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Behaviour of Engineered Cementitious Composites Under Fatigue Loading

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ABSTRACT: Engineered cementitious composite (ECC) is a high-performance fiber reinforced composite with high ductility which exhibits strain-hardening and multiple-cracking behaviour. The relative high cost remains an obstacle for wider commercial use of ECC. The replacement of cement by supplementary cementing materials (SCMs) and the use of local aggregates can lead to greener ECC with lower cost. This paper investigates the fatigue flexure performance of specimens made with ECC mixtures produced by incorporating micro-silica/local crushed sand with class F fly ash (FA). The results showed that ECC specimens produced with crushed sand exhibited strain hardening behaviour with deformation capacities comparable with the standard micro-silica sand. ECC specimens with silica sand developed more damage under fatigue loading of up to 400000 cycles due to higher deflection evolution than FA-ECC mixtures with local crushed sand. The study demonstrated the viability of producing greener, sustainable and cost-effective ECCs using locally available aggregates and fly ash of up to 70% of total cementitious material.

1. Introduction

Engineered Cementitious Composite (ECC) is a special type of high performance fiber-reinforced cementitious composite featuring high ductility and damage tolerance under mechanical loading, including tensile and shear loadings (Li, V. C., 1997; Li, V. C. et al., 2001; Li, V. C., 2003). By employing micromechanics-based material optimization, tensile strain capacity in excess of 3% under uniaxial tensile loading can be attained with only 2% fiber content by volume (Li, 1997; Lin and Li, 1997; Lin et al., 1999). The characteristic strain hardening after matrix first cracking is accompanied by sequential development of multiple micro cracking and the tensile strain capacity is 300-500 times greater than that of normal concrete. The formation of multiple micro cracking is necessary to achieve high composite tensile ductility. Even at ultimate load, the crack width remains on the order of 50 to 80 micrometer. This tight crack width is self-controlled and, whether the composite is used in combination with conventional reinforcement or not, it is a material characteristic independent of rebar reinforcement ratio.

In contrast, normal concrete and fiber reinforced concrete (FRC) rely on steel reinforcement for crack width control. By suppressing cracks in the presence of large imposed structural deformations, ECC can offer structural durability improvements in addition to water-tightness and other serviceability enhancements. These properties, together with a relative ease of production including self-consolidation casting (Kong et al., 2003a; Kong et al., 2003b) and shotcreting (Kim et al., 2003), make ECCs suitable for various civil engineering applications.

Aggregates play an intrinsic role as economic filler in conventional concrete and help to control dimensional stability of cement-based materials. However, the presence of coarse aggregates in a paste tends to increase the tortuosity of the fracture path, and leads to a tough matrix which delays crack initiation and prevents steady-state flat-crack propagation in ECC, resulting in loss of tensile ductility. Moreover, the increase in aggregate size makes it more difficult to achieve a uniform dispersion of fibers. The greater the size of aggregates, the more clumping and interaction of fibers would occur. Therefore, the size of the aggregates is expected to have a significant influence on the properties of composite. Hence, in spite of positive effects of aggregates on dimensional stability and economy of fiber reinforced cement composites, there are limits on aggregate size beyond which problems with fiber dispersability, fresh mix workability and matrix toughness may start to damage the composite material performance characteristics (Sahmaran et al., 2009).

Therefore, instead of coarse aggregate, standard ECC incorporates fine aggregate with an aggregate to binder ratio (A/B) of 0.36 to maintain adequate stiffness and volume stability (Li et al., 1995). The binder system is defined as the total amount of cementitious material, i.e. cement and SCMs, generally FA, in ECC. The silica sand has a maximum grain size of 250 μm and a mean size of 110 μm. Another purpose of using fine silica sand is to obtain the optimum gradation of particles to produce good workability (Fischer et al., 2003).

Due to environmental and economic reasons, there is a growing trend to use industrial wastes or by-products as supplementary materials or admixtures in the production of cementitious composite. Among the various supplementary materials, fly ash (FA) is the most commonly available SCM. Because of several potential benefits, fly ash has increasingly found use in high performance concrete in the last few decades (Mehta, 1985). It has been found that incorporating high amount of FA, especially Class F fly ash, can reduce the matrix toughness and improve the robustness of ECC in terms of tensile ductility. Additionally, un-hydrated FA particles with small particle size and smooth spherical shape serve as filler particles resulting in higher compactness of the fiber/matrix interface transition zone that leads to a higher frictional bonding. This aids in reducing the steady-state crack width beneficial for long-term durability of the structure (Lepech and Li, 2005a,b; Wang and Li, 2007; Yang et al., 2007).

Since the increase in aggregate size leads to an increase in the matrix toughness while the use of SCMs leads to reduce the matrix toughness, locally available aggregate could successfully be used in conjunction with high volume SCMs in the production of ECC. Very limited information is currently available in the published literature revealing the influence of aggregate size on the performance (ductility and mechanical behaviour) of ECC (Sahmaran et al., 2009). Accordingly, one of the current research goals is to design a new class of ECCs with a matrix incorporating locally available aggregates that can show similar mechanical properties compared to standard ECC mixtures containing microsilica sand.

Lack of research studies especially in Canada warrants extensive research investigations on various aspects such as: optimization of ECC mix design parameters, short/long term mechanical/durability properties of ECC and structural performance of ECC based structural components. The full understanding of the behaviour of ECC material is very important for this new technology to be adopted in bridges and other types of structures. Accordingly, the main objective of the current research is to explore the development of greener ECCs and analyze the mechanical properties such as flexural strengths and fatigue loading performance of ECCs for construction application.

The present study contributes to the existing knowledge of ECC by incorporating locally available crushed sand instead of silica sand and by employing cement replacement rate of up to 70%. It is well known that commercially microsilica sand is relatively expensive and difficult to obtain compared with commonly available crushed sand. Therefore, the effects of microsilica sand, locally crushed sand and high volume fly ash on the flexural properties and fatigue performance were experimentally determined to identify/select best ECC mixtures for structural applications. Overall, the research will lead to the development cost-effective and greener ECC mixes.

2. Experimental Programs

2.1 ECC Materials

The material used in the production of standard ECC mixtures were Portland cement (C) Type I general use (GU); class-F fly ash (FA) with calcium content 5.57%; microsilica 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 flay ash are presented in Table 1.

Table 1: Chemical composition and physical properties of Portland cement, fly ashes and slag

Chemical composition (%)	Cement (C)	Fly Ash (F)
Calcium Oxide CaO	61.40	5.57
Silicon Dioxide SiO_2	19.60	59.5
Aluminium Oxide Al_2O_3	4.90	22.2
Ferric Oxide Fe_2O_3	3.10	3.90
Magnesium Oxide MgO	3.00	-
Sulfur Trioxide SO_3	3.60	0.19
Alkalis as Na_2O	-	2.75
Loss on ignition LOI	2.30	0.21
Sum (SiO_2+Al_2O_3+Fe_2O_3)	27.60	85.6
Physical properties	Cement (C)	Fly Ash (F)
Residue 45 μm (%)	3.00	9.60
Density (g/cm^3)	3.15	2.18
Blaine fineness (m^2/kg)	410	306

The commercially available microsilica sand is relatively expensive and difficult to obtain when compared with commonly available sand (Sahmaran et al., 2009). For this purpose locally available crushed sand was incorporated in the production of nonstandard ECC mixtures with maximum size of 1.18 mm. The grain size distributions for both sands are tabulated in Table 2.

Table 2: Grain size Sieve analysis of silica sand and crushed sand

U.S. Sieve number	16	20	30	40	50	70	100	140	200	270
% retained (crushed sand)	0.00	6.00	17.5	-	60.0	-	90.3	-	98.8	-
% retained (silica sand)	-	-	-	0.0	2.2	14.7	47.5	28.8	6.4	0.4

The PVA fibers with a diameter of 39 μm and a length of 8 mm are purposely manufactured with a tensile strength (1620 MPa, elastic modulus (42.8 GPa), and maximum elongation (6.0%) matching those needed for strain-hardening performance. Additionally, the surface of the PVA fibers is coated with a proprietary oiling agent 1.2% by mass to tailor the interfacial properties between fiber and matrix for strain-hardening performance (Li et al., 2002).

2.2 ECC Mixture Proportions

In order to investigate the influence of aggregate type and size on the mechanical properties of ECC, two mixtures of ECC have been designed and selected. The first ECC mixture was produced using microsilica sand. The second ECC mixture was composed of the same first ECC mixture but was produced using local crushed sand. The Supplementary Cementitious Material (SCM) used in both mixtures was Class-F fly ash. This SCM was used as Portland cement replacement at ratio of 2.2 (70%). Mixture proportions and designations for both mixtures of ECC mixtures are given in Table 3.

Table 3: ECC mixture proportions

Groups	Mixture ID	Ingredients, kg/m^3						FA/C	w/b
		Water	Cement	FA	Sand	PVA	HRWRA		
Silica Sand	F_2.2_SS	327	386	847	448	26	4.15	2.2	0.27
Crushed Sand	F_2.2_CS	319	376	825	436	26	4.3	2.2	0.27

HRWRA: High range water reducing admixture, C: Cement, FA: fly ash, F: class-F Fly Ash,
W/B: water to binder ratio (binder = C+SCM)

The water to binder ratio (W/B) was kept in the range of 0.27. The variable parameters in these mixtures were the aggregate type and size, and SCM cement replacement rate (SCM/C of 2.2). In both mixtures, the amount of aggregate and SCM to binder were held constant. As shown in Table 2, the ECC mixtures are labeled such that the ingredients are identifiable from their Mix IDs. The first letter in the mixture designations indicates the SCM type (F = class-F fly ash). The numbers after the letter indicate the FA/C ratio and last letters represent aggregate type (SS or CS).

2.3 Testing and Specimen Preparation

To investigate the performance of ECC mixtures designed and selected in the present study, two phases of tests were carried out. The first phase was flexural strength test applied at 28 days for both ECC mixtures. The second phase was applying different fatigue cycles namely 200,000, 300,000 and 400,000 cycles at 4 Hz cyclic loading rate and fixed 55% fatigue stress level.

At least six specimens of each ECC mixture were tested under each type of loading condition for testing age 28. (355×50×76) mm prism specimens were prepared for the four-point bending test. The total number of all prismatic specimens prepared for this study was 28 beams. All specimens were demolded after 24 hours and moisture cured in plastic bags at 95 ± 5% relative humidity (RH), 23 ± 2 °C. The specimens were kept in the curing room until the day of testing.

2.4 Test Procedure

To measure the flexural strength of ECC specimens (Modulus of rupture), six prismatic samples of 355x50x76 mm were prepared for age 28 days. ECC samples were cleaned and sanded to obtain a flat surface for balancing the crack propagation into the samples, and then four-point bending test was performed under displacement control condition at a loading rate of 0.005 mm/s on a closed-loop controlled servo-hydraulic material test system. The span length of flexural loading was 304.8 mm with a 101.6 mm center span length. During the flexural tests, the load and the mid-span deflection were recorded on a computerized data recording system. Test setup is presented in Figure 1. Flexural strength of the specimens was calculated in accordance with (ASTM C 78, 2002).

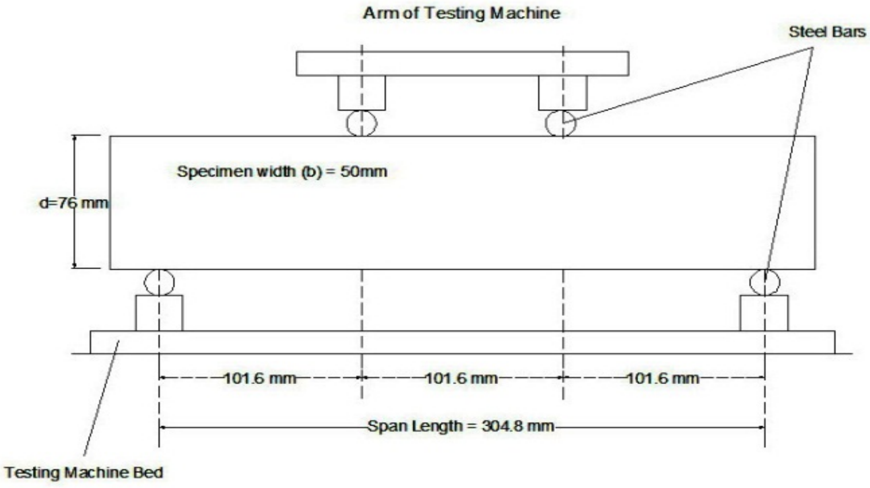

Figure 1: Four Point Bending Test Setup

To investigate the ECC concrete performance under fatigue flexural test, eight prismatic samples of 355x50x76 mm were prepared for the age of 28 days. The four-point bending test was conducted under both static and fatigue loading. Four out of eight samples were prepared for static loading tests as control specimens which were carried out under displacement control conditions, while the other four samples were prepared for fatigue loading tests which were performed under load control conditions. Specimens were simply supported on a span of 304.8 mm and subjected to two-point loads at one-third of the span as shown in Figure 1.

Under fatigue flexural tests, static flexural tests were conducted before fatigue flexural tests and were applied at the constant rate of 0.005 mm/s. The static flexural strengths were determined by averaging the flexural strength results of ECC control specimens. Based on their averaged value, 55% of fatigue stress level value was chosen and tests were conducted at different fatigue cycles namely 200,000, 300,000 and 400,000 cycles at 4 Hz cyclic loading rate.

Fatigue flexural tests were performed under load control conditions. The ratio between minimum and maximum flexural stress was set equal to 0.30 for all specimens in order to avoid any impact and slip of specimens during testing. At the first cycle of each specimen, load was gradually applied to the maximum stress level at 0.50kN/min static loading rate in order to avoid any sudden collapse in the specimen. The cyclic fatigue loading was then applied. The fatigue testing technique mentioned above was adopted In accordance with (Suthiwarapirak et al., 2004). During the fatigue flexural tests, the mid-span deflection evolutions were recorded on data sheet and at the end of the fatigue flexural tests; static flexural tests were conducted on the fatigued ECC specimens to calculate the fatigue residual value for both strength and mid-span deflection.

3. Results and Discussions

3.1 Flexural Strength

The test results in terms of flexural strength and ultimate mid-span deflection are given in Table 4 at the age of 28 days. Typical flexural strength-mid span deflection curves of ECC mixtures at the age of 28 days are shown in Figure 2. The strength and deflection values in Table 4 are the average of six test specimens.

Table 4: Flexural strength and ultimate deflection at 28 days

Mix No.	Mix Designation	Flexural Strength (MPa)	Deflection (mm)
1	F_2.2_SS	10.84	4.45
2	F_2.2_CS	10.48	4.27

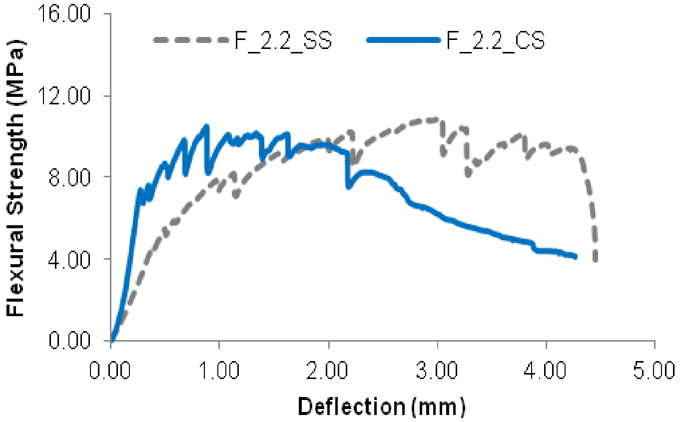

Figure 2: Typical flexural strength-mid span deflection curves of ECC beams at 28 days

3.1.1 ECC's Deflection and Flexural Strength vs. SCMs Cement Replacement Rate

The use of high volume fly ash content of up to 70% of total cementitious material enhanced the bending capacity of ECC mixtures. The high flexural capacity can be attributed to the reduction of the PVA fiber/matrix interface chemical bond and matrix toughness while increasing the interface frictional bond as described in previous research studies (Wang and Li, 2007; Sahmaran et al., 2009). To understand more, un-hydrated FA particles with a small particle size (<45 μm) and smooth spherical shape serve as filler particles resulting in higher compactness of the fiber/matrix interface transition zone that leads to a higher frictional bond, which aids in reducing the steady-state crack width beneficial for the long-term durability of the structure (Wang and Li, 2007; Yang et al., 2007).

The use of fly ash to cement ratio (FA/C) of up to 2.2 (70% of total cementitious material) did not significantly influence the flexural strength values of studied crushed sand ECC mixtures relative to standard silica sand ECC mixtures especially at the age of 28 days as shown in Figure 2. However, flexural strength of studied ECC mixtures at 28 days was significantly higher than that of conventional concrete and fiber reinforced concrete.

3.1.2 ECC's Deflection and Flexural Strength vs. Aggregate Size

Figure 2 shows the effect of increased aggregate size on flexural strength-deflection response of ECC mixtures when 1.18 mm maximum size crushed sand was used instead of 0.30 mm maximum size silica sand with round particles. The increase in aggregate size of up to 1.18 mm (for the case of crushed sand) slightly reduced the total mid-span beam deflection and increased the stiffness of ECC mixtures as shown in Figure 2 and Table 4. This negative effect of increasing aggregate size may be attributed to the adverse effect on the uniform dispersion of fibers. The balling of fibers encouraged by coarser sand at constant sand content prevents sufficient coating of fibers by the matrix, and thus reduces the fiber-to-matrix bonding, which is an important factor influencing ductility (Sahmaran et al., 2009). Moreover, for ECC with the larger aggregate size, a higher degree of aggregate interlock is expected, resulting in higher matrix toughness and work-of-fracture during crack propagation. According to the micromechanical model of steady state cracking, which is essential to achieving strain hardening behavior, high matrix fracture toughness reduces the margin to develop multiple cracking (Li, et al., 1995). However, aggregates within the size range studied (as long as they do not interfere with the uniform dispersion of fibers) did not negatively influence the ductility of ECC (Sahmaran et al., 2009). More investigations are needed on this aspect.

As in the case of cement replacement rate, the aggregate particle size had no or only a minor effect on the flexural strength. Simultaneously, flexural strength and mid-span deflection obtained with crushed sand is within the permissible limit of silica sand.

It could be concluded that the most important feature of ECC (high deflection capacity with multiple cracking behavior) was protected and is not sacrificed by replacing cement with a maximum of 70% FA or by replacing 0.3 mm maximum size silica sand with 1.18 mm maximum size local crushed sand.

3.2 Fatigue Flexure Performance

In this phase, fatigue flexure tests were conducted on beam specimens by applying different fatigue cycles namely 200,000, 300,000 and 400,000 cycles at 4 Hz cyclic loading rate and 55% fatigue stress level.

3.2.1 Mid-span Deflection Evolution

The evolution of mid-span deflection as function of the number of cycles is plotted in Figure 3 for both silica sand and crushed sand based ECC specimens with 55% fixed fatigue stress level. In tests conducted up to 400000 cycles as shown in Figure 3(a), FA-ECC specimens with silica sand (F_2.2_SS) under fatigue loading developed much more damage in terms of deflection than FA-ECC specimens with crushed sand (F_2.2_CS). Up to 0.70 mm mid-span deflection was evolved in silica sand ECC specimens compared to 0.27 mm of crushed sand ECC specimens. In general, silica sand ECC specimens consistently exhibited higher mid-span deflection compared to crushed sand ECC specimens tested up to 400000, 300000 and 200000 cycles as shown in Figures 3(a-c).

The reason behind this is not completely clear, but is likely be associated the presence of more un-hydrated spherical FA particles in the interfacial zone of FA-ECC mixtures which makes FA particles difficult to connect with other cement product crystals (Gao and Zijl, 2005). This is consistent with the fact that around 25-30% in the paste with 50% replacement of fly ash did not hydrate and the unreacted fly ash may act like a micro-aggregate (Termkhajornkit et al., 2005). According to this, 70% of cementitious material replacement was used in the present study which means around 30-40% of un-hydrated fly ash particles did not participate in the hydration process, but could be seen as mere filler material, or aggregate.

Therefore, the use of crushed sand in FA-ECC mixtures facilitated to keep more un-hydrated fly ash particles (compared to silica sand) as filler materials along with the PVA fibers due to its high porosity and because of silica sand's higher fineness (than crushed sand). Accordingly, when the fatigue loading was applied on the crushed sand ECC specimens, the friction between cement crystals and the more stored un-hydrated fly ash particles along with the confined PVA fibers in the fly ash zones would be increased due to the fatigue vibration compared to that in silica sand specimens.

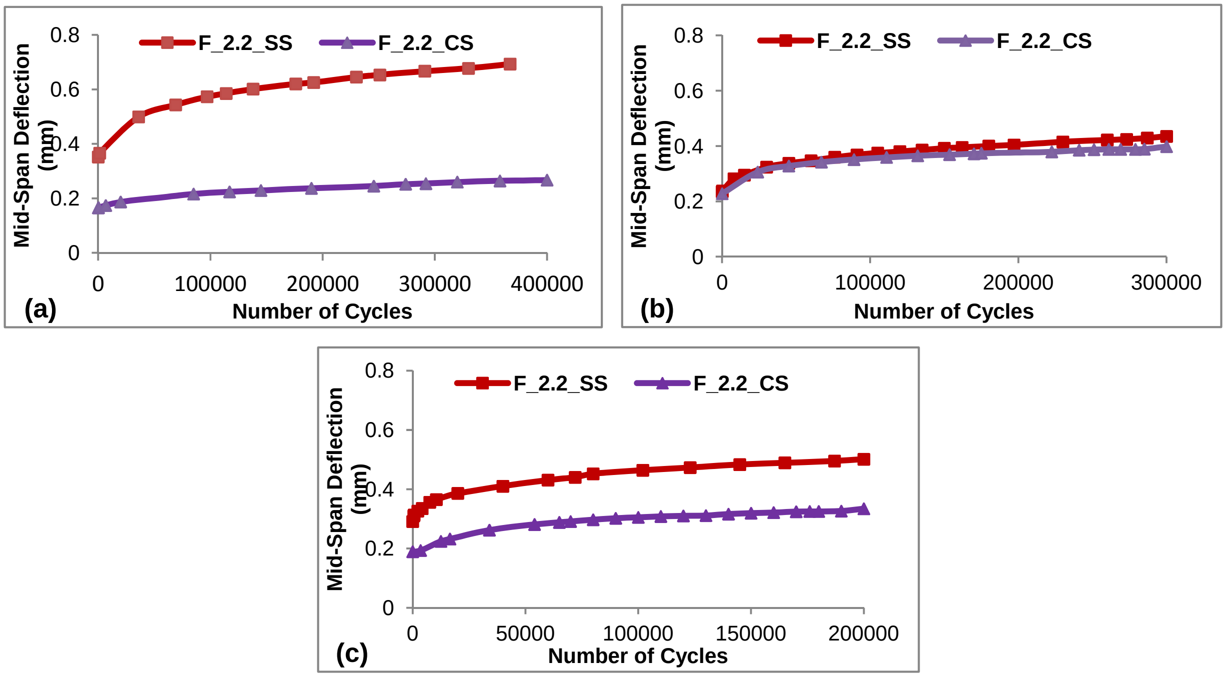

Figure 3: Evolution of mid-span deflection at different fatigue number of cycles: (a) 400000 cycles, (b) 300000 cycles (c) 200000 cycles

3.2.2 Static Loading Following Fatigue Loading

Static flexural tests were applied on the fatigued ECC specimens to calculate the residual energy in terms of strength and mid-span deflection at the end of the fatigue flexural tests of up to 400000 cycles. The post-fatigue flexural test results were expressed as percentages of static flexural test results (in terms of residual strength and deflection) and are presented in Figure 4.

Figure 4 shows that at higher number of cycles, FA-ECC mixtures with crushed sand exhibited higher residual energy in terms of flexural strength capacity than ECC mixtures with silica sand, while both ECC mixtures exhibited lower residual energy in terms of deflection capacity. These results are consistent with the mid-span deflection evolution results (Figure 3). It is found that the relation between the residual strength and the mid-span deflection evolution is inversely proportional. The lower the mid-span deflection evolution, the higher the residual fatigue flexural strength and vice versa. F_2.2_CS mixture shows the highest performance consistently for all number of cycles with respect to fatigue stress and mid-span deflection as shown in Figure 4.

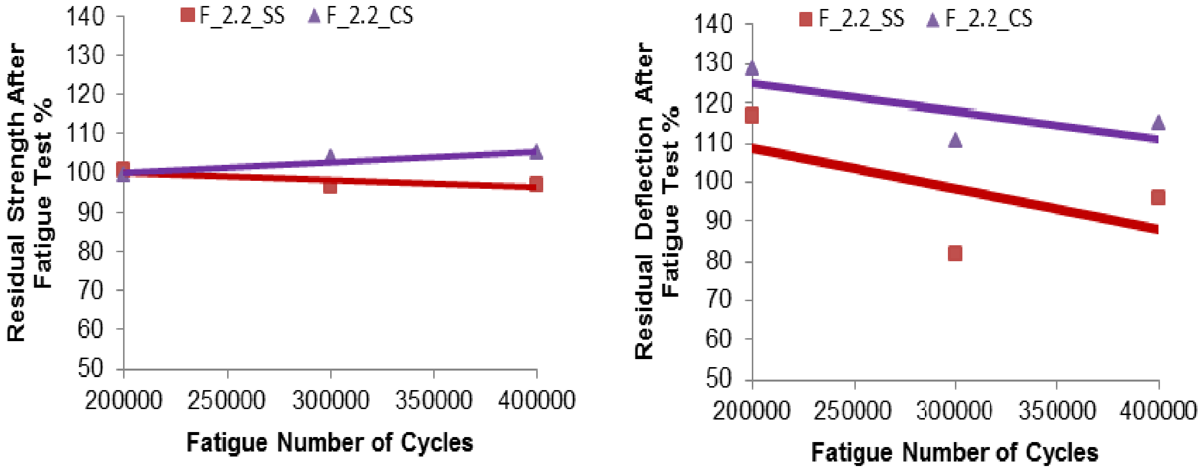

Figure 4: Percentages of Residual Strength and Mid-Span Deflection after Fatigue Test

The good performance in residual energy of crushed sand ECC mixtures even after applied 400,000 cycles could be attributed to the decrease in the maximum fatigue stress level. The stress level used herein was somewhat low, 55%. According to this, Awad (1971) reported that when normal concrete is subjected to high repeated stresses, a decrease of maximum stress level results in an increase of the number of cycles to failure. In addition to the decrease in fatigue stress level, high volume fly ash concrete subjected to high fatigue number of cycles at lower fatigue stress level as well would improve the performance of concrete. Furthermore, Ramakrishnan et al. (1991) revealed that the high-volume fly ash concrete has slightly higher (7%) endurance limit when expressed as a ratio (ratio of flexural fatigue strength to static flexural strength) compared to plain Portland cement concrete. The results further indicated that there was an increase (15 to 30%) in static flexural strength for high-volume fly ash concrete which was previously subjected to four million cycles of fatigue stresses at their respective lower fatigue limit load (10%) (Ramakrishnan et al., 1991). In the present study, both the decrease in fatigue stress level which was 55% and the production of fly ash ECC mixtures with 70% cement replacement could be the reasons to the superior performance in residual fatigue energy of crushed sand ECC mixtures.

To highlight the practical application of this finding; Li et al. (2004) confirmed that the most important properties required for structural applications (such as link slab in bridge decks) are tensile strain capacity (ductility) and crack width control for durability purposes. The minimum ductility required to withstand temperature and drying shrinkage stress, as well as live loads, was computed to be 1.4% using a factor of safety of two. These requirements are difficult, if not impossible, to attain for normal concrete, but are easily achievable with fly ash ECC mixtures with silica sand (Li, et al., 2004). The current study revealed that the performance of fly ash ECC mixtures with crushed sand was comparable with that of silica sand mixtures under static loading while they exhibited much better performance under fatigue loading in terms of both residual fatigue flexural strength and deflection capacity.

4. Conclusions

This paper describes the influence of aggregate types and size (silica sand and crushed sand) on the mechanical performance of ECC with high volume of fly ash content. A series of tests were carried out to study the flexural behaviour of ECC mixtures under static and fatigue loading. The following conclusions were drawn from the study:

- The use of crushed sand in place of standard silica sand in ECC mixtures did not significantly influence the flexural strength and deflection capacity of beam specimens.
- The evolution of mid-span deflection in beam specimens (subjected to fatigue loading of up to 400, 000 cycles) made with silica sand ECC was higher compared to those made with crushed sand. Micro-structural investigation on these ECC mixtures should be conducted in future to find out the mechanism behind such performance.
- FA-ECC mixtures with crushed sand seems to have exhibited better performance under fatigue loading in terms of higher residual flexural strength and deflection compared with their silica sand counterparts. In general, the lower the deflection evolution the higher the residual fatigue flexural strength.

Finally, the results presented in this study provide a positive preliminary step for the suitability of crushed sand in the production of cost-effective ECC mixtures, and indicate that crushed sand with relatively higher aggregate size can also be successfully used to produce an ECC having similar or better mechanical properties than corresponding ECC made with microsilica sand. This conclusion is confined to the ECC mixtures described in this study.

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