Flow characteristics of concrete-equivalent mortar

Concrete-equivalent mortar (CEM) mixtures were used to evaluate the influence of HRWRA type on the minimum water content and relative water demand. In the design of the CEM, additional content of sand is used to provide an equivalent surface area of the coarse aggregate that is not employed in the CEM formulation. For a given binder type (B1 binder), three CEM mixtures were prepared with various types of HRWRAs (Table 2). The HRWRAs included PNS-based HRWRA (PNS) and two PCP-based HRWRAs (PCP1 and PCP2). The dosage rate of the HRWRA was fixed at 0.2% solid content, by mass of cementitious materials, to eliminate the effect of different HRWRA dosages on the flow characteristics. The CEM was prepared in 2-L batches using an epicyclic type mixer of 4.73-L capacity, in compliance with ASTM C 305.

The mortar flow test was used to evaluate the flow characteristics of CEM. The test consists of determining the variations of fluidity of a given mortar with changes in water-to-powder ratio (Vw/Vp), by volume. As indicated in Fig. 1, the intercept of the curve with the ordinates axe (Vw/Vp) and the slope of the curve represent the minimum water content that is needed to initiate flow and the relative water demand required to increase a given fluidity, respectively. The reduction of minimum water content corresponds to an increase in packing density and, for the same cementitious materials, can lead to decrease in HRWRA demand. As indicated in Fig. 1, for a given increase in water content (ΔW), a CEM that has higher relative water demand would exhibit smaller increase in fluidity compared to that of similar mixture with lower relative water demand. This indicates that the former mixture has greater tolerance to undergo same addition of water with limited increase in fluidity; this would lead to greater robustness.

Test methods for SCC

Workability of SCC was evaluated using the slump flow, V-funnel, L-box, caisson filling capacity, and surface settlement tests. Detail descriptions of these tests are elaborated in reference 4. The apparent yield stress (g) and torque plastic viscosity (h) were evaluated using a modified two-point workability rheometer. The workability testing was carried out within 20 min after the end of mixing.

A number of 100 × 200 mm cylinders were cast to determine compressive strength (ASTM C 39) and modulus of elasticity (ASTM C 469) at 28 and 56 days of moist curing Prisms measuring 75 × 75 × 355 mm were prepared to evaluate frost durability (ASTM C 666, A). The prisms were moist-cured for 56 days before starting freeze-thaw testing given the fact that concrete containing high volume of supplementary cementitious materials necessitates curing period longer than 28 days to develop its mechanical properties and durability. Samples of 280 × 230 × 75 mm were cast to evaluate the scaling resistance (ASTM C 672). The samples were moist-cured for 42 days, then stored at 50% relative humidity at 23 ± 1 °C for 14 days before frost testing. The air-void system of the hardened concrete was determined in accordance with ASTM C 457.
Rapid chloride-ion permeability (RCP) testing (ASTM C 1202) was carried out after 56 days of moist curing. The chloride-ion diffusion coefficient was evaluated using steady

state migration test similar to the setup used by Truc et al. (5). Relatively low electrical potential of 12 Volt was applied to reduce the effect of temperature rise given the high voltage used during the testing. The alkaline solution of 20 L was used as non-chloride solution in this migration test. Such high volume can mitigate chloride concentration increase in the downstream solution (anode). This can help keep the chloride ion flux constant during the testing. A chloride solution made with NaCl (0.338 mol/L), NaOH (0.025 mol/L) and KOH (0.083 mol/L) was used for the upstream (cathode). Diffusion coefficient was determined from changes in chloride-ion concentration with time (5).

Prismatic concrete samples measuring 76 × 76 × 285 mm were used to evaluate drying shrinkage (ASTM C 157). The samples were immersed in water for 7 days after casting then were stored at 23 ± 1 °C and 50% relative humidity for 56 days. Drying shrinkage was monitored between 7 and 63 days using a digital-type extensometer. An instrumented ring test similar to the setup used by See et al. (6) was performed to determine restrained shrinkage cracking of concrete. As shown in Fig. 2, concrete ring specimens are dried from only outer circumferential surface with the top surface sealed. Concrete was moist-cured for 24 hours under wet burlap after casting before demolding and thereafter for additional 2 days before initiating the drying process at 23 ± 1 °C and 50% relative humidity. A sudden increase in steel strain corresponds to cracking of the concrete ring specimen. Detail procedures of the ring test can be found in reference 6.

TEST RESULTS AND DISCUSSION

Effect of HRWRA type on flow characteristics of concrete-equivalent mortar

In general, the SCC made with PNS-based HRWRA exhibited higher HRWRA demand compared to that prepared with PCP-based HRWRA. Similar findings were obtained for the flow characteristics of CEM, as shown in Fig. 3. For a given HRWRA concentration, CEM made with PNS-based HRWRA exhibited higher MWC to initiate flow compared to similar mixture prepared with PCP-based HRWRA (1.23 versus 0.86 and 0.81). This can be due to lower packing density of the CEM made with PNS-based HRWRA compared to that prepared with PCP-based HRWRA. Furthermore, it may be attributed to the relatively lower dispersing force of the PNS-based HRWRA. It is worthy to note that CEM proportioned with PNS-based HRWRA developed significantly higher RWD to increase a given fluidity than the other mixtures made with PCP-based HRWRA (0.15 versus 0.05 and 0.06). Therefore, for a given change in water content (ΔW), the CEM mixture made with PNS-based HRWRA exhibited smaller increase in fluidity, which reflects the greater robustness than mixtures made with PCP-based HRWRA. The CEM mixtures exhibited similar MWC and RWD values when PCP-based HRWRAs were used.

Effect of HRWRA type on workability responses of SCC

Fresh properties of SCC mixtures are summarized in Table 3. Regardless of the HRWRA and binder types, the targeted air content of 5% to 8% was achieved because AEA dosage was adjusted to secure the targeted value. Regardless of the binder type, concrete made with PNS-based HRWRA exhibited much higher AEA demand of 350 to 400 mL/m^3 compared to 20 to 90 mL/m^3 for the other mixtures prepared with PCP-based HRWRA. The HRWRA demand of the evaluated concrete varied from 1.7 to 7.0 L/m^3, depending on HRWRA-binder combination. As presented in Table 3, concrete made with PNS-based HRWRA had a significantly higher HRWRA demand of 7.0 and 5.8 L/m^3 when the B1 and B2 binders were used. The HRWRA demand ranged from 1.7 to 3.8 L/m^3 for mixtures made with PCP-based HRWRA. Regardless of the HRWRA, all of the optimized mixtures exhibited high passing ability with L-box blocking ratio (h_2/h_1) greater than 0.70, high filling capacity with caisson filling capacity greater than 80%, and adequate static stability with maximum surface settlement lower than 0.5%. The slump flow loss of the SCC after one hour of occasional agitation was limited to 50 mm.

The effect of HRWRA type on surface settlement varied with the binder type. In the case of SCC made with the B1 blended cement, the PNS mixture exhibited higher settlement value of 0.44% compared to 0.16% and 0.21% obtained for SCC prepared with PCP-based HRWRA, as presented in Fig. 4. This is attributed to the retarding effect of the PNS incorporated at relatively high concentration. On the other hand, SCC mixtures made with the B2 blended cement and two types of HRWRAs exhibited the same surface settlement of 0.49%. It is important to note that, regardless of the binder and HRWRA types, maximum settlement values of the evaluated mixtures are lower than 0.5%, which is recommended by Hwang et al. (7).

Effect of HRWRA type on mechanical and visco-elastic properties of SCC

Compressive strength, modulus of elasticity, drying shrinkage, and restrained shrinkage cracking results of the evaluated mixtures are summarized in Table 4. In general, the two SCC mixtures proportioned with PNS-based HRWRA developed lower 1-d compressive strength of approximately 4 and 11 MPa compared to 14 to 16 MPa for the three similar mixtures made with PCP-based HRWRA. This can be due to the relatively longer setting time of the PNS mixtures (Table 3). As presented in Table 4, the former SCC exhibited lower 56-d compressive strength of 40 to 45 MPa compared to 40 and 53 MPa for the SCC made with PCP-based HRWRA. Similarly, mixtures made with PNS-based HRWRA and the B1 binder had lower 56-d elastic modulus of 28.5 GPa compared to 30 to 35 GPa for similar mixtures prepared with PCP-based HRWRA and the same binder type (B1).

For a given HRWRA type (PNS), SCC made with the B2 binder developed higher 1-d compressive strength of 10.6 MPa compared to 3.7 MPa for the concrete prepared with the B1 binder. Similarly, the former concrete had higher 28- and 56-d compressive strength than the SCC made with the B1 binder. This can be in part due to the relatively high reactivity of blast-furnace slag in the B2 binder compared to fly ash in the B1 binder and lower air content of 5.8% for the B2 mixture compared to 7.0% for the SCC containing the B1 binder.

In general, SCC proportioned with PNS-based HRWRA and the B1 binder exhibited higher drying shrinkage after 56 days of drying compared to similar concrete made with

PCP-based HRWRA. For example, mixtures made with PNS HRWRA had higher shrinkage values of 660 μstrains compared to 615 and 555 μstrains for those prepared with PCP1 and PCP2 HRWRAs, respectively, when the B1 blended cement was used. However, for a given binder type (B1), SCC made with PNS-based HRWRA had significantly longer time to cracking of 17.2 days (restrained ring test) compared to 6.3 and 8.8 days for similar SCC prepared with PCP1 and PCP2 HRWRAs, respectively, despite the lower compressive strength and higher drying shrinkage values of the former concrete (Fig. 5). This is in part due to the relatively low elastic modulus of the PNS mixture, thus leading to greater tensile creep coefficient. Similarly, SCC proportioned with PNS HRWRA and B2 binder had longer time to cracking of 4.5 days compared to 2.8 days for the SCC made with PCP1 HRWRA and the same binder.

For a given HRWRA type, SCC made with the B1 binder exhibited longer time to cracking than similar SCC prepared with the B2 binder. For example, the B1-PNS mixture developed longer time to cracking of 17.2 days compared to 4.5 days for the B2-PNS mixture. As presented in Fig. 5, this spread is mainly due to relatively greater tensile creep coefficient and stress relaxation in tension for the B1-PNS mixture, thus reducing tensile stress by restrained shrinkage. On the average, at a given time, the B1-PNS mixture had approximately 60% lower tensile stress compared to the B2-PNS mixture. Similarly, the B1-PCP1 mixture exhibited relatively long time to cracking of 6.3 days compared to 2.8 days for the SCC made with the B2 binder and the same HRWRA (PCP1).

Effect of HRWRA type on transport properties and frost durability of SCC

The results of the transport properties, air-void system, frost durability, and resistance to de-icing salt scaling are summarized in Table 5. The mean 56-d RCP and chloride-diffusion coefficient values are compared in Fig. 6. For a given binder type, the SCC mixtures made with PNS-based HRWRA exhibited slightly lower diffusion coefficients of 2.2 and 2.6 × 10^{-12} m^2/s compared to the SCC made with PCP-based HRWRA that had values of 2.6 to 3.5 × 10^{-12} m^2/s. On the other hand, no significant spread was found in the RCP results of mixtures made with PNS- and PCP-based HRWRA. The B2-PCP1 concrete had the highest diffusion coefficient of 3.5 × 10^{-12} m^2/s and RCP value of 905 coulomb. The remaining mixtures had 56-d RCP values ranging between 505 to 620 coulomb.

The results of frost durability and de-icing scaling resistance of the mixtures made with various HRWRAs and different binder types are compared in Fig. 7. Regardless of the HRWRA, the optimized SCC exhibited excellent frost durability with durability coefficient greater than 94%. All mixtures had spacing factor lower than 200 μm, except for the B1-PCP2 concrete that had a spacing factor of 260 μm. The optimized SCC mixtures had excellent resistance to de-icing salt scaling with cumulative mass loss after 50 freeze-thaw cycles less than 80 g/m^2, regardless of the HRWRA type. This is in exception of the B1-PCP2 concrete that had a scaling value of 375 g/m^2, given its higher spacing factor value of 260 μm and lower hardened air content of 3.7% (Table 5).

The effect of the HRWRA type on the performance of hardened SCC is discussed in Fig. 8. The octagon plots are used to represent the data of eight response types determined for the five optimized SCC mixtures developed for repair applications. The responses include 56-d compressive strength, 56-d modulus of elasticity, drying shrinkage after 56 days of drying, time to cracking by restrained shrinkage (t_{cr}), 56-d chloride-diffusion coefficient, 56-d RCP, frost durability coefficient, and cumulative mass of scaling residues. Each branch of the octagon plot represents a response with the test value indicated at the extremity of that branch. The scale of each branch varies from the minimum result obtained for the five tested mixtures at the center of the plot, to the maximum value indicated at the extremity. Frost durability coefficient of 80% was used for the minimum value. For the drying shrinkage, elastic modulus, diffusion coefficient, RCP, and mass of scaling residue values are expressed in the opposite direction. This is done to maintain a representation whereby a broader plot would correspond to better performance.

For a given binder type, SCC made with PNS-based HRWRA exhibited relatively higher "closed-loop area" values of 15,660 and 17,600 compared to 8,720 to 14,600 for similar concrete prepared with PCP-based HRWRA, indicating superior performance of the former set of mixtures. The main difference between the performance of the hardened SCC made with PNS- and PCP-based HRWRAs lies in the time to cracking by restrained shrinkage that was longer for the former set of mixtures compared to similar mixtures made with PCP-based HRWRA. As presented in Fig. 8, the SCC mixtures made with PNS-based HRWRA had relatively longer time to cracking of 4.2 and 17.2 days compared to 2.8 to 8.8 days in the case of similar SCC mixtures prepared with PCP-based HRWRA. This is despite the relatively lower compressive strength and higher drying shrinkage of the SCC made with PNS-based HRWRA.

For a given HRWRA type, SCC proportioned with the B2 binder exhibited higher compressive strength, lower drying shrinkage, higher frost durability, and higher resistance to de-icing salt scaling. As presented in Fig. 8, mixtures proportioned with the B2 binder and the PNS- and PCP-based HRWRAs exhibited greater "closed-loop area" values of 17,600 and 14,600, respectively, compared to 15,660 and 8,720 for similar mixtures made with the B1 binder and the same HRWRA. SCC proportioned with B1 binder exhibited higher resistance to restrained shrinkage cracking than similar concrete made with B2 binder.

CONCLUSIONS

Given the testing program presented in this paper to evaluate the performance of SCC mixtures for repair of concrete infrastructures that were proportioned with 0.42 *w/cm* and two different types of ternary cements, the following conclusions can be made:

1. CEM and SCC mixtures proportioned with PNS-based HRWRA necessitated higher values of minimum water content to initiate flow and higher HRWRA demand, respectively, compared to mixtures prepared with PCP-based HRWRA. The CEM proportioned with PNS-based HRWRA exhibited higher relative water demand

values indicating lower sensibility of the mixtures made with PNS-based HRWRA to a given variation in water content than those made with PCP-based HRWRA.

2. For the selected binder type (B1 binder), the SCC proportioned with PNS-based HRWRA had greater maximum settlement values of 0.44% compared to 0.16% to 0.44% obtained in the case of similar SCC made with PCP-based HRWRA.

3. Concrete proportioned with PNS-based HRWRA and the B1 binder exhibited slightly higher drying shrinkage compared to similar concrete made with PCP-based HRWRA and the same binder (660 µstrains versus 555 to 615 µstrains). However, the PNS mixture developed longer time before cracking due to restrained shrinkage of 17.2 days compared to 6.3 to 8.8 days for similar SCC prepared with PCP-based HRWRA.

4. The HRWRA type does not seem to have any significant effect on transport properties, frost durability, and de-icing salt scaling resistance for the optimized SCC made with the same cement and *w/cm*. Optimized SCC mixtures exhibited 56-d RCP values lower than 900 coulomb, frost durability coefficients higher than 90%, and cumulative mass of scaling residues lower than 400 g/m^2, regardless of the HRWRA and binder type.

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Table 1 – Characteristics of chemical admixtures supplied by three different suppliers

Admixture codification	Solid content (%)	Specific gravity	Manufacturer recommended range of additions
PNS	40.5	1.21	400 – 4000 mL / 100 kg of binder
WRA3*	28.5	1.15	Up to 200 mL / 100 kg of binder
VEA3	42.5	1.21	1100 – 2700 mL/100 L of water
AEA3	10.5	1.00	30 – 100 mL/100 kg of cement
PCP1	27.1	1.09	260 – 780 mL/ 100 kg of binder
VEA1	39.1	1.12	130 – 920 mL / 100 kg of binder
AEA1	10	1.01	8 – 98 mL/ 100 kg of cement
PCP2	20	1.06	325 – 1300 mL/100 kg of binder
VEA2	50	1.35	Unknown
AEA2	19.3	1.02	30 – 320 mL/100 kg of cement
SRA**	49.3	1.23	130 – 520 mL / 100 kg of binder

*WRA = Water-reducing admixture, ** SRA = Set-retarding agent

Table 2 – Mixture proportioning of SCC and CEM mixtures (kg/m³)

Mixture	Binder (type)	Water	Coarse agg.	Sand	HRWRA L/m³ (type)	VEA L/m³ (type)	AEA mL/m³ (type)
B1-PNS*	475 (B1)	200	800	774	7.0 (PNS)	3.7 (VEA3)	400 (AEA3)
B1-PCP1	475 (B1)	200	800	774	2.9 (PCP1)	1.6 (VEA1)	90 (AEA1)
B1-PCP2**	475 (B1)	200	800	774	3.8 (PCP2)	0.2 (VEA2)	20 (AEA2)
B2-PNS*	475 (B2)	200	811	785	5.8 (PNS)	3.3 (VEA3)	350 (AEA3)
B2-PCP1	475 (B2)	200	811	785	1.7 (PCP1)	2.0 (VEA1)	45 (AEA1)
CEM-PNS	475 (B1)	200	-	828	0.2%*** (PNS)	-	-
CEM-PCP1	475 (B1)	200	-	828	0.2% (PCP1)	-	-
CEM-PCP2	475 (B1)	200	-	828	0.2% (PCP2)	-	-

* B1-PNS and B2-PNS were incorporated with a water-reducing admixture

** B1-PCP2 was proportioned with a set-retarding admixture

*** 0.2% solid content by mass of cementitious materials

Table 3 – Fresh properties of SCC made with various HRWRA and binder types

			w/cm = 0.42				
			B1-PNS	B1-PCP1	B1-PCP2	B2-PNS	B2-PCP1
HRWRA demand, L/m³			7.0	2.9	3.8	5.8	1.7
Slump flow, mm		10 min	650	670	665	675	670
		70 min	600	640	650	635	630
Filling capacity, %		10 min	94	88	91	94	93
		70 min	85	94	96	82	83
V-funnel flow time, sec		10 min	4.0	2.7	3.0	4.4	3.1
		70 min	4.3	2.8	3.2	4.4	4.0
L-box blocking ratio, h_2/h_1		10 min	0.83	0.78	0.80	0.82	0.75
		70 min	0.72	0.87	0.74	0.73	0.67
Rheological parameters	g, N.m	10 min	0.6	0.4	0.2	0.4	0.7
		70 min	0.6	0.4	0.3	0.6	0.9
	h, N.m.s	10 min	6.0	4.0	5.2	8.1	4.6
		70 min	7.3	4.6	4.9	10.6	7.0
Air volume, %		10 min	6.2	7.2	6.4	6.8	7.1
		70 min	5.0	7.0	5.7	5.0	7.4
Max. surface settlement, %			0.44	0.21	0.16	0.49	0.49
Rate of settlement at 30 min, %/h			0.14	0.08	0.07	0.15	0.16
Initial setting time, hour			13.5	9.2	8.7	9.7	8.0
Final setting time, hour			15.0	11.0	10.0	11.0	10.3

Table 4 – Mechanical and visco-elastic properties of SCC made with various HRWRA and binder types

		B1-PNS	B1-PCP1	B1-PCP2	B2-PNS	B2-PCP1
Compressive strength, MPa	1 d	3.7	14.8	15.7	10.6	16.1
	28 d	34.7	29.8	46.1	42.2	46.0
	56 d	40.2	40.0	52.9	45.1	51.8
Modulus of elasticity, GPa	28 d	27.0	28.0	32.0	28.5	29.5
	56 d	28.5	30.0	35.0	29.5	31.0
Drying shrinkage @ 56 d of drying, µstrain (after 7 d of water curing)		660	615	555	560	560
Time to cracking, d		17.2	6.3	8.8	4.5	2.8

Table 5 – Transport properties, air-void system, frost durability, and de-icing salt scaling of SCC made with various HRWRA and binder types (at 56 days)

	B1-PNS	B1-PCP1	B1-PCP2	B2-PNS	B2-PCP1
Rapid chloride-ion permeability, Coulomb	620	505	575	615	905
Chloride-diffusion coefficient, 10^{-12} m^2/s	2.6	3.4	2.6	2.2	3.5
	Air-void system				
Hardened air volume, %	8.0	8.2	3.7	5.8	7.5
Specific volume, α, mm^{-1}	29.1	27.7	24.7	26.0	31.2
Spacing factor, $\overline{L}$, µm	155	145	260	200	145
	Frost durability and de-icing salt scaling				
Elongation after 300 cycles, $\Delta L/L$, µm/m	80	125	130	60	185
Durability coefficient after 300 cycles, %	98	94	98	98	100
Scaling residue after 50 cycles, g/m^2	80	30	375	35	30

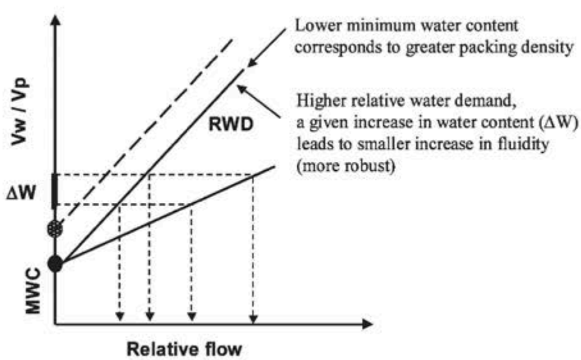

Fig. 1 – Variations in relative flow of concrete-equivalent mortar (CEM) and water-to-powder ratio

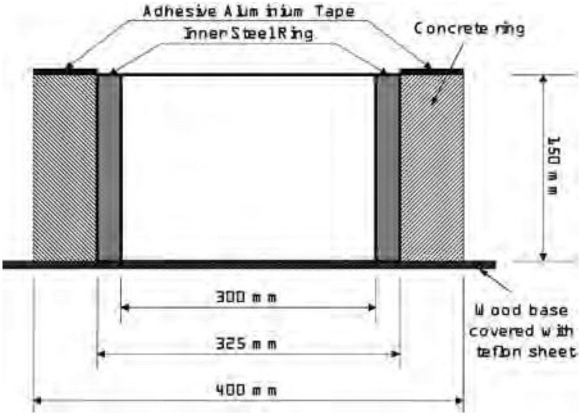

Fig. 2 – Dimensions of ring setup used for restrained shrinkage testing

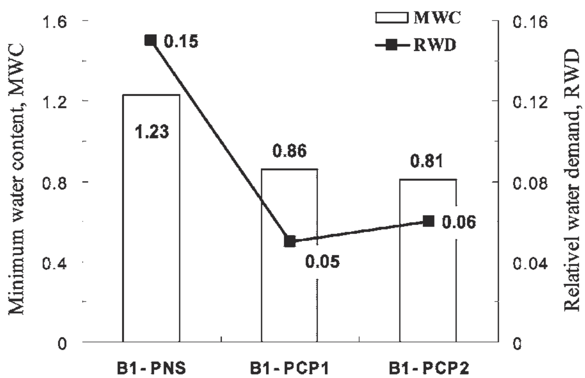

Fig. 3 – Effect of HRWRA type on flow characteristics of CEM

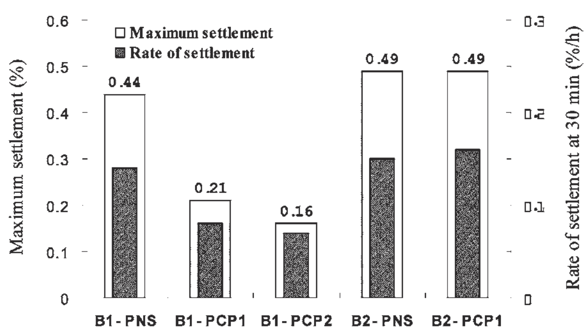

Fig. 4 – Comparison of static stability of SCC made with various HRWRA and binder types