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Vancouver, Canada

May 31 – June 3, 2017/ *Mai 31 – Juin 3, 2017*

STRUCTURAL PERFORMANCE OF ENGINEERED CEMENTITIOUS COMPOSITES SUBJECTED TO PRE AND POST-FATIGUE MONOTONIC LOADING

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Abstract: This paper presents the effect of fatigue loading on the flexural performance of Engineered Cementitious Composite (ECC) prismatic beams. ECC has been designed for high ductility, durability and strain hardening capacity with multiple-cracking behavior in addition to be cost-effective and green through the replacement of cement by Class-F fly ash and the use of local aggregates (mortar sand in place of silica sand). The main variables in this study were, Class-F fly ash as cement replacement of 55% and 70%, type and size of aggregates while maintaining fatigue stress level and number of fatigue cycles constant. ECC prismatic beam samples were loaded to failure under static monotonic loading after the application of 400000 cycles of fatigue loading to study performance based on strength, deflection capacity, stiffness and energy absorbing capacity. The mortar sand based ECC specimens showed better fatigue performance in terms of higher residual strength, deflection, stiffness and energy absorbing capacities compared to their silica sand counterparts.

1 Introduction

Engineered cementitious composite (ECC) is a class of high performance fiber reinforced concrete (HPFRCC) which is designed in order to achieve high durability, high ductility under tensile loading (Li, 1998, 2003; Suthiwarapirak et al., 2004). The formation of multiple micro cracks in ECC leads to attain tensile strain capacity after the formation of the first crack of over 300 times that of normal concrete by using only 2% volume of well distributed short fiber in the ECC mix. Moreover, ECC has the ability to maintain the micro crack width to less than 60~80µm even under ultimate loading; this intrinsic material property can stimulate crack self-healing behaviour which improves the mechanical properties, durability and serviceability of structural elements (Herbert and Li, 2013; Özbay 2012).The tensile strain hardening behaviour of ECC is achieved by the multiple non-localized cracks that sustain and pass the load without any catastrophic damage in the structure regardless the length of the crack and type of the loading (Li, 1998, 2003). ECC is designed for several types of applications such as ECC largescale on site construction applications, high-early-strength ECC applications, Lightweight ECC applications, Green ECC applications and Self-healing ECC applications; that show the ability of ECC to heal cracks over time (Tittelboom, 2013). It was proved by the gradual reduction in permeability of cracked concrete as water penetrates through the cracks; which is caused by the crack width shrinking as healing occurs.

Research has been conducted to develop green ECC through cement replacement by different types and sizes of local aggregates (silica sand or crushed sand) and supplementary cementing materials (SCMs) such as fly ash, slag, volcanic ash etc.) for economic and environmental reasons (Sahmaran et al. 2009;

Hossain and Anwar 2014; Maulin 2012; Sherir 2012; Sherir et al. 2016). The use of high volume fly ash in ECC mixtures reduces the matrix toughness which must be controlled to form multiple cracking before reaching maximum stress, and also leads to fiber pullout rather than rupture during debonding which significantly enhanced the ductility of the mix. In addition, the unhydrated fly ash particles may also improve the compactness and the frictional bonding between fiber and matrix. Therefore, steady-state crack opening will be reduced and durability and sustainability of the ECC mixture will be enhanced (Maulin 2012; Sherir 2012; Sherir et al. 2016; Sahmran et al. 2009; Wang and Li 2007). The particle size of aggregate significantly affects the fracture matrix toughness, clumping and interaction of fibers which reduces the ductility of the ECC mixture (Sahmaran et al. 2009). The incorporation of micro-silica sand and crushed sand in ECC mixtures can sustain adequate stiffness and stability (Sherir 2012, Maulin 2012). The development of low cost green ECC mixtures with locally available aggregates instead of silica sand is important for construction of structures with enhanced durability and ductility and service life.

This paper presents the results of an experimental investigations studying the mechanical properties of new green ECC mixtures made of mortar sand replacing silica sand as well as the structural performance of ECC beams subjected to monotonic and fatigue flexural loadings. The influence of type and size of aggregates (silica sand and mortar sand) as well as different fly ash content as replacement of cement is described based on residual flexural strength, bending capacity, stiffness and energy absorbing capacity of beam specimens subjected to fatigue flexural loading for 400000 cycles compared to their non-fatigued counterparts. The outcome of this research will contribute to better understand the static and fatigue flexural performance of ECC beams made of mortar sand compared to their silica sand counterparts.

2 Experimental Investigations

2.1 Materials and ECC Mixture proportions

The materials used in the production of ECC mixtures were micro-silica sand and mortar sand with maximum grain sizes of 0.3 mm and 1.18 mm, respectively; Portland cement (C) Type I general use (GU); Class-F fly ash (FA); polyvinyl alcohol (PVA) fibers; a polycarboxylic-ether type high-range water-reducing admixture (HRWRA) and water. PVA fiber used in this study had diameter, length, nominal strength and modulus of elasticity of 39 μm, 8 mm, 1620 MPa and 42.8 GPa, respectively. Table 1 presents the chemical composition and physical properties of Portland cement and class-F fly ash (ASTM C618 2012).

Aggregates are considered to be an economic filler and a framework in the paste material where the aggregates enhance the dimensional stability and restrain the large shrinkage movements in the paste. However, the size of the aggregates affects several characteristics; for instance, the use of coarse aggregates will create fibers clump and lead to tough ECC mixtures that cause delay in the initiation of the first crack and failure of the multiple crack behavior due to the low tensile ductility. However, fine aggregates are commonly used for ECC mixtures in order to attain the anticipated multiple cracking behavior and the strain hardening (Li, 2003). Hence, the size of aggregates has an imperative impact on the properties of mixture such as workability, volume stability, stiffness and fiber dispersibility (Sherir et al. 2016).

In the last few decades, supplementary cementing materials such as fly ash have been widely used in the applications of ECC. Fly ash is a by-product of the coal power plant and it’s use as replacement of cement leads to green ECC mixtures in addition to reducing the flexural stresses and crack tip matrix toughness resulting from the reduction of fiber/matrix interfacial chemical bond enhancing tensile ductility and tensile strain capacity (Wang and Li, 2007; Sahmaran et al., 2009).

Table 1: Chemical Composition and Physical Properties of Portland cement and Class-F Fly Ash

Chemical Composition (%)	**Cement**	**FA**
Calcium Oxide CaO	61.4	5.57
Silicon Dioxide SiO_2	19.6	59.5
Aluminium Oxide Al_2O_3	4.9	22.2
Ferric Oxide Fe_2O_3	3.1	3.9
Magnesium Oxide MgO	3	-
Sulfur Trioxide SO_3	3.6	0.19
Alkalis as Na_2O	-	2.75
Loss on ignition LOI	2.3	0.21
Sum (SiO_2 + Al_2O_3 + Fe_2O_3)	27.6	85.6
Physical properties	**Cement**	**FA**
Residue 45 µm (%)	3	9.6
Density (g/cm^3)	3.15	2.18
Blaine fineness (m^2/kg)	410	306
Air Content (%)	7.79	-
Initial Setting time (min)	113	-
Compressive Strength (MPa), 1 day	19.41	-
Compressive Strength (MPa); 3 day	30.35	-
Compressive Strength(MPa); 28 day	41.47	-

PVA fibers are considered to be the most common type of fiber used in ECCs. PVA fibers can elongate up to 6.0% of their original length. In addition, the surface of PVA fibers is coated with 1.2% mass of oil that reduces the interfacial bonding properties between the fiber and matrix and increases the tensile strain capacity of the mix, hence, fibers tend to rupture under tensile stresses (Li 2003). Those properties help in carrying the tensile stresses, boosting strain-hardening performance and increasng the matrix's toughness due to the fiber bridging behavior. Fiber bridging behavior of ECC is based on the micromechanics of the fiber/matrix interface where fibers transfer the stresses and maintain the low crack widths (Li 1998; Suthiwarapirak et al., 2004; Hossain et al. 2015).

Two groups of 4 ECC mixtures have been selected in order to examine the influence of Class-F FA/C ratios as cement replacement (1.2 and 2.2 representing 55% and 70% replacement), type (silica sand 'SS' mortar sand 'SS') and size of aggregates on the mechanical properties of ECC. The four mixture proportions of ECC including different amounts of fly ash and sand aggregates are presented in Table 2.

Table 2: Mixture proportions of ECC materials

Groups	Mixture ID	Ingredients by mas of cement					
		Water	Cement	FA	Sand	PVA kg/m^3	HRWRA L/m^3
Silica Sand	F_1.2_SS	0.58	1.0	1.2	0.8	26	5.4
	F_2.2_SS	0.85	1.0	2.19	1.16	26	4.15
Mortar Sand	F_1.2_MS	0.58	1.0	1.2	0.8	26	5.4
	F_2.2_MS	0.85	1.0	2.19	1.16	26	4.2

** HRWRA: High range water reducing admixture, C: Cement, FA: Class-F fly ash, PVA: poly vinyl alcohol fiber, w/b: water to binder ratio; SS: silica sand; MS: mortar sand*

2.2 Specimen Preparation and Test Procedure

Three 355×50×76 mm prism specimens for each ECC mixture were prepared and tested at 28, 56 and 90 days to investigate the flexural strength performance. In addition, two prism specimens were prepared for each of the two different fatigue testing conditions at 28 days. All specimens were demolded after 24 hours and kept covered in plastic bags in the curing room (95 ± 5% RH, 23 ± 2 °C) until the day of testing.

Two different phases of testing were carried out in order to examine the performance of the 4 ECC mixtures. The first phase included flexural strength test conducted at 28, 56 and 90 days under static monotonic loading. While, the second phase involved fatigue flexural testing conducted by applying 400000 cycles at 4 Hz at constant 50% ±15% fatigue flexural stress level.

2.2.1Flexural Strength

Three 355×50×76 mm prism specimens for each ECC mixture were tested at 28, 56 and 90 days to determine the flexural strength (Modulus of rupture). At the three different ages, static monotonic loading was applied through the four-point bending test under displacement control condition at a loading rate of 0.005 mm/s on a closed-loop servo-controlled loading system. As shown in Figure 1, the four-point bending test for measuring the flexural strength requires a span length of 304.8 mm with a center span length of 101.6 mm. Finally, the load and mid-span deflection throughout the flexural test were recorded on a computerized data acquisition system.

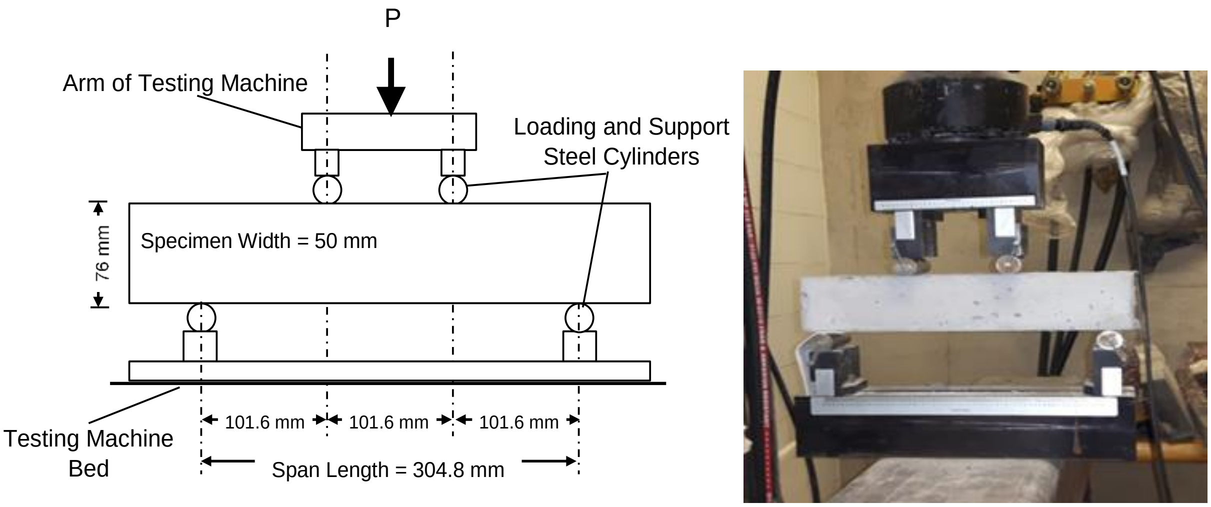

Figure 1: Four-point bending test setup

2.2.2 Fatigue Flexure

The flexural fatigue testing was performed under load control conditions in order to investigate the ECC mechanical properties and the structural performance. The testing was based on applying fatigue stress level of 50% (50% of the ultimate load of virgin specimens tested to failure under monotonic loading) at 400,000 cycles and 4 Hz cyclic loading. To avoid any slip or collapse of specimens during fatigue testing, static loading rate of 0.50kN/min was used for the load to reach the maximum stress level. During the cyclic fatigue tests, the mid-span deflection evolutions were recorded. At the end, flexural monotonic testing was applied on the exhausted fatigued specimens for determining the residual strength and bending capacity,

3 Results and Discussion

3.1 Flexural Strength

The test results of flexural strength and ultimate mid-span beam deflection at the age of 28, 56 and 90 days are shown in Table 3. In addition, the relationship curves between the flexural strength and mid-span deflection for each FA-ECC mixture are provided in Figure 2. In general, based on the mix design parameters, ECC can exhibit a range of flexural strength that varies from 5 to 16 MPa (Wang and Li 2007). The flexural strength of the ECC mixtures in this study ranged between 8.90 and 11.59 MPa while the bending capacity ranged between 1.88 and 7.61 mm. Both flexural strength and deflection decreased with the increase of age

Table 3: Flexural strength and ultimate mid-span deflection of ECC mixtures

Groups	Mixture ID	Flexural Strength (MPa)			Mid-Span Deflection (mm)		
		28 Days	56 Days	90 Days	28 Days	56 Days	90 Days
Silica Sand	F_1.2_SS	11.18	9.82	10.06	3.04	2.72	2.96
	F_2.2_SS	9.68	8.90	8.91	7.61	3.71	2.26
Mortar Sand	F_1.2_MS	11.59	10.89	11.17	2.64	2.11	1.88
	F_2.2_MS	10.63	9.76	10.29	4.17	3.34	2.14

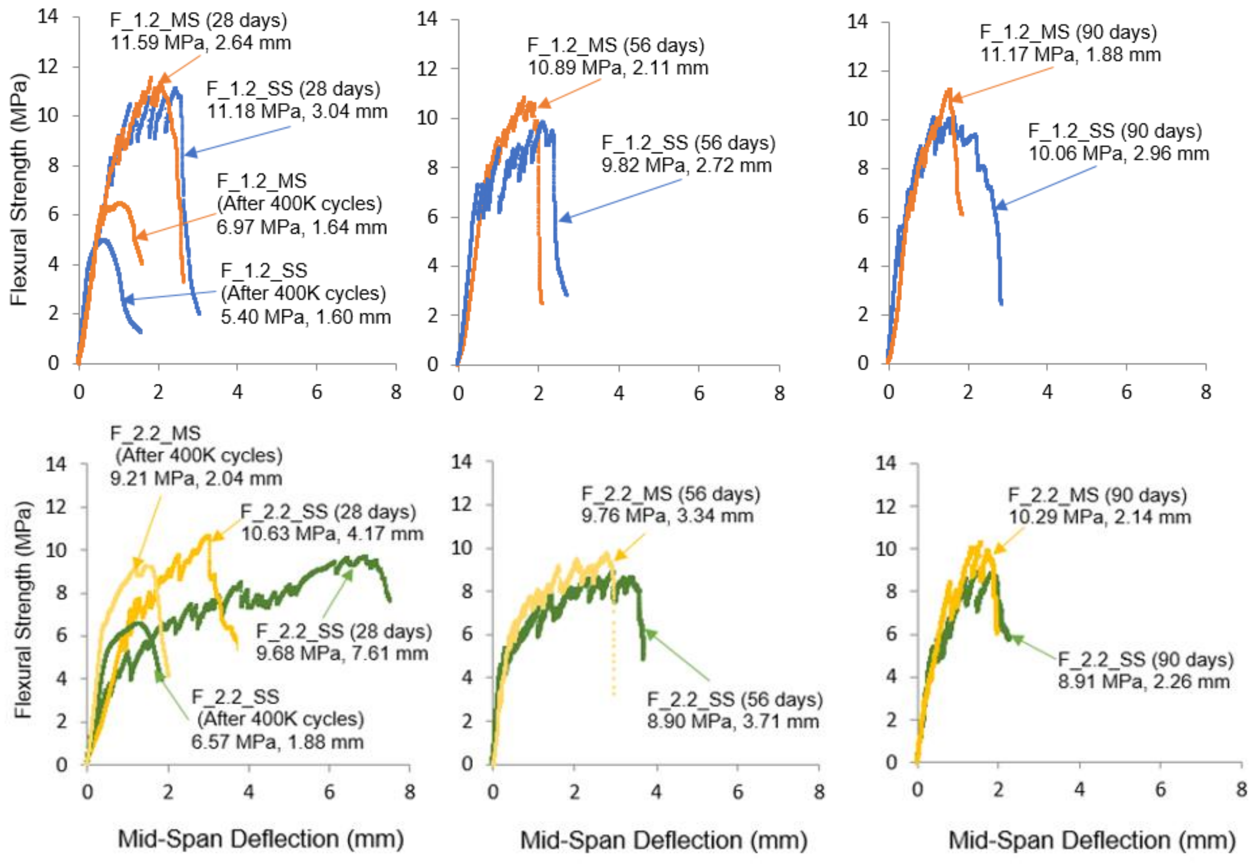

Figure 2: Flexural strength vs. mid-span deflection curves of ECC mixtures

3.1.1 Influence of Fly Ash

It was noted from the results that the increase of Class F-fly ash replacement with cement from 1.2 to 2.2 without changing the type and size of aggregates resulted in a negligible influence on the flexural strength while the mid-span deflection and the bending capacity were notably enhanced (Table 3). The enhanced bending capacity was attributed to the increase of fly ash causing a reduction in chemical bonding and improving the frictional bond between the PVA fibers and matrix due to the presence of the extra un-hydrated fly ash particles that functioned as filler materials (Wang and Li, 2007).

3.1.2 Influence of Different Aggregate Types and Sizes

The incorporation of larger aggregate size in ECC, such as using mortar sand (1.18 mm) instead of micro-silica sand (0.30 mm), without changing the cement replacement rate improved the ultimate load capacity (Table 3). This improvement is attributed to the enhancement of aggregate interlocking with the use of larger aggregate size. On the other hand, the reduction in mid-span deflection was caused by the reduction of the fiber-matrix frictional interface bond (Table 3) as large size of the aggregates did not aid the fibers to be coated with the matrix (Sahmaran et al. 2009; Li 1995; Sherir et al., 2014).

3.2 Fatigue Flexure Performance

3.2.1 Mid-span Deflection Evolution

The mid-span deflection after every cycle was recorded on a computerized data acquisition system during the fatigue loading. The mid-span deflection evolution curves shown in Figure 3 illustrate the development of large deformation in the ECC specimens at the initial fatigue cycles. This was caused by the stress jump from the mean stress range to high fatigue stress ranges (±15%).

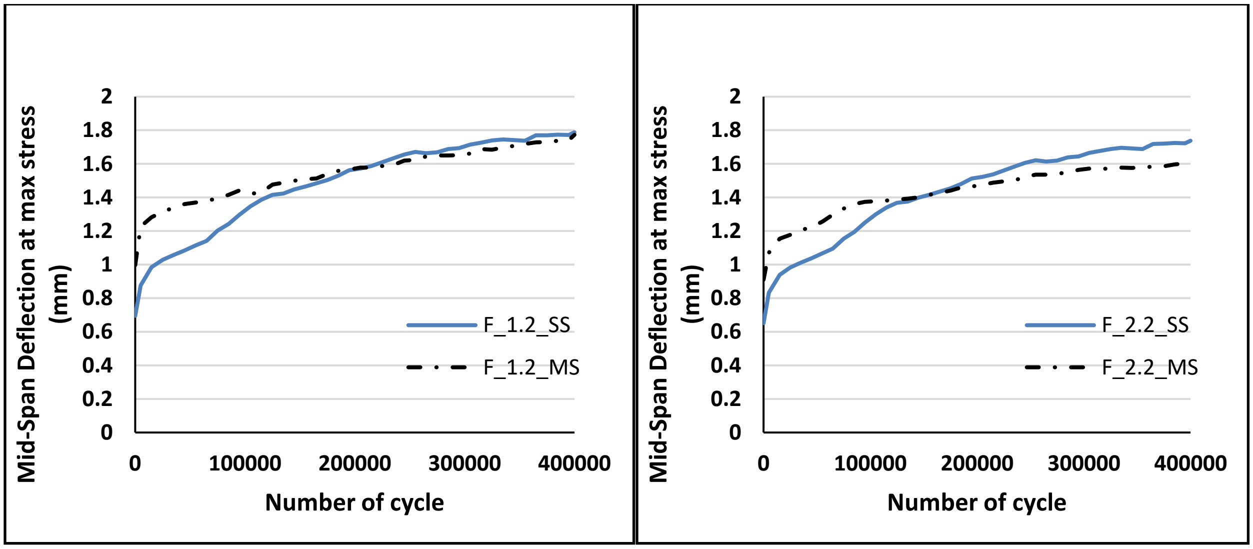

Figure 3: Mid-span Deflection Responses of ECC beams subjected to (50% ± 15%) Fatigue Stress Level

The fatigue flexural tests were conducted for 4000000 cycles at 4 Hz cyclic loading rate which means that the duration of the test was 1664 min. The difference between initial and final value of mid-span deflection was calculated as well as the evolution speed rate that demonstrates the relationship between speed rate and the aggregate type. The results shown in Table 4 are consistent with the mid-span deflection evolution curves for all ECC mixtures. The high deflection evolution speed rate associated with the FA-ECC mixtures with silica sand reflected the tendency of generating more damage under fatigue loading.

Table 4: Mid-Span Deflection Evolution at (50% ± 15%) Fatigue Stress Level

Groups	Mixture ID	Ultimate Strength (kN)	Initial Deflection (mm)	Final Deflection (mm)	Difference between First and Last value of Mid-Span Deflection (mm)	Mid-Span Deflection Evolution Speed Rate (μm/1664 min)
Silica Sand	F_1.2_SS	11.18	0.69	1.79	1.10	0.66
	F_2.2_SS	9.68	0.65	1.73	1.08	0.65
Mortar Sand	F_1.2_MS	11.59	0.99	1.77	0.78	0.47
	F_2.2_MS	10.63	0.91	1.61	0.7	0.42

3.2.2 Static Tests after Fatigue Loading

Table 5 summarizes the flexural performance of ECC beams - monotonically loaded to failure without fatigue loading (virgin beams) and after subjected to fatigue loading (fatigued beams), The performance was judged based on ultimate flexural strength, mid-span deflection at ultimate/peak load, the energy absorbing capacity (area under the load-deflection curve) and stiffness (slope of initial part of load-deflection response).

Table 5: Summary of pre-fatigue and post-fatigue flexural performance at the age of 28 days

Mixture ID	Ultimate Strength			Ultimate Deflection			Stiffness			Energy at 85% ultimate load		
	Virgin kN	Fatig-ued kN	Ratio *	Virgin mm	Fatig-ued mm	Ratio	Virgin kN/mm	Fatig-ued kN/mm	Ratio	Virgin J	Fatig-ued J	Ratio
F_1.2_SS	11.18	4.94	0.44	3.04	1.59	0.52	10.87	3.11	0.29	19.2	4.1	0.21
F_2.2_SS	9.68	5.85	0.60	7.61	1.83	0.24	7.31	3.19	0.44	48.3	8.4	0.17
F_1.2_MS	11.59	6.43	0.55	2.64	1.52	0.58	10.11	4.23	0.42	19.7	7.7	0.39
F_2.2_MS	10.63	7.26	0.68	4.17	1.92	0.46	6.50	3.78	0.58	24.3	10.9	0.45

**ratio: fatigued to virgin*

Figure 2 compares flexural strength-deflection responses of fatigued samples compared to their virgin counterparts. Table 5 compares the flexural strength, deflection, stiffness and energy absorbing capacity fatigued samples compared to their virgin counterparts. The residual flexural strength of fatigued samples (compared to their virgin counterparts) ranged between 44% and 68% with mortar sand based ECC samples showing higher residual strength (ranging between 55% and 68%) compared to their SS counterparts (ranging between 44% and 60%). The increase in FA content increased the residual strength for both SS and MS based ECC samples. The residual deflection capacity of fatigued samples (compared to their virgin counterparts) ranged between 24% and 58%. Mortar sand based ECC samples showed higher residual deflection capacity (ranging between 46% and 58%) compared to their SS counterparts (ranging between 24% and 52%). The increase in FA content decreased the residual deflection capacity of both SS and MS based ECC samples.

The first cracking stiffness (slope of load deflection curve) of SS samples was higher compared to their MS counterparts. MS fatigued samples showed higher residual stiffness (42% to 58% of virgin) compared to their SS counterparts (29% to 44%). The use of higher FA content increased the residual stiffness capacity of both MS and SS based ECC samples. The increase in FA content and the use of MS increased the energy absorbing capacity of ECC samples. The residual energy absorbing capacity of fatigued MS-ECC samples was higher (ranging between 39% and 45% with respect to virgin) compared to their SS counterparts (ranging between 17% and 21%).

The higher strength, deflection and energy absorbing capacity of mortar sand based ECC mixtures under fatigue loading can be attributed to the large aggregate size that enhances friction and aggregate interlocking (Sherir et al. 2015). Similar superior fatigue performance of crushed sand based ECC link slab in joint-free bridge deck was observed by Hossain et al. (2015).

4 Conclusions

This paper presents the structural performance of engineered cementitious composite (ECC) beams subjected to pre and post-fatigue monotonic loading. Four different types of ECC mixtures were tested to study flexural strength and deflection characteristics by analyzing the influence of aggregate type (mortar and crushed sand), size and different percentage of class-F fly ash (FA) as cement replacement (55% and 70%). The fatigue tests were performed on beams at 28 days by applying 400,000 cycles at 4 Hz at 50 ±15% stress level before tested to failure under static monotonic loading.

- The increase of class F-fly ash replacement level from 55% to 70% had negligible influence on the flexural strength but enhanced bending and energy absorbing capacity of ECC both mortar sand (MS) and silica sand (SS) based ECC beams.
- The use of MS with bigger aggregate sand in place of SS had negligible influence on flexural strength capacity but reduced ductility or bending capacity of ECC beams.
- The MS ECC beams showed superior fatigue performance compared to their SS counterparts by exhibiting higher residual flexural strength, stiffness, bending capacity and energy absorbing capacity.
- The use MS in place of SS can be used to produce cheaper ECC mixes with satisfactory mechanical properties for structural elements subjected to static and fatigue loading.

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