Deformational Behavior of Fiber Reinforced Cement Based Materials Under Repeated Loading

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ABSTRACT

Bond degradation of the constitute materials of the structure causes an increase in residual deflection and total surface crack width which reduces overall performance of structures. Advanced construction materials such as ultra-high strength fiber-reinforced concrete, commonly known as engineered cementitious composite (ECC) and fiber-reinforced strain-hardening cement-based composites (SHCC)are designed to offer superior mechanical properties with multiple fine cracks and deformability than conventional concrete materials because of the bridging effect of embedded fibers. In general, both ECC and SHCC can be suitable for applications involving repeated loadings. However, the performance depends on magnitude, type of loads, etc. In this study, deformational behavior of fiber reinforced cement-based materials, ECC and SHCC, under repeated loading (low cycle fatigue) were investigated. Test results showed that, ECC is bendable, the deformation can be easily detected and has high impact resistance. On the other hand, SHCC has the potential for multiple cracking and strain-hardening behavior. ECC and SHCC can thus be used for strengthening and retrofitting of structural elements in addition to their benefits for new construction works.

Keywords: Crack width; Deformational behavior; ECC; Impact resistance; Repeated loading; SHCC.

1. INTRODUCTION

ECC is an ultra-ductile mortar based composite reinforced with short random fibers. ECC, unlike common fiber reinforced concrete, is a micromechanically designed material [1]. ECC has high bond strength of embedded fibers as well as compressive strength and bending toughness. It uses steel and the curing process takes place in a high temperature chamber. Since the hydration process of ECC is completed by high temperature curing, the creep recovery of ECC specimen is insignificant and can be neglected. Under distributed loads ECC gives multiple finite micro cracks due to the bridging effect of fibers [2]. This behavior exists even under the action of concentrated loads. Some of the advantages of bendable concretes include; ability to bend like a metal, higher durability and lower emission of harmful gases as compared to that of conventional concrete [3], resistance to cracking and fire resistance at elevated temperatures [4], etc.

The specific benefits stated vary depending on the volume and type of fibers used in the mix. So far, they have been mainly used for pavement overlay, link-slab for bridge expansion joints, repair of existing concrete structures, footbridge construction and so on [5, 6]. Fischer and Li [7] examined the behavior of ECC elements reinforced with fiber-reinforced polymer (FRP), focusing on the failure mode and residual deflection under reversed cyclic loading. However, the research did not address the performance of ECC members for repeated number of impact loading with and without FRP.

On the other hand, SHCC use plastic fibers and cure under controlled conditions. SHCC exhibit superior crack width and spacing control in the pseudo strain hardening phase. SHCC, distinguished by its ability to develop multiple, finely spaced cracks of tight crack widths, generally below 100 µm. This crack control may be exploited for its potential inherent durability and the durability it may afford structures [8, 9]. Studies showed that polyvinyl alcohol-engineering cementitious composites (PVA-ECCs) reduce the brittle nature of concrete and have been widely used for repairing bridge deck, widening, asphalt overlay, etc. However, use of PVA-ECCs as a major structural material does not have economic benefits [10].

Addition of polypropylene (PP) fibers up to a volume ratio of 1.5 % to PVA-ECC mixes significantly increases its impact strength of PP-PVA-ECC [11]. Research conducted on reinforced concrete (RC) slabs showed that use of SHCC layers on the tension side enabled the slab to resist high impact resistance as compared to the un-strengthened RC slab [12]. The residual deformation of structures due to repeated loadings increases as a result of bond degradation of the constitute materials. Structural deterioration is increased by loading condition and the type of loads as well as environmental factors [13].

Many studies on the deformation behavior of fiber reinforced cement-based materials have been conducted, with a particular emphasis on static, impact, torsional, and reverse cyclic loading. However, researches on the performance of ECC and SHCC under repeated static and impact loading with different level of loading is limited. In this study, deformational behavior of ECC and SHCC under different level of repeated loadings (low cycle fatigue) and damping properties is investigated. The objectives of this study aim to enhance the understanding and performance of ECC and SHCC materials, ensuring their capacity to withstand the demands of real structural applications to resist sudden impacts.

2. MATERIALS AND METHODS

2.1 Materials

Mix proportions for ECC and SHCC were made as per the JSCE recommendations for design and construction of ultra-high strength fiber reinforced concrete structures [14]. In all cases, Type II fly ash was used.

2.1.1 ECC mix proportion

Table 1 shows the total quantities of component materials of ECC used in this study. Steel fiber used for ECC was as per JSCE with tensile strength not less than $2x10^3$ N/mm^2 [14]. Steel fibers had a diameter of 0.2 mm. Figure 1 shows the sample of steel fibers used in the study.

Table 1 Component materials of ECC

Materials	Quantity (kg)	(%)
Water	19.18	6.30
Binder (cement and fly ash)	154.44	50.74
Fine aggregate	107.30	35.25
Super plasticizer	5.41	1.78
Shrinkage reducing agent	1.54	0.51
Steel fiber, 15mm and 22mm in length (1.75% by vol.)	16.49	5.42

Figure 1 Steel fiber

2.1.2 SHCC mix proportion

The mix proportion for SHCC is shown in Table 2. For SHCC specimens, a water to binder ratio of 43.2 %, sand to binder ratio of 72 %, fiber volume of2 %, air content of 9.6 % and 12 mm PVA fibers with 0.04 mm in diameter were used. The tensile strength of the fiber is 1500 MPa and the Young's modulus is 40 GPa [14]. PVA fibers used in this study are shown in Figure 2.

Table 2 Mix proportion of SHCC

Materials	Quantity (kg/m^3)	(%)
Water	353	19.51
Cement	571	31.56
Fly ash (Type II)	245	13.54
Expansion admixture	20	1.11
Silica sand	585	32.34
PVA fiber (1.2% by vol.)	25	1.38
Super plasticizer	8.36	0.46
Viscous additive	1.67	0.09

Figure 2 PVA fibers

2.1.3. Mixing procedure and curing

In preparing ECC and SHCC mixes, the following mix procedures were used [14]:

- The dry ingredients were thoroughly mixed for 2 to 5 minutes
- 2/3 of the amount of water was added to the dry mix and mixing was continued for 1 minute
- Super plasticizer was added and mixed for 1.5 minutes
- The remaining water (1/3) was added and mixed for 1.5 minutes
- Finally, the fibers were added and mixed for 3 minutes

Casting of specimens with different depths was made by putting the mixes in a mold and tamping with a metal rod. Plastic sheets were used to cover the ECC specimens during the curing process. For SHCC specimens, the specimens were placed in a curing pond for 28 days. The specimen size, particularly the depth, was selected based on the experimental test results of trial ECC specimens with various depths loaded at mid-span. Because the overall effects (deflection and surface crack widths) were found small, a 2 cm deep specimen was chosen for repeated static and impact load tests. The ECC specimens (2cm thick) are shown in Figure 3.

Figure 3 ECC specimens (2cm thick)

2.2 Test Equipment and Setup

Hydraulic jack machine, data logger, impact loading apparatus, dynamic data logger, laser displacement sensor, crack width scale and Linear Variable Displacement Transducers (LVDT) were used. The specimen was simply supported with a span length of 120 mm and for repeated static load test case, it was loaded with two-point loads spaced at 40mm apart. Hence, the specimen size considered in this study was 16 cm×4 cm×2 cm.

2.2.1. Static loading apparatus

Hydraulic jack was used for static load testing and measurements of deflection and crack widths were made using LVDT and crack width scale, respectively. Clamping of specimen at the ends was made using steel plates and bolts as shown in Figure 4.

The residual deflection and crack widths were measured indirectly by taking out the specimens at every 50 cycles as shown in Figure 4, in which the LVDT was fixed to the loading frame. Loading rates were set as per the specification stipulated in JIS R 5201. For compressive strength test, load rates of 2400±200 (N/s) and for flexural strength tests 50±10 (N/s) have been used [15].

Figure 4 Measuring deflection using LVDT

2.2.2. Impact loading apparatus

The drop weight impact loading method used in this study was based on the method proposed by ACI Committee 544 [16]. A schematic diagram of a drop-weight impact testing apparatus is shown in Figure 5.

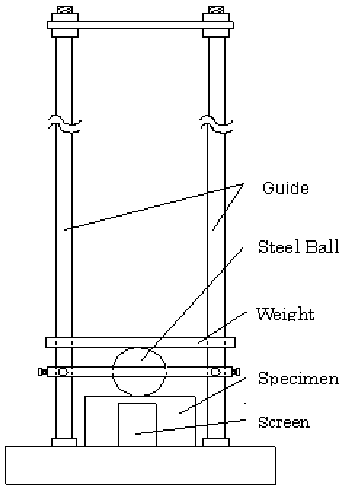


Figure 5 Schematic diagram of a drop-weight impact testing apparatus

A 5 kg square steel plate with dimensions of 250 mm by 10 mm thick and a 2 kg square steel tube of 40 mm in side length, 4mm in thickness, and 45 cm in length were applied through a steel ball to the top surface of ECC and SHCC specimens, respectively. As the drop-weight impact testing apparatus has a guide post spacing of 200 mm, in this study, the specimen's length was considered to be 160 mm.

2.2.3. Vibration loading test

ECC and SHCC specimens were subjected to drop-weight at different heights, and the vibration responses were recorded using a dynamic data logger. A picture showing the experimental set-up for direct measurement of impact/ dynamic test using laser displacement sensor is shown in Figure 6.

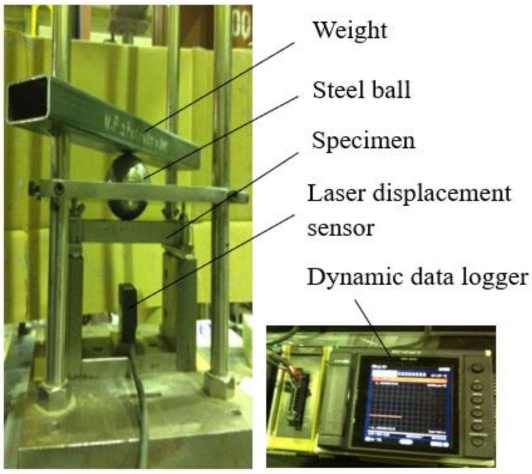


Figure 6 Direct measurement setup of impact test

2.3 Loading Conditions

Initially, a reference load of 75 % of the maximum load was applied statically to all ECC and SHCC specimens (maximum load carrying capacity of ECC specimens was 4kN and for that of SHCC specimens was 1.6 kN). This initial loading was used to generate finite multiple cracks.

2.3.1. ECC specimens

The loading condition of specimens due to static load (SL) and impact load (IL) for ECC is shown in Table 3.

Table 3 Loading conditions for ECC

Specimen	Loading condition
SL-1	3kN (high load level)
SL -2	3kN and 1.5 kN with an interval of 50 times (medium load level)
SL -3	1.5 kN (low load level)
IL -1	Drop height of 30 mm
IL-2	Drop heights of 20 and 30 mm with an interval of 50 times
IL -3	Drop height of 20 mm

2.3.2. SHCC specimens

The loading condition of specimens due to impact load (IL) for SHCC is shown in Table5. The impact loading test was repeated for 1000 times. The loading condition for SHCC is shown in Table 4.

Table 4 Loading conditions for SHCC

Specimen	Loading condition
IL -1A	Drop height of 30 mm
IL -2A	Drop heights of 20 and 30 mm with an interval of 50 times
IL -3A	Drop height of 20 mm

3. RESULTS AND DISCUSSION

3.1 Mechanical Properties

3.1.1. ECC specimens

The compressive and flexural strengths of ECC specimens are shown in Table 5 below.

Table 5 Mechanical properties of ECC

Properties	Strength (MPa)
compressive strength	186.9
Flexural strength	30.9

3.1.2. SHCC specimens

Mechanical properties of SHCC specimens are shown in Table 6.

Table 6 Mechanical properties of SHCC

Properties	Strength (MPa)
compressive strength	41.29
Flexural strength	16.39

3.2 Static Load Test Results

A hydraulic jack was used to apply load to ECC and SHCC specimens, with the load rates being manually controlled. In some cases, the load-deflection curves might not appear smooth due to fluctuations in the applied load and minor disturbances in the test set-up. In this study, for the first load cycle, the data points are adjusted to fit a smooth curve.

3.2.1 ECC Specimens

From test results, it was observed that ECC's ability to resist loads at higher number of loadings was found to be good. The load-displacement diagrams of ECC specimens under repeated static loadings (with 75% of the maximum load) are shown in Figure 7. Due to slight differences in the specimens' depth, the defections of the specimens for the first load cycle were found to be different.

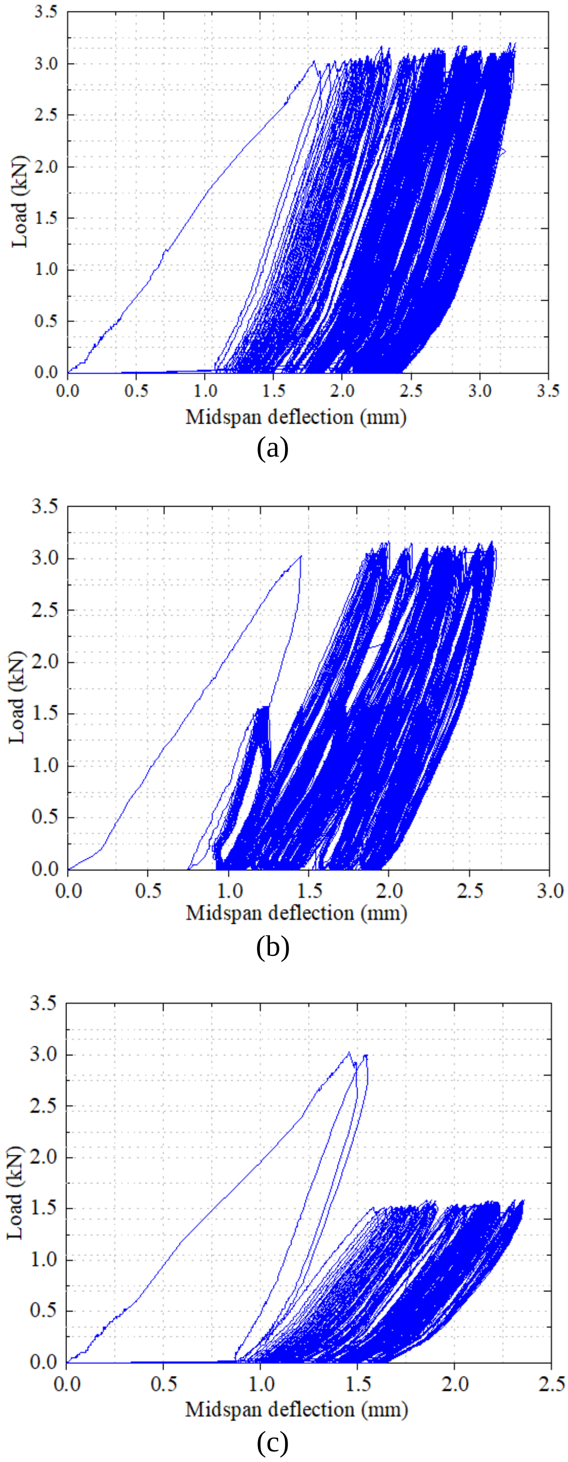
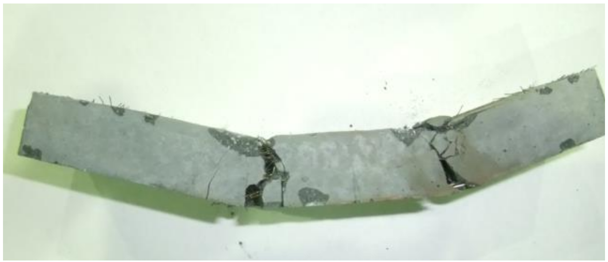


Figure 7 Load deflection diagram of ECC (a) SL-1 (b) SL-2 and (c) SL-3

The maximum deflection of the ECC specimen after the end of the 1000th static load was 3.25 mm with a residual deflection of 2.40 mm (for SL-1 loading condition). For the first load cycle, the total crack width for high level of static loadings remained below 0.35 mm and for that of low load level was found below 0.10 mm. The crack width result is in line with related researches conducted on fiber reinforced polypropylene ECC beams under reverse cyclic loadings [17]. Test results shown in Figure 7 revealed that the deformations of ECC specimens due to repeated static loading was increased gradually and it was small. This is due to the bridging effect of randomly distributed small diameter micro-fibers with high tensile strength and their ability to resist cracks as studied by Yang et al. [18].

Deformed and cracked ECC specimen under repeated static loading (SL-1) is shown in Figure 8.



(a)

(b)

Figure 8 Deformed ECC specimen under (a) high load level (SL-1) and medium load level (SL-2)

3.2.2 SHCC Specimens

SHCC beam specimens could not be loaded repeatedly as the member failed after a few numbers of static loadings. This is due to the fact that performance of SHCC under repeated static loading is relatively poor as studied by Zhu et al. [19]. The load-displacement diagram of SHCC specimen during the initial load cycle is shown in Figure 9.

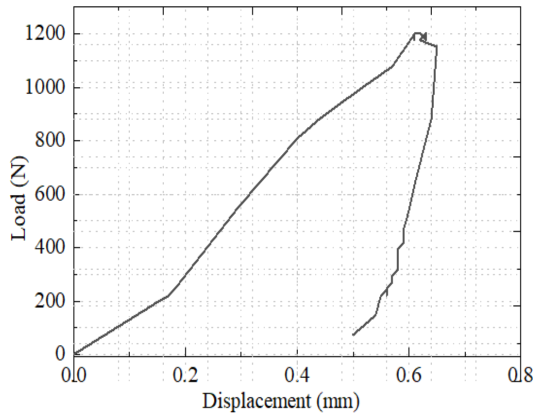


Figure 9 Load-displacement diagram of SHCC

3.3 Impact Load Test Results

3.3.1 ECC Specimens

The drop weight impact loading test results of ECC specimens for residual deflection and total crack widths are summarized in Figures 10 and 11, respectively. The residual deflectionswere computed with reference to the residual deflection of the first load cycle.

As shown in Figures 10 and 11, three different deformation zones of ECC, for IL-1 load case were observed. These zones are initial, steady and saturated zones. Initially, finite cracks are generated in this zone which is referred to as a pre-processing zone. This zone allows for a more accurate assessment of material behavior under practical loading conditions. This result is consistent with related research published by Yoo and Banthia [20], which shows that the fibers that are evenly distributed can sustain initial impacts without suffering substantial internal damage, leading to a linear deformation behavior.

Secondly, especially for medium level of impact loading, uniform and gradual increase in residual deflection was recorded. Finally, after the steady zone was completed, remarkable and substantial pull-out of steel fibers has occurred and there was a rapid increase in residual deflection and crack width than expected. This condition leads to ductile failure of specimens, undesirable and the ECC specimen is no more useful. It is also observed that crack width varies as the cycle increases and it is an indication for the number of overloading. Deformed and cracked (1.2 mm) ECC specimen under the bottom side (IL-1) are shown in Figure 12.

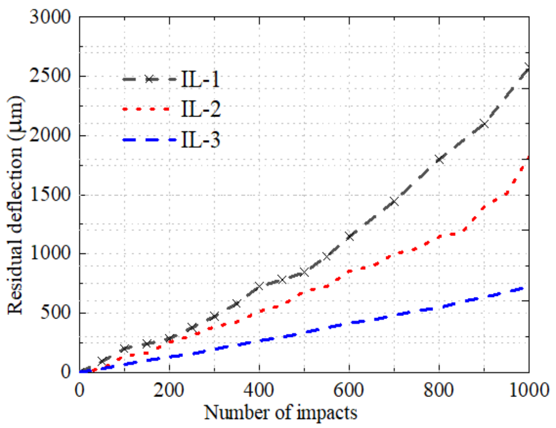


Figure 10 Residual deflection curves

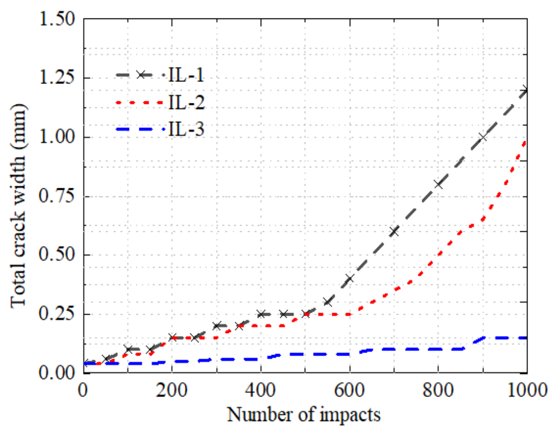
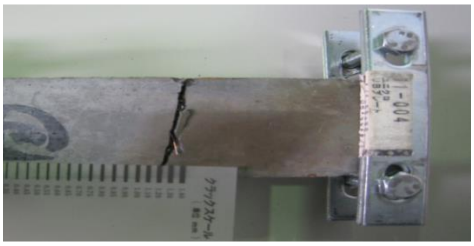


Figure 11 Total crack width curves

(a)



(b)

Figure 12 (a) deformed and (b) cracked pattern of ECC specimen (IL-1)

However, all the three zones were not observed for IL-2 and IL-3 loading conditions because the damages to these specimens due to 1000 number of low-level impact loading were found relatively small. Similar results have been found by Yoo and Banthia [20], showing that ECC tends to form small micro cracks rather than large, discrete cracks under low impact loading. The fibers within ECC bridge these micro cracks, controlling their growth and allowing the material to deform uniformly.

The test results from this study are comparable to those reported by Zhang et al. [21], wherein a uniform and gradual deformation was obtained by ECC's ability to deform under repeated impact loads without experiencing sudden failure. Further cracks eventually developed and as a result of this, increasing the residual deflection. ECC provides better impact resistance and load carrying capacity than conventional RC elements [22].

3.3.2 SHCC Specimens

The curves of residual deflection of SHCC specimens due to repeated impact loadings are shown in Figure 13. Unlike ECC, SHCC exhibited unusual deformation zones for load cases IL-1A and IL-2A due to their weak impact resistance, especially for the first 150 number of impacts.

In Figure 13, it is shown that at high level of impact loading, the deflection curve of IL-3A is non-linear and SHCC's resistance to impact is not good. Furthermore, with 1000 number of impacts, particularly specimen IL-1A (low load level) exhibited remarkable cracks at the center, unable to resist the load and finally the specimen failed as shown in Figure 14. This could be due to an inconsistency mix of PVA fibers in the matrix [23]. As a result, crack width curves for SHCC specimens could not be measured. Recent research has demonstrated that ductility enhanced high strength SHCC (dHS-SHCC) can improve the drop-weight impact behavior of SHCC specimens [24].

As demonstrated in Figures 10 and 13, ECC exhibited large impact resistance as compared to SHCC specimens. The result is consistent with related experimental results where an ECC panel has a significant impact resistance with reduced damage [21, 22]. The residual deflection of ECC was found to be 28 % to 54 % smaller than that of SHCC.

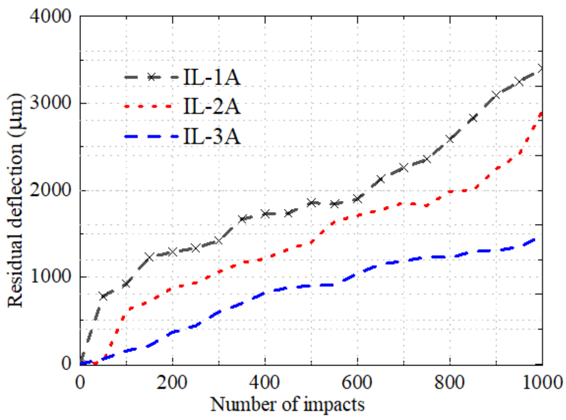


Figure 13 Residual deflection curves of SHCC

Figure 14 Deformed and cracked SHCC specimen under impact loading

3.4 Vibration Test Results

3.4.1 Dynamic responses

A direct measurement of deflection of ECC and SHCC specimens under impact loading with drop heights of 30mm and 40mm was carried out by the use of laser displacement sensor and a dynamic data logger. The impact load in the case of ECC was 5 kg and for that of SHCC was 2 kg. The displacement histories are shown in Figure 15.

In Figure 15, it is shown that, even under the action of smaller impact loads, the impact resistance of SHCC is lower than ECC specimens, i.e., the deflection of SHCC is significantly greater than that of ECC. Moreover, due to number of impacts, closely spaced micro cracks have been developed in ECC specimens. These micro-cracks with low crack width show that the ability of ECC materials to resist cracks is excellent. This makes ECC a better choice of material than SHCC for impact loads. The result on crack width formation is comparable with the research conducted by Qin et al. [25].

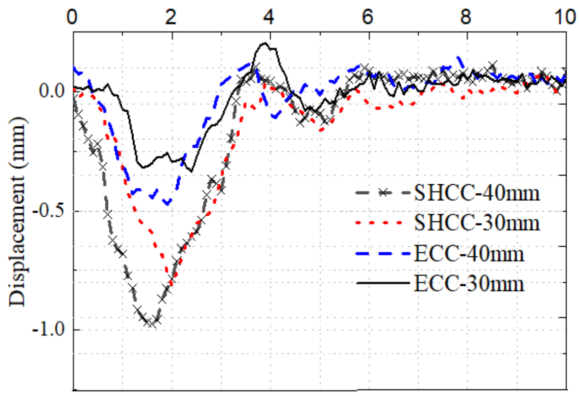


Figure 15 Displacement histories/ dynamic response of ECC and SHCC specimens

3.4.2 Damping Property

The free vibration decay method calculates a logarithmic decrement which helps to find the damping ratio [26]. From the amplitude records of the impact load tests (Figure 15), the values of the damping ratio were calculated using Eq. (1) [27, 28] and the results are summarized in Table 7.

$$\xi = \frac{1}{2n\pi}\ln\left(\frac{A_o}{A_n}\right) \quad (1)$$

where:

ξ is the damping ratio (%)
A_o is an initial amplitude
A_n is the amplitude after *n* cycles

Table 7 Damping ratios of ECC and SHCC

Specimens	Amplitudes		ξ (%)
	A_1	A_3	
ECC-40	0.44	0.03	14.25
ECC-30	0.33	0.02	14.89
SHCC-40	0.94	0.14	10.11
SHCC-30	0.81	0.09	11.65

From Table 7, it is observed that damping ratios of ECC and SHCC range from 10% to 15% and ECC shows a higher damping capacity (on average, ECC had a 34 % higher damping property than SHCC). The average damping ratio of ECC specimens is 26.56 % higher than recent research conducted by Tian, Y., et al. [29], in which the maximum damping ratio of fiber containing cement-based mortar specimens reached to 10.7 %.

3.5 Comparison of ECC and SHCC

Summary of comparison of ECC and SHCC specimens is shown in Table 8.

Table 8 Comparison of test results

Properties		ECC	SHCC
Strength (MPa)	Compression	186.9	41.29
	Flexural	30.90	16.39
Load carrying capacity of specimens for two-point loads (N)		3,500	1,200
Residual deflection(mm) for impact loading		2.60 (IL-1)	3.45 (IL-1A)
Maximum crack width (mm) for impact loading		1.2 (h=30mm & w=5kg)	6 (h=30mm & w=2kg)
Vibration response (mm)		0.44	0.94
Damping ratio (%)		14.57	10.88

From Table 8, for the specific mixes, ECC exhibited less damage during deformation and maintained high impact resistance as specified in other researches [30, 31] than equal-sized SHCC specimens even with a reduced drop weight and height. This behavior is also reflected on the residual deflection and crack width patterns, where SHCC specimens loaded with a 2 kg impact load, cracked five times wider than ECC specimens subjected to a 5 kg drop weight.

Therefore, based on the benefits of ECC material and experimental results of this study, it was observed that ECC can last longer without remarkable deterioration and withstand impact loading safely as compared to SHCC.

4. CONCLUSIONS

According to the experimental test results of this study, ECC specimens exhibited uniform behavior under low loading levels and showed a better resistance to repeated static and impact loads with insignificant damage. It was observed that, on average, the residual deflection of ECC specimens caused by repeated impact loads was less than those of SHCC by 40 %.

For the same drop heights, the vibration response of SHCC specimens was two times larger than that of ECC specimens. The vibration test result also showed ECC had a 34% higher damping ratio than SHCC. Because of this, ECC can be used appropriately for the construction of bridges, pavement overlays, retrofitting and strengthening of structural elements subjected to high impact and repeated loads.

SHCC's resistance to repeated impact loads is much lower than ECC specimens even under low-level of impact loads (60 % of the weight applied to ECC specimen was applied to SHCC specimen) with a reduced height (33.33 % lower than the level where the load was dropped to ECC specimens).

For future work, it is recommended to evaluate the sustainability of ECC and SHCC using a comprehensive life cycle analysis.

CONFLICT OF INTEREST

The author declares that there is no conflict of interest.

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