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MECHANICAL & DURABILITY PROPERTIES OF ENGINEERED CEMENTITIOUS COMPOSITES WITH DIFFERENT AGGREGATES

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ABSTRACT

This paper presents the outcome of a study conducted to exhibit the effect of micro-silica sand and mortar sand on fresh, mechanical and durability properties of Engineered Cementitious Composites (ECCs). ECC is a ductile concrete characterized by strain hardening and multiple-cracking behavior under tension and shear. This study used locally available aggregates instead of standard micro-silica sand to produce cost-effective, sustainable and green ECC mixtures to be used for construction applications. ECCs prepared by both types of sands exhibited almost similar behaviour in terms of fresh, mechanical and durability properties which indicated the viability of producing ECC mixtures with mortar sand. In addition, the behaviour of a standard ECC can still be achieved when producing ECCs made of high volume fly ash (up to 70% cement replacement) along with local mortar sand. By employing results of this research, correlations were derived between mechanical and durability properties.

Keywords: Sustainable, green, ECC, fresh, mechanical, durability

1. INTRODUCTION

Engineered Cementitious Composites (ECCs) have been developed in the last decade. It is one of special types of concrete that feature high ductility and damage tolerance under maximum loadings, such as tensile and shear loadings (Li 2003; Li 1997). ECC is differentiated from normal and Fiber Reinforced Concrete (FRC) through its matrix design; the latter relies on steel reinforcement for crack width control while ECC relies on micromechanics of first crack initiation, fiber bridging and steady-state flat-crack propagation mode. By crack width control, ECC can achieve up to 3% tensile strain capacity under uniaxial tensile loading, 300-500 times greater than normal concrete, by employing only 2% of PVA fiber content by volume (Li 1997). In order to achieve high composite tensile ductility, the formation of multiple cracking properties in ECC is essential. Even at ultimate loadings, ECC can still supress crack widths to less than 60 μm which helps to improve the long-term durability, water tightness and serviceability. These properties, together with relative ease of production, including self-consolidating casting (Kong et al. 2003a; Kong et al. 2003b) and shotcreting (Kim et al. 2003), make ECC suitable for various civil engineering applications. Although, ECC typically uses a mix design similar to many different fiber concretes, it can show unique characteristics. This depends on achieving the unique strain-hardening and multiple-cracking behaviours by tailoring ECC microstructure (Li 1997).

To achieve strain hardening behavior in ECC, two criteria should be considered; the first is strength which is responsible for initiating the cracks in ECC composites and assures that the applied tensile stresses are always kept below the maximum capacity of fiber bridging to form additional cracks in the crack plan; otherwise multiple cracking behaviour terminates earlier. The second criterion is energy which is responsible for switching the crack type from Griffith-type cracks in the case of FRC tension-softening behaviour to a steady-state, flat-crack propagation mode in the case of ECC strain-hardening behaviour. Therefore, once the crack initiated in FRC, its crack length and width increases faster than in the case of ECC which is characterized by constant crack width during crack elongation. In other words, the energy that comes from applied loads in ECC composites has to be always less than or equal to the energy absorbed by fiber bridging process during the crack propagation in order to keep the crack opening constant; otherwise localized crack formation occurs leading to terminate ECC multiple-cracking behaviour earlier (Kanda & Li 1998; Nawy 2008)

It is well known that aggregates occupy most of concrete volume. Therefore, aggregates have a significant role in conventional concrete to work as economic filler, in addition to enhancing the dimensional stability and increasing the wear resistance for normal concrete (Mindess et al. 2003). Due to the strength increase induced by the presence of aggregates, a production of tougher concrete pastes results (Mehta & Monteiro 2006). This can delay the crack initiation and increase the fracture energy for the matrix when the tortuosity of the crack path is increased. However, once the crack has initiated, crack propagation increases and the crack width widens dramatically which is not a favored situation in ECC. In contrast, controlled crack initiation is needed for EEC, keeping a steady-state flat-crack propagation mode and resulting in multiple cracking as well. In addition, when the size of aggregate increases in ECC, the uniform dispersion of fibers will be difficult to achieve, leading to more clumping. Therefore, the use of aggregates in standard ECC mixes was recommended to be micro-silica sand with maximum grain size of 250 μm and a mean size of 110 μm instead of coarse aggregate (Sahmaran et al. 2009).

Based on ASTM C618-12, there are two types of fly ash, high calcium Class-C which is a by-product normally produced from burning sub-bituminous coals and low calcium Class-F which is a by-product normally produced from bituminous coals. Class-C fly ashes differ from Class-F fly ashes in that they are self-hardening even without the presence of cement. Supplementary cementing materials (SCM's) such as fly ash are materials that can be added as cement replacement to achieve several advantages. When cement is properly replaced by fly ash, it can improve the properties of fresh and hardened concrete, in some cases reduce the material cost of concrete, and reduce the environmental impacts (Mehta 1985; Mindess et al. 2003). Moreover, it was reported that the addition of High Volume Fly Ash (HVFA) enhanced the fiber pull-out but reduced the composite strength (Peled & Shah 2003). In addition, the spherical shape of fly ash can improve the workability that enhances fiber dispersion in ECC mixes and reduces the water demand as well (Wang & Li 2007; Mindess et al. 2003). Moreover, increased fineness of fly ash especially Class-F can reduce the fiber/matrix interface bond and matrix toughness of ECCs by increasing the packed amount of un-hydrated fly ash particles leading to enhancement of the tensile strain capacity, allowing for more multiple-cracking formation. Fineness of fly ash can improve concrete long-term durability by improving the permeability against the ingress of aggressive environments (Lepech & Li 2009; Wang & Li 2007; Yang et al. 2007).

Although the use of aggregates in ECCs with bigger grain size will increase the fracture energy and the use of fly ash in ECC mixtures will reduce the fracture energy, an efficient combination can still be obtained with locally available mortar sands and high volume SCM's such as Class-F fly ash to produce effective ECC mixtures. The production of ECC mixtures by using locally available aggregates has not received enough attention, such as the use of silica sand to demonstrate the performance of ECC's (Sahmaran et al. 2009). Therefore, the significance of this research is to design a new class of ECC's produced by locally available sands instead of standard ECC mixtures produced with micro-silica sand without sacrificing the strain hardening and multiple cracking behaviours of standard ECC mixtures.

Deterioration of expansion joints of a bridge due to the accumulation of debris can lead to severe damage to the bridge decks and substructures. The durability of the bridge as a whole can be compromised by water leaking and aggressive chemicals flowing through concrete cracks which will lead to cracking, wearing, corrosion, spalling and eventual disintegration of the concrete deck slabs. In contrast, budget allocations in North America for maintenance bridges and infrastructure continuously decreases as the age of infrastructure increases. Therefore, the need to develop cost-effective material technology such as ECC with greater durability is essential (Caner & Zia 1998; Hossain & Lachemi 2014).

In order to develop new ECC technology in Canada and to promote applications, wide range of research should be conducted related to short/long-term mechanical/durability properties of ECC. The main goal of this research is to study the performance of greener ECC mixtures under fresh, mechanical and durability properties such as heat of hydration, compressive and rapid chloride permeability resistance for construction applications.

2. EXPERIMENTAL PROGRAMS

2.1 ECC Materials

The materials used in the production of standard ECC mixtures were CSA General Use Portland cement (C); Class-F fly ash (FA) with calcium content of 3.55%; micro-silica sand (SS) with an average and maximum grain size of 0.30 and 0.40 mm, respectively; polyvinyl alcohol (PVA) fibers; water; and a polycarboxylic-ether type high-range water-reducing admixture (HRWRA). The chemical composition and physical properties of Portland cement and Class-F fly ash are presented in Table 1.

Table 1: Chemical composition and physical properties of Portland cement and Class-F fly ash

Chemical composition (%)	Cement (C)	Class-F Fly Ash
Calcium Oxide CaO	61.40	3.55
Silicon Dioxide SiO_2	19.60	46.19
Aluminium Oxide Al_2O_3	4.90	23.39
Ferric Oxide Fe_2O_3	3.10	21.81
Magnesium Oxide MgO	3.00	0.82
Sulfur Trioxide SO_3	3.60	1.13
Alkalis as Na_2O	-	0.51
Loss on ignition LOI	2.30	2.12
Sum (SiO_2+Al_2O_3+Fe_2O_3)	27.60	91.39
Physical properties	**Cement (C)**	**Class-F Fly Ash**
Residue 45 μm (%)	3.00	18
Density (g/cm^3)	3.15	2.54
Blaine fineness (m^2/kg)	410	306

In this research, locally available mortar sand with a maximum size of 1.18 mm was used instead of commercially available relatively expensive micro-silica sand to optimize the cost of ECC mixtures (Sahmaran et al., 2009). The grain size distributions of silica sand (SS) and mortar sand (MS) are given in Figure 1.

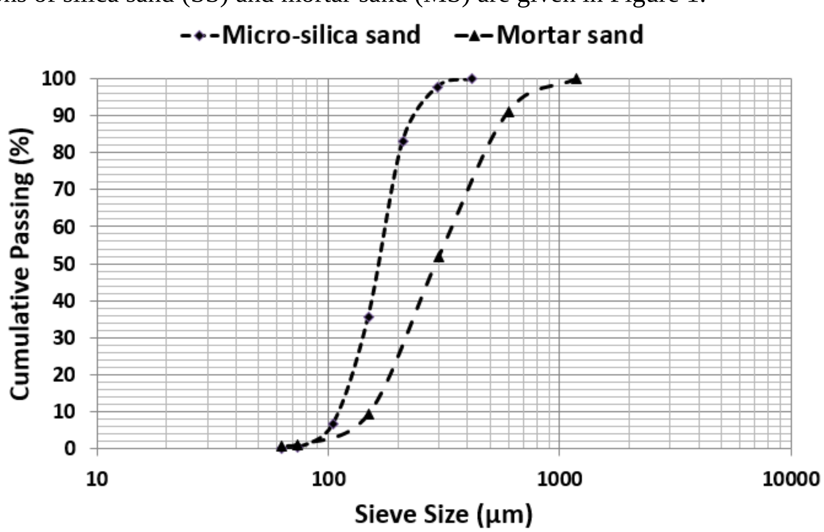

Figure 1: Grain size distribution of Silica Sand (SS) and Mortar Sand (MS)

PVA fiber with a length of 8 mm, diameter of 39 μm, tensile strength (1620) MPa, elastic modulus (42.8 GPa), and maximum elongation (6.0%) was used to meet the requirements of strain-hardening performance of ECC material (Li et al. 2002).

2.2 ECC Mixture Proportions

To investigate the influence of aggregate type/size and FA/C ratios (where Class-F fly ash was used as cement replacement) on mechanical properties, two ECC groups were selected. The first group was composed of two FA-ECC mixtures produced by using micro-silica sand. The second group was produced by using local mortar sand. Class-F FA was used as cement replacement at ratios of 1.2 and 2.2, respectively. Mixture proportions and designations for both ECC groups are given in Table 2.

The water/binder (w/b) ratio was kept in the range of 0.27 (binder means cement and fly ash content). The variable parameters in these mixtures were the aggregate type and size (0.3 mm micro-silica sand and 1.18 mm mortar sand), and FA cement replacement rate (FA/C=1.2 or FA/binder=55%, and FA/C=2.2 or FA/binder=70%). In both groups, the amount of aggregate was held constant. As shown in Table 2, ECC mixtures could be recognized from their Mixture IDs. The first letter stands for Class-F fly ash. The numbers after the letter stand for FA/C ratio and the last letters stand for aggregate type (SS or MS).

Table 2: ECC mixture proportions

Groups	Mixture ID	Ingredients, kg/m^3							
		Water	Cement	FA	Sand	PVA	HRWRA	FA/C	w/b
Silica Sand	F_1.2_SS	331	570	684	455	26	5.4	1.2	0.27
	F_2.2_SS	327	386	847	448	26	4.15	2.2	0.27
Mortar Sand	F_1.2_MS	327	559	671	446	26	5.4	1.2	0.27
	F_2.2_MS	319	376	825	436	26	4.2	2.2	0.27

*HRWRA: High range water reducing admixture, C: Cement, FA: Class-F fly ash, w/b: water to binder ratio

2.3 Test Procedures and Specimen Preparation

Mechanical and durability properties of ECC mixtures namely heat of hydration, compressive strength and Rapid Chloride Permeability (RCP) for both groups of ECC mixtures were evaluated. Compressive strength tests were conducted at 7, 28, 56 and 90 days while the RCP test was conducted at 28, 56, 90 and 118 days.

Heat of hydration of FA-ECC mixtures was determined using 150 x 300 mm cylindrical samples using isothermal calorimetry (using calorimeter apparatus) in accordance with ASTM C1679-14. The total heat of hydration released during the hydration is a function of chemical composition and the amount of cementitious materials in FA-ECC mixes. During the FA-ECC mixing process, the temperature of all mixed materials (even water) was identical to the room temperature (when the sample was molded into the calorimeter at 23 ± 2°C). After the mixing process, each ECC sample was placed into calorimeter within 5 min; and the data acquisition of heat of hydration was started right away and continuously recorded for 72 hours. Figure 2 shows the setup for the heat of hydration test

For compressive strength, at least three 50-mm cubic specimens were prepared for each ECC mixture for the testing ages of 7, 28, 56 and 90 days. The compression test was carried out on the cubic specimens by using a compression testing machine with a capacity of 400,000 lbs as per ASTM C39, 2012.

For RCP test, two discs (for each ECC mixtures) with a size of 100 mm in diameter and 50 mm in thickness were cut from 150 x 300 mm cylinders at the age of 28 days. RCP test to measure the resistance to chloride ion penetration was conducted as per ASTM C1202-12. Figure 2 shows the setup of rapid chloride permeability test.

Figure 2: Test setup for heat of hydration (left) and rapid chloride permeability test (right)

3. RESULTS AND DISCUSSIONS

3.1 Heat of Hydration

The isothermal calorimetry test is a tool that can measure the rate of heat of hydration with time. The more heat evolution, the higher rate of reactivity of the cementitious materials. The use of isothermal hydration curves provides more knowledge of setting time of different types of cements, compatibility of materials in blended cements and of early strength development. In addition, it can show the effects of curing temperatures, curing methods, and mixing times (Mindess et al. 2003; Mavani 2012).

The heat of hydration test was conducted on all types of FA-ECC mixes at fresh state in accordance with ASTM C1679-14. For comparison purposes, all the heat of hydration curves for FA-ECC mixes were plotted in Figure 3. Figure 3 shows that the addition of high volume of fly ash (HVFA) as cement replacement to ECC mixes (FA/C=2.2) has significant effect in reducing the rate of the heat of hydration and increasing the dormant period. Once, the water is mixed with cement grains, the C_3S existing within the cement grains starts to release rapidly the calcium and hydroxide ions. This stage of hydration slows down quickly (usually within 15 minutes) but continues slowly during the dormant period. The hydration of C_3S remains slow in this stage (usually takes several hours); waiting for a certain concentration of calcium ions to produce $Ca(OH)_2$ crystals in pore solution and for hydroxide ions to form C-S-H products at the surface of C_3S grains. Once hydration proceeds, more C-S-H layers will form at the surface of C_3S grains. The more thickness of C-S-H layers produced, the longer diffusion paths formed inside C-S-H layers and hence, more time is needed for calcium and hydroxide ions to diffuse and reach the un-hydrated C_3S grains. At the end of the dormant period, the C_3S will restart its reaction rapidly leading to reach a maximum rate of heat of hydration at the end of the accelerated period. The addition of high volume fly ash to ECC matrix is equivalent to replacing the content of highly reactive C_3S in cement by silicon ions presented in fly ash. Due to prolonged pozzolanic reaction, a significant delay occurs to reach the critical concentration of calcium and hydroxide ions to form hydration products leading to extending the dormant period. The delay of this stage is denoted by two aspects; the first is shifting the heat of hydration curves slightly to the right which results in reducing the temperature. The second is decreasing the rate of heat of hydration at the end of the accelerated period (Mindess et al. 2003).

Furthermore, higher rates of heat of hydration were observed at the end of the accelerated period for SS-ECC mixes compared with those produced by mortar sand. It is known that the micro-silica sand is amorphous in nature and highly reactive material. Therefore, the presence of silicon ions in micro-silica sand will stimulate the C_3S reaction to reach the critical concentration of calcium and hydroxide ions and forming the hydration products. This can be seen clearly in Figure 3 when the heat of hydration curves shifted slightly to the left direction and hence, a significant reduction occurs in dormant period (Kurdowski & Nocun-Wczelik 1983; Mindess et al. 2003).

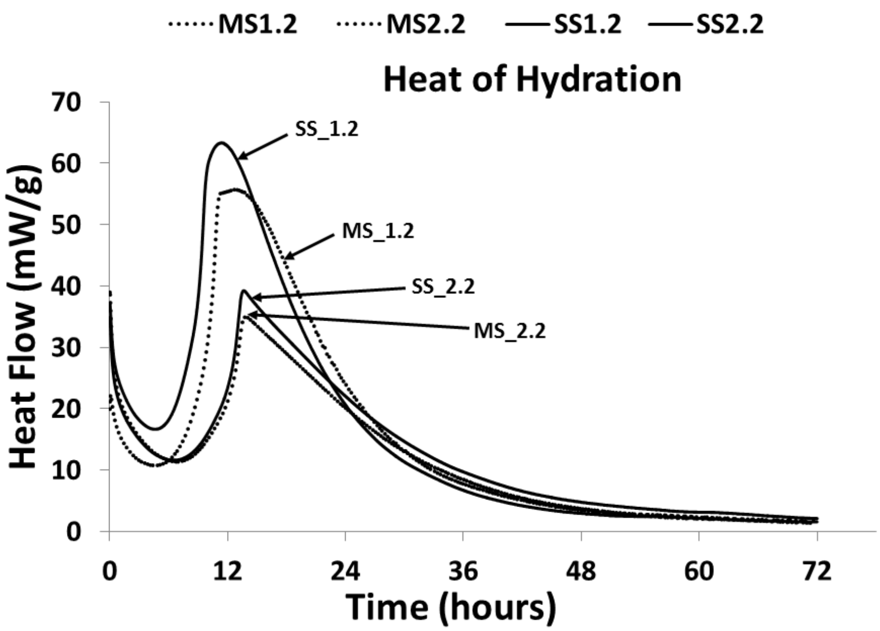

Figure 3: Heat of hydration of different mixes

3.2 Compressive Strength

Table 2 and Figure 4 present the compressive strength results of ECC mixtures using different aggregate sizes and types with Class-F fly ash. In order to explore the performance of ECC mixtures as a function of time, at least three cubic specimens (50 x 50 x 50 mm) were tested at the age of 7, 28, 56 and 90 days.

Table 2: Compressive strength values of ECC mixtures

Mix No.	Mix ID.	Compressive Strength (MPa)			
		7 days	28 days	56 days	90 days
1	SS_1.2	33±1.84	61±2.44	63±3.38	65±2.75
2	SS_2.2	27±0.92	54±1.80	58±2.68	60±3.92
3	MS_1.2	40±0.72	64±2.59	66±0.57	68±1.13
4	MS_2.2	27±1.67	51±2.02	54±2.65	56±1.71

For same type of sand, the compressive strength values decreased with the increase of fly ash content as cement replacement (Figure 4 and Table 2). Replacing the cement with low calcium fly ash is equivalent to reducing the overall amount of CaO content and hence, reducing the reactivity of the matrix. Further, the addition of fly ash is equivalent to increasing the content of C_2S that lead to the lower rate of hydration and slower strength development especially at early ages compared to highly reactive C_3S. Therefore, compressive strength values of ECCs decreased with the increase of fly ash content due to slower reactivity of pozzolanic reaction. Although the addition of HVFA to ECC produced by silica sand or mortar sand will lead to slower matrix reactivity compared to cement, all compressive strength values at 28 days of FA-ECC mixtures exceeded the compressive strength values of normal concrete at 28 days (~30MPa) (Sahmaran et al. 2009).

For the same cement replacement (FA/C=1.2), FA-ECC mixtures produced by using micro-silica sand (0.30mm) exhibited lower compressive strength values than those produced by using mortar sand (1.18mm) (Figure 4 and Table 2). Use of smaller aggregate size in ECC matrix decreased the volume of Interfacial Transition Zones (ITZ) between the aggregates, the PVA fiber, and the cementitious grains. This might lead to the decrease of the amount of moisture within the ITZ volumes (Mehta & Monteiro 2006). In addition to ITZ, the amount of highly reactive C_3S content in cement powder decreased and replaced by low reactive C_2S content. Consequently, when both moisture and C_3S content decreased within the volumes of ITZ, less products of C-S-H by pozzolanic reaction will be formed leading to decrease in the compressive strength values of FA-ECC mixtures produced with FA/C =1.2.

On the other hand, the use of FA/C = 2.2 in the production of FA-ECC mixtures exhibited lower compressive strength values when mortar sand (1.18mm) was used instead of micro-silica sand (0.30mm). This might be attributed to the presence of high volume of Class-F fly ash which served as fillers within the microstructure. Therefore, higher frictional bond will be produced within ITZ leading to the reduction of compressive strength of FA-ECC mixtures (Wong et al. 1999; Wang & Li 2007; Yang et al. 2007; Mindess et al. 2003). In addition, the use of HVFA will increase the content of C_2S instead of C_3S, and will reduce the CaO content in the ITZ (Mindess et al. 2003). Therefore, slow reactivity may occur within ITZ leading to lower compressive strength of FA-ECC mixtures produced by FA/C=2.2 ratio.

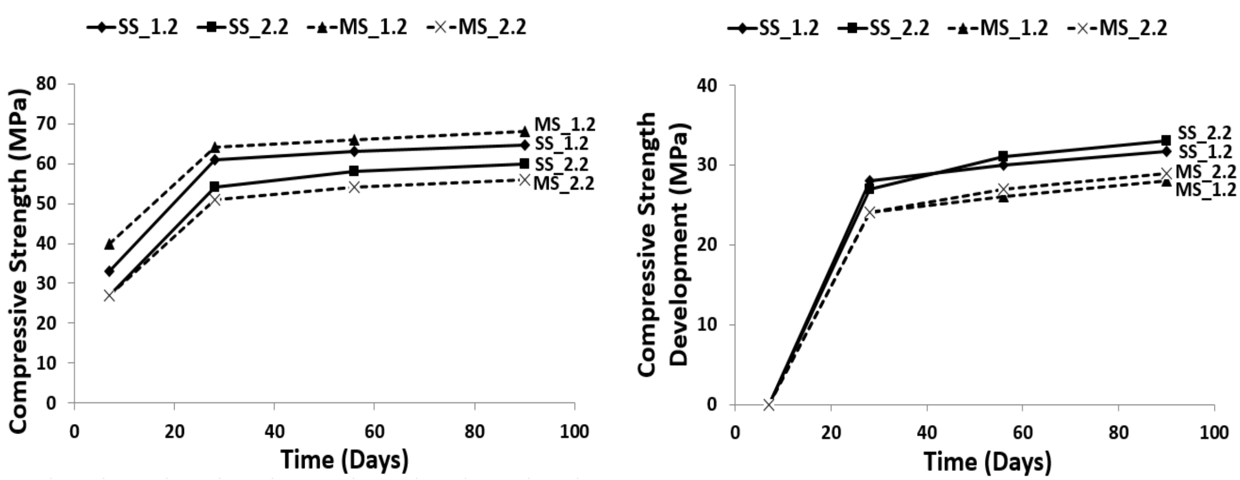

Figure 4: Compressive strength of FA-ECC mixtures (left) and their development (right) as a function of time and fly ash content.

The prolonged strength development of ECC mixtures produced by low calcium Class-F flay ash is shown in Figure 4 as a function of time and fly ash content. In order to do so, the compressive strength values at 7 days were considered as control values to calculate the residual compressive strength values at 28, 56 and 90 days for FA-ECC mixtures (right figure). It was observed that FA-ECC mixtures produced by FA/C=2.2 had slower strength development at early ages (28 days) and the rate of strength development started to increase significantly (more than those produced by FA/C=1.2 ratio) after 60 days for the same type of sand. This might be attributed to the prolonged pozzolanic reactions at later ages.

3.3 Rapid Chloride Permeability

The results of RCP test of FA-ECC mixtures produced by using micro-silica and mortar sand are shown in Figure 5. In this test, the specimens (100mm diameter and 50mm thick discs) were subjected to 60 Volt dc for 6 hours passed across the ends of the specimen in order to monitor the resistance of the specimen to chloride ion penetration expressed as Coulombs.

As per Figure 5, FA-ECC mixtures with FA/C ratio of 1.2 containing micro-silica sand or mortar sand exhibited lower permeability than those with FA/C ratio of 2.2. These results were comparable with Sahmaran & Li (2009) who revealed that the use of FA/C ratio of 2.2 reduced the chloride ion penetration resistance for FA-ECC matrix. However, ASTM C1202-12 has recommended that the addition of HVFA positively influenced the chloride ion penetration resistance of concrete samples. Accordingly Amrutha et al. (2011) justified this contradiction by the presence of high volume of fine fly ash particles which served as filler. In addition, Sahmaran & Li (2009) revealed that the increase in permeability occurred when FA/C ratio was 2.2 in ECC mixtures. They defended their results to the presence of extreme amounts of un-hydrated fly ash particles caused by inadequate moist curing for ECC specimens cured in air. However, as shown in Figure 5, chloride ion penetration resistance for FA-ECC mixtures whether produced by FA/C ratios of 1.2 or 2.2 were complied with ASTM standards at later ages (<1000 coulombs especially at 90 days). Furthermore, the results of ECC mixtures produced with FA/C ratio of 2.2 approached the values of those samples produced with FA/C ratio of 1.2 at later ages due to slower pozzolanic reactions.

From Figure 5, it is clear that the effect of aggregate size did not influence the durability of FA/ECC mixtures in terms of chloride ion penetration resistance. In other words, using aggregate size whether 1.18mm (as in mortar sand) or 0.30mm (as in silica sand) did not affect the permeability of FA-ECC mixtures. Only the addition of high volume of fly ash was playing a significant role in influencing the permeability at early and later ages.

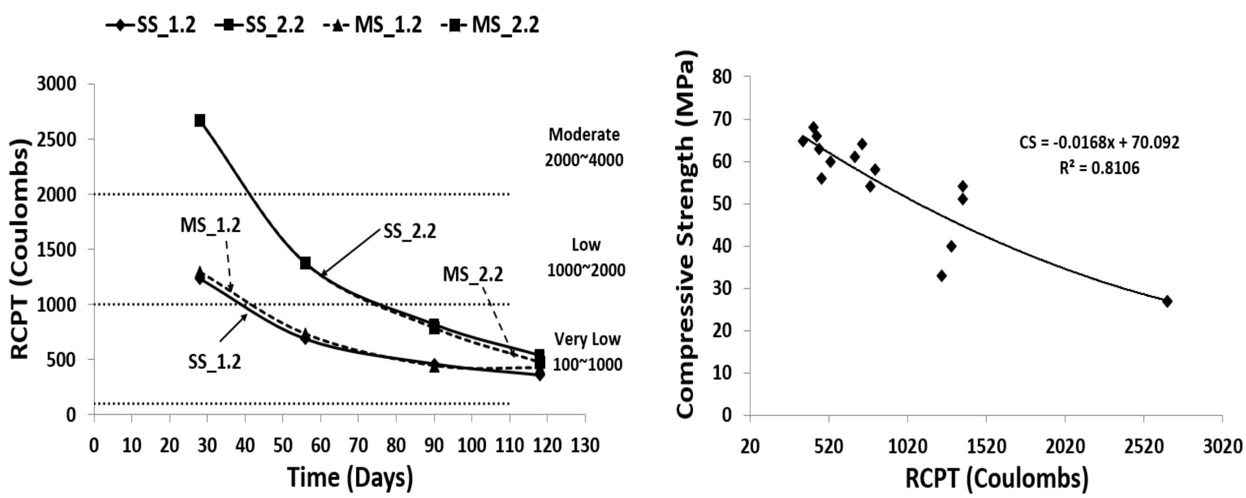

Figure 5: Rapid chloride ion permeability test results of FA-ECC mixtures with different sands (left) and relationship between RCPT and compressive strength (right)

Figure 5 shows the relationship between compressive strength and the RCP of FA-ECC mixtures. The permeability of FA-ECC mixtures decreased with the increase of compressive strength.

4. CONCLUSIONS

The influence of aggregate type and size (micro-silica sand and mortar sand) on mechanical and durability performance of FA-ECC mixtures with high volume fly ash is described in this paper. A series of tests were carried out to study the heat of hydration, compressive strength and rapid chloride permeability of FA-ECC mixtures. The following conclusions were drawn from the study:

1. High volume fly ash (FA) content when added as a cement (C) replacement to ECC mixes (FA/C=2.2) reduced the maximum rate of heat of hydration at the end of acceleration period and also increased the length of the dormant period by shifting the thermal power curves slightly to the right compared to other mixes.
2. The addition of micro-silica sand to FA-ECC mixes resulted in a higher rate of heat of hydration compared to the use of mortar sand by shifting the thermal power curves slightly to the left compared to other mixes.
3. The compressive strength of FA-ECC mixtures decreased when Class-F fly ash content was increased up to 70% and maximum particle size of aggregate was increased up to 1.18 mm as well. However, only at 1.2 cement replacement, (FA/C=1.2), FA-ECC mixtures with mortar sand (1.18 mm) exhibited higher compressive strength values than those with micro-silica sand (0.3 mm).
4. Due to prolonged pozzolanic reaction, continuous hydration of Class-F fly ash ECC mixtures with FA/C=2.2 ratio started to increase after 60 days.
5. Chloride ion permeability for all ECC mixtures produced with 1.2 or 2.2 of FA/C ratios were comparable at later ages due to slower pozzolanic reactions.

6. No significant influence was observed on FA-ECC RCP values when aggregate size was increased from 0.30 mm up to 1.18 mm.
7. In general, the permeability of fly ash ECC mixtures decreased when compressive strength values increased within the range of cement replacements and aggregate type and size studied.
8. Finally, it could be concluded that the expected behaviour of ECC was maintained when using up to 70% fly ash content as a cement replacement and when combined with aggregate of particle size up to 1.18 mm instead of standard micro-silica sand. This conclusion is confined to the FA-ECC mixtures described in this study.

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