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Durability of self-consolidating concrete incorporating high-volume replacement composite cements

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Abstract

Self-consolidating concrete (SCC) decreases construction time, labor and equipment on construction sites, makes the construction of heavily congested structural elements and hard to reach areas easier, reduces noise- and vibration-related injuries, and helps in achieving higher quality finish surfaces. However, because it usually requires a larger content of binder and chemical admixtures compared to ordinary concrete, its material cost is generally 20–50% higher, which has been a major hindrance to a wider implementation of its use. There is growing evidence that incorporating high volumes of mineral admixtures and microfillers as partial replacement for portland cement in SCC can make it cost effective. However, the durability of such SCC needs to be proven. This research investigates the rapid chloride ion penetrability, sulfate expansion and deicing salt surface scaling resistance of SCC mixtures made with high-volume replacement binary, ternary, and quaternary cements. The fresh concrete properties and compressive strength at 1, 7, 28 and 91 days of such SCC mixtures were measured. Moreover, rapid chloride ion penetrability was investigated for the various SCC mixtures at 28 and 91 days, while the deicing salt surface scaling under 50 freezing–thawing cycles and sulfate expansion after up to 9 months of immersion in a 5% Na_2SO_4 solution were investigated as per the ASTM C-672 and ASTM C1012 guidelines, respectively. Results indicate that SCC can be made with high-volume replacement composite cements and achieve good workability, high long-term strength, good deicing salt surface scaling resistance, low sulfate expansion and very low chloride ion penetrability.

Keywords: Durability; Blended cement; Chloride; Sulfate attack; Self-consolidating concrete

1. Introduction

Self-consolidating concrete (SCC) has emerged in Japan in the late 1980s as a material that can flow under its own weight, so that it can be easily placed, without need for additional mechanical compaction, in complicated formwork, congested reinforced structural elements and hard to reach areas. The key performance criterion of this technology is attaining a highly fluid behavior while preventing bleeding and segregation of the mixture components. Researchers [1] have set some guidelines for the mixture proportioning of SCC, which include (i) reducing the volume ratio of aggregate to cementitious material; (ii) increasing the paste volume; (iii) carefully controlling the total volume of the coarse aggregates and its maximum particle size; and (iv) using various chemical admixtures, such as superplasticizers and viscosity-modifying admixtures (VMAs) to fine-tune the balance between deformability and stability.

In recent years, substantial research has been conducted on SCC in Japan, Europe and North America [2–4]. Although SCC has been used in Japan in large-scale civil engineering structures [5], and in commercial and precast applications in Sweden [6] and the Netherlands [7], its use in North America has been limited, namely, in the precast industry and in some repair jobs. It is believed that full realization of the benefits that SCC can bring to the concrete industry will only occur when the material becomes perceived as a cost-effective viable technology. Because of its higher binder and chemical admixture content, SCC is usually associated with 20–50% higher material cost compared to that of an ordinary concrete with comparable

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compressive strength. For instance, Schlagbaum [8] found that the material cost of SCC is 38% and 23% higher than that of ordinary concrete in residential and structural applications, respectively. Martin [9] reports that depending on the fly ash content of SCC, its material cost is 10–17% higher than that of ordinary concrete, while Ambrose and Péra [10] claim that the cost difference is around 15%. The elimination of vibration work, reduction of labor and construction time can recover some of the extra material cost of SCC compared to that of ordinary concrete. However, there is still need to make SCC more cost competitive.

The concept of developing inexpensive SCC is not new. For instance, Bouzoubaâ and Lachemi [11] attempted to design high-volume fly ash (HVFA)–SCC by replacing up to 60% of portland cement with class F fly ash. It was found that producing HVFA–SCC with a 28-day compressive strength of 35–40 MPa was possible at a competitive cost. The 1-day compressive strengths of mixtures in the reported study ranged between 5 and 16.6 MPa. Ribeiro and Gonç alves [12] used high dosages of mineral admixtures in combination with a low-cost superplasticizer and a high water content to produce low-cost SCC. Ghezal and Khayat [13] used statistical experimental design to optimize cost-effective SCC incorporating up to 120 kg/m^3 of limestone filler. Nehdi et al. [14] conducted a study to optimize cost-effective high-volume replacement SCC for deep foundation applications that does not compromise early-age strength. It was concluded that producing economically competitive SCC can be achieved by replacing up to 50% of ordinary portland cement with mineral admixtures, such as fly ash, ground granulated blast furnace slag and limestone filler. Incorporating such mineral admixtures in binary (two-component), ternary (three-component) or quaternary (four-component) blends enhanced the rheological behavior of SCC and decreased its material cost. Excellent compressive strength values, even at early ages, could also be achieved.

However, the durability of high-volume replacement SCC, in which a high proportion of OPC is replaced with supplementary cementitious materials and/or fillers, needs to be established. For instance, there has been concern over the resistance to deicing salt surface scaling of HVFA concrete [15] and whether such a problem can occur in SCC made with high-volume replacement ternary and quaternary cements needs to be assessed. Synergistic durability effects can be expected in multicomponent (ternary and quaternary) cementitious systems (such synergistic effects have been discussed in detail elsewhere, Ref. [16]), and whether such benefits can occur in SCC made with high-volume replacement composite cements also needs investigation.

2. Research significance

SCC can be made an economically competitive alternative via the use of high volumes of supplementary cementitious materials and microfillers, which can achieve excellent fluidity and stability without the need for high dosages of costly chemical admixtures. For this purpose, ternary and quaternary cementitious blends having synergistic effects (such synergistic effects have been discussed in detail in Ref. [16]) can be optimized to achieve adequate rheological and mechanical properties of high-volume replacement SCC. This research provides results on the resistance of such concrete to deicing salt surface scaling, sulfate expansion and chloride ion penetration to provide the designer with knowledge on the long-term performance of such concrete and establish its potential life cycle cost savings. Other long-term properties, such as drying shrinkage and creep, need further investigation.

3. Materials

A Type 10 Canadian cement (CSA3-A5-M93) similar to ASTM Type I cement was used to make the various SCC mixtures. In addition, a class F fly ash, a ground granulated blast furnace slag and silica fume were used as supplementary cementitious materials. In some mixtures, rice husk ash (RHA) was also used. Table 1 summarizes physical and chemical properties of the various components used to make the binary, ternary and quaternary cementitious blends. Well-graded local sand and continuously graded hard crushed stone were used as the fine and coarse aggregates, respectively. The particle size gradation (obtained using sieve analysis) of the fine and coarse aggregates is presented in Fig. 1. Specific gravity and water absorption of the fine aggregate were 2.65 and 1.50%, respectively. Those of the coarse aggregate were 2.68 and 0.80%, respectively. A polysaccharide welan gum powder (WG) was employed as a VMA and a commercial synthetic detergent-based air-entraining admixture was used. A naphthalene-sulfonated superplasticizer having 42% solid content was employed. Although more effective superplasticizers currently exist on the market and could have been used herein to produce SCC, it was decided to use a conventional superplasticizer because the focus is to achieve cost-effective SCC. It is, however, possible that the use of a third or fourth generation superplasticizer at a lower dosage can be equally or even more economical while achieving better workability, but this was not investigated in this study.

4. Experimental program

Seven air-entrained SCC mixtures (including a reference mixture) having a constant water/binder ratio of 0.38 were made following the same mixing technique in a rotary planetary mixer. First, the coarse aggregates, which were saturated surface dry, were placed in the mixer. The binder and fine aggregates were added and mixing resumed for 3 min while gently adding the mixing water, which was

Table 1
Physical and chemical properties of Type 10 Portland cement and mineral admixtures

Properties	Type 10 cement	Class F fly ash	Slag	Silica fume	RHA
Silicon oxide (S_iO_2)	19.5	48.9	34.8	94.0	89.1
Aluminum oxide (Al_2O_3)	5.2	23.3	9.8	0.1	0.1
Ferric oxide (Fe_2O_3)	2.4	14.9	0.6	0.1	0.04
Calcium oxide (CaO)	61.3	3.8	38.3	0.4	0.6
Magnesium oxide (MgO)	2.5	0.7	9.6	0.4	0.5
Sodium oxide (Na_2O)	0.3	0.6	0.4	0.1	0.2
Potassium oxide (K_2O)	1.2	1.7	0.4	0.9	1.0
Equivalent alkali ($Na_2O + 0.658K_2O$)	0.8	0.4	0.7	0.7	0.8
Phosphorous oxide (P_2O_5)	0.1	–	–	< 0.01	0.9
Titanium oxide (TiO_2)	0.3	–	0.8	0.3	0.01
Sulfur trioxide (SO_3)	4.1	0.2	3.5	1.3	–
Loss on ignition	2.8	0.3	–	2.7	7.0
Tricalcium silicate (C_3S)	51.14	–			
Dicalcium silicate (C_2S)	17.40	–			
Tricalcium aluminate (C_3A)	9.74	–			
Tetracalcium alumino-ferrite (C_4AF)	7.35	–			
Specific surface area (m^2/kg)	412	280	468		
Specific gravity	3.17	2.08	2.90	2.02	2.06
Initial setting, Vicat test (min)	180	–	–		
Final setting, Vicat test (min)	350	–	–		
f'_c of standard cube (MPa)					
7 days	32.1	–	–		
28 days	38.8	–	–		

premixed with the superplasticizer and the VMA when applicable. After 2 min of rest, the air-entraining admixture was added, mixing for an additional 2 min was carried out and the mixer was immediately covered with a plastic sheet. Binary, ternary and quaternary cementitious blends in which a high proportion of portland cement was substituted with cementitious materials were used as a binder in the various mixtures.

The mixture proportions of the various concrete mixtures are shown in Table 2. The slump flow, L-box flow, and entrained air content were evaluated for each mixture. A significant variation of the air content of the various mixtures was observed. Two 100 × 450 mm cylinders from each mixture were cast in sonotube cylinders and placed in a freezer after 1 h from casting. After freezing, the cylinders were cut in three equal parts and the coarse aggregates from the top and bottom thirds of each cylinder were washed out, dried in an oven and weighed. A simple segregation index was calculated as $(1 - W_T/W_B) \times 100$ where W_T and W_B are the weights of coarse aggregates

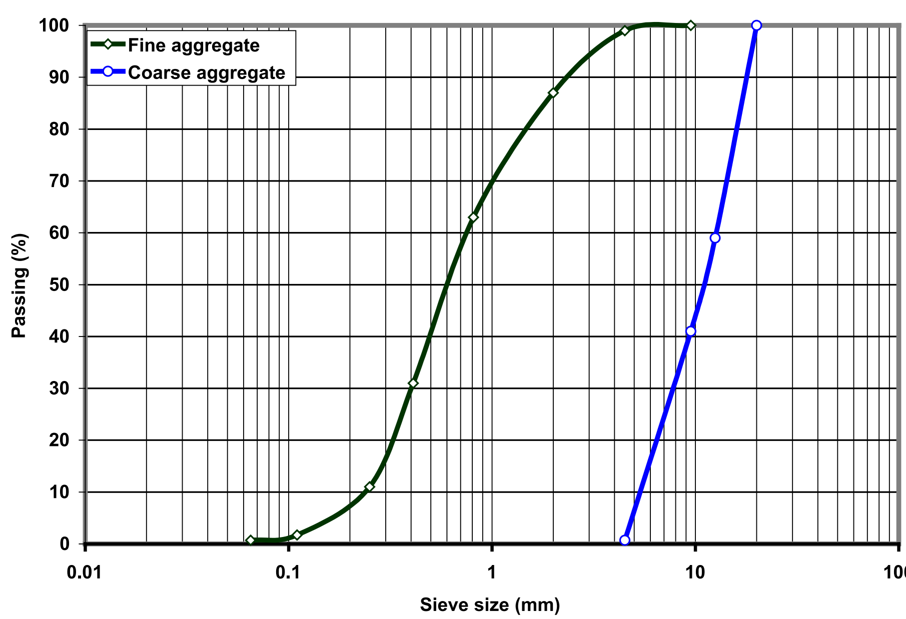

Fig. 1. Particle size distribution of fine and coarse aggregates.

Table 2
Mixture proportions of the self-consolidating concrete mixtures investigated (constant water/binder = 0.38)

Mixture		Portland cement (kg/m^3)	Fly ash (kg/m^3)	Slag (kg/m^3)	RHA (kg/m^3)	Silica fume (kg/m^3)	Gravel (kg/m^3)	Sand (kg/m^3)	VMA (kg/m^3)	HRWR (l/m^3)	Density (kg/m^3)
Reference	1	425					900	930		1.9	2255
Binary a	2	215	215				905	925		1.5	2260
Binary b	3	215	215				905	925	0.1	3.3	2260
Ternary a	4	215	105	105			905	920		1.3	2255
Ternary b	5	215	105	105			905	920	0.2	4.9	2250
Quaternary a	6	215	100	85		25	910	915		3.0	2260
Quaternary b	7	215	100	85	25		910	915		3.2	2250

VMA = viscosity-modifying admixture; HRWR = high-range water reducer.

in the top and bottom thirds of the cylinders, respectively. Moreover, 100 × 200 mm cylinders for compressive strength at 1, 7, 28 and 91 days (at least three cylinders at each age) and for rapid chloride ion penetrability (ASTM C1202) at 28 and 91 days (four specimens at each age) were prepared in plastic moulds (no vibration or other means of consolidation was used). In addition, concrete slabs (200 × 230 × 75 mm), for the determination of the resistance to deicing salt surface scaling of concrete (ASTM C672), were made. The cylinders and slabs were covered with plastic sheets and wet burlap for 24 h, then demoulded and cured in a moist chamber at 23 °C and relative humidity higher than 95%. The cylinders for compressive strength were capped with a sulfur solution prior to testing. Disks 50 mm thick were cut from 100 × 200 mm concrete cylinders for the chloride ion penetrability test 48 h prior to testing.

After curing the slabs in the moist chamber described above for 14 days, the specimens were cured in laboratory conditions at a temperature of 23 ± 2 °C and relative humidity of 35 ± 5%. To eliminate surface-finishing effects, only the bottom surfaces of slabs (those in contact with wooden formwork) were subjected to deicing salt scaling tests. Strips of high-density Styrofoam were attached to the sides of slabs with an exterior grade adhesive to create a watertight brine pond with a 6-mm thickness and a concentration of 4% CaCl. Starting at an age of 28 days, the slabs were subjected to 50 cycles of freezing–thawing following the ASTM C672 guidelines. A freezing–thawing cycle consisted of 16 h at a temperature of − 18 °C followed by 8 h at a temperature of 23 ± 1.7 °C. The freezing rate was 8 °C per hour. The amount of scaled-off material was measured after each five cycles and scaling was given a visual rating according to ASTM C672.

For each fresh SCC mixture, mortar was extracted using a 5-mm sieve and used to cast eight bars (25 × 25 × 285 mm) for the ASTM C1012 sulfate expansion test. These test specimens were stored in lime-saturated water in a curing room at 23 ± 1.7 °C until they reached a compressive strength of 20.0 ± 1.0 MPa (compressive strength was measured using standard 100 × 100 mm cubes made from the same mortar). The bar specimens were then immersed in a sulfate solution (5% by weight of Na_2SO_4) that was maintained at 23 °C. The containers in which the bars were immersed were made of plastic and a means for supporting the bars was included so that no end or side of a bar specimen rested against the container. The pH value of the sulfate solution was maintained in the range of 6–8 by replacing the solution with a fresh one when needed. Before placing the bar specimens in the sulfate solution, their length was measured using a high-accuracy digital length comparator. The length change of the specimens was then monitored at 1, 2, 3, 4, 8, 13 and 15 weeks after they were placed in the sulfate solution. If slight, gradual and uniform length change was taking place, the next measurements were made at 4, 6 and 9 months. When expansion was occurring rapidly at any stage of the test, the interval between readings was adequately shortened.

5. Results and discussion

Compressive strength results shown in Table 3 are average values obtained on at least three specimens at

Table 3
Experimental results

Mixture		Air content (%)	Slump flow (mm)	L-box h_2/h_1	Segr. index (%)	1-day f'_c (MPa)	7-day f'_c (MPa)	28-day f'_c (MPa)	91-day f'_c (MPa)	28-day Cl penetrability (C)	91-day Cl penetrability (C)
Reference	1	8.0	660	0.86	14	18.5	30.4	35.5	40.7	4700	3575
Binary a	2	6.7	635	0.84	8	2.7	15.8	20.4	28.1	2480	925
Binary b	3	7.2	640	0.80	6	1.6	12.2	18.2	26.5	3040	900
Ternary a	4	5.5	690	0.85	5	7.1	25.1	36.9	46.5	1900	650
Ternary b	5	7.0	615	0.82	4	6.1	24.6	36.9	47.0	1375	500
Quaternary a	6	7.3	620	0.79	5	4.3	14.7	24.7	30.8	1100	400
Quaternary b	7	7.3	650	0.80	3	4.2	13.9	22.2	28.0	1200	470

each age, results of rapid chloride ion penetrability are average values obtained on four specimens tested simultaneously in four parallel cells for each mixture (Table 3), and surface scaling results are average values obtained on two slabs for each concrete mixture (Table 4). Sulfate expansion results are average values obtained on eight identical bars (Fig. 6).

5.1. Workability and flow properties

The ability of SCC mixtures to flow was evaluated using the slump flow test and the L-box test. Table 3 shows that the slump flow for the various SCC mixtures varied between 615 and 690 mm. It should be noted that using recent developments in chemical admixtures, stable mixtures with low segregation and slump flows higher than 700 mm can be produced. This approach was not used herein because the focus is to develop cost-effective SCC mixtures. It can be observed in Table 2 that the superplasticizer dosage required in SCC mixtures made with composite cements incorporating 50% replacement of portland cement by mineral admixtures was lower than that of the reference mixture made with pure OPC, unless a VMA or high surface area mineral admixtures, such as silica fume or RHA, were used. When the VMA was used, the superplasticizer requirement to achieve a certain slump flow increased substantially. The approach of using VMAs to achieve stability of SCC mixtures and adding more superplasticizer to bring back the flow properties to an adequate self-consolidating range is the main reason (along with the need for a higher binder content) for the significant material cost increase of SCC compared to that of ordinary concrete with similar compressive strength. A more economic alternative approach is to increase the binder content of SCC mixtures via the addition of low-cost mineral admixtures and microfillers to provide a high colloidal volume that reduces internal friction and assures good flow properties, while also assuring the stability of SCC.

Generally, the SCC mixtures exhibited good ability to flow through the rebar of the L-box. Desired L-box test results should have $h_2/h_1 > 0.8-0.9$. Results from the L-box for all SCC mixtures are shown in Table 3; they ranged between 0.79 and 0.86 and there was no blockage of flow for all mixtures. The lower bound L-box values were obtained for mixtures with the VMA or incorporating RHA or silica fume that typically required high superplasticizer dosage. It was decided not to increase the SP dosage any further to maintain cost-effective mixtures and to avoid set-retarding problems. Furthermore, the segregation index for the 100% OPC was 14%, but this value decreased for SCC mixtures with high-volume replacement composite cements, especially those incorporating silica fume, RHA or the VMA. Based on slump flow, L-box flow, segregation index and visual inspection, the self-consolidating property for all mixtures was considered satisfactory.

5.2. Compressive strength

The compressive strength values measured at 1, 7, 28 and 91 days for all SCC mixtures are summarized in Table 3 and illustrated in Fig. 2. The binary 50% OPC–50% fly ash mixtures had the lowest early-age strength due to the slower reactivity of class F fly ash. Adding a VMA to the 50%OPC–50% fly ash mixture increased its superplasticizer dosage, thereby delaying its setting further and reducing its early-age compressive strength even more. Some of this strength decrease may also be due to the increase in the air content of the mixture by 0.5% when the VMA was added. When class F fly ash was used in a ternary blend of 50% OPC–25% fly ash–25% slag, the early age compressive strength was improved. The 28- and 91-day compressive strengths of this ternary mixture exceeded that of the reference mixture. Adding a VMA in the ternary mixture did not have a significant detrimental effect on its compressive strength. In fact, it improved the strength somewhat although the air content of the ternary mixture incorporating the VMA was 1.5% higher than that of the ternary mixture without VMA. This is probably due to increased homogeneity and reduced bleeding due to the VMA.

Quaternary mixtures incorporating 6% of either silica fume or RHA were tested because it was believed that such highly reactive pozzolans can increase the early age strength when used to replace an equal mass of the less reactive class F fly ash or slag. Table 3 and Fig. 2 show that such anticipated strength gain was not observed. Indeed, the 1-day compressive strength of quaternary 50% OPC–24% fly ash–20% slag–6% silica fume and 50% OPC–24% fly ash–20% slag–6% RHA mixtures did not exceed that of ternary 50% OPC–25% fly ash–25% slag mixtures. The reason for this is apparently the higher superplasticizer requirement for quaternary mixtures incorporating silica fume or RHA, which delayed their setting and decreased their early-age strength. However, this effect was still observed at 91 days. It is suggested that long-term monitoring of the compressive strength of concrete made with high-volume replacement ternary and quaternary cements be conducted to better understand the kinetics of strength development in such mixtures.

5.3. Rapid chloride ion penetrability

The rapid chloride ion penetrability measured at 28 and 91 days for all SCC mixtures is illustrated in Fig. 3, including the ASTM C1202 rapid chloride ion penetrability classification ranges. The pure OPC SCC mixture achieved rapid chloride ion penetrability in the high range at 28 days (>4000 C). At 28 days, binary mixtures incorporating 50% class F fly ash decreased the rapid chloride penetrability from a high to a moderate range. In SCC made with high-volume replacement ternary and quaternary cementitious

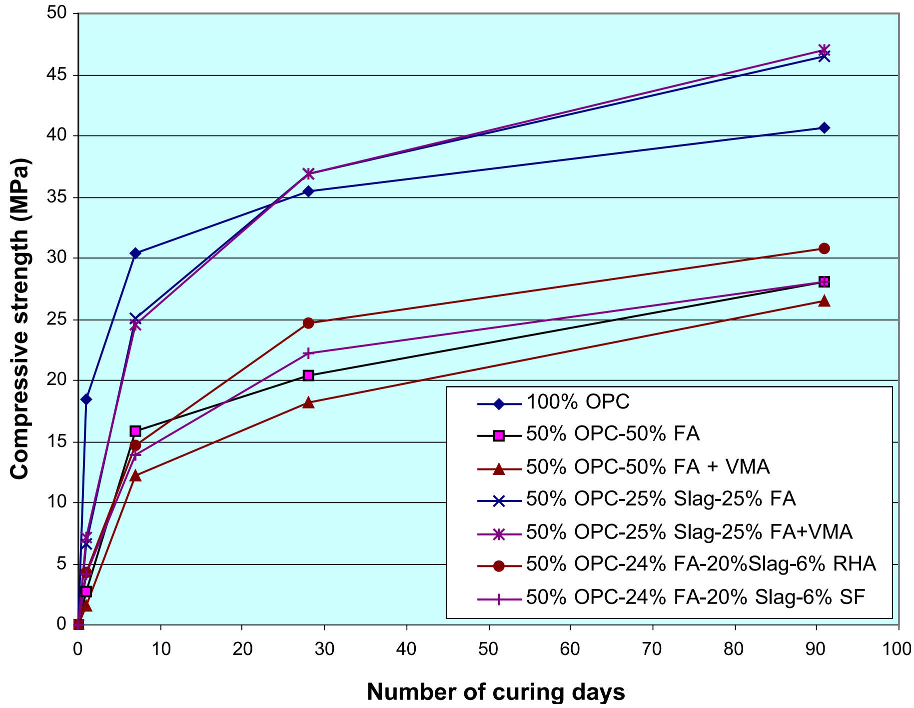

Fig. 2. Compressive strength versus time for the various SCC mixtures.

blends, the 28-day rapid chloride ion penetrability was decreased from a high range for the reference 100% OPC mixture to a low range (less than 2000 C). The most efficient mixtures in decreasing the 28-day chloride ion penetrability were quaternary mixtures incorporating either 6% silica fume or 6% RHA. It is recommended that further testing of chloride concentration versus depth of penetration be conducted to gain a better understanding of how multi-component blended cements affect chloride diffusion in SCC.

At 91 days, the reference 100% OPC SCC mixture had rapid chloride ion penetrability in the top moderate range

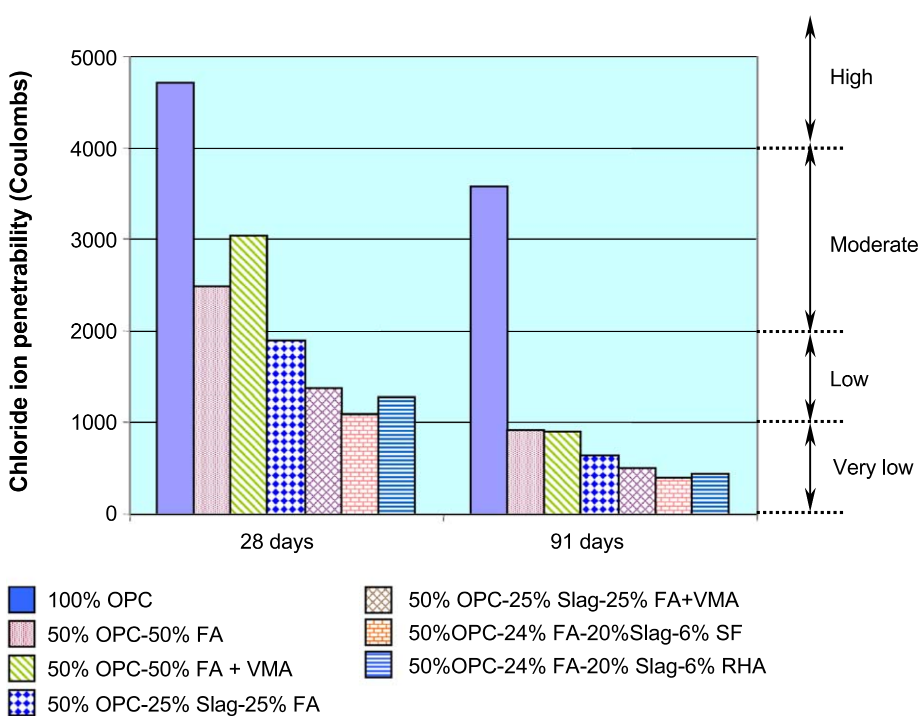

Fig. 3. Chloride ion penetrability at 28 and 91 days for the various SCC mixtures.

Table 4
Deicing salt surface scaling test results

Mixture		Cumulative mass of scaled-off particles after 50 cycles (kg/m^2)	Visual rating (ASTM C672 scale of 1–5)
Reference	1	0.065	1
Binary a	2	0.575	4
Binary b	3	0.130	2
Ternary a	4	0.090	2
Ternary b	5	0.080	1
Quaternary a	6	0.100	2
Quaternary b	7	0.080	2

(between 3000 and 4000 C). All SCC mixtures made with high-volume binary, ternary and quaternary cementitious blends reduced the rapid chloride ion penetrability to the very low range (less than 1000 C). Quaternary mixtures incorporating 6% silica fume or RHA were most efficient in this regard than ternary OPC–fly ash–slag mixtures, which in turn were more efficient than binary OPC–fly ash mixtures. Thomas and Evans [17] report that the use of fly ash as partial replacement for Type 10SF blended cement (equivalent to ASTM Type I cement with 6.0–9.5% silica fume) decreased the rapid chloride penetration Coulomb value of concrete. The implications of such substantial decreases in chloride ion penetrability should be seriously considered in the design of offshore structures, bridge decks, parking garages and other structures that are vulnerable to corrosion of reinforcing steel under chloride ion attack. Not only would SCC made with high-volume replacement composite cements provide excellent workability at a competitive cost [14], but the repair, maintenance and overall life cycle costs would make such a material more appealing.

5.4. Deicing salt surface scaling

The average cumulative mass of scaled-off material obtained from two slabs made of each SCC mixture after 50 freezing–thawing cycles is shown in Table 4 along with average visual surface scaling ratings determined as per the ASTM C672 scale of 1–5. Moreover, the average cumulative mass of scaled-off material versus number of freezing–thawing cycles for each SCC mixture is shown in Fig. 4. It can be observed that the 50% OPC–50% class F fly ash SCC mixture had the largest mass of scaled-off material and the worst visual scaling rating among all other SCC mixtures made with high-volume replacement composite cements. It is interesting to note that when the VMA was added in the HVFA–SCC mixture, the mass of scaled-off material was significantly reduced and the visual rating improved from a 4 to 2 rating. The difference can be observed by visually comparing Fig. 5b and c. This result could be of important practical value, but because this finding is not consistent with previous knowledge, it must be first verified whether it can be reproduced under different testing conditions or whether it is a special occurrence in the specific materials and experimental procedures of this particular research. Khayat [18] investigated the effect of the sequence of adding an air-entraining admixture, two commonly used VMAs, namely, welan gum and hydroxypropyl methylcellulose, and a superplasticizer on the frost durability and scaling resistance of fluid concrete mixtures. He concluded that regardless of the air-spacing factor and presence of the VMA, such fluid concrete mixtures can have

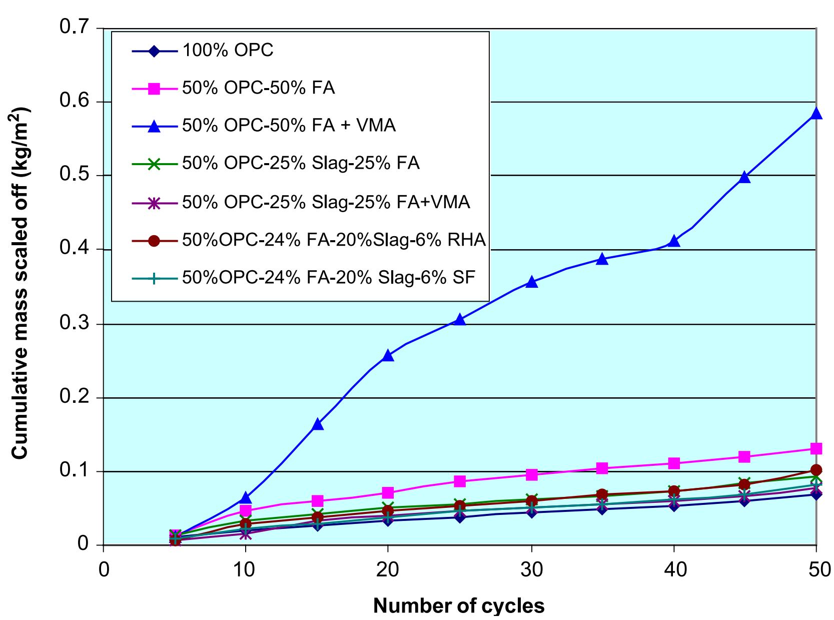

Fig. 4. Cumulative mass scaled off versus number of freezing–thawing cycles.

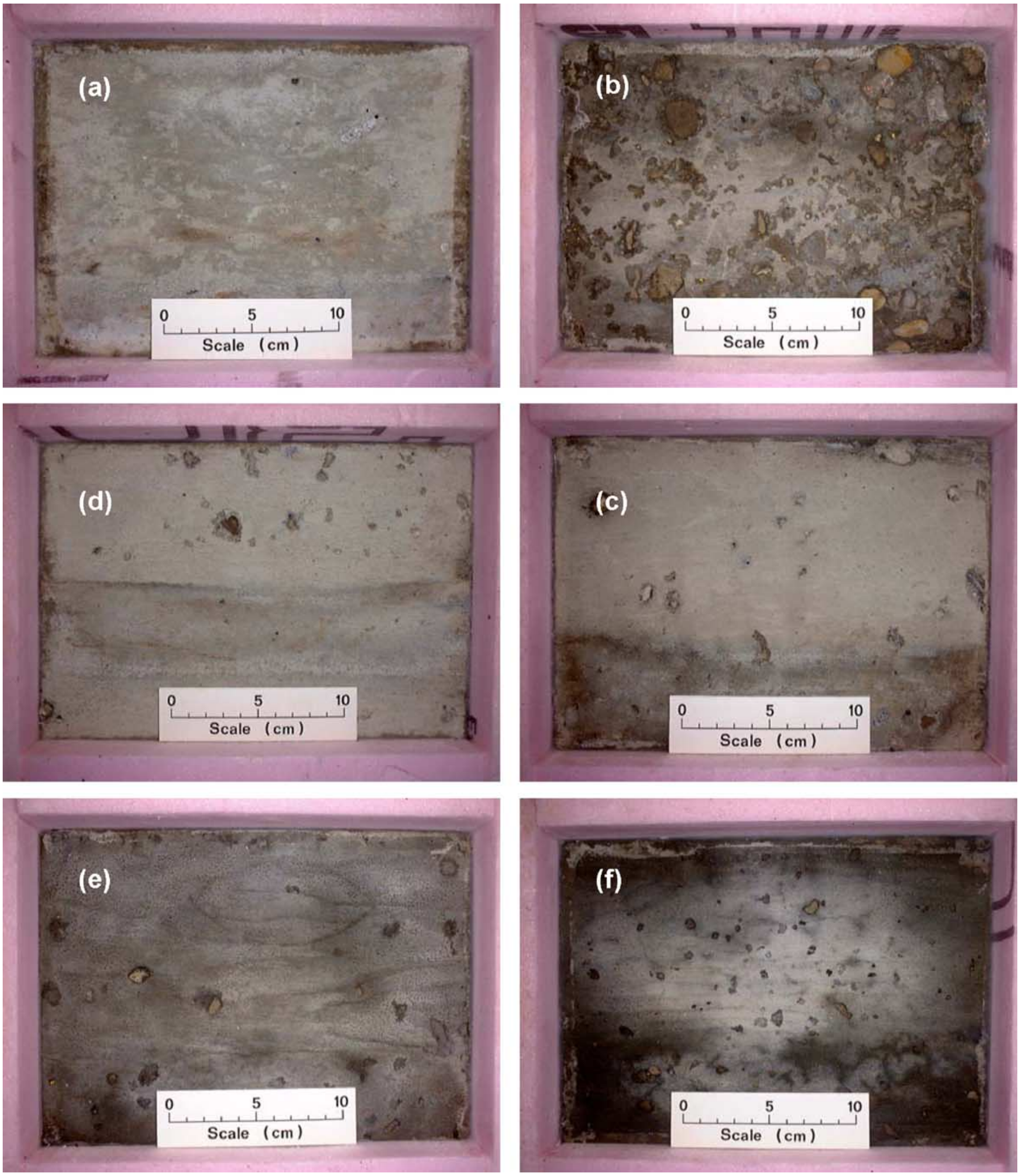

Fig. 5. Deicing salt surface scaling after 50 freezing–thawing cycles of: (a) reference mixture with 100% OPC, (b) 50% OPC–50% fly ash, (c) 50% OPC–50% fly ash with a VMA, (d) 50% OPC–25% slag–25% fly ash, (e) 50%OPC–24% fly ash–20% slag–6% RHA, and (f) 50% OPC–24% fly ash–20% slag–6% silica fume.

poor surface scaling resistance, which was attributed to the relatively high porosity of the skin of concrete.

An SCC ternary 50% OPC–25% fly ash–25% slag mixture with a VMA achieved a comparable resistance to deicing salt surface scaling to that of the reference 100% OPC SCC mixture. It can also be noted that a quaternary SCC mixture incorporating 6% RHA achieved somewhat better resistance to surface scaling than that of a similar quaternary SCC mixtures incorporating 6% silica fume (Fig. 5e and f). It should be remembered that all deicing salt surface scaling results of this study were obtained on the bottom surfaces of slab specimens (the surfaces in contact with the wooden formwork). This was purposely done to eliminate any surface-finishing effects. Thus, surface-finishing issues at times cited to explain the poor deicing salt surface scaling performance of HVFA concretes in the laboratory is not substantiated by the current results. It is worth noting that SCC is usually not vibrated, which limits the transport of fines and water to the surface and sidewalls of formwork, thereby enhancing the resistance of the SCC to deicing salt surface scaling compared to that of vibrated conventional concrete. Such effect was observed in field Norwegian applications of SCC [19] and under laboratory conditions [20]. Recently, Persson [21] investigated the surface scaling of SCC mixtures incorporating proportions of slag, fly ash, silica fume and limestone filler. No difference was observed between the frost scaling resistance of SCC and ordinary concrete. However, the OPC replacement rates were generally much lower than those used in this study.

5.5. Resistance to sulfate expansion

The sulfate expansion after 9 months of immersion in a 5% solution of Na_2SO_4 for bar specimens made of mortar extracted from the various SCC mixtures is illustrated in Fig. 6. Bars made from mortar extracted from the reference SCC mixture incorporating 100% OPC exhibited by far the largest expansion due to sulfate immersion. When 50% of the cement was replaced with class F fly ash, the sulfate expansion at 9 months was decreased substantially. This effect is well documented; for instance, ACI Committee 232 recognizes that the use of low-calcium fly ash should significantly decrease sulfate expansion [22]. However, bars made of a mortar extracted from a SCC mixture incorporating a ternary 50% OPC–25% fly ash–25% slag cement achieved lower sulfate expansion after 9 month immersion in a 5% solution of Na_2SO_4 compared to that of the binary 50% OPC–50% fly ash bar specimens described above. This result was unexpected because slag was much richer in calcium compared to fly ash. It is possible that the faster strength development due to the presence of slag made the ternary mortar specimens less permeable compared to the binary specimens and decreased the ingress of sulfate ions. This synergistic effect needs further investigation. The lowest sulfate expansion values were achieved by bars of mortar extracted from SCC mixtures incorporating quaternary 50% OPC–24% fly ash–20% slag–6% silica fume or RHA cementitious blends. Combined with their very low chloride ion penetrability, such quaternary cements provide attractive design alternatives for structures in aggressive environments, such as offshore applications [16].

6. Conclusions

SCC can be made cost effective by replacing high proportions of OPC by cementitious materials and low-cost microfillers, and reducing the dosage of chemical admixtures, such as superplasticizers and VMAs [14]. Multicomponent cements with synergistic rheological and mechanical effects can be optimized for this purpose [16], but the durability of such systems needs to be proven prior to their full-scale implementation. In this study, SCC mixtures made with high-volume replacement multicomponent (binary, ternary and quaternary) cementitious blends were made. Their workability and compressive strength at various ages were measured. Moreover, their sulfate expansion, resistance to deicing salt surface scaling and rapid chloride ion penetrability were examined. From the test results, the following conclusions can be warranted:

1. Cost-effective SCC can be made with 50% replacement of portland cement while achieving good workability and higher 28- and 91-day strength values than those of a reference SCC made with 100% OPC.
2. High-volume replacement of OPC generally leads to lower early-age compressive strengths. Although this strength decrease can be minimized in carefully optimized multicomponent cementitious blends, research is needed to overcome this difficulty using innovative chemical admixtures and/or other activation methods.
3. High-volume replacement SCC made with ternary and quaternary cements can have dramatically lower chloride ion penetrability compared to that of a reference SCC made with 100% OPC.

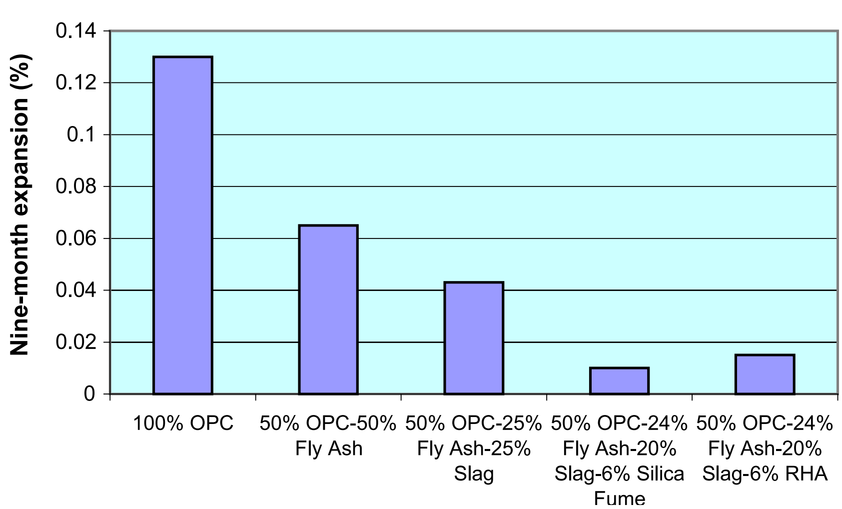

Fig. 6. Expansion of bar specimens of mortar extracted from SCC mixtures submerged in a 5% Na_2SO_4 solution for 9 months.

4. Although HVFA–SCC had poor performance under deicing salt surface scaling in the laboratory, high-volume replacement ternary and quaternary SCC can be designed to achieve comparable deicing salt surface scaling resistance to that of a reference SCC mixture made with 100% OPC.
5. The use of a VMA in high-volume replacement SCC seemed to enhance its resistance to deicing salt surface scaling. Whether this result can be consistently obtained or whether it is a particular occurrence in this study needs further investigation.
6. SCC made with high-volume replacement binary, ternary and quaternary cements achieved very low sulfate expansion compared to that of a reference SCC made with 100% OPC.
7. There appears to exist synergistic rheological, mechanical and durability effects between ingredients in multicomponent cementitious blends, not only from the workability and strength point of view, but also from the durability point of view [16]. Much research is needed to optimize such effects and understand the mechanisms underlying them.
8. High-volume replacement SCC cannot only have the workability and ease of construction benefits associated with conventional SCC, but also achieve much enhanced long-term durability. Added to the environmental benefits of using high-volume replacements of portland cement, this makes this material very appealing for future challenging construction projects. However, other long-term performance criteria of SCC made with high-volume replacement multicomponent cements, including shrinkage and creep, need further investigation before field implementation of such concrete.

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