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Transport and mechanical properties of self consolidating concrete with high volume fly ash

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ABSTRACT

This paper presents the transport and mechanical properties of self consolidating concrete that contain high percentages of low-lime and high-lime fly ash (FA). Self consolidating concretes (SCC) containing five different contents of high-lime FA and low-lime FA as a replacement of cement (30, 40, 50, 60 and 70 by weight of total cementitious material) are examined. For comparison, a control SCC mixture without any FA was also produced. The fresh properties of the SCCs were observed through, slump flow time and diameter, V-funnel flow time, L-box height ratio, and segregation ratio. The hardened properties included the compressive strength, split tensile strength, drying shrinkage and transport properties (absorption, sorptivity and rapid chloride permeability tests) up to 365 days. Test results confirm that it is possible to produce SCC with a 70% of cement replacement by both types of FA. The use of high volumes of FA in SCC not only improved the workability and transport properties but also made it possible to produce concretes between 33 and 40 MPa compressive strength at 28 days, which exceeds the nominal compressive strength for normal concrete (30 MPa).

1. Introduction

Self consolidating concrete (SCC) is a concrete which has little resistance to flow so that it can be placed and compacted under its own weight with no vibration effort, yet possesses enough viscosity to be handled without segregation or bleeding [1,2]. The most important advantage of SCC over conventional concrete is its flowability. Other advantages of using SCC include shorter construction periods, reduction in the labor cost, and better compaction in the structure especially in confined zones where compaction is difficult.

The common practice to obtain self-compactibility in SCC is to use new generation high range water reducers, to limit the maximum coarse aggregate size and content, and to use low water-powder ratios or use viscosity modifying admixtures. Therefore, one of the disadvantages of SCC is its cost, associated with the use of chemical admixtures and use of high volumes of Portland cement. High cement content usually introduces high hydration heat, high autogenous shrinkage and high cost. Moreover, the consumption of natural resources and carbon dioxide emissions associated with cement production can cause serious environmental impacts. One solution to reduce the cost of SCC is the use of mineral admixtures such as limestone powder, natural pozzolans, ground granulated blast furnace slag and fly ash (FA). Among these materials FA, a by-product of thermal power plants, has been reported to improve the mechanical properties and durability of concrete when used as a cement replacement material [3]. In Turkey, more than 13 million tons of FA has been produced per year, unfortunately, because of insufficient data on the properties of fly ash and concrete incorporating FA, only 5% of this amount is utilized in construction industry [4].

The amount of FA in concrete for structural use is generally limited to 15–25% of the total cementitious materials. Concretes having large amounts of FA (usually above 50%) are termed as high-volume FA (HVFA) concrete. HVFA concrete was initially developed for mass concrete applications to reduce the heat of hydration [5]. Canada Centre for Mineral and Energy Technology first developed high volume FA concrete for structural use by the late 1980's [6]. In a study undertaken by Bouzoubaâ and Lachemi, it was shown that it was possible to design SCC with high volumes of FA by replacing up to 60% of cement with Class F FA [7]. Moreover, Nehdi et al. also studied the durability of SCC with high volume replacement materials (FA and ground granulated blast furnace slag), and concluded that SCC with 50% replacement with Portland cement of FA and slag can improve the workability and durability [8].

The objective of this study was to determine the effects of high volumes of high-lime and low-lime FA replacement on the transport and mechanical properties of SCC. The workability properties of SCCs were observed through, slump flow time and diameter,

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V-funnel flow time, L-box height ratio, and segregation ratio. Later, hardened properties were evaluated by compressive strength, split tensile strength and drying shrinkage, and the transport properties were evaluated by absorption, sorptivity and rapid chloride permeability tests. The control mixture included only Portland cement (PC) as a binder. Remaining mixtures had high-lime and low-lime FAs replacing from 30% to 70% by weight of PC. For all the mixtures, the total amount of cementitious material (cement + fly ash) and the amount of high range water reducer were kept constant.

2. Experimental studies

2.1. Materials and mixture proportions

The cement used in all mixtures was a normal Portland cement CEM I 42.5R (PC), which correspond to ASTM Type I cement. Throughout the study, two different fly ashes were used. One FA, which had a lime content of 10.07%, was called high-lime FA (FA_H). The other FA, which had a lime content of 2.21%, was called low-lime FA (FA_L). Limestone powder (LP) was used as a fine material (5 μm average diameter) in all mixtures. The chemical and physical properties of the cement, two types of FA, and limestone powder are given in Table 1. The particle size distributions of these materials were obtained by a laser scattering technique and are given in Fig. 1. It can be concluded from Fig. 1 that FA_L was finer than FA_H. However, this observation was contradictory to the specific surface data, as the blaine fineness of FA_H and FA_L were 3060 and 2890 cm^2/gr, respectively. Therefore, the particle morphology of FAs was also determined as shown in Fig. 2. The scanning electron microscope (SEM) images showed that the particles of low-lime FA (FA_L) had rather smooth spherical particles in comparison to the high-lime FA (FA_H). A crushed limestone with a maximum nominal size of 20 mm was used as the coarse aggregate and natural river sand was used as the fine aggregate. The coarse and fine aggregates had specific gravities of 2.70 and 2.40, and water absorptions of 0.3% and 2.4% respectively. A polycarboxylic-ether type high range water reducer (HRWR) with a specific gravity of 1.08, pH of 5.7 and a solid content of 40% was also used in all concrete mixtures.

Table 1
Chemical composition and physical properties of the Portland cement, fly ashes and limestone powder.

Chemical composition	PC	FA_H	FA_L	LP
CaO (%)	63.27	10.07	2.21	54.97
SiO_2 (%)	19.61	48.08	54.13	0.01
Al_2O_3 (%)	5.86	25.87	25.73	0.17
Fe_2O_3 (%)	3.40	4.54	6.43	0.05
MgO (%)	0.95	1.46	2.12	0.64
SO_3 (%)	2.45	0.55	0.11	0.00
K_2O (%)	0.54	1.22	4.33	0.00
Na_2O (%)	0.47	0.73	0.47	0.00
Loss on Ignition (%)	3.02	1.01	1.34	43.66
Physical properties				
Specific gravity	3.18	2.27	2.08	2.70
Blaine fineness (cm^2/g)	3629	3060	2890	–

The mixture proportions of the mixtures are summarized in Table 2. As seen from Table 2, eleven concrete mixtures were prepared. As a binder, the control mixture included only PC. Remaining mixtures had a high-lime FA and a low-lime FA replacing from 30% to 70% by weight of PC. For all the mixtures, the total amount of cementitious material (PC + FA) and the amount of chemical admixture were kept constant. Water was added to the mixture until the SCC characteristics, i.e. adequate slump flow diameter, V-funnel flow time and L-box height ratio [9], were observed; therefore, the water-cementitious material ratio (W/CM) was not kept constant and was observed to change between 0.30 and 0.35.

2.2. Experimental program and test procedures

When the mixing procedure was completed, tests were conducted on the fresh concrete to determine slump flow time and diameter, V-funnel flow time, L-box height ratio and segregation ratio. Segregation was also visually checked during the slump flow test. From each concrete mixture, 100 × 200-mm cylinder specimens were cast for the determination of compressive strength, split tensile strength and durability tests (absorption, sorptivity and rapid chloride permeability tests) and four 70 × 280-mm cylinder specimens were cast for the determination of drying shrinkage. All specimens were cast in one layer without any compaction. At

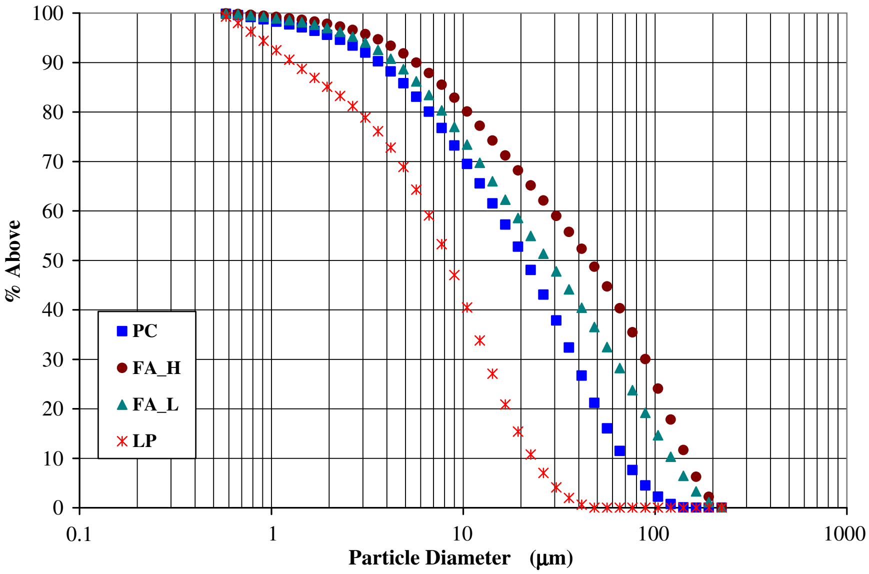
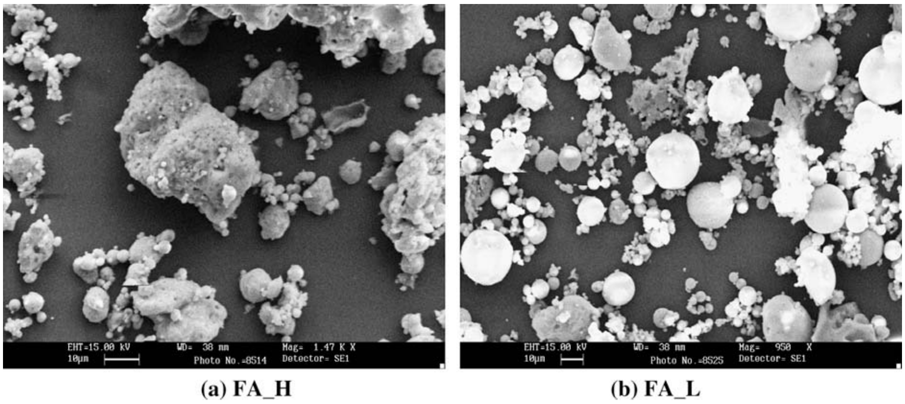


Fig. 1. Particle size distribution of Portland cement, fly ashes, and limestone powder.



(a) FA_H (b) FA_L

Fig. 2. Secondary electron images of the fly ashes showing their particle morphology.

Table 2
Mixture proportions of SCC.

Mix ID	W/CM[a]	Ingredient (kg/m^3)							
		Water	PC	FA_H	FA_L	LP	Aggregate		HRWR
							Fine	Coarse	
1	0.35	173.5	500	0	0	71.0	967	639	6.75
2	0.35	173.5	350	150	–	69.2	939	621	6.75
3	0.35	175.5	300	200	–	68.3	927	613	6.75
4	0.35	173.9	250	250	–	67.8	920	608	6.75
5	0.35	173.5	200	300	–	67.1	912	603	6.75
6	0.35	173.5	150	350	–	66.4	902	597	6.75
7	0.34	169.0	350	–	150	69.0	937	620	6.75
8	0.32	162.0	300	–	200	68.9	935	618	6.75
9	0.30	149.5	250	–	250	69.3	941	622	6.75
10	0.30	149.5	200	–	300	68.4	929	614	6.75
11	0.30	142.8	150	–	350	68.2	927	613	6.75

[a] CM: cementitious material (PC + FA).

the age of 24 h, the specimens were removed from the molds and stored in lime saturated water at 21 ± 2 °C until the date of testing.

2.2.1. Tests on fresh concrete

Workability properties of SCC mixtures was evaluated through the measurement of slump flow time (T_{50}) to reach a concrete 50 cm spread circle, slump flow diameter (D), V-funnel flow time ($t_{\text{V-f}}$), L-box height ratio and GTM sieve stability (segregation ratio) according to the "Specification and Guidelines for SCC" prepared by EFNARC (European Federation for Specialist Construction Chemicals and Concrete Systems) [9]. All tests were repeated twice with a new batch of SCC mixture and the results indicate that the tests were repetitive.

2.2.2. Tests on hardened concrete

Tests performed on hardened concrete can be grouped into two; tests to determine the mechanical properties and tests to determine the transport properties. As for the mechanical properties, the compressive strength of the concrete specimens was determined at 7, 28, 90, 180 and 365 days in accordance with ASTM C39, the split tensile strength of the concrete specimens was determined at 28, 90 and 180 days using three specimens in accordance with ASTM C42, and the drying shrinkage of the concrete specimens was measured up to 365 days using four specimens in accordance with ASTM C157. The transport properties were determined at 28, 90, 180 and 365 days through the absorption, sorptivity and rapid chloride permeability tests using four specimens at each age. Brief explanation of the transportation test procedures are provided in the following sections.

2.2.2.1. Absorption test. This test is based on ASTM C 642 for testing the voids in hardened concrete. Four 100 mm in diameter and 50 mm in height disc specimens were dried in an oven at 105 ± 5 °C to constant weight. The specimens were then immersed in tap water and weighed every 24 h to check the increase in mass, until the increase in mass was less than 0.5% of the heavier mass which defines the saturation stage. In this test, water absorption can only take place in pores which were emptied during drying and filled with water during the immersion period. At the result of this test, the total volume of penetrable pores was determined.

2.2.2.2. Sorptivity test. The sorptivity test was based on Hall's sorptivity test [10]. The sorptivity test consisted of registering the increase in mass of a disc specimen (100 mm in diameter and 50 mm in height) at given intervals of time (1, 2, 3, 4, 6, 8, 12, 16, 20, 25, 36, 49, 64, 81, and 120 min) when permitted to absorb water by capillary suction. The specimen was first dried according to the procedure described in the absorption test. Only one surface of the specimen was allowed to be in contact with water, with the depth of water between 3 and 5 mm. The sides of the specimen were sealed with a silicone coating in order to have one-directional flow through the specimen. The rate of absorption (i in mm), defined as the change in mass (g) divided by the cross sectional area of the test specimen (mm^2) and the density of water at the recorded temperature (g/mm^3), was plotted against square root of time ($t^{1/2}$ in min$^{1/2}$). The slope of the obtained line defines the sorptivity of the specimen during the initial two hours of testing. This test was chosen as it measures the rate of ingress of water through unsaturated concrete.

2.2.2.3. Rapid chloride permeability test (RCPT). The RCPT test is based on the ASTM C 1202 for determining the chloride permeability of hardened concrete. In this test, a water saturated 50-mm thick, 100-mm diameter concrete specimen is subjected to a 60 V applied DC voltage for 6 h. One end of the specimen is in contact with 0.3 M NaOH solution, the other end with 3.0% NaCl solution. The total charge passed during 6 h is determined. The total charge passed, in coulombs, is related to the concrete's ability to resist chloride ion penetration. As more chloride ions migrate into the concrete, more current can pass through, and the total charge passed increases.

3. Results and discussions

3.1. Fresh concrete properties

Basic workability requirements for an acceptable SCC are summarized by Khayat [11] as; excellent deformability, good stability, and lower risk of blockage. In this experimental program these three properties are measured respectively by, slump flow, V-funnel, GTM sieve stability and L-box tests. Table 3 lists the test results performed on fresh concrete. Also included in that table are the water-cementitious material ratio (W/CM) of the mixture, % FA replacement and the fresh concrete air content. The slump flow diameters of all mixtures were in the range of 665–775 mm, slump flow times are less than 4.4 s, the V-funnel flow times ($t_{\text{V-f}}$) were in the range of 9.4–19.2 s, the L-box height ratios were in the range of 0.85–0.95, and the segregation ratio as measured by the GTM sieve stability test was less than 15%. All workability test results were in the range established by EFNARC [9] except some V-funnel flow times. V-funnel measurements of some mixtures exceeded the upper limit; however, all concrete mixtures filled the molds by its own weight without the need for vibration. In addition to the above properties, visual inspection of fresh concrete did not indicate any segregation or considerable bleeding in any of the mixtures during the slump flow test. Therefore, all mixtures were considered to be SCC.

Also observed in Table 3 is the change in W/CM for approximately similar workability measure, i.e. similar D, T_{50}, and $t_{\text{V-f}}$. The control and the high-lime FA (FA_H) mixtures had slightly higher W/CM than low-lime FA (FA_L) mixtures. The water-reducing effect of FA_L was more pronounced with increased replacement which was not observed in mixtures with a FA_H. This could be explained by the morphology of the FAs obtained through secondary electron images of the FAs (Fig. 2). The geometry of the FA_H consisted of irregular shapes with a rough surface texture. However, the FA_L had a spherical shape with a smooth surface texture. Therefore, the lubricating effect of the spherical particle shape and the smooth surface characteristics are the main reasons for a decrease in the W/CM, which was also reported by other researchers [12–14].

3.2. Hardened concrete properties

3.2.1. Mechanical properties

The compressive strength, split tensile strength and drying shrinkage test results are given in Table 4. Table 4 presents the average of the compressive strength as determined from three cylindrical specimens at each age. As it was expected, increasing

Table 3
Fresh properties of the SCC mixtures.

Mix. ID	W/CM	FA (%)	L-box (h_2/h_1)	Slump flow		V-funnel flow time, $t_{\text{V-f}}$ (s)	Segregation ratio (%)	Air content (%)
				D (mm)	T_{50} (s)			
1	0.35	0	0.87	665	4.2	12.7	1.4	1.4
2	0.35	30	0.95	715	3.1	15.8	1.6	1.6
3	0.35	40	0.85	730	2.0	10.7	2.6	2.6
4	0.35	50	0.90	710	4.4	19.2	2.2	2.2
5	0.35	60	0.85	740	2.5	12.8	3.4	3.4
6	0.35	70	0.85	725	3.9	15.8	3.2	3.2
7	0.34	30	0.95	765	1.3	10.2	3.2	3.2
8	0.32	40	0.95	745	2.3	11.7	3.2	3.2
9	0.30	50	0.88	738	3.5	15.1	2.5	2.5
10	0.30	60	0.95	770	1.9	9.4	3.2	3.2
11	0.29	70	0.95	775	2.2	10.9	4.0	4.0
EFNARC		Min	0.80	655	2.0	6.0	0.0	–
Recommends		Max	1.00	800	5.0	12.0	15.0	–

Table 4
Compressive strength, split tensile strength and drying shrinkage test results of the SCC mixtures.

Mix. D	Drying shrinkage strain × 10^{-6} 365 days	Compressive strength (MPa)					Split tensile strength (MPa)		
		7 days	28 days	90 days	180 days	365 days	28 days	90 days	180 days
1	695	55.9	62.2	69.9	71.0	74.1	5.07	5.14	5.55
2	499	40.6	57.3	64.9	66.2	70.7	4.39	4.89	4.94
3	457	37.4	59.1	61.5	68.3	67.3	4.50	4.84	5.64
4	462	24.5	40.8	47.1	51.0	54.6	3.40	4.36	4.73
5	411	21.9	38.1	48.8	51.7	56.4	3.21	3.92	4.35
6	452	14.9	34.4	39.4	43.0	51.8	3.44	3.64	4.19
7	362	38.6	52.4	64.9	69.2	75.6	4.71	5.06	5.09
8	449	34.5	52.3	63.2	67.2	75.6	3.87	4.15	5.29
9	473	32.0	47.5	59.9	68.7	70.0	4.03	4.74	5.22
10	598	22.8	39.9	52.1	62.6	65.8	3.69	4.44	4.90
11	427	18.3	32.8	45.0	53.7	61.6	3.26	3.72	4.55

the FA content are reduced the compressive strength considerably, especially at earlier ages. At 7 days, compared to the control mixture the cylinder compressive strength was reduced by 29% in average for a 30% FA replacement, and by 70% for a 70% FA replacement. While at 28 days, the strength of the 30% FA containing SCC mixtures was only slightly lower (12% in average) than the control mixture, though a 70% FA replacement still resulted in a 46% average strength reduction.

At later ages, the contribution of FA to compressive strength became more pronounced. At 90 and 180 days the differences between compressive strength of the control mixture and the mixtures containing FA are reduced, especially for the mixtures with low-lime FA. The reason behind this observation was the slower activity of the low-lime FA. Moreover, the 90, 180 and 365-day compressive strengths were higher for the low-lime FA when compared to the high-lime FA because of the reduced W/CM ratio for those mixtures. At the end of 365 days, the compressive strength of SCC mixtures with 30% and 40% low-lime FA replacement were equal (75.6 MPa) and higher than the control mixture (74.1 MPa). Dunstan points out that the contribution of FA to strength is more sensitive to the W/CM ratio than the contribution of cement, and consequently concrete containing FA should be prepared at a W/CM ratio as low as possible [15]. The results of equal strength at the end of 365 days for 30% and 40% of low-lime FA replacement confirmed that at a lower W/CM ratio, the contribution to concrete strength by FA was greater than at a higher W/CM ratio as the W/CM ratio was 0.34 and 0.32 for the SCC incorporating 30% and 40% low-lime FA, respectively.

The results of split tensile strength tests at 28, 90 and 180 days are presented in Table 4. Each value in Table 4 represents the aver-

Table 5
Absorption and sorptivity tests results of the SCC mixtures.

Mix ID	Volume of penetrable pores (%)				Sorptivity index (mm/min$^{1/2}$)			
	28 days	90 days	180 days	365 days	28 days	90 days	180 days	365 days
1	10.4	8.5	8.5	8.7	0.104	0.09	0.053	0.059
	[5.6][a]	[9.3]	[6.6]	[10.8]	[25.3]	[20.2]	[20.7]	[9.5]
2	8.3	7.3	7	6.8	0.09	0.063	0.056	0.055
	[3.5]	[6.6]	[4.0]	[8.8]	[2.5]	[7.4]	[27.6]	[19.4]
3	8.8	6	6.3	6.3	0.079	0.042	0.051	0.052
	[4.6]	[9.1]	[15.7]	[6.4]	[11.3]	[6.3]	[21.5]	[19.1]
4	13	6.4	6.6	6.1	0.123	0.052	0.057	0.053
	[11.3]	[6.0]	[2.1]	[11.9]	[1.3]	[11.5]	[15.0]	[2.2]
5	10	6.5	6.3	6.3	0.077	0.047	0.047	0.046
	[12.1]	[4.8]	[15.7]	[5.2]	[25.2]	[7.3]	[14.8]	[22.3]
6	9.7	7.9	7.4	7.2	0.074	0.067	0.066	0.063
	[5.3]	[10.9]	[5.6]	[7.7]	[1.4]	[8.5]	[10.8]	[9.5]
7	8.8	6.5	5.4	5.3	0.071	0.038	0.046	0.044
	[4.9]	[13.0]	[15.9]	[16.1]	[8.0]	[13.3]	[16.2]	[16.4]
8	8.3	7.1	6.1	5.6	0.074	0.036	0.04	0.04
	[3.9]	[7.9]	[7.2]	[4.5]	[16.1]	[14.0]	[26.4]	[16.2]
9	6.1	5.7	6.1	5.4	0.057	0.041	0.043	0.04
	[4.6]	[5.6]	[9.2]	[12.4]	[2.6]	[13.4]	[6.2]	[16.1]
10	5.7	5.5	5.3	5.2	0.048	0.043	0.039	0.038
	[8.1]	[13.9]	[3.5]	[0.8]	[10.5]	[22.0]	[17.2]	[18.9]
11	5.7	5.1	4.9	5	0.048	0.039	0.023	0.034
	[9.0]	[5.5]	[5.5]	[1.4]	[10.4]	[6.6]	[16.7]	[9.3]

[a] Numbers in parentheses are the coefficients of variation (%).

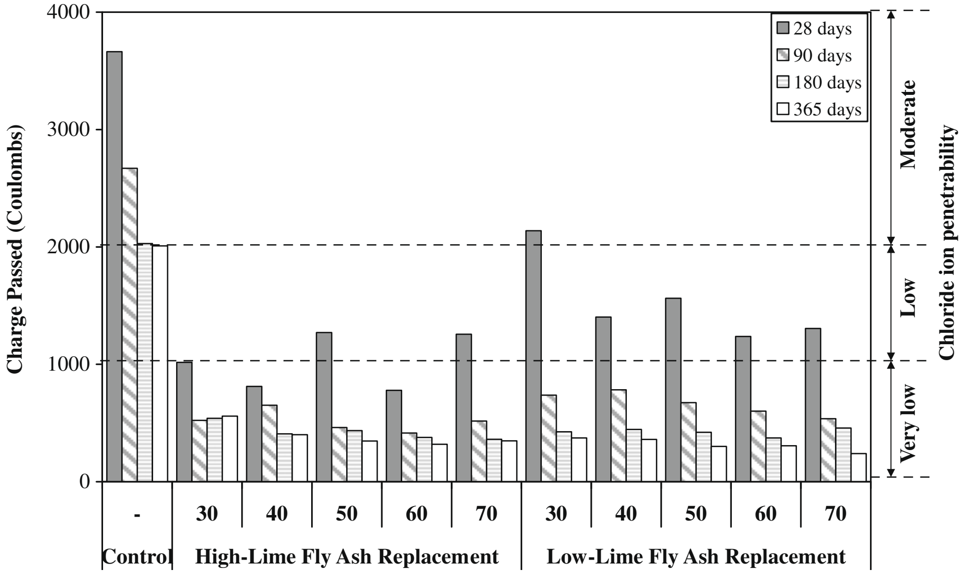


Fig. 3. Total charge passed after 6 hours for SCC mixtures.

age split tensile strength results of three specimens. The split tensile strength ranges from 3.21 to 5.07 MPa, 3.64 to 5.14 MPa and 4.19 to 5.64 MPa at 28, 90 and 180 days, respectively. The split tensile strength of all SCC mixtures increased with age. The results showed that, an increase in the FA content decreased the split tensile strength of the SCC especially at 28 days. SCC mixtures containing 30–50% FA replacement showed higher split tensile strength than SCC mixtures containing 60–70% FA replacement. This indicates that up to a 50% of FA replacement may have positive effects on the interfacial bond between the paste and aggregates. The mixtures containing 60–70% FA showed lower tensile strength probably due to the weaker bond between the matrix and the aggregates.

Drying shrinkage test results obtained at 365 days for all SCC mixtures are also presented in Table 4. The drying shrinkage strains at the age of 365 days ranged between 362 and 695 micro-strain. SCC mixtures with no FA (Control Mixture) had exhibited the highest drying shrinkage of 695 micro-strain at the end of 365 days. The incorporation of low-lime and high-lime FAs reduced the drying shrinkage in comparison with the control SCC mixture. A possible mechanism contributing to the reduction of drying shrinkage in ECCs is the matrix densification due to FA addition, which may prevent internal moisture evaporation [16]. The matrix densification is typically attributed to the shape, pozzolanic property, and micro-filler effect of FA. An alternative mechanism is that unhydrated FA particles serve as fine aggregates to restrain

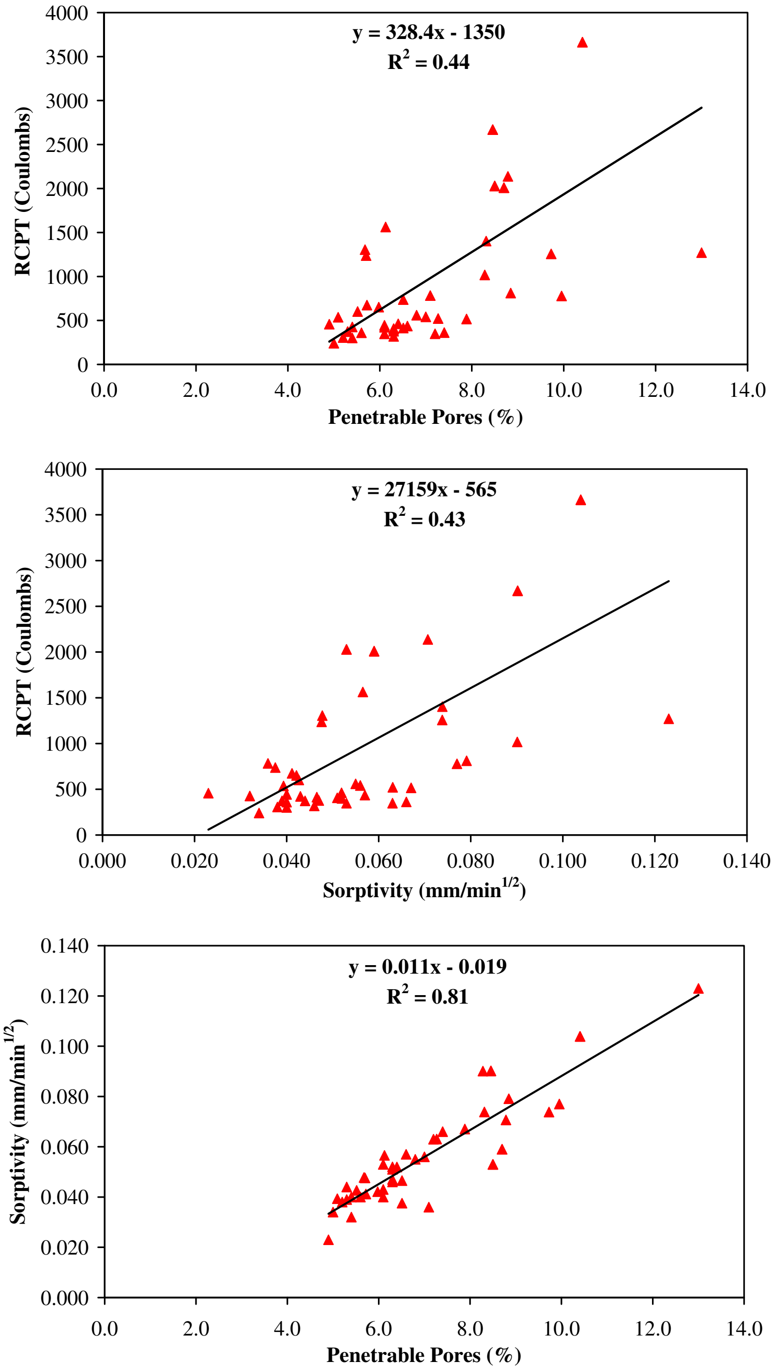


Fig. 4. Relations of different transport properties of SCC mixtures.

the shrinkage deformation [14,17,18]. On the other hand, there are no definite trends relating FA content to shrinkage which are consistently visible throughout the data. Bouzoubaa and Lachemi also reported that any significant difference for drying shrinkage between normal concrete and SCC incorporating FA up to 60% by mass could not be found [7].

3.2.2. Transport properties

Table 5 presents the absorption and sorptivity of the SCC mixtures determined at 28, 90, 180 and 365 days, respectively. Both absorption and sorptivity tests are based on water flow into unsaturated concrete, through large connected pores. As seen in Table 5, both of these test methods resulted a rather crude resolution as dictated by their relatively high coefficient of variation at all ages. The reduction in transportation properties calculated from sorptivity and absorption tests from 28 days of age to 90 days of age was measurable. On the other hand there was not any measurable reduction in the transport properties as measured by absorption and sorptivity tests beyond 90 days of age. This might be attributed to the high hydration degree of all SCCs studied in this work.

Fig. 3 shows the rapid chloride ion migration of all SCC mixtures measured at 28, 90, 180 and 365 days. The classification ranges given in the ASTM C 1202 are illustrated graphically in Fig. 3 by horizontal gridlines. When FA was incorporated in the SCC mixtures, RCPT tests showed a reduction in total charge passed regardless of the FA type. Total charge passed results for SCC mixtures containing high-lime FA were always lower than that for the control concrete at the same W/CM ratio. On the other hand, increases in high-lime FA content showed no significant effect on chloride ion penetration. The chloride ion penetration of concrete with low-lime FA was also lower than the concrete mixture without FA and the reductions increased with the increasing FA content. At the end of 180 and 365 days, all total charge passed results for the high and low-lime FA were nearly same. The effect of FA on the chloride ion penetration of concretes was also studied by other researchers. For example, Shi states that the use of supplementary cementing materials such as FA may have a significant effect on the chloride migration of concrete as measured by the RCPT test [19].

The reason for the lower chloride ion penetration of concrete with FA may be attributed to the presence of FA. The use of FA probably resulted in a denser matrix, by reducing the pore size and thickness of transition zone between aggregate and surrounding cementitious matrix [20,21]. It should also be noted that the RCPT results depends on the electrical conductivity of pore solution, which is determined by the composition of the pore solution. The electrical conductivity or RCPT value of a concrete can be reduced by lowering the alkalinity of concrete pore solution. When FA (especially with low-lime and low alkali contents) is used to partially replace PC, the concentration of alkali ions and associated hydroxyl ions in the pore solution generally decreases significantly, and the extent of this reduction depends also on FA replacement level [22]. Because of the expected differences in electrical resistance between two ECC mixtures, however, the electrical conductivity values may also be different. As a result, the RCPT values may reflect this difference and therefore should be interpreted with care.

Absorption and sorptivity tests are based on measuring the ingress of water to the capillary pores of an unsaturated concrete, whereas RCPT test is based on the electrical conductivity of the concrete specimen through its connected capillary pores. The relations between each of these permeability measures are presented in Fig. 4. As seen in that figure, the highest correlations ($R^2 = 0.81$) were observed between the volume of penetrable pores and the sorptivity, as they measure the same property, i.e. the ingress of water to unsaturated concrete. On the other hand, the correlations between RCPT and the other two permeability measures are quite weak.

4. Conclusions

This study discusses an experimental program carried out to investigate the effects of incorporating high volume fly ash replacement on the flow characteristics of SCC in the fresh state, and mechanical and transport properties in the hardened state. The following conclusions can be drawn according to the results of this study:

- The geometry and surface roughness of the fly ash affected the workability properties of SCC. In this study, the low-lime FA particles had a spherical geometry and a smooth surface, therefore caused a reduction in the water requirement of SCC.
- Incorporation of both types of fly ashes at high volumes resulted in an acceptable SCC in terms of compressive strength. Even though, replacing 60% and 70% Portland cement with fly ash resulted in considerable compressive and split tensile strength reductions at early ages, these reductions were partially off-set after 28 days. Moreover, it can be concluded that incorporating high volumes of fly ash made it possible to produce normal strength SCC with 28 day compressive strengths of 33–40 MPa, which is the regular strength grade for concrete in many applications. High volume fly ash SCCs with different compressive strength may be selected for use in different applications.
- For the drying shrinkage, both low-lime and high-lime fly ashes reduced the drying shrinkage of SCC mixtures. It may be a result of matrix densification and/or unhydrated fly ash constraint effect. However, there are no definite trends relating fly ash inclusion level to drying shrinkage.
- When evaluating the durability of SCC by its transport properties as measured by rapid chloride permeability test, absorption and the sorptivity tests, the addition of fly ash at high volumes seemed to be beneficial (especially low-lime fly ash), leading to a more durable concrete. The volume of penetrable pores as measured with the absorption test had a reasonably good linear correlation with the sorptivity test as measured within the first two hours of immersion due to the fact that both tests were based on measuring the ingress of water to the capillary pores of an unsaturated concrete. However, both of these test methods could not measure the reduction in transport properties after 90 days. After 90 days, the reduction in the transport properties was measurable, especially with the rapid chloride permeability test.

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