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Effect of metakaolin and silica fume on the durability of self-consolidating concrete

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ABSTRACT

Metakaolin (MK) is a valuable admixture for concrete/cement applications that can enhance the performance of cementitious composites through high pozzolanic reactivity, much like silica fume (SF). While SF concrete is characterized by superior mechanical and durability performance, concrete containing MK achieves comparable properties at a lower price and with better workability. The objective of this study is to investigate the effect of cement replacement by MK on the durability of self-consolidating concrete (SCC); the effect of SF at similar levels of MK replacement has also been included for comparison. The durability performance of SCC was evaluated based on the results of drying shrinkage, freezing and thawing, salt scaling, and rapid chloride permeability tests. The results of these tests indicate that highly durable SCC mixtures can be produced using a high MK content with an optimum percentage of around 20%. The results also show that the durability of SCC, especially with high MK content, is higher than that of SCC containing SF.

1. Introduction

Pure metakaolin (MK) has been successfully used as a supplementary cementing material (SCM) in concrete since 1990. Recently, one of the largest deposits of kaolin in North America was discovered in southern Saskatchewan, yielding large volumes that make MK an economical choice for use in concrete. When heated to 700–900 °C, kaolin becomes calcined, losing up to 14% hydroxyl water and changing into MK [1]. Because the production of MK can be closely controlled, a higher degree of purity and pozzolanic reactivity can be obtained [2] with proper quality control. Like silica fume (SF), MK reacts with the calcium hydroxide formed during Portland cement hydration, creating additional cementitious products which modify the concrete structure and enhance its overall mechanical and durability performance [3–5].

While the production of self-consolidating concrete (SCC) commonly involves the use of some SCM such as fly ash or slag [6–10] using MK as a SCM in the development of self-consolidating concrete (SCC) is a relatively new approach in concrete technology [5]. Metakaolin has a particle size that is much finer than cement but not as fine as SF, and it therefore offers better workability and requires smaller amounts of high-range water-reducing admixture to obtain slump comparable to SF concrete [1,11]. MK has a number of other benefits as well; it has a creamier texture, generates less bleed water, and has better finishability than concrete with SF [1,12].

According to previous studies [13,14], compressive and indirect tensile strengths were slightly improved in MK mixtures with 5–10% MK by mass of cement, compared to mixtures with the same amount of SF replacement. MK was also found to increase the autogenous shrinkage when measured from the age of 24 h [15,16]. In terms of drying shrinkage, the effect of replacing part of cement with 10% high-reactive MK was a 33% reduction in concrete shrinkage after 156 days of exposure [1]. The influence of MK and SF on the drying shrinkage has also been investigated by Brooks and Megat Johari [17]. In their study, both MK and SF were found to reduce drying shrinkage after 200 days by about 50% and 35% for MK and SF, respectively. In addition, Brooks and Megat Johari found that increased levels of cement replacement by either SF or MK caused a greater reduction in drying shrinkage.

The permeability, scaling resistance, chemical resistance, and freezing and thawing durability of the MK concrete mixture were similar or slightly better than those of the SF mixture [13,14]. Improvement in other aspects of durability such as sulfate resistance, rapid chloride ion permeability, and expansion due to alkali-silica reaction are also confirmed in MK mixtures (with increased MK replacement levels of up to 25%) compared with control and SF mixtures [18,19].

Metakaolin reduces chloride diffusion and increases the percentage of Cl/OH ions dissolved in the pore water [4]. Therefore,

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mixtures containing MK can be expected to provide a high degree of protection against corrosion. However the overall strength and durability of the MK mixture are greatly affected by the physical and chemical properties of the MK [20–22].

Currently, very little information is available about the properties of SCC containing MK, and there is no durability data regarding the use of MK in SCC. Therefore, investigating SCC containing MK is beneficial and requires more study, since it is expected to have comparable mechanical and durability performance to SF concrete – at a lower price and with better workability. The main objective of this study was to develop and evaluate different SCC mixtures containing various amounts of MK by weight of cement (0%, 3%, 5%, 8%, 11%, 15%, 20%, and 25%). SCC mixtures containing SF (0%, 3%, 5%, 8%, and 11% cement replacement) were also chosen for comparison. The tested mixtures were evaluated based on their fresh properties (slump flow, L-box, V-funnel, and HRWR demand), hardened properties (compressive strength and air void characteristics), and durability performance (drying shrinkage, freezing and thawing, salt scaling, and rapid chloride permeability).

2. Experimental program

2.1. Materials and mixture proportions

The MK used in this investigation was delivered from southern Saskatchewan. SF and Type GU Canadian cement (similar to ASTM Type I) were also used. The physical and chemical properties of cement, SF and MK are presented in Table 1. Natural sand and 10 mm maximum size stone were used as fine and coarse aggregates, respectively. The coarse and fine aggregates each had a specific gravity of 2.70 and water absorptions of 0.5% and 0.64%, respectively. High range water reducer (HRWR) similar to Type F of ASTM C 494 was used to adjust the flowability of the SCC mixtures. The specific gravity, volatile weight, and pH of the HRWRA were 1.2, 62% and 9.5, respectively.

The mixture proportions of SCC containing different percentages of MK and SF are presented in Table 2. A total of twelve SCC mixtures were tested in this program, including seven mixtures containing 3%, 5%, 8%, 11%, 15%, 20%, and 25% MK as a partial cement replacement (designated as 3MK, 5MK, 8MK, 11MK, 15MK, 20MK, and 25MK), four mixtures containing 3%, 5%, 8%, and 11% SF (designated as 3SF, 5SF, 8SF and 11SF), and one control mixture containing no SCM. It should be noted that to achieve successful SCC mixtures, the maximum percentage of SF used in this study was 11%. Using a higher percentage of SF required excessive amounts of HRWR and created difficulties in obtaining the desired fresh properties. All the mixtures were produced at a slump flow of about 650 mm and a constant w/b of 0.4. The amounts of HRWR were varied in all the mixtures to obtain the desired slump flow. No air entraining admixtures were used.

2.2. Fresh and hardened properties tests

The deformability and flowability of fresh SCC were evaluated using V-funnel and slump flow tests. Final diameter was determined in the slump flow test, and the time required for the concrete to spread to a diameter of 500 mm (T50) was recorded using a video tape recorder. The L-box test was conducted to evaluate passing ability (the ability of SCC to flow around obstructions). The air void characteristics, including total air content, specific surface and spacing factor, were determined for hardened concrete samples in accordance with standard test method ASTM C 457. The compressive strength of the concrete was determined using 100×200 mm cylinders as per ASTM C 39.

The drying shrinkage for each specimen was measured using three $75 \times 75 \times 285$ mm prisms as per ASTM C 157 procedure. In this test, the specimens were removed from the molds at the age of 24 h and placed in lime-saturated water for 30 min. The specimens were then removed from the lime-saturated water and the initial comparator readings were taken.

After the initial comparator reading, the specimens were stored in lime-saturated water until they have reached 28 days. At the end of the 28 day curing period, the specimens were stored in air until the time of testing.

The rapid chloride permeability test (RCPT) was carried out on 50 mm-thick specimens cut from 100 mm diameter concrete cylinders, as per ASTM C 1202. The scaling resistance of SCC was determined as per ASTM C 672. Accumulated mass loss and a visual rating of the specimen surface (on a scale of 0–5) were used to measure the deterioration of the specimen's surface at the end of the 50th cycle. The resistance of SCC to repeat cycles of freezing and thawing was determined as per ASTMC 666, procedure A. This test was terminated after 300 cycles, or when the specimen broke. In this test, the deterioration of specimens over time was measured using weight change and pulse velocity techniques [23,24]; the weight change was used to indicate the amount of moisture that had been absorbed due to cracking caused by expansion of the cement paste. The pulse velocity readings were taken at four points around the perimeter of the specimen at each cycle and the average value was recorded.

Table 1
Physical and chemical properties of cement, silica fume, and metakaolin.

Chemical analysis (%)	Cement	SF	MK	Physical analysis	Cement	SF	MK
SiO_2	19.64	89.1	–	Residue 45 μm, %	8.42		3
Al_2O_3	5.48	0.67	–	Blaine fineness, m^2/kg	410		
Fe_2O_3	2.38	0.49	–	Air content, %	7.78		
Sum (SiO_2, Al_2O_3, Fe_2O_3)	–	–	93.6	Initial set, mins.	103		
CaO	62.44	6.12	–	Auto. expansion, %	0.14		
MgO	2.48	0.31	–	Sulf. Expansion, %	0.013		
SO_3	4.32	0.16	0.06	Moisture content		15.6	0.2
K_2O	–	0.49	–	Density, t/m^3	3.15	2.2	2.56
Na_2O	–	0.26	0.22	Autoclave expansion, %			0.02
Cl	–	0.04	–				
Total alkali	0.97	–	1.4	Compressive strength			
Free lime	1.03	–	–	1 day	19.23 MPa		
LOI	2.05	2.81	1	3 days	29.12 MPa		
C_3S	52.34	–	–	7 days	33.82 MPa		121% of control
C_2S	16.83	–	–	28 days	41.45 MPa		116% of control
C_3A	10.5	–	–				
C_4AF	7.24	–	–				

Table 2
Concrete mixture proportions.

Mixture ID	w/b	SF (kg/m^3)	MK (kg/m^3)	Cement (kg/m^3)	Aggregates (kg/m^3)		HRWR (ml/m^3)
					Fine	Coarse	
11SF	0.4	49.5	–	400.5	921	891	4862
8SF	0.4	36	–	414.0	923	893	4500
5SF	0.4	22.5	–	427.5	926	896	4292
3SF	0.4	13.5	–	436.5	927	898	3792
Control	0.4	–	–	450.0	930	900	3615
3MK	0.4	–	13.5	436.5	929	899	4038
5MK	0.4	–	22.5	427.5	928	898	4231
8MK	0.4	–	36	414.0	926	897	4231
11MK	0.4	–	49.5	400.5	925	895	4308
15MK	0.4	–	67.5	382.5	923	893	4462
20MK	0.4	–	90	360.0	921	891	4577
25MK	0.4	–	112.5	337.5	919	889	4692

3. Results and discussions

3.1. Fresh and hardened properties

3.1.1. Viscosity/flowability

Table 3 and Fig. 1 present the slump flow and V-funnel results for all tested mixtures. As mentioned above, the target slump flow for all mixtures was 650 mm. The twelve mixtures achieved slump flow values around 650 ± 10 mm, using different percentages of HRWR. As seen from the results, the V-funnel flow times for SF mixtures were close to the control mixture and ranged between 6 and 7.5 s. Also, the T50s for all SF mixtures didn't show significant variation, falling within ±0.1 s of the control mixture. On the other hand, SCC mixtures with a higher percentage of MK had higher values of T50 and V-funnel time. When the percentage of MK was increased from 0% to 25%, the T50s increased from 2.5 to 4.5 s and the V-funnel time increased from 7.5 to 13.5 s. This result indicates that the addition of MK increases the viscosity of SCC mixtures, while adding SF does not appear to have any effect on viscosity. It should be noted that all mixtures contained the same total amount of cementitious materials (450 kg/m^3), the same percentage of coarse/fine aggregate (0.967), and had similar final slump flow diameters (650 ± 10 mm). Therefore, the flow time of the V-funnel or T50 is only affected by mixture viscosity; the addition of SF/MK in the tested mixtures was the main factor influencing that viscosity (the collision among coarse aggregate particles at the tapered outlet of the V-funnel apparatus is not a factor contributing to the relative flow time of the mixtures).

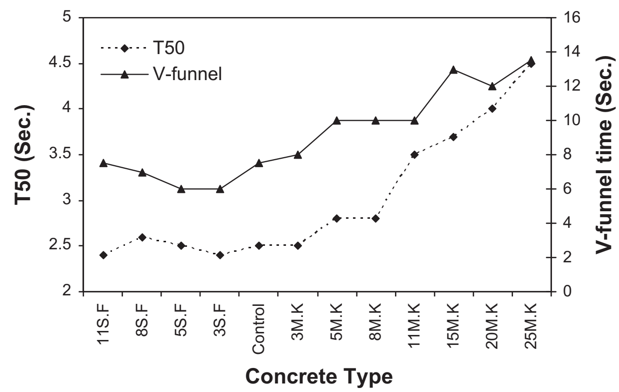


Fig. 1. V-funnel and T50 times for all tested SCC.

3.1.2. Passing ability

All mixtures exhibited acceptable passing ability values (indicated by L-box index H2/H1 values, obtained from the L-box test) except for the control mixture, which showed slightly less than the minimum desired value for SCC [25,26]. The H2/H1 values increased from 0.63 to 0.89 when the percentage of MK increased from 0% to 25% (Table 3). Also, the H2/H1 values for SCC with SF were higher than those of the control mixture, and increased as the percentage of SF increased (0.63–0.76 when the percentage of SF increased from 0% to 11%), showing that the addition of SF appears to enhance passing ability as well. This result matches that of Khayat and Assaad [27], who found that an increased amount of SCM increases deformability and passing ability of SCC mixtures. The H2/H1 results also indicated that SCC with MK exhibited slightly higher passing ability than SCC with SF at similar levels

Table 3
Fresh and hardened properties of tested SCC.

Mixture ID	Slump flow		L-Box % H2/H1	V-funnel (Sec.)	28 day f'_c	Air void parameters		
	Dia. (mm)	T50 (Sec.)				Total air content (%)	Specific surface (mm^{-1})	Spacing factor (mm)
11SF	650 ± 0	2.4	0.76	7.5	41.3	3.3	11.87	0.491
8SF	640 ± 0	2.6	0.72	7.0	45.9	2.2	13.48	0.506
5SF	650 ± 0	2.5	0.72	6.0	41.9	3.3	11.45	0.537
3SF	660 ± 10	2.4	0.68	6.0	37.9	2.9	11.88	0.554
Control	640 ± 0	2.5	0.63	7.5	40.2	2.8	6.94	0.874
3MK	650 ± 10	2.5	0.74	8.0	39.4	2.6	9.06	0.742
5MK	650 ± 10	2.8	0.72	10.0	42.6	3.6	9.3	0.605
8MK	650 ± 10	2.8	0.76	10.0	45.6	1.8	15.55	0.532
11MK	650 ± 10	3.5	0.82	10.0	43.9	1.1	16.29	0.621
15MK	650 ± 0	3.7	0.85	13.0	45.9	1.3	17.57	0.531
20MK	650 ± 0	4.0	0.85	12.0	48.9	2.2	16.83	0.417
25MK	650 ± 10	4.5	0.89	13.5	48.9	1.8	18.82	0.414

of cement replacement (0–11%). Moreover, increasing the percentage of MK to a higher level than 11% (up to 25%) resulted in the highest H2/H1 values (Fig. 2).

3.1.3. HRWR content

Table 2 presents the amounts of HRWR admixtures used in all SCC mixtures to obtain a slump flow of around 650 mm. As seen from the table, the addition of MK increased demand for HRWR. When the percentage of MK in SCC mixtures increased from 0% to 25%, the demand went up by about 30%. However, the addition of MK appears to require less HRWR than the addition of SF at the same level of cement replacement (Fig. 2). For example, 8% and 11% MK additions consumed 17% and 19% more HRWR than the control mixture, respectively, while 8% and 11% SF consumed 24.5% and 34.5% more HRWR, respectively. The demand for HRWR increased slightly when MK increased from 0% to 25%; when the percentage of SF was increased from 0% to 11%, demand increased sharply. Moreover, the demand for HRWR at 11% SF was even higher than at 25% MK. This result is in agreement with Caldarone et al. [1] and Ding and Li [11], which shows that MK offers much better workability than SF for given mixture proportions.

3.1.4. Compressive strength

The results of the 28 day compressive strengths of MK and SF, presented in Table 3, show that the addition of either MK or SF increases the 28 day compressive strength of SCC. The maximum compressive strength for SF mixtures (at 8% SF) was about 14% higher than that of the control mixture (Fig. 2). On the other hand, the compressive strength of SCC mixtures containing MK increased as the percentage of MK increased. This result corresponds with other investigations in which compressive strength increased with the increase percentage of MK [28,29]. The maximum compressive strength of SCC containing 8% SF was comparable to that of the SCC containing 8% MK; both enhanced the strength of the control mixture by about 14%. However, increasing the amount of MK from 8% to 25% only enhanced the compressive strength by 7% (with respect to 8MK).

3.1.5. Air-void parameters of hardened concrete

Table 3 presents the results of the air-void parameters of all tested mixtures. Since no air entertaining admixtures were used in any of the tested mixtures, they all presented low air content. The air content of all SF and MK mixtures was close to that of the control mixture. Average air content for SF and MK mixtures was around 2.9% and 2.1%, respectively, and 2.8% in the control mixture, indicating that MK or SF inclusion does not affect total air content.

The inclusion of SF and MK reduced the size of voids in hydrated cement pastes, a reduction that was more pronounced in MK mixtures than SF mixtures. For example, the specific surface areas of the air voids of 11SF and 11MK were 11.87 mm^{-1} and 16.29 mm^{-1}, respectively, compared to 6.94 mm^{-1} in the control mixture. This corresponds with the results of other studies [30], confirming that the inclusion of highly reactive pozzolans reduces the size of voids in hydrated cement pastes, significantly reducing permeability and improving concrete durability.

The results of the air void parameters also indicated that using a higher percentage of SF or MK reduced the air void spacing factor. For example, the spacing factors of 11SF and 25MK were 0.491 mm and 0.414 mm, respectively, compared to 0.874 mm in the control mixture. It should be noted that the values of the spacing factors of all tested mixtures were relatively high compared to those recommended for frost-resistant concretes [31]. This is because no air-entraining admixtures were used in any of the tested mixtures. The proper utilization of an air-entraining admixture usually results in an air-void spacing factor of less than the usual 200 μm limit [32]. On the other hand, mixtures without air-entraining admixtures are more likely to have low air content and higher spacing factors [32,33].

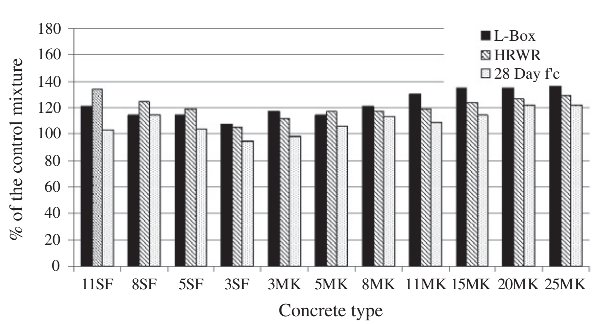


Fig. 2. L-Box, HRWR, and 28 day strength values relative to those of the control mixture.

3.2. Durability characteristics

3.2.1. Drying shrinkage

Drying shrinkage results for the 12 tested mixtures are summarized in Table 4. The drying shrinkage of SCC with MK after 400 days ranged from 0.042% to 0.066%. On the other hand, the drying shrinkage of SCC with SF ranged from 0.052% to 0.069%. SCC made with SF exhibited lower drying shrinkage after 400 days, compared to SCC made with MK at the same level of replacement (Fig. 3). Drying shrinkage (after 400 days) decreased from 5% to 28% when SF increased from 0% to 11% compared with a decrease from d 8% to 22% when MK content increased from 0% to 11%. However, drying shrinkage exhibited the lowest values at 15MK, 20MK and 25MK, with a minimum shrinkage at 20MK (Fig. 3).

Fig. 4 shows the variations of drying shrinkage over time for SCC made with different percentages of SF and MK. As seen from the figure, both SF and MK reduced the drying shrinkage of the SCC mixture; it decreased as the percentage of MK or SF increased. However, the drying shrinkage for 20MK was similar to that of 25MK up to 250 days, then showed a minor improvement at up to 400 days.

3.2.2. Freezing and thawing

As mentioned earlier, the freezing and thawing test was evaluated using weight change and pulse velocity at each cycle; weight gain and pulse velocity reduction percentages for each cycle are presented in Figs. 5 and 6. In general, the weight of the samples and the reduction in pulse velocity increased as the number of cycles rose. The optimum percentage of MK was 20%, while the optimum percentage of SF was 8%. As the percentage of MK went up to 20%, weight gain and reduction of pulse velocity increased. However, the performance of 25MK along 300 cycles was very close to that of 20MK. On the other hand, weight gain and reduction of pulse velocity increased as SF content went up to 8%, then dropped sharply when it increased to 11%.

The 20MK mixture exhibited the lowest weight gain and pulse velocity reduction of all tested mixtures, indicating that it absorbed less water and had fewer internal cracks. Also, all MK specimens with more than 5% MK did not break up to the end of the test (300 cycles). This result concurs with Girodet et al. [34], who concluded that the addition of MK enhances the resistance of concrete to freezing and thawing. SCC with MK exhibited better freezing and thawing performance compared to SCC with SF at the same level of cement replacement. 3MK, 5MK, and 8MK showed less weight gain and less pulse velocity reduction throughout testing, and broke after more cycles than 3SF, 5SF and 8SF, respectively.

Table 4
Test results of drying shrinkage, RCPT, salt scaling, and freezing and thawing.

Mixture ID	Drying shrinkage (400 day) %	RCPT charge coulomb	Salt scaling		Freezing and thawing No. of cycles
			Scaled materials (50 cycle) (kg/m^2)	Scaling factor	
11SF	0.052	1276	0.229	2	150
8SF	0.054	1150	0.211	1	270
5SF	0.058	1580	0.233	2	180
3SF	0.069	2255	0.274	2	150
Control	0.072	2817	0.330	3	150
3MK	0.066	2197	0.246	2	210
5MK	0.066	1937	0.225	2	240
8MK	0.056	1299	0.197	1	300
11MK	0.056	667	0.192	1	300
15MK	0.043	448	0.178	1	300
20MK	0.042	316	0.152	0	300
25MK	0.044	353	0.197	1	300

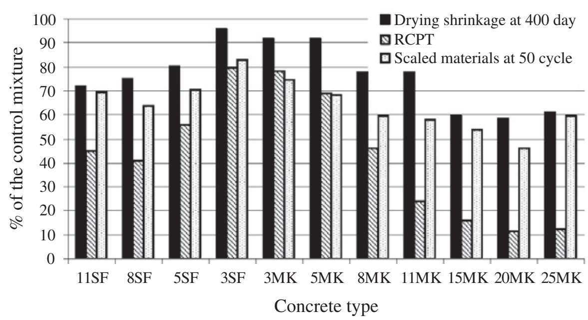
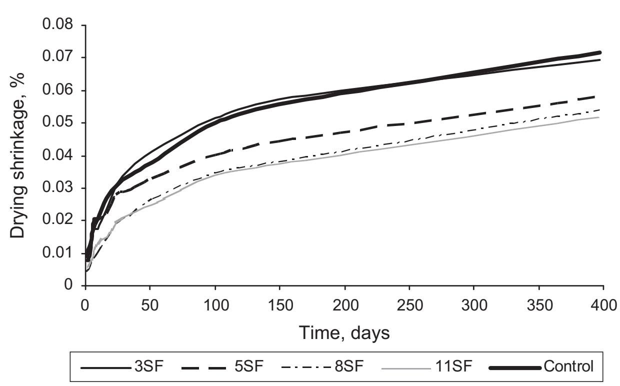
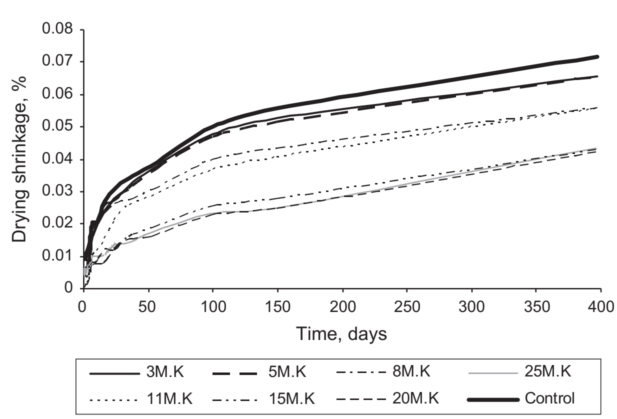


Fig. 3. Drying shrinkage, RCPT, and scaled materials results relative to those of the control mixture.

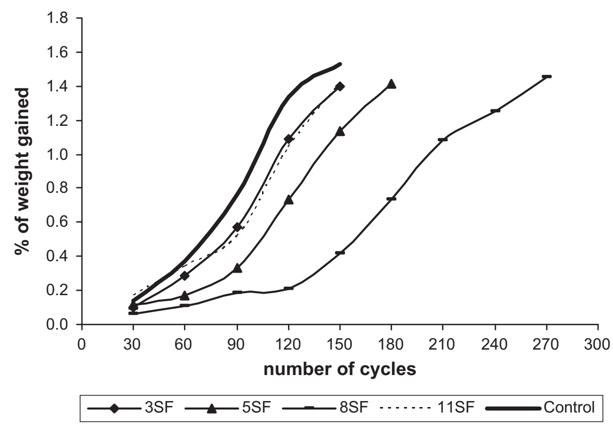


(a) SCC with SF

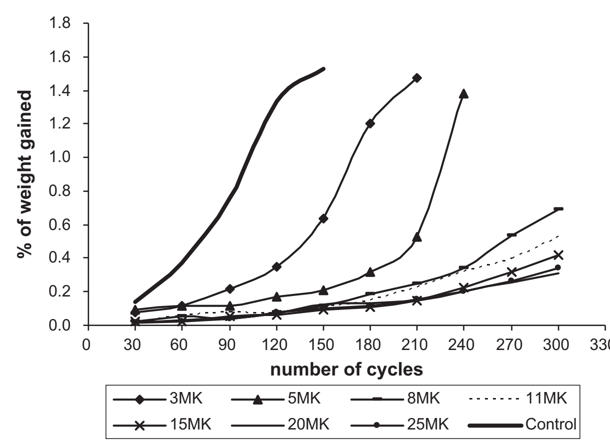


(b) SCC with MK

Fig. 4. Variations of drying shrinkage with time for all tested SCC.



(a) SCC with SF



(b) SCC with MK

Fig. 5. Percentage of weight gained of freezing and thawing specimens for all tested SCC.

3.2.3. Salt scaling

Total weight of scaled materials after 50 cycles and the scaling factor for all tested samples are presented in Table 4. Surface conditions of all tested SCC specimens after 50 cycles are presented in Fig. 7. Scaled materials and scaled factor for SCC with MK after 50 cycles ranged between 0.152–0.246 kg/m^2 and 0–2, respectively. For SCC with SF, the scaled materials and scaled factor ranged between 0.211–0.274 kg/m^2 and 1 – 2, respectively. The addition of MK greatly enhanced scaling resistance; replacement of cement by 20% MK reduced the weight of the scaled materials of the control

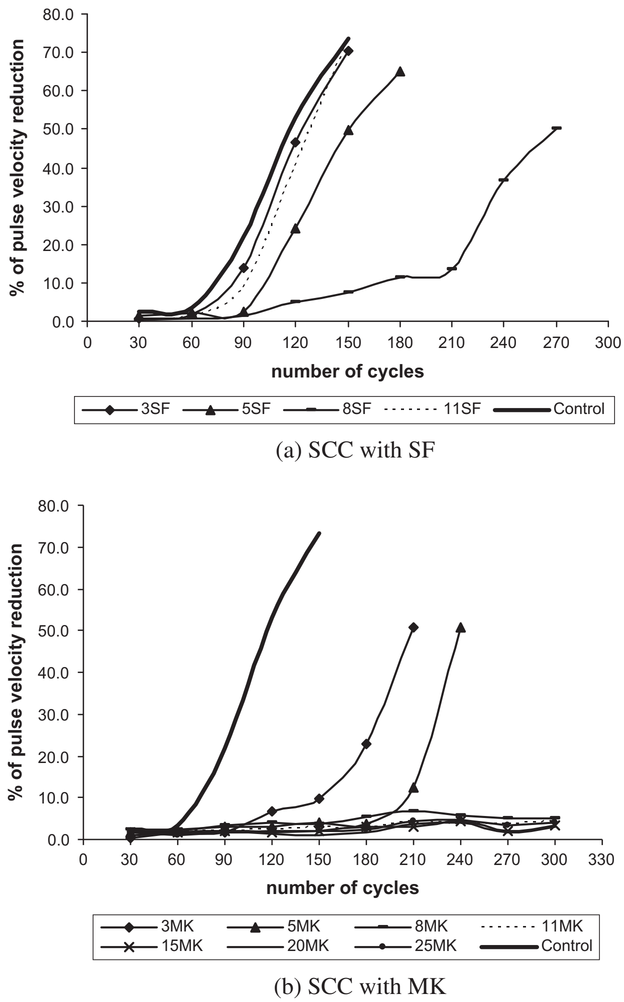


Fig. 6. Percentage of pulse velocity reduction of freezing and thawing specimens for all tested SCC.

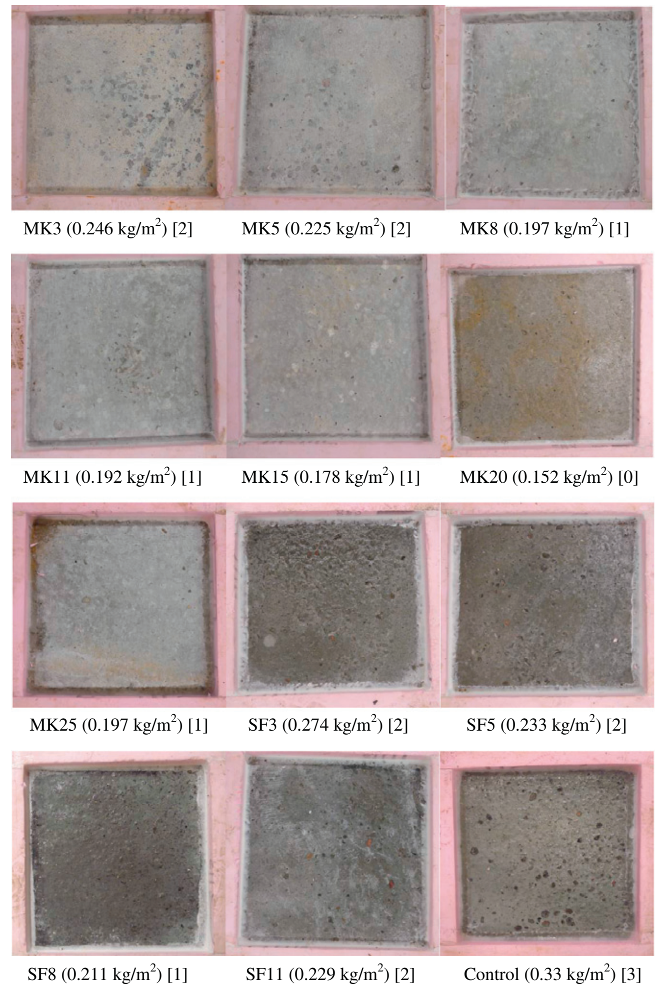


Fig. 7. Salt scaling specimens after 50 cycles.

mixture by about 54%. The results also showed that the optimum percentages of MK and SF were 20% and 8%, respectively. Mixtures with 20% MK and 8% SF had 46% and 63% of the scaled materials weight of the control mixture (Fig. 3). The weight of the scaled materials decreased as MK content increased up to 20%; when MK increased from 20 to 25%, weight went up by 29%. For SCC with SF, the weight of the scaled materials decreased with up to 8% addition of SF, then went up by 9% when SF increased from 8 to 11%.

SCC with MK showed lower scaled materials after 50 cycles than SCC with SF at similar levels of cement replacement (Fig. 3). For example, after 50 cycles, the scaled materials were at about 60% and 58% of the control mixture for 8MK and 11MK, respectively, and 64% and 69% for 8SF and 11SF. This result indicates that the addition of MK is more effective than the addition of SF in terms of scaling resistance.

3.2.4. Rapid chloride

The results of the RCPT test are presented in Table 4. The RCPT values ranged between 1150–2255 coulomb for mixtures with SF and between 316 – 2197 coulomb for those with MK. In general, MK was very effective in reducing chloride ion penetration in SCC mixtures. Replacing cement with 20% MK reduced the total charge of the control mixture by 89% (Fig. 3). For SF mixtures, the total charge passed in coulombs decreased as the percentage of SF decreased. On the other hand, in MK mixtures, the total charge decreased when MK was increased from 0% to 20%, then increased slightly at 25% MK.

The results also showed that replacing cement with up to 8% SF was more effective than similar levels of replacement with MK. For example, the total charged passed in coulomb decreased by about 44% and 59% with 5SF and 8SF, respectively, and by about 31% and 54% with the same percentages of MK. However, 11MK, 15MK, 20MK and 25MK exhibited the lowest values of chloride permeability.

4. Conclusions

The effect of cement replacement by MK on the durability of self-consolidating concrete (SCC) is studied and compared with those of SCC containing silica fume (SF) at similar levels of MK replacement. The durability performance of SCC is evaluated based on the results of drying shrinkage, freezing and thawing, salt scaling, and rapid chloride permeability tests. The following conclusions can be drawn from this study:

The addition of MK increases the viscosity of SCC mixtures, while the addition of SF does not have any effect on viscosity. This conclusion is based on the results of T50 and V-funnel tests, which showed an increase in flow time with the increased percentage of MK in SCC mixtures.

MK enhances the passing ability of SCC mixtures. When MK content increased from 0% to 25%, the values of H2/H1 (L-box index) increased from 0.63 to 0.89, indicating better passing ability.

- The addition of MK increases the viscosity of SCC mixtures, while the addition of SF does not have any effect on viscosity. This conclusion is based on the results of T50 and V-funnel tests, which showed an increase in flow time with the increased percentage of MK in SCC mixtures.
- MK enhances the passing ability of SCC mixtures. When MK content increased from 0% to 25%, the values of H2/H1 (L-box index) increased from 0.63 to 0.89, indicating better passing ability.
- The addition of MK increases the demand for HRWR in SCC mixtures. When MK content increased from 0% to 25%, the amount of HRWR increased by about 30%. However, the addition of MK demanded less HRWR than the addition of SF at the same level of cement replacement.
- The compressive strength of SCC containing MK increased as MK content increased from 0% to 25% (as a partial replacement of cement). On the other hand, the optimum percentage of SF in terms of compressive strength was 8%, and was similar to that of 8% MK (both increased the strength of the control mixture by about 14%). However, raising the amount of MK from 8% to 25% only enhanced the compressive strength by 7% (with respect to 8MK).
- The addition of MK or SF did not affect the total air content of the hardened SCC mixtures. However, it reduced the size of voids in hydrated cement pastes, a reduction that was more pronounced in MK mixtures than SF mixtures. Also, using a higher percentage of SF or MK reduced the air void spacing factor of the hardened SCC mixtures.
- The drying shrinkage of SCC decreased as the percentage of MK or SF increased. The drying shrinkage of SCC with SF was lower than that of SCC with MK at the same level of cement replacement. However, the drying shrinkage of SCC with 15MK, 20MK and 25MK exhibited the lowest values, with minimum shrinkage at 20MK.
- The addition of MK to SCC mixtures improves resistance to freezing and thawing. As the percentage of MK increased, resistance increased as well. The optimum percentage of MK was 20%, while the optimum percentage of SF was 8%. Freezing and thawing resistance was higher with MK than SF at the same level of addition.
- The scaling resistance of SCC is greatly enhanced by the addition of MK. Replacement of cement by 20% MK reduced the weight of the scaled materials (after 50 cycles) by about 54%. The optimum percentages of MK and SF in terms of scaling resistance were 20% and 8%, respectively. MK also proved to be more effective than SF in terms of scaling resistance at the same level of cement replacement.
- MK significantly reduces the chloride permeability of SCC. When 20% MK was used (as a partial replacement of cement), the chloride permeability of the control mixture was reduced by 89%. The optimum percentage of MK in terms of chloride permeability was 20%, while SF showed a decrease in total charges as SF content increased from 0% to 11%. SF reduced the chloride permeability of SCC more than MK at the same level of cement replacement. However using 11%, 15%, 20%, and 25% MK exhibited the lowest chloride permeability values.

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