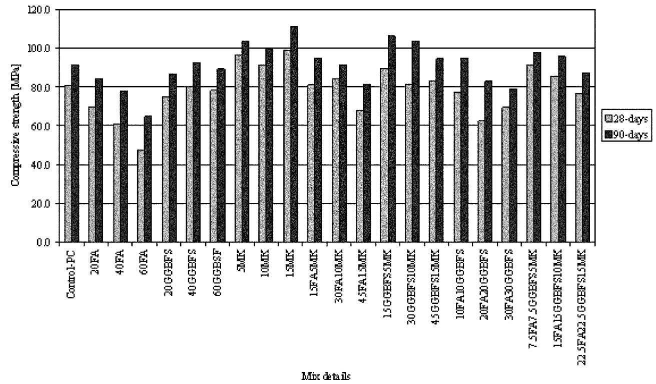

Fig. 3—Variation in compressive strength of SCCs. (Note: 1 MPa = 145.037 psi.)

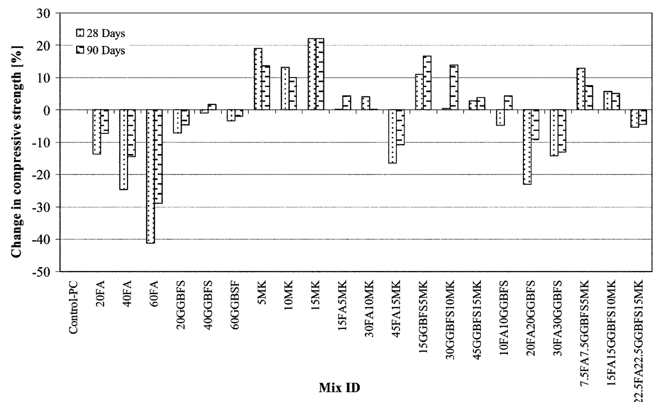

Fig. 4—Normalized compressive strength of concretes with respect to control specimen.

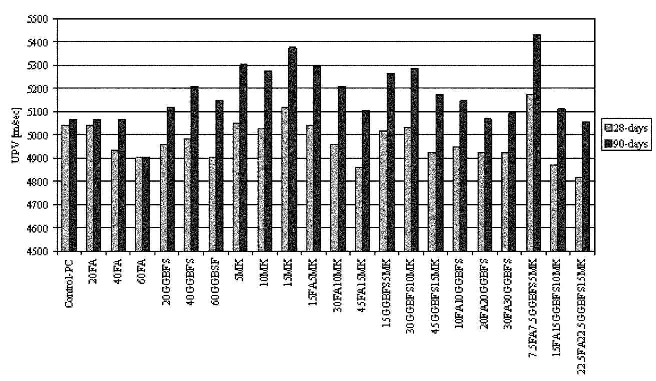

Fig. 5—Variation in UPV of SCCs. (Note: 1 m/s = 3.28 ft/s.)

respect to the control specimen. It was found that the control concrete had a UPV of 16,537.75 and 16,623.04 ft/s (5042 and 5068 m/s) for 28 and 90 days, respectively. The concretes with mineral admixtures, however, had UPVs ranging from 15,793.2 to 16,964.16 ft/s (4815 to 5172 m/s) and 16,078.56 to 17,810.4 ft/s (4902 to 5430 m/s) for 28 and 90 days, respectively, mainly depending on the type and amount of the mineral admixture used. The concrete with quaternary blends of 7.5% FA, 7.5% GGBFS, and 5% MK exhibited the highest UPV values, irrespective of the testing age, whereas the lowest UPV values were measured for 22.5FA + 22.5GGBFS + 15MK and 60FA mixtures at 28 and 90 days, respectively. Moreover, Whitehurst[29] classified the concretes as "excellent," "good," "doubtful," "poor," and "very poor" for UPV values of 14,760 ft/s (4500 m/s) and above—11,480 to 14,760; 9840 to 11,480; 6560 to 9840; and 6560 ft/s (3500 to 4500; 3000 to 3500; 2000 to 3000; and 2000 m/s), respectively. All the concretes produced in this study had UPV values greater than 14,760 ft/s (4500 m/s), so the rating of concretes was found to be excellent.

Chloride ion permeability

The results of the rapid chloride ion permeability test are given in Table 4. Figure 7 also demonstrates the normalized chloride ion permeability of the concretes with respect to the control specimen. As shown in Table 4 and Fig. 7, the total charge passed decreased with the use of mineral admixtures. The concretes containing binary blends of MK showed much higher resistance to chloride ion permeability. The total charge that passed through the control concrete was approximately 1009 coulombs, which rated the concrete as low. The rating of the concretes shifted to very low, however, for all the concretes with mineral admixtures. The use of MK appeared to be the most effective in the reduction of chloride ion permeability, especially as the effect was increased with increasing MK content. The total charge that passed through the concrete made with 15% MK was as low as 164 coulombs, whereas the total charges of the concrete with 60% FA and 60% GGBFS were nearly 715 and 264 coulombs, respectively. Table 4 shows that the concretes seemed to be much more resistant to chloride ion permeability when the FA, GGBFS, and MK were used in ternary or quaternary blends. Interestingly, the total charge that passed through the control concrete was approximately five times higher than that of the quaternary blends (Mixtures M21 and M22), and 1.45 times higher than that of the concrete incorporating binary blends of FA.

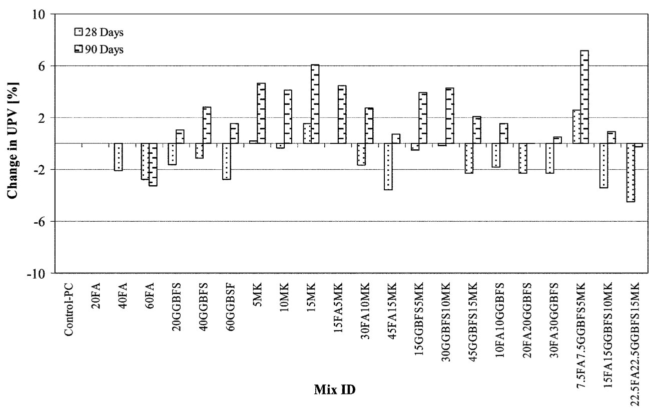

Fig. 6—Normalized UPV values of concretes with respect to control specimen.

The major contribution of the mineral admixtures has been identified to be a refinement of the pore structure of the cement matrix, involving the transformation of a network of large permeable pores into discrete, smaller, and less permeable pores. For instance, in the study performed by Bouikni et al.,[30] the pore size was considerably reduced in mature cement matrixes containing 50 and 65% of slag when compared with the PC paste without slag. Moreover, Güneyisi and Gesoglu[31] investigated the chloride ion permeability of high-performance concretes incorporating the high replacement level of slag (up to 80%). They reported that the large decrease in the chloride ion permeability with the use of a high replacement level of slag in the concretes was due to the change in the pore structure of the hydrated cementitious system. The influence of MK on the microstructure and diffusion properties of mortar has been studied by Kostuch

Table 4—Permeability properties of SCCs

Mixture no.	Mixture ID	Chloride ion permeability		Water permeability, mm	Sorptivity index, mm/min$^{1/2}$
		Charge passed, coulombs	Rating		
M1	Control-PC	1009	Low	21	0.082
M2	20FA	679	Very low	14	0.080
M3	40FA	666	Very low	12	0.071
M4	60FA	715	Very low	9	0.062
M5	20GGBFS	509	Very low	14	0.079
M6	40GGBFS	293	Very low	11	0.063
M7	60GGBFS	264	Very low	12	0.057
M8	5MK	381	Very low	8	0.057
M9	10MK	174	Very low	5	0.058
M10	15MK	164	Very low	4	0.039
M11	15FA5MK	353	Very low	3	0.054
M12	30FA10MK	228	Very low	7	0.043
M13	45FA15MK	186	Very low	9	0.051
M14	15GGBFS5MK	312	Very low	5	0.028
M15	30GGBFS10MK	188	Very low	5	0.047
M16	45GGBFS15MK	206	Very low	4	0.039
M17	10FA10GGBFS	554	Very low	14	0.065
M18	20FA20GGBFS	370	Very low	13	0.046
M19	30FA30GGBFS	231	Very low	14	0.041
M20	7.5FA7.5GGBFS5MK	383	Very low	5	0.051
M21	15FA15GGBFS10MK	219	Very low	5	0.044
M22	22.5FA22.5GGBFS15MK	208	Very low	4	0.045

Note: 1 mm = 0.0393 in.

et al.[32] It was observed that the average pore size significantly reduced when the cement was replaced with 20% MK. It was also found that MK seemed to be effective in reducing the rate of diffusion of Cl^- and Na^+ ions in mortar.

Water permeability

The water permeability test describes the ease with which a fluid may flow through a porous body based on a pressure differential. The variation in the water permeability of the SCCs is presented in Table 4. Moreover, the normalized water permeability of the concretes with respect to the control specimen was plotted in Fig. 8. The results of the water permeability test displayed a similar pattern to that observed in the RCPT. Replacing the PC with mineral admixtures significantly lessened the water permeability of the concretes, depending on the type of mineral admixture used and the replacement level. The highest water permeability of 0.8267 in. (21 mm) was achieved for the control concrete (Mixture M1), followed by the concretes with binary and ternary blends of FA and/or GGBFS, which had a depth of water ingress ranging from 0.354 to 0.551 in. (9 to 14 mm). When compared to that of the control concrete, incorporating MK in the binary blends of 5, 10, and 15% caused a reduction of 62%, 76%, and 81% in the water permeability, respectively. Regarding the water permeability of the concretes with quaternary blends, it was very interesting to note that the concretes with MK had water permeability less than or equal to 0.1968 in. (5 mm), irrespective of the MK, FA, and GGBFS content. Therefore, the test results suggested that it was the MK among the mineral admixtures used that governed the reduction in the water permeability of the SCCs.

Sonebi and Nanukuutan[33] studied the single and combined effects of limestone filler, pulverized FA, and viscosity-modifying admixtures on the permeation properties of medium- and high-strength SCC. They indicated that both the medium- and high-strength SCC mixtures with pulverized FA had the lowest water permeability indexes compared with all other mixtures. Moreover, the SCC mixtures incorporating pulverized FA led to a better water permeability that may be attributed to their less porous interfacial zone and the refined pore structure of the paste matrix.

Sorptivity index

The sorptivity test is based on water flowing into the concrete through large connected pores. Thus, it is considered as a relative measure of the permeability. Table 4 presents the sorptivity test results of the produced SCCs measured at 90 days, whereas Fig. 9 displays the normalized water sorptivity of the concretes with respect to the control specimen. As shown in Table 4 and Fig. 9, the plain control concrete had the highest sorptivity. Incorporating the mineral admixtures, however, continuously decreased the sorptivity of the SCCs. Similar to the water permeability test, the lowest sorptivity index was measured for the concretes with the ternary blends of 15% MK and 45% GGBFS and the binary blends of 15% MK. The use of MK appeared to be much more effective in reducing the sorptivity due to the reduced pore volume. Using FA and/or GGBFS with MK provided a marked decrease in the sorptivity as well. Mixtures M20, M21, and M22 had sorptivity indexes as low as 0.045 mm/mm$^{0.5}$ (0.0089 in./in.$^{0.5}$).

Khatib and Clay[34] studied the water sorptivity characteristics of the MK-blended concrete. They reported that the beneficial effect of MK on reducing the water sorptivity was even apparent from visual inspection at the end of the capillary water test. After the test ended, the water could be seen on the top surface of samples for the control mixture. For the mixtures containing 15 and 20% MK, however, no water on the top surface was observed. This behavior was attributed to the discontinuity of pores (that is, the pore-blocking effect) when cement was partially replaced with MK.

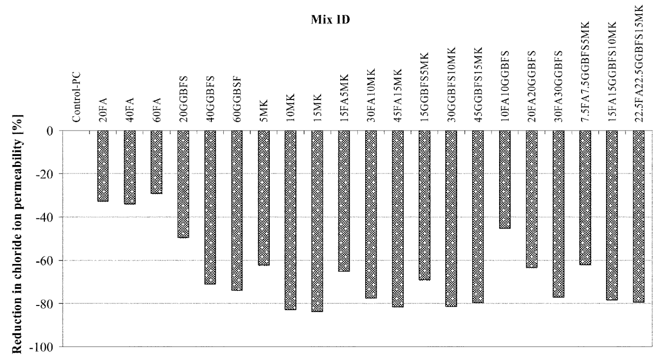

Fig. 7—Normalized chloride ion permeability of concretes with respect to control specimen.

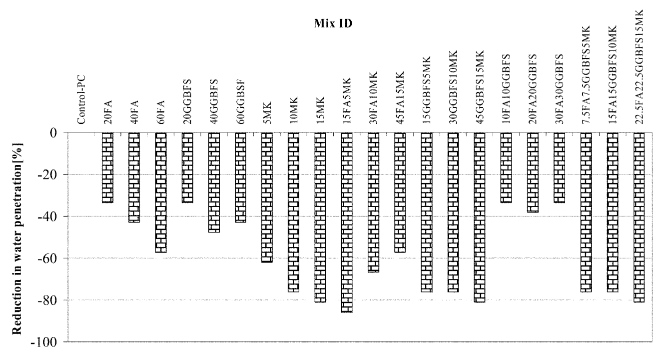

Fig. 8—Normalized water permeability of concretes with respect to control specimen.

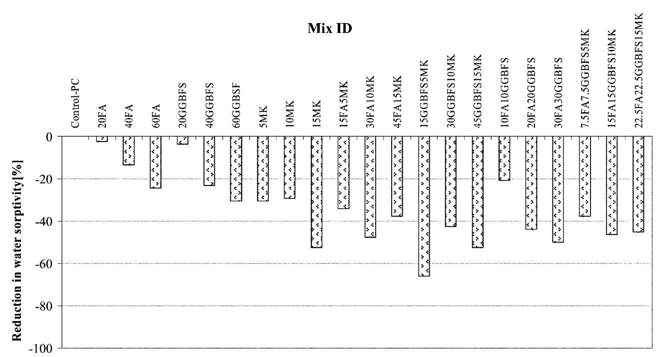

Fig. 9—Normalized water sorptivity of concretes with respect to control specimen.

STATISTICAL ASSESSMENT OF EXPERIMENTAL RESULTS BY ANALYSIS OF VARIANCE (ANOVA)

ANOVA allows the evaluation of whether an independent variable has an effect on the dependent variable. In addition, it can also be used to identify whether the interactions of independent variables have an effect on the dependent variable. Sometimes it may be difficult to analyze the effect of different factors on the variation of dependent variables; ANOVA results can be useful to see the effect.[35]

The response data given in Table 4 and Fig. 3 and 5 were analyzed using the ANOVA technique by means of a software called "Minitab" at a 0.05 level of significance to examine the variation in the measured properties of the concretes. The types of the mineral admixtures (namely, FA, GGBFS, and MK) were selected as independent factors, whereas the hardened properties of the concretes (compressive strength, UPV, chloride ion permeability, water permeability, and water sorptivity) were dependent variables. The independent and dependent factors are presented in Table 5. A statistical analysis was performed to determine the statistically significant (p-level < 0.05) factors, and the results of the analysis are given in Table 6. After that, the total sum of squares was calculated, which was partitioned into the sum of squares (SS) for individual factors and the SS for the residual random error. Next, the mean squares (MS) of the factors were calculated by dividing their corresponding SS by the associated degrees of freedom (DF). Then, the effect of individual factors was evaluated by testing the hypothesis of the equality of variances, which was the test of null hypothesis or simply the significance test at a particular probability level.

Table 5—Independent and dependent variables for ANOVA

Independent variables	Dependent variables
FA	Compressive strength
GGBFS	Ultrasonic pulse velocity
MK	Chloride ion permeability
—	Sorptivity
—	Water permeability

For this, the ratio of MS of factors to the MS of the residual error—that is, the F-statistic—was calculated and compared to the tabulated F-values related to Fisher distribution. The F-values related to Fisher distribution depend on the number of DF of the individual factors, the number of DF of the residual error, and the probability level.[35,36] The degree of contribution ρ% of each significant factor was also obtained to determine the level of its statistical importance in the model. The column under ρ% in Table 6 gives an idea about the degree of contribution of the factors to the measured response. If the ρ% is high, the contribution of the factors to that particular response is higher. Likewise, the lower the ρ%, the lower the contribution of the factors to the measured response.[37]

It can be observed in Table 6 that incorporating the mineral admixtures significantly affected the hardened properties of the SCCs. The use of mineral admixtures appeared to be highly significant in reducing the permeability of the concretes in terms of chloride ion permeability, water permeability, and sorptivity. Among the mineral admixtures used, MK was found to be the most effective in enhancing the permeability resistance of the concretes. For example, regarding the chloride ion permeability of the SCCs, MK, GGBFS, and FA had contributions of approximately 48%, 30%, and 11%, respectively, in the general model. For compressive strength and UPV, however, the test results suggested that FA governed the variation, having contributions of approximately 68% and 50%, respectively, on these properties of the SCCs, as clearly seen in Table 6. A similar finding was reported by Patel et al.,[38] who found that at a given total binder content, the 28-day compressive strength decreased with the increase in FA content. FA, however, lowered the chloride ion penetration in the RCPT. Therefore, Patel et al.[38]

Table 6—Statistical evaluation of hardened properties by ANOVA

SCC properties	Parameter	DF	RDF	Sequential sum of squares	Mean square	Computed value of F-distribution	P value	% ρ
Compressive strength	FA	9	9	3435	381.6	32.9	0.00000011	67.9
	GGBFS	9	6	670	111.7	9.7	0.000016	13.3
	MK	3	3	661	220.2	19.0	0.000012	13.1
	Error	22	25	289	11.6	—	—	5.7
	Total	43	43	5055	—	—	—	—
UPV	FA	9	9	169,138	18,793.1	16.1	0.00000024	50.1
	GGBFS	9	6	116,122	19,353.7	16.6	0.0000012	34.4
	MK	3	3	23,518	7839.33	6.7	0.0017	7.0
	Error	22	25	29,094	1163.6	—	—	8.6
	Total	43	43	337,872	—	—	—	—
Chloride ion permeability	FA	9	9	182,533	20,281.4	2.7	0.024	10.5
	GGBFS	9	6	523,999	87,333.2	11.7	0.000032	30.3
	MK	3	3	838,346	279,448.7	37.4	0.0000022	48.4
	Error	22	25	187,035	7481.4	—	—	10.8
	Total	43	43	1,731,913	—	—	—	—
Sorptivity	FA	9	9	0.0021	0.000233	8.8	0.000076	24.0
	GGBFS	9	6	0.0025	0.000411	15.5	0.0000023	28.2
	MK	3	3	0.0035	0.001178	44.5	0.00000036	40.3
	Error	22	25	0.0007	0.000026	—	—	7.6
	Total	43	43	0.0088	—	—	—	—
Water permeability	FA	9	9	356	39.5	10.1	0.000023	30.8
	GGBFS	9	6	128	21.3	5.5	0.001	11.1
	MK	3	3	576	192.0	48.9	0.00000013	49.7
	Error	22	25	98	3.9	—	—	8.5
	Total	43	43	1159	—	—	—	—

Notes: RDF is reduced degree of freedom; ρ is contribution of factor in model.

reported that the FA replacement percentage was statistically significant and had a positive effect on the self-consolidating properties of the concrete mixtures.

CONCLUSIONS

Based on the findings of this study, the following conclusions may be drawn:

1. Concretes containing FA had a generally lower compressive strength, whereas GGBFS and MK concretes had comparable and higher strength values than those of the control concrete, respectively. Even though the FA decreased the compressive strength, the ternary use of FA and MK mostly improved the compressive strength of the concretes. Similarly, the combined use of GGBFS and MK gives the concretes a higher compressive strength than those containing binary blends of GGBFS, especially at 90 days.

2. All the concretes produced in this study had UPV values greater than 14,760 ft/s (4500 m/s), indicating excellent ratings. Moreover, the concrete with quaternary blends of 7.5% FA, 7.5% GGBFS, and 5% MK exhibited the highest UPV values, irrespective of the testing age, whereas the lowest UPV values were measured for 22.5FA + 22.5GGBFS + 15MK and 60FA mixtures at 28 and 90 days, respectively.

3. It was observed in the chloride ion permeability test that concretes with mineral admixtures showed very low ratings, whereas the control concrete had a low rating. The concretes seemed to be much more resistant to chloride ion permeability when FA, GGBFS, and MK were used in the ternary or quaternary blends. The use of MK appeared to be the most effective in reducing the chloride ion permeability.

4. A similar pattern seen in the RCPT was also observed in the water permeability test of the concretes, in that MK made the concretes highly resistant to the ingress of water. Incorporating MK in the binary blends of 5, 10, and 15% caused a reduction of 65%, 78%, and 82% in the water permeability, respectively. Regarding the water permeability of the concretes with quaternary blends, it was very interesting to note that the concretes with MK had water permeability less than or equal to 0.1968 in. (5 mm), irrespective of MK, FA, and GGBFS content.

5. Similar to the water permeability test, incorporating the mineral admixtures continuously decreased the sorptivity of the SCCs. Apart from the use of MK only, the combination of FA and/or GGBFS with MK provided a marked decrease in the sorptivity.

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