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16. Abstract

Engineered cementitious composites (ECC) is a class of high-performance fiber reinforced cementitious composites featuring the metal like strain hardening behavior under tension. The high tensile ductility of ECC results in high impact resistance and energy absorption capacity which make the ECC ideal for application in impact resistance structures, like crash barriers compare to regular concrete. It was envisioned that by employing ECC in the design of concrete crash barriers, the impact resistance of the barriers will be effectively improved; damage to vehicles and passengers during vehicle-barrier collisions will be reduced; the service life of concrete barriers will be extended; and maintenance cost will be reduced. This research presents the results of tailoring ECC mix composition to allow using domestically available poly-vinyl alcohol (PVA) fibers and locally available river sand for impact resistance. Material tailoring was conducted under the guidance of micromechanics design principle by adjusting the fiber, matrix and interface properties to retain the tensile ductility. The tensile and flexural behavior of the developed material were characterized under pseudo-static loading as well as high strain rate loading up to 10^{-1} s^{-1}. Direct drop-weight impact test was also conducted to assess the impact resistance and energy absorption capacity of the material. It was ensured that the ECC maintains the tensile strain capacity above 1.8% under all tested strain rates. Comparing the damage characteristics, energy absorption capacity and load-bearing capacity during repeated impact loading with regular R/C panels, ECC was found to have superior energy dissipation capacity, and damage tolerance. Investigation of the long-term performance of the newly designed ECC mixture under chloride environment and tropical weather condition was also conducted. The experimental result demonstrated that the ductile tensile behavior, high impact resistance, and high energy absorption capacity is maintained after up to four months of conditioning in chloride environment or hot water immersion. The research result has demonstrated that the newly developed ECC has a great potential for crash barrier applications.

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ABSTRACT

Engineered cementitious composites (ECC) is a class of high-performance fiber reinforced cementitious composites featuring the metal like strain hardening behavior under tension. The high tensile ductility of ECC results in high impact resistance and energy absorption capacity which make the ECC ideal for application in impact resistance structures, like crash barriers compare to regular concrete. Concrete crash barriers, due to the low energy absorption capacity and rigidity of concrete, possess severe safety threats to the vehicles and passengers. It was envisioned that by employing ECC in the design of concrete crash barriers, the impact resistance of the barriers will be effectively improved; damage to vehicles and passengers during vehicle-barrier collisions will be reduced; the service life of concrete barriers will be extended; and maintenance cost will be reduced.

This research presents the results of tailoring ECC mix composition to allow using domestically available poly-vinyl alcohol (PVA) fibers and locally available river sand for impact resistance. Material tailoring was conducted under the guidance of micromechanics design principle by adjusting the fiber, matrix and interface properties to retain the tensile ductility. The tensile and flexural behavior of the developed material were characterized under pseudo-static loading as well as high strain rate loading up to 10^{-1} s^{-1}. Direct drop-weight impact test was also conducted to assess the impact resistance and energy absorption capacity of the material. It was ensured that the ECC maintains the tensile strain capacity above 1.8% under all tested strain rates. Comparing the damage characteristics, energy absorption capacity and load-bearing capacity during repeated impact loading with regular R/C panels, ECC was found to have superior energy dissipation capacity, and damage tolerance. Investigation of the long-term performance of the newly designed ECC mixture under chloride environment and tropical weather condition was also conducted. The experimental result demonstrated that the ductile tensile behavior, high impact resistance, and high energy absorption capacity is maintained after up to four months of conditioning in chloride environment or hot water immersion. The research result has demonstrated that the newly developed ECC has a great potential for crash barrier applications.

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IMPLEMENTATION STATEMENT

The research results in a new ductile concrete mixture that shows high tensile and flexural ductility, high impact resistance and energy absorption capacity in long-term. The ECC mixture developed in the proposed project will be implementable to concrete crash barrier applications by LaDOTD. Additionally, the ECC mixture can also be implemented in other structures that are prone to impact damage, such as exterior girders of highway overpass bridges, bridge piers, airport runway pavement, etc.

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INTRODUCTION

Crash barriers are the structures installed alongside the road and used to contain and direct errant vehicles, prevent the vehicles from entering opposing travel lanes, driving off the road into ravines, or crashing into more dangerous roadside objects. So, these crash barriers are prone to impact loading during vehicle collision. Considering the strength limit to sustain the impact during collision from small to large vehicles, concrete barriers (rigid) are preferred over plastic barriers (flexible) or steel beam or rails (semi-rigid) system. Plastic barriers can be used when reinforced by metal to resist vehicle collision but still it can only be effective for low speed smaller vehicle collision. Steel barriers provide significant strength and reliable protection, but they tend to deflect during collision and generally requires repair and replacement after every impact which can be expensive. However, concrete barriers are heavier and provide exceptional level of strength, reliability, and are more effective in preventing the vehicle penetration [1], therefore they are extensively used in highways and bridges. However, the past studies have shown that the concrete barriers, due to material rigidity and low energy absorption capacity, tend to cause more severe damage during vehicle-barriers collisions [2] putting the traveling vehicle and passengers at high risk.

As concrete barriers are most extensively used barriers, considering the safety of the vehicles and passengers, there is a greater need for an ideal concrete barrier material which has high fracture resistance and high energy dissipation capacity under impact. Apart from the safety performance, durability of concrete barriers is also important to maintain their performance in long-term and reduce maintenance cost. This is of particular concern to the State of Louisiana, where the tropical climate and coastal environment lead to severe corrosion induced deterioration of concrete infrastructures.

In this research, application of engineered cementitious composite (ECC) technology into the design of concrete barriers to enhance the safety performance and durability of concrete crash barriers is reported. As an alternative to conventional concrete, ECC exhibits a ductile behavior under flexure and tension by forming multiple fine cracks (typically less than 60μm wide) along the tension face. The highly ductile behavior and deformation capacity of ECC results in high fracture resistance and energy absorption capacity under static and impact loading [3]. Unlike conventional concrete which often shatters under impact, ECC absorbs significantly higher amount of energy through the formation of multiple fine cracks and prevents catastrophic failure [4]. Additionally, the controlled tight crack width of ECC, compared to large localized cracks typically found in conventional concrete, have been demonstrated to effective reduce the penetration of water and aggressive ions. Together with its high fracture resistance, ECC shows much higher durability against chloride attack, corrosion induced deterioration, tropical weather and freeze-thaw cycles [5].

However, the large-scale application of this material is significantly limited due to its high material cost. The relatively high material cost of ECC is mostly associated with the high cost and lack of local availability of raw ingredients including polymer fibers and fine silica sand. Among various polymeric fibers, PVA-ECC is most widely used in research and demo projects as it has relatively lower cost and higher tensile strength and elastic modulus [6] compared to other polymeric fibers. Considering typical PVA-ECC mixtures, although only less than 2% by total mixture volume of PVA fibers are used, it is estimated that the fiber cost makes up more than half of the total material cost. Furthermore, previously developed ECC mixtures use PVA fibers that are deliberately treated with oil surface coatings [7], which have been demonstrated to favor the tensile performance of ECC. However, such treated fibers were less available from the local market. In many previous projects, the PVA fibers were imported from Japan, which increases the cost and further limits large-scale application of ECC.

Besides fibers, coarse aggregates are generally eliminated from the mix proportion of ECC to facilitate uniform fiber distribution and to favor tensile ductility. Even coarser sand is not desirable in the mix and rather fine silica sand with average particle size around 100~200 µm are usually used. These fine silica sand, compared to river sand or crushed sand, are also of higher cost and are often not locally available, which further contributes to higher material cost in producing ECC. So, the main aim of this research is to lower the material cost by using locally available materials including river sand, and domestically manufactured poly-vinyl alcohol (PVA) fibers, increasing the feasibility of large quantity field implementation of ECC barriers.

For proposed crash barriers application of ECC, accessing the performance of ECC under high rate loading and impact loading is of special interest. It is reported that the ECC has mechanical properties which shows rate dependency [8], [9]. For the proposed application, ECC needs to maintain its ductile behavior under impact loading thus enabling high impact resistance and energy absorption capacity during vehicle-barrier collisions. The tensile ductility of ECC M45, a version of ECC that is most widely studied and already applied in engineering practice, reduces significantly as strain rate increased from 10^{-5} (quasi-static) to 10^{-1} s^{-1} (low speed impact) [8]. The rate dependent behavior of ECC is attributed to the rate sensitive micromechanical parameters, including the interfacial bond properties between fiber and cementitious matrix and the matrix toughness, which result in reduction in tensile ductility of ECC [10].

In addition to behavior under high rate loading, several researches pointed out that ECC shows a slight reduction in ductility when exposed to chloride [11] and hot and humid environment [12] (which are very relevant to the State of Louisiana) due to alterations in fiber/matrix interfacial bond. Immersion of ECC in hot water for 26 weeks at 60^o C showed reduction in strain capacity from 4.5% to 2.75% [12]. Also, immersion of ECC in chloride solution had minimum effect in tensile ductility [11]. Although these researches only showed a slight reduction in ductility under static loading, the impact behavior of ECC under such environments could be more notably affected due to the combined effects of loading rate and environmental conditions., particularly for the proposed mixture made with domestic fibers. However, the coupled effects of loading rate and environmental exposure have never been studied before.

In this research, a new impact resistant ECC mixture was developed using economical and locally accessible raw materials, including river sand, and domestically manufactured poly-vinyl alcohol (PVA) fibers. The tensile, flexural properties, energy absorption capacity, and impact resistance of the ECC mixture under static, high rate and impact loadings were accessed and reported. To ensure adequate long-term performance of ECC crash barrier, the mechanical properties under high rate loading, impact resistance and energy absorption capacity of ECC under chloride environment and hot and humid weather were conducted.

Design Philosophy of ECC

Customizing ECC mixtures requires basic understanding of the micromechanics-based ECC design theory, which links the microstructural and micromechanical properties of ECC (matrix properties, fiber properties, matrix/fiber interfacial properties, etc.) to the macro-level material properties (tensile strength, tensile ductility, cracks width, etc.). The core of the ECC design theory are two strain-hardening conditions, energy and strength-based criteria that both need to be satisfied to achieve the ductile tensile strain-hardening and multiple cracking behavior [13] [14].:

Energy based criterion: $$J_{tip} \le \sigma_0\delta_0 - \int_0^{\delta_0} \sigma(\delta)d\delta \equiv J'_b \quad (1)$$

Strength based criterion: $$\sigma_0 > \sigma_{cs} \quad (2)$$

Equation (1) describes the energy balance in the crack extension process; it requires that the fracture energy of the matrix J_{tip} (which is approximately equal to K_m^2/E_m, where K_m is the matrix fracture toughness, and E_m is the matrix Young's modulus) to be less than or equal to the fiber bridging complementary energy J'_b. The fiber bridging complementary energy J'_b, as stated in the right-hand side of Equation (1) and illustrated in Figure 1 [15], is essentially governed by the fiber bridging stress v.s. crack opening relationship ($\sigma(\delta)$ relationship) of the crack plane. Equation (2) describes the strength criterion, which requires the fiber bridging strength σ_0 to be higher than the matrix cracking strength σ_{cs} that is governed by the matrix fracture toughness and flaw size. If either Equation (1) or Equation (2) is not satisfied, the composite fails with a single localized crack, instead of multiple cracking, and a typical tension-softening behavior of normal fiber reinforced concrete is observed.

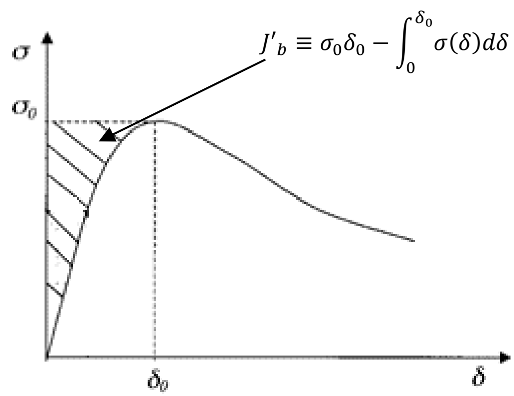


Figure 1 Calculation of fiber bridging complementary energy [15].

PVA fibers, without surface oil treatment, have a hydrophilic surface nature often resulting in strong chemical bond to cementitious matrix. However, this excessive bond causes a stiffer fiber bridging ($\sigma(\delta)$) behavior that tends to lower J'_b and violate Equation (1). Often, satisfaction of the energy criterion represents the major challenge of developing PVA-ECC mixtures

To satisfy the energy criterion, the composition needs to be tailored to limit the matrix fracture energy J_{tip} and/or increase the complementary energy J'_b. In the previous studies, techniques used to limit J_{tip} include controlling the particle size of aggregates, use high content of fly ash, incorporation of lightweight aggregates, etc. [16], [17]. To increase the complementary energy J'_b, selection of fibers of appropriate geometry, strength, and stiffness, adjustment of fiber content and fiber surface treatment are all useful techniques [7], [18], [19]. Additionally, altering the matrix composition, e.g. increase the fly ash content, also alters the interfacial bond properties between the fibers and matrix, thus altering J'_b [16], [17]

The focus of present study is to customize ECC proportions to allow using domestically manufactured PVA fibers and local sand; there is less freedom in choosing aggregate size, fiber geometry and properties. As a result, the material tailoring in the present study is mainly done through tailoring the matrix composition. In particular, to compensate for the potential increase of matrix toughness caused by coarser sand and high chemical bond between non-oil coated PVA fibers and cementitious matrix, ECC matrix with higher fly ash content is employed since high fly ash content tends to simultaneously lower the matrix toughness and interfacial chemical bond. As interfacial chemical bond drops with increase in fly ash content [21] it also becomes effective in minimizing the rate dependency of PVA-ECC thus making the mix suitable for high rate and impact loading.

OBJECTIVE

The overall goal of this research is to improve the impact resistance and energy absorption capacity of concrete barriers via incorporating ECC technology. Ultimately, this research aims at reducing the fatalities and injuries of passengers during vehicle-barrier collisions and at the same time, reducing the maintenance cost of the crash barriers. The specific objectives of this research to achieve the above-mentioned goal are:

1. Develop a new ECC mixture with high energy absorption capacity and impact resistance using economical and locally accessible raw materials;
2. Characterize mechanical properties of the ECC mixture under static and high rate loadings; evaluate the impact resistance and energy absorption capacity of the ECC mixture via direct impact testing;
3. Investigate the long-term impact resistance and energy absorption capacity of the ECC mixture under chloride environment and tropical weather.

SCOPE

For this research, a new ECC mixture was developed through material tailoring. Mechanical performance of ECC are characterized based on compressive test, direct tensile test and four-point bending test under static and high strain rate loading (up to 10^{-1}/s). Impact resistance and energy absorption capacity of the developed ECC mixture are characterized under direct impact testing. The mechanical performance, impact resistance, and energy absorption of ECC after long-term exposure to chloride environment and hot weather conditioning are also evaluated.

METHODOLOGY

The research involves three part, first is the material development, second part is impact behavior of the ECC mixture and third part, long-term impact resistance and energy absorption capacity of the ECC mixture under chloride environment and tropical weather. In material development, a new ECC mixture was developed using locally accessible material which included domestically available PVA fibers and river sand. The mechanical performance of ECC was involved the compression, tension and flexural behavior was measured at pseudo-static strain rate. The best performing mixture was further tested under high rate loading and impact loading in second part to examine the performance. Compressive test (per ASTM C109), direct tension test and three-point bending test (per ASTM C1609) under static loading and high strain rate loadings (up to 10^{-1}/s) will be conducted to characterize the performance of the ECC mixture. In third part, long term performance, effect of chloride environment and hot and humid environment was accessed. To examine the effect of chloride environment in impact resistance and energy absorption capacity ECC tensile, and impact panel specimens were immersed in 3% NaCl solution at room temperature for 1, 2, 3, and 4 months. Similarly, to examine the effect of hot and humid environment ECC tensile and impact panel specimens were immersed in hot water for at 60^{o} C for 1, 2, 3, and 4 months. After respective exposure, they were tested for their tensile performance under static and high rate loadings, and for their impact resistance and energy absorption capacity under direct impact test.

Experimental program

Materials The material used to develop ECC mixture are Type 1 Portland cement, class F fly ash, river sand, high range water reducing admixture (HRWRA), PVA fibers. The base mixture adopted from literature had F75 silica sand and imported Japanese fibers (1.2% surface oil coated). A type of non-surface treated domestically manufactured PVA fibers were used to replace the Japanese PVA fibers to develop new ECC mixture. Domestically available PVA fiber was used named RECS-15 supplied by Nycon Corporation. The F75 silica sand in the base mixture was replaced with river sand in resulting ECC mixture. The particles that are larger than 0.187 in (approximately the largest 2% particles) were removed from the local river sand by sieving to control the negative effects of coarser particle size.

Mix proportion. Considering the effect of the non-surface coated PVA fibers and coarser river sand on the micromechanical parameter like matrix toughness and chemical bond between fiber and matrix, high volume fly ash ECC (HVFA-ECC) mixture [21] were adopted for the base mix. Previous research [22] indicated that the use of fly ash in ECC reduces the matrix toughness and fiber/matrix interfacial chemical bond. HVFA-ECC with fly ash to cement ratio (FA/C) of 2.2 was selected as a base mixture. The base mixture was developed with sieved river sand and non-coated domestically manufactured PVA fibers. To further compensate the negative effect of non-coated PVA fibers and river sand the FA/C was increased to 2.4, 2.8, and 3.2. All the ECC mix proportion examined are summarized in Table 1. The water-cement ration for all mixture was controlled at 0.25 ±0.01. High-range water-reducing admixture for each was adjusted to achieve similar rheological properties for better dispersion of fiber in the mixture.

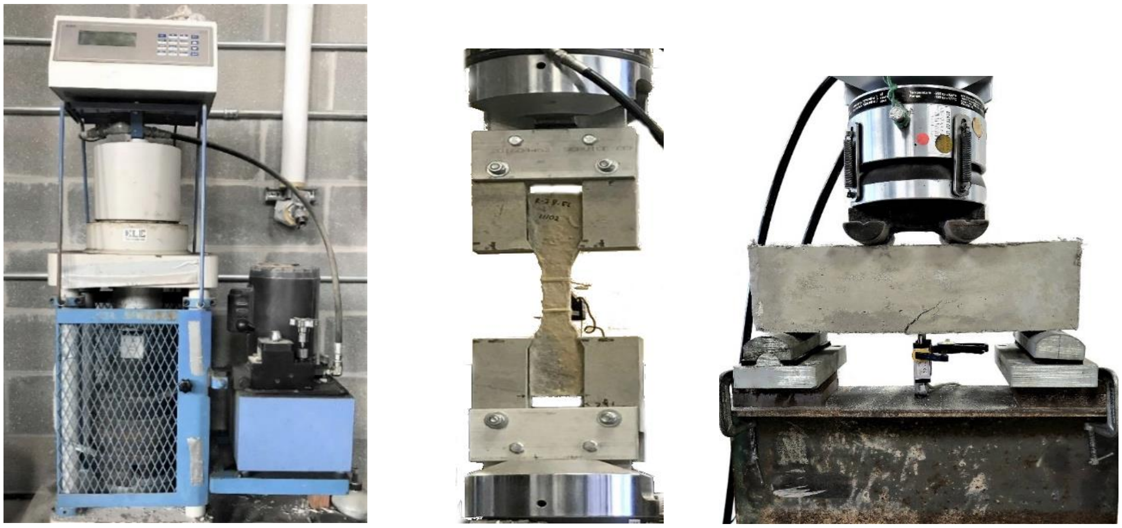
Table 1 Mix Design of ECC (lb/ft^3)

Mix ID	Cement	Fly Ash	River Sand	Water	HRWRA	PVA fiber
FA 2.2	24.9	54.7	29.4	20.7	0.30	1.62
FA 2.4	23.4	56.1	29.4	20.7	0.28	1.62
FA 2.8	20.9	58.4	29.3	20.6	0.25	1.62
FA 3.2	18.8	60.3	29.3	20.6	0.23	1.62

Specimens. A dogbone-shaped specimens were used for the tensile testing as recommended by the Japan Society of Civil Engineers (JSCE) [23]. Dog bone sample has a length of 13 in and the thickness of 0.5 in. The sample had a reduced width of 1.18 in for the length of 3.15 in to form a dog bone shape. In addition to dogbone specimens compression test was performed on a 2 in cube sample as per ASTM C109 [24]. A prism specimen measuring 14 in x 4 in x 4 in was prepared for four-point bending test. Three samples each for compression and tension test and two sample for flexural test were prepared and tested for each mixture and average test data are presented. For impact behavior ECC panels measures 12 in x 12 in x 1 in was prepared as shown in Figure 2. For comparison reinforced concrete (fc'= 8000 psi) panel of similar geometry with a steel reinforcement ratio of 0.017 was prepared and tested under the direct impact load. Steel wire mesh of 1.4 x 1.4 mesh size and 0.625 in opening size was used as steel reinforcement.

Figure 2 ECC panel sample for impact test

Test Setup: The compression test is performed on a concrete compression testing machine. The compression test setup is shown in Figure 3 a. The dogbone-shaped specimens were tested under uniaxial tension loading to access their mechanical performance under tension. The specimens were mounted on the support constraints gripped to the MTS loading frame with 22 kips capacity as shown in Figure 3 b. The tests were conducted at displacement-controlled rate of 0.02 in/min. The tensile strain was measured using the extensometer which is attached at the middle of the specimen and has a gauge length of 2 in. Four-point bending test was also conducted under a displacement controlled at rate of 0.02 in/min using 22 kips capacity MTS machine as shown in Figure 3 c. The span length of flexural loading was 12 in and center span of 4 in. The mid span deflection was measured at all times during testing using 2 LVDT along with corresponding load using national instrument data acquisition system.



a) b) c)

Figure 3 Test Setup a) Compression test b) Tension test c) Four point bending test

For high strain rate, the dog bone specimens were tested for direct tension on MTS loading frame with 22 kips capacity under three different strain rates of 10^{-4} s^{-1}, 10^{-2} s^{-1} and 10^{-1} s^{-1} to evaluate the performance of the ECC mixture under high rate loadings. The corresponding displacement rates were 0.023 in/min, 2.3 in/min and 23 in/min respectively. In order to evaluate the flexural behavior of the ECC mixture under high rate loadings, four-point flexural test was conducted at three different compression displacement rates of 0.023 in/min, 2.3 in/min and 23 in/min.

Performance of the ECC mixture under low-velocity impacts was directly assessed using a drop weight impact test setup which is shown in Figure 4. A drop-weight assembly of total 25 lbs consists of an impact head with diameter of 3 in, a loading tray, and pillow blocks. A dynamic load cell with a maximum capacity of 20,000 lbf is used to record the impact force during the test. It is sandwiched between the loading tray and the impact head. The acceleration time history was recorded using the accelerometer with a maximum capacity of 2000g, which is mounted to the back side of the impact head. The locations of the dynamic load cell and accelerometer are shown in Figure 4. Both of these sensors are connected to a high-frequency data acquisition system and were sampled at maximum frequency of 15 kHz. The recorded acceleration time history can be used to calculate the displacement of the impact head during the test. The velocity and displacement can be derived by integrating the acceleration with respect to time. When contact force is not zero, the impact head and the specimen are in full contact, then this displacement also equals to the displacement of the specimen at impact location. Therefore, with such instrumentation, the time history of both the impact contact force and displacement of the specimen can be obtained.

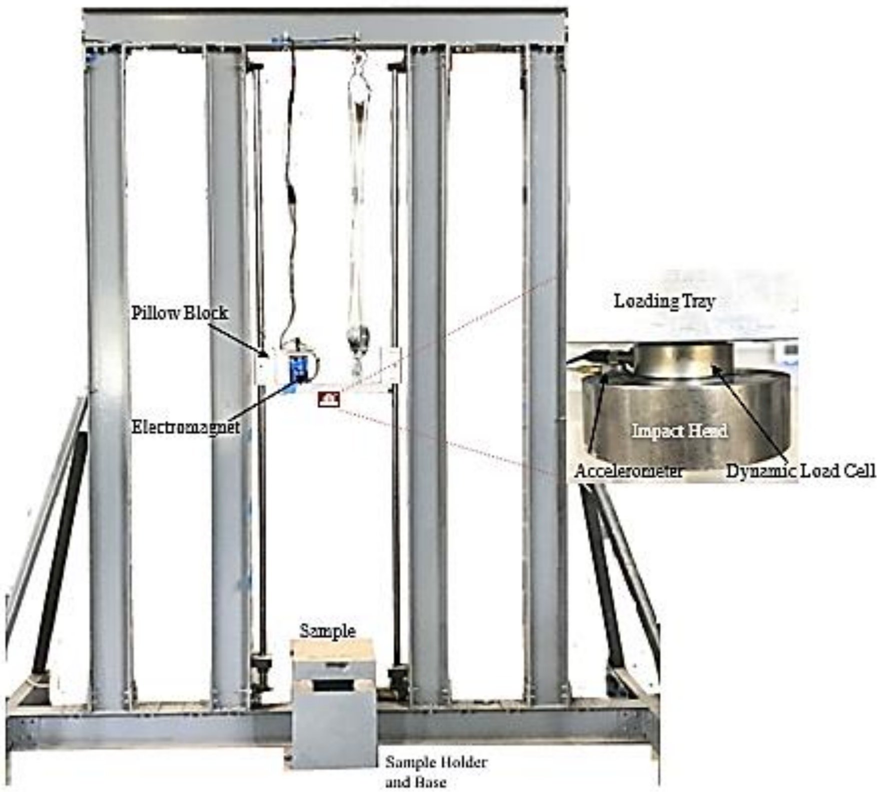


Figure 4 Drop -weight impact test setup

In this study, a constant drop-weight of 25 lbs was used. Three different drop-heights: 22 in, 30 in, and 38 in were used to induce impacts to the ECC specimens with varying kinetic energy. For impact on R/C panel performance, the intermediate height of 30 in was selected. For each set of impact test, the drop-weight impact was repeated for 20 times or until the sample fails depending on which occurred earlier. The sample is considered having failed when there was no rebound of the impact head due to head penetration into the panel. For each drop height, two panel specimens were tested.

To assess the long-term performance of the developed ECC mixture, dogbone, flexural, and impact panel specimens were prepared and cured under lab condition for 28 days prior to immersion in a 3% NaCl solution at room temperature and in hot water at 60ºC for 1, 2, 3, and 4 months, respectively. After respective exposure, they were tested for their tensile and flexural performance under pseudo static and high rate loadings and for their impact resistance and energy absorption capacity using direct impact test.

DISCUSSION OF RESULTS

Material Development

Compressive Properties

The compressive strength of ECC mixtures with domestically available PVA fibers and river sand at 28 days is summarized in Figure 5. Three samples were tested and averaged for each mixture. The compressive strength of mixture FA 2.2, FA 2.4, FA 2.8, and FA 3.2 were measured to be 6262 ± 458 psi, 5540 ± 318 psi, 4510 ± 491 psi and 4336 ± 463 psi respectively. As the data shows, the compressive strength of the ECC decreased with increase in fly ash content. Fly ash serves mainly as filler material rather than pozzolanic material, which causes the reduction of the compressive strength. Hydration of the fly ash is limited due to the relatively high fly ash to cement ratio and also due to lower water/cementitious material ratio. Nevertheless, all the mixture have average compressive strength above 4000 psi, which is adequate for most transportation applications.

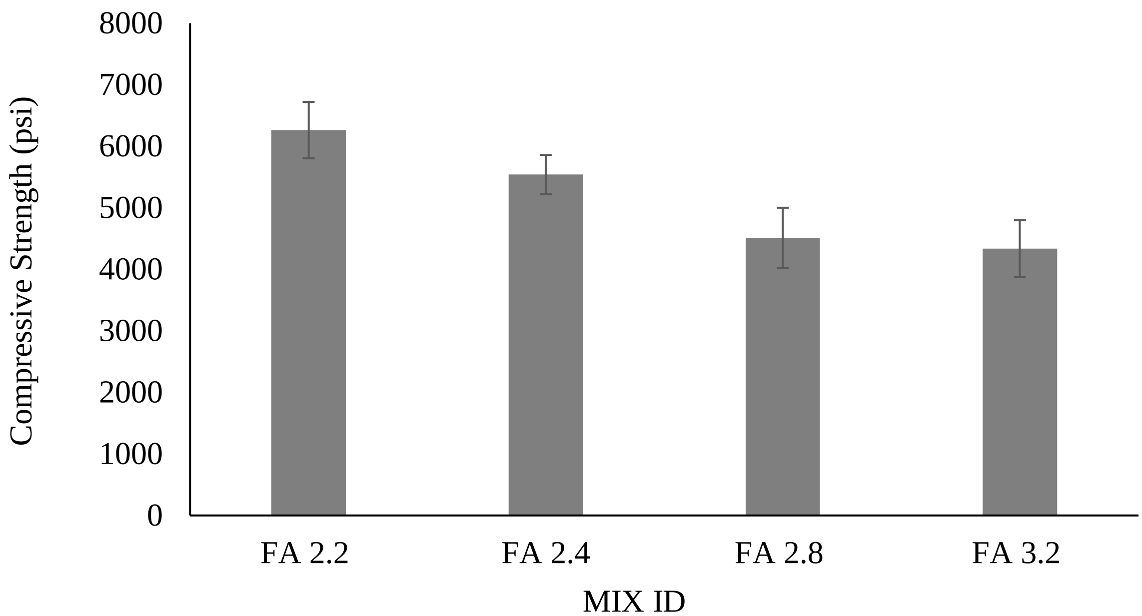


Figure 5 Compressive Strength of ECC mixture at 28 days

Tensile Properties

The measured 28-days tensile stress-strain curve for all ECC mixtures are shown in Figure 6. Measured tensile properties of ECC mixture are summarized in Table 2. The first cracking strength corresponds to the strength at the end of the elastic portion of the stress-strain curve, tensile strength is the maximum tensile stress reported and tensile strain capacity is the maximum strain corresponding to tensile strength. Each data points in Table 2 is an average of 3 sample tested for each mixture. The representative photos of tested specimens showing multiple cracking behavior are presented in Figure 7.

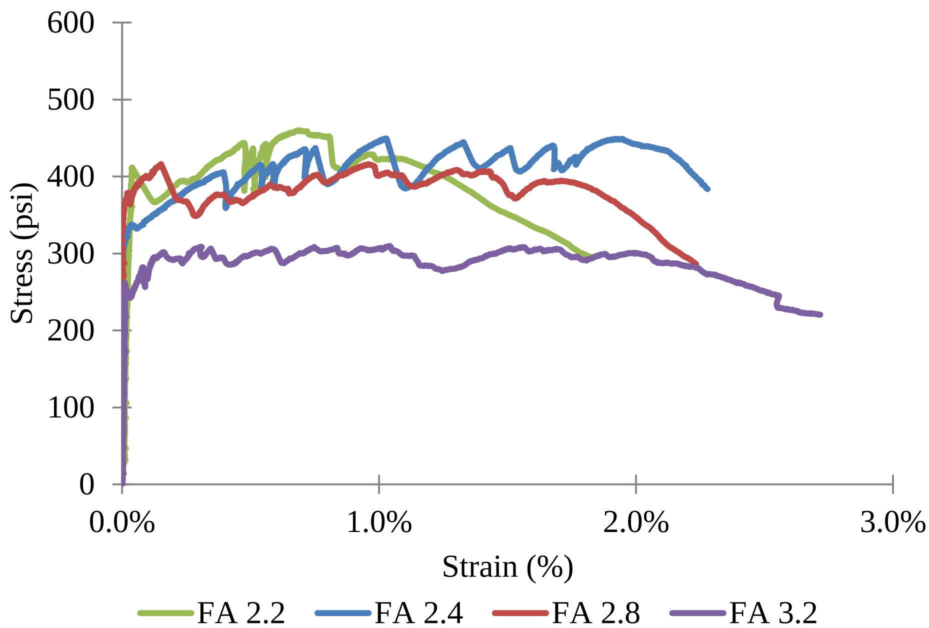


Figure 6 Tensile stress-strain curve for representative sample

Table 2 Measured tensile Properties of all Mixtures

Mix ID	First cracking strength (psi)	Tensile strength (psi)	Tensile strain capacity (%)
FA 2.2	398.9 ± 1.5	461.2 ± 27.6	1.17 ± 0.42
FA 2.4	366.9 ± 30.5	411.9 ± 43.5	1.24 ± 0.61
FA 2.8	368.4 ± 20.3	407.6 ± 18.9	1.54 ± 0.31
FA 3.2	291.5 ± 27.6	342.3 ± 43.5	2.58 ± 1.53

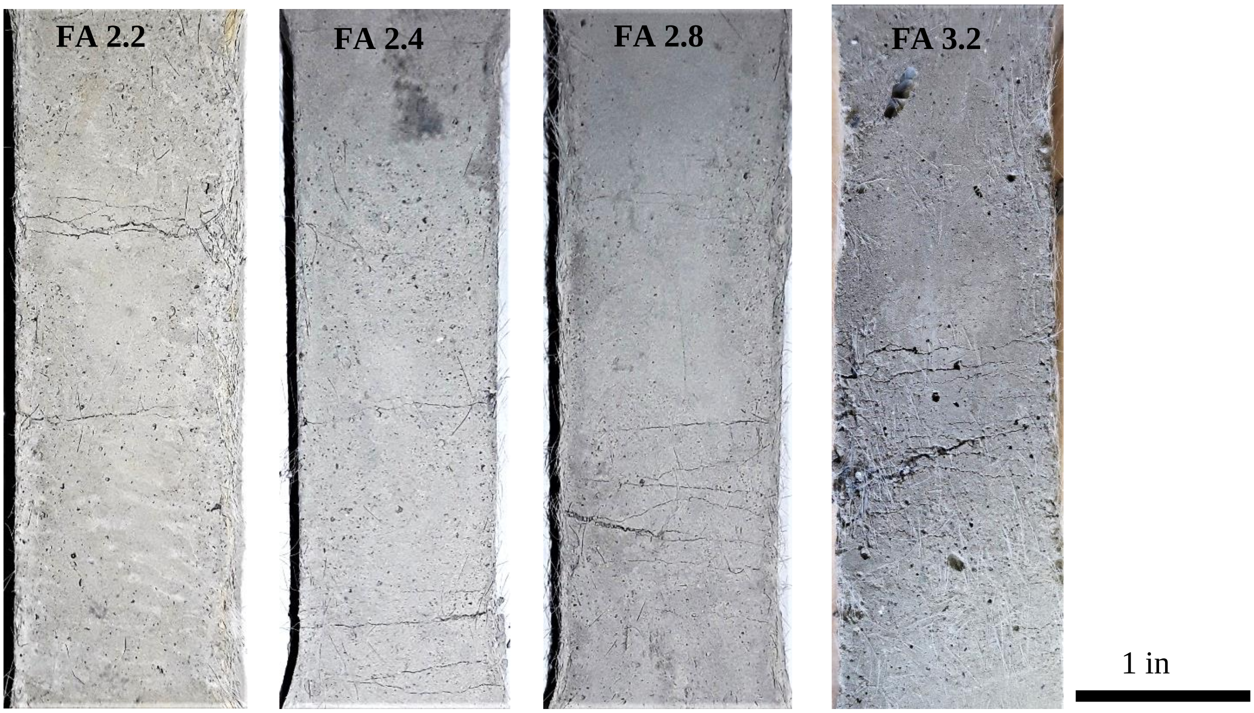


Figure 7 Representative specimens of all ECC mixtures

All the mixture exhibits tensile strain hardening behavior with multiple cracking and the tensile strain capacity ranging between 1.17% to 2.58%. The base mixture FA 2.2 shows an average tensile strain capacity of 1.17% and average tensile strength of 461.2 psi. The tensile ductility of ECC mixture is accompanied by the multiple cracking as seen in Figure 6 and 7. The tensile test data of the FA 2.2 shows that ECC mixture developed with non-surface coated domestically available PVA fibers and river sand with MAS of 0.187 in are still able to achieve a ductile tensile behavior.

Further increase in fly ash content in mixture FA 2.4, FA 2.8 and FA 3.2 shows an increase in strain capacity. These mixtures show the improvement of the tensile strain capacity of 1.24%, 1.54% and 2.58% respectively. Increase in fly ash also affected the fracture toughness of the matrix. According to fracture mechanics, the first cracking strength of the ECC material is largely dependent on the fracture toughness. As per the test results, the first cracking strength of ECC decreases from 398.9 psi to 291.5 psi as fly ash to cement ratio increases from 2.2 to 3.2. The result was expected as further replacement of cement with a large volume of low reactive fly ash will effectively reduce the matrix fracture toughness and thus the composite strength. As a result, increasing the fly ash content effectively reduces J_{tip} in favor of satisfying the energy criterion for achieving strain-hardening and multiple cracking behaviors. Apart from that, non-surface coated PVA fibers has hydrophilic surface and is expected to form strong chemical bond which will affect the strain hardening behavior. However, the high volume of fly ash content in matrix is expected lower chemical bond between matrix and PVA fibers [16]. The chemical bond between PVA fibers and the cementitious matrix is believed to be governed by the concentration of metal cations (Al^{3+} and Ca^{2+}) at the interface, which are diluted by use of low calcium fly ash, reducing the possibility of developing a strong chemical bond. Fly ash, with fine particle size, also densifies the fiber/matrix interface. It may also improve the frictional bond between the fibers and matrix, which enhances the tensile strength, increases J'_b and favors the satisfaction of energy criterion. Consequently, a more saturated multiple cracking behavior and improved tensile ductility was observed in FA 2.8 and FA 3.2 as compared to FA 2.2.

Among all the mixture tested, FA 3.2 was selected for the further testing as a best performing mixture with satisfactory compressive strength and higher tensile ductility.

Flexural Properties

Flexural test was performed on the best performing mix which is mix FA 3.2. Flexural stress versus mid span deflection curve from the four-point bending test is shown in Figure 8. As seen from the figure that after the first cracking which corresponds to the end of the linear elastic range in the stress-strain curves, the ECC beam continues to deform due to its strain hardening behavior until the fiber-bridging stress at one location has been exhausted causing localized deformation at that section. The flexural stress increases at slower rate beyond elastic behavior which is accompanied by formation of multiple cracks on the tension face of the specimens. The microcracks formed are spread out in the midspan of the flexural beam between two load points as shown in the representative specimen in Figure 9. The flexural strength was reported to be 1457.6±55 psi and the maximum mid span deflection was 0.115±0.016 in (average of two LVDT measurement). The ratio of flexural strength to tensile strength is found to be 4.25. It the strain hardening behavior of ECC which led to high flexural strength to tensile strength ratio. For a linear elastic brittle material, the flexural strength is equal to tensile strength and as material shows the ductile behavior like ECC, the ratio increases [25]. So, ECC material have added advantages under flexural loading due to strain-hardening behavior post first cracking.

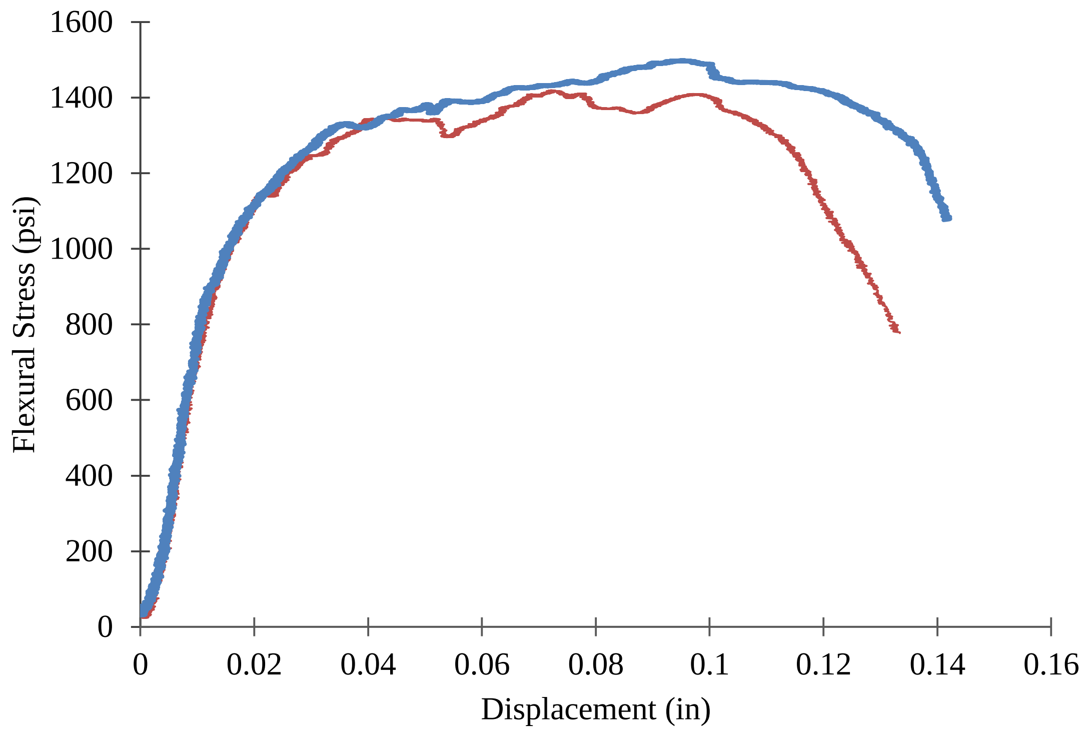


Figure 8 Flexural Stress mid span deflection curve of FA 3.2 mixture.

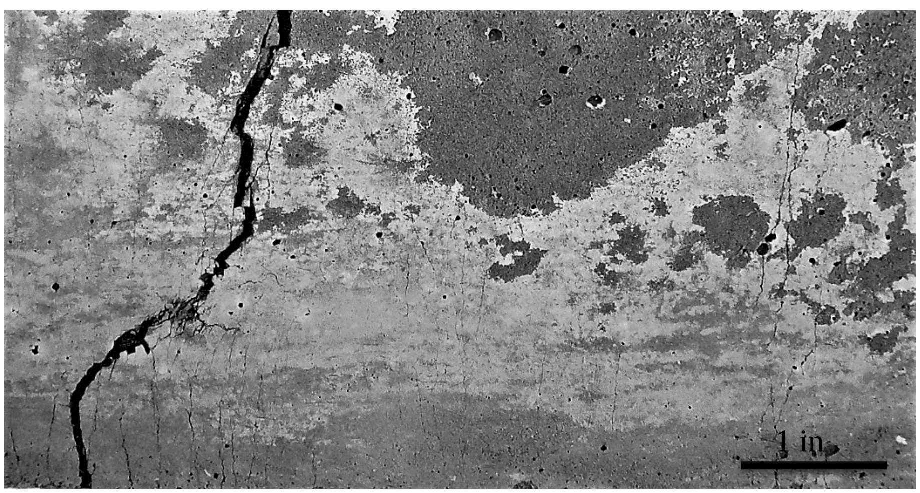


Figure 9 Crack pattern of flexural sample (tension face)

Impact Resistance Behavior of ECC

High rate Tension Test

The statistics for first cracking strength (the strength at the end of the elastic portion of the stress-strain curve), tensile strength (maximum tensile stress), and tensile strain capacity (strain corresponding to tensile strength) are also summarized in Table 3. The observed direct tensile stress-strain curve for each strain rate is shown in Figure 10.

Table 3 Tensile properties of ECC under different strain rate

Strain Rate (s^{-1})	First cracking strength (psi)	Ultimate Tensile strength (psi)	Tensile strain capacity (%)
10^{-4}	298.8±16	443.8±13.1	2.57±0.24
10^{-2}	442.4±14.5	478.6±37.7	2.01±0.46
10^{-1}	498.9±5.8	567.1±39.2	1.88±0.25

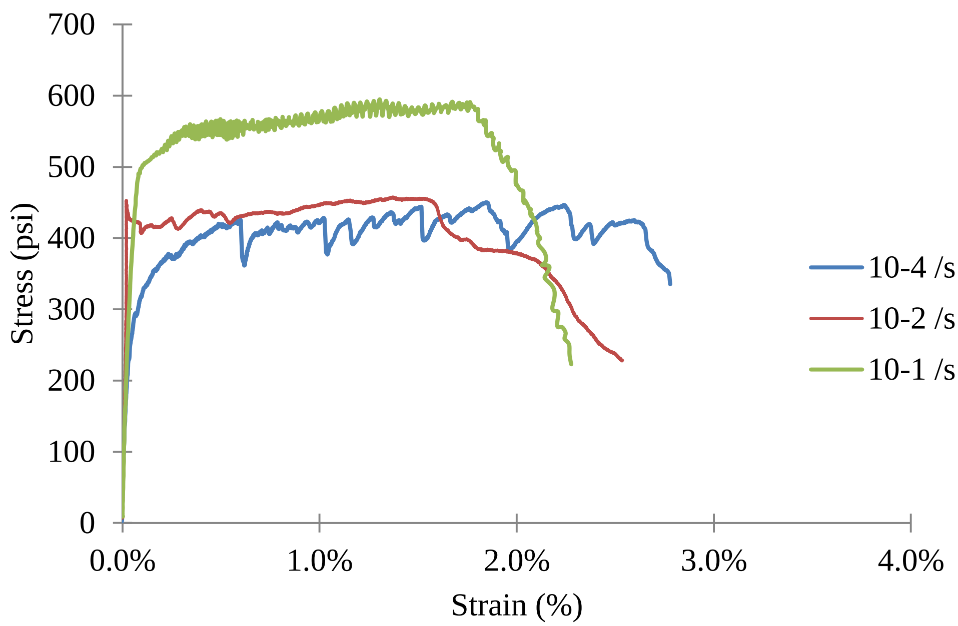


Figure 10 Measured Tensile Stress Strain Curve at different strain rate tested at 28 days

As per the results, the material shows similar stress-strain behavior at higher loading rate as it does at pseudo-static loading rate. The test results show that the first cracking strength and ultimate tensile strength both increase with the strain rate. Comparing the results from 10^{-4} to 10^{-2} and 10^{-1} strain rate, the ultimate tensile strength increases from 443.8 psi to 478.6 psi and

567.1 psi, respectively. Similarly, the first cracking strength also increases notably with strain rate whereas the strain capacity was comparable for all tested strain rates.

This behavior is attributed to rate dependent micro-scale behavioral change in fiber-matrix interface properties and matrix fracture toughness. According to the literature, the frictional bond and slip hardening coefficient between fiber and matrix shows negligible rate dependencies whereas the fiber modulus E_f, fiber strength σ_f, matrix toughness J_{tip} and chemical bond G_d notably increases with loading rate [8]. At higher rate, the cracks tend to cut through the aggregate instead going through weak cement paste aggregate interface leading to higher matrix toughness and first cracking strength [26]. Increase in interface properties and fiber modulus causes steeper σ-δ curves and increase in fiber-bridging capacity (σ_o) with increasing loading rate which implies increased tensile strength [27].

Also, increase in fiber modulus and more importantly increase in interfacial chemical bond with rate will result in decrease of complimentary energy (J_b') that affects the strain hardening behavior. Although produced with non-oil coated PVA fibers, the high-volume fly ash incorporated in the ECC mix reduces the chemical bond between fiber matrix interface and matrix fracture toughness [3] and therefore reduces the rate sensitivity. The tensile strain capacity for all tested strain rate shows significant strain capacity (greater than 1.8%) and has a slight decreasing trend with increase in strain rate. It may be because the rate sensitive chemical bond was effectively reduced but not completely absent. Nevertheless, it was concluded that the new ECC mix does not lose the tensile ductility even at higher strain rate.

Flexural Test

The flexural test results which include flexural strength and mid-span deflection capacity are presented in Table 4. The flexural strength vs. mid-span deflection curve measured under all strain rates are plotted in Figure 11. As seen in the results, the flexural strength of the beam increased from 1457.6 psi to 1860.8 psi and 1979.8 psi as the strain rate increased from 10^{-4} to 10^{-2} and 10^{-1} respectively, while the deflection capacity remains relatively constant with slight reduction. The ultimate mid span deflection decreased by 8.93% as strain rate increased from 10^{-4} to 10^{-1} s^{-1}. This trend is similar to that of the tensile behavior.

Table 4 Flexural properties of ECC specimen under different strain rate

Strain Rate (s^{-1})	Flexural Strength (psi)	Ultimate Deflection (in)
10^{-4}	1457.6±56.6	0.115±0.016
10^{-2}	1860.8±82.7	0.112±0.012
10^{-1}	1979.8±85.6	0.104±0.002

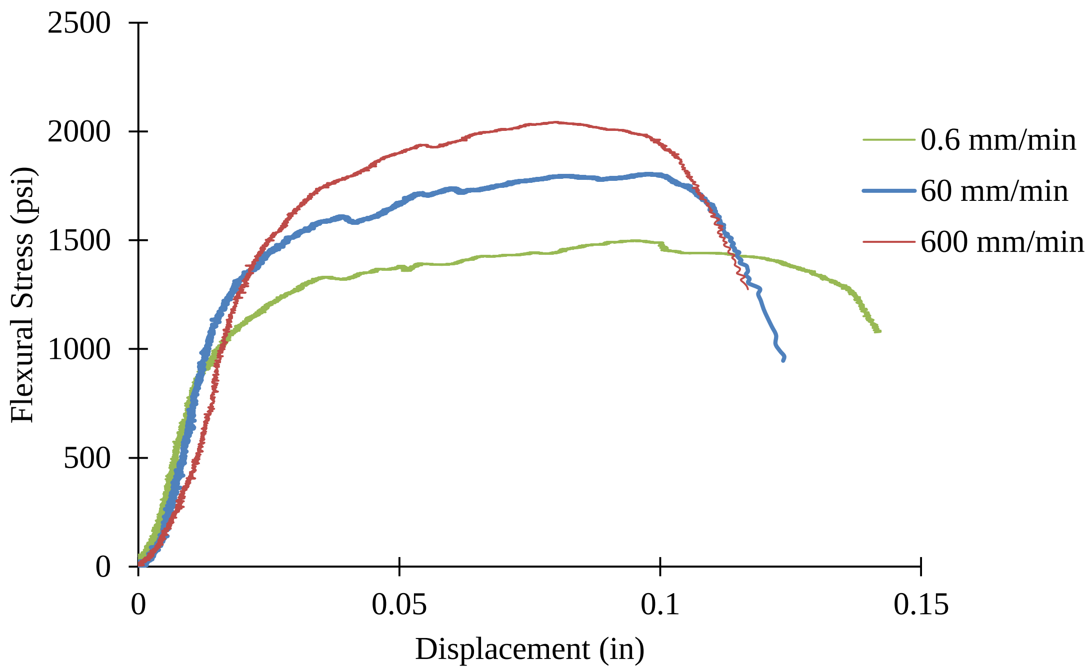


Figure 11 Typical flexural stress-midspan deflection curves at different loading rate

Impact Test

Examples of the measured impact force-time history and acceleration-time history are shown in Figure 12 and 13, respectively. These data are measured during the first impact on one of the ECC panels tested at a drop height of 22 in. The process of impact can be explained from the force time history curve. The force quickly reaches its peak when the impact head strikes the panel which is equal to the rate of change of momentum of drop-weight assembly. The peak contact force is governed by different factors like panel mechanical and physical properties, its surface texture and sampling frequency of DAQ system. Given the same material, the peak contact force will be maximum if the contact surface is perfectly smooth. In case of rough surface, momentum transfer from impact head to panel is slowed down due to crushing of surface particles resulting in a decrease in peak contact force. Also, the sampling frequency determines the measured peak force; higher the sampling frequency, a higher peak force will be recorded. This test was conducted at the frequency of 15 kHz. After first peak, drop-weight assembly continue to transfer remaining momentum and depresses the panel further. However, the impact head and panel oscillate at different frequency until panel is sufficiently deformed. It is when force reaches the second peak as seen in Figure 12 up to about 1 ms. The panel and the drop weight assembly then move together until the maximum displacement (bottommost position) after which the force starts to drop. The force reaches zero when contact between impact head and panel is lost during rebound of the drop weight assembly.

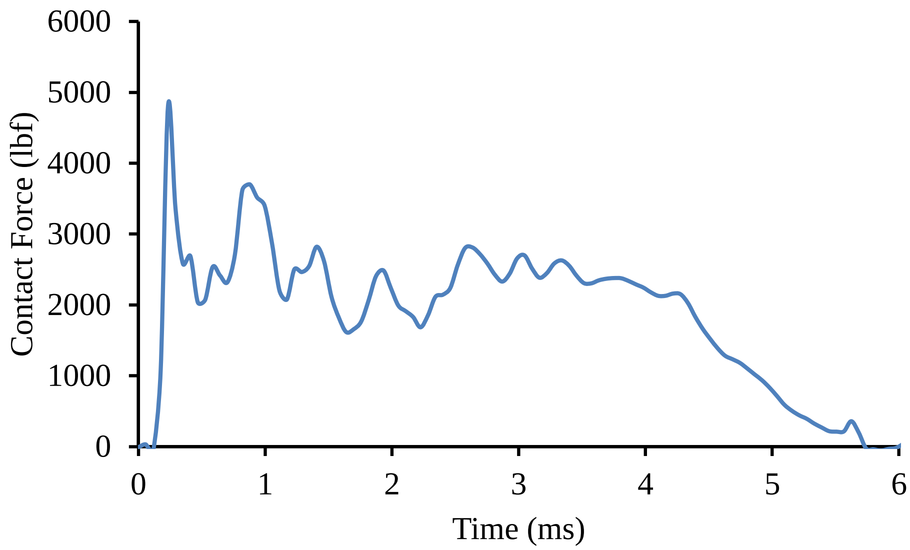


Figure 12 Contact force vs. time for the first impact

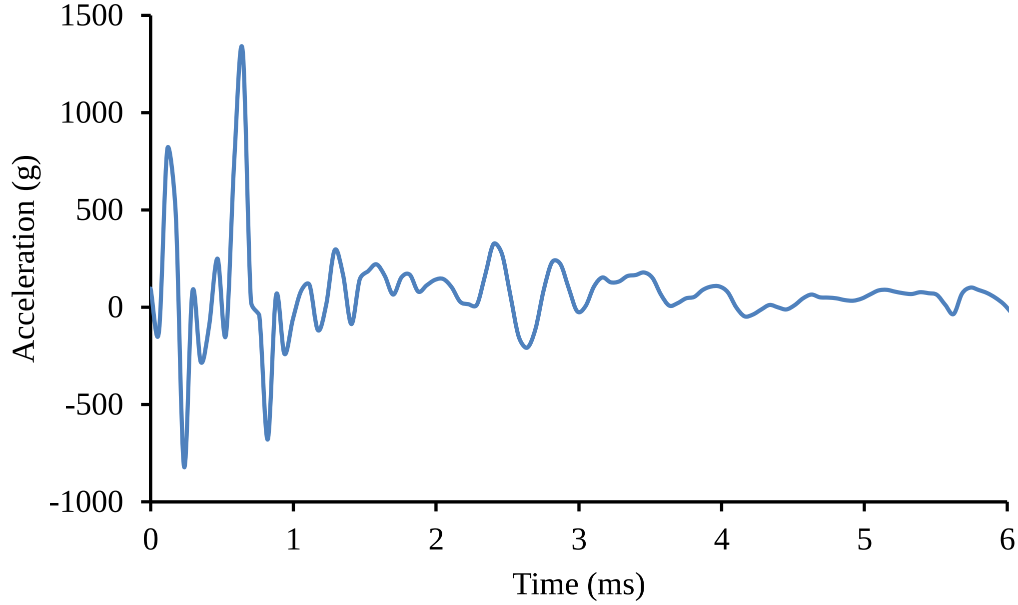


Figure 13 Acceleration vs. time for the first impact

The representative curves for velocity-time history and displacement-time history for a drop height of 22 in under first impact are shown in Figure 14 and 15 respectively. The velocity-time history curve was produced by integrating the acceleration-time history data with respect to time, and the displacement-time history curve was produced by integrating the velocity-time history data with respect to time. As seen in the velocity time history, the zero velocity indicates the drop weight assembly has reached the bottommost position during the impact. The time at which the velocity became zero was used to compute the maximum displacement from displacement time history. The test statistics for the first impact under different drop height is shown in Table 5**.**

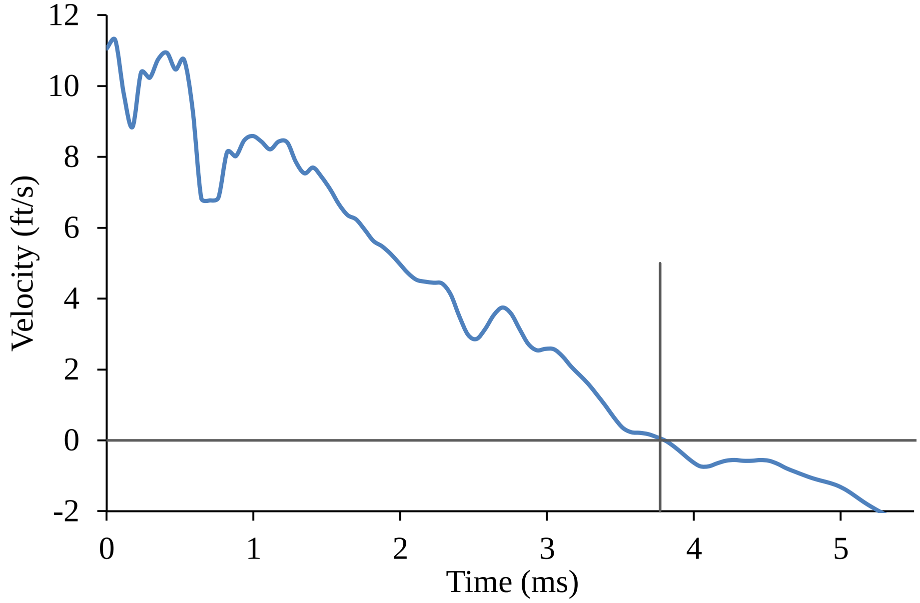


Figure 14 Derived velocity-time history for the first impact

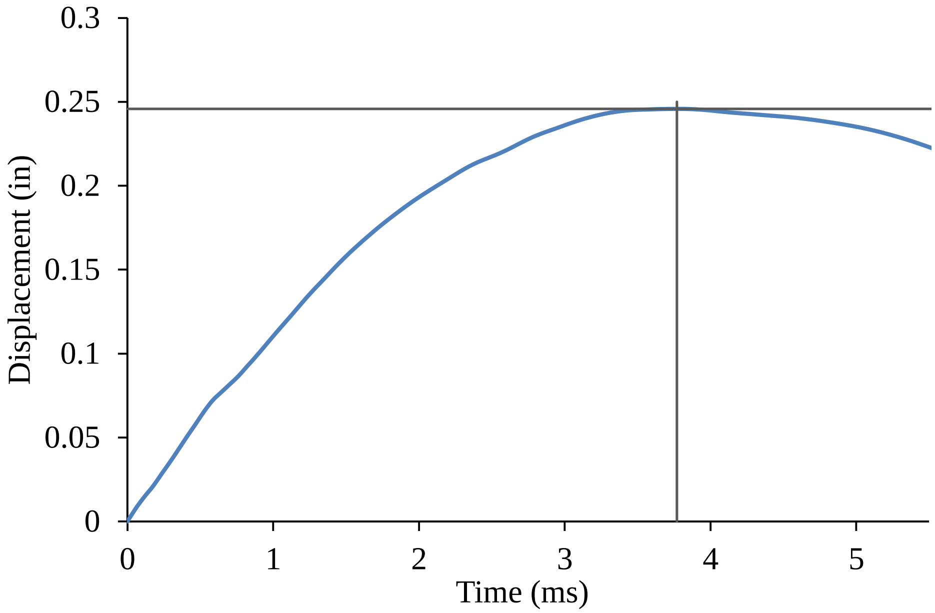
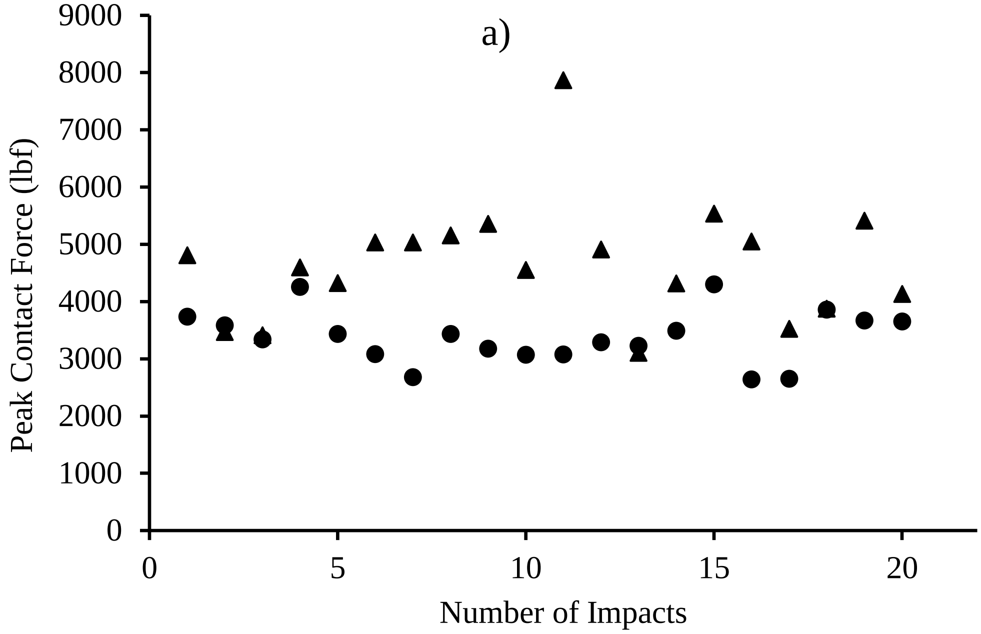


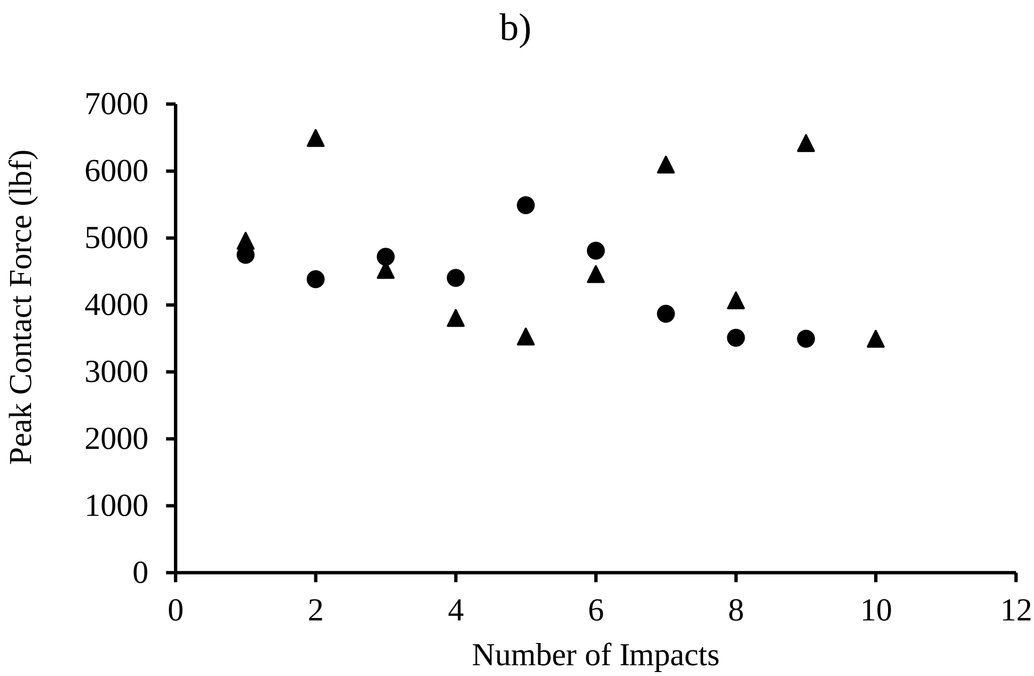
Figure 15 Derived displacement-time history for the first impact

Table 5 Test Statistics for different drop height

Drop Height	Sample	Peak Contact Force (lbf)	Max Displacement (in)
22 in	1	3734.1	0.246
	2	4810.9	0.336
	Average	4272.5 ± 761	0.291 ± 0.06
30 in	1	4748.0	0.244
	2	4959.3	0.316
	Average	4853.65 ± 149	0.280 ± 0.05
38 in	1	5836.0	0.285
	2	6526.2	0.278
	Average	6181.2 ± 243	0.281 ± 0.002

As mentioned before, the impact test was performed at three different drop heights of 22 in, 30 in, 38 in to evaluate the performance of the ECC mixture under different level of impacts. The impact test was repeated for 20 times or until the sample fails depending on which one occurred earlier. The peak contact force vs. number of impact is plotted in Figure 16 for all ECC specimens and all drop heights. The peak contact force experienced by the panel increases with increase in the drop height due to increasing kinetic energy of drop weight assembly. Also, the number of impact required till failure decreases as the drop height increases. For the drop height of 22 in, the test was terminated after 20 impacts as the samples did not fail even after 20th impact. For drop height of 30 in and 38 in, the sample failed before the 20th impact as the impact head penetrated the sample and test was stopped. From Figure 16, we can see that on increasing the drop height to 30 in impacts required for a specimen to fail decreases to 10 for one sample and 9 for second sample. Further increasing drop height to 38 in the number of impacts required for a specimen to fail further decreases to 6 or 7. This is expected since the drop-weight imparts higher energy when released from higher height and therefore more energy is absorbed by the panel during each impact leading to earlier failure.


a)
9000
8000
7000
6000
5000
4000
3000
2000
1000
0
Peak Contact Force (lbf)
0
5
10
15
20
Number of Impacts


b)
7000
6000
5000
4000
3000
2000
1000
0
Peak Contact Force (lbf)
0
2
4
6
8
10
12
Number of Impacts

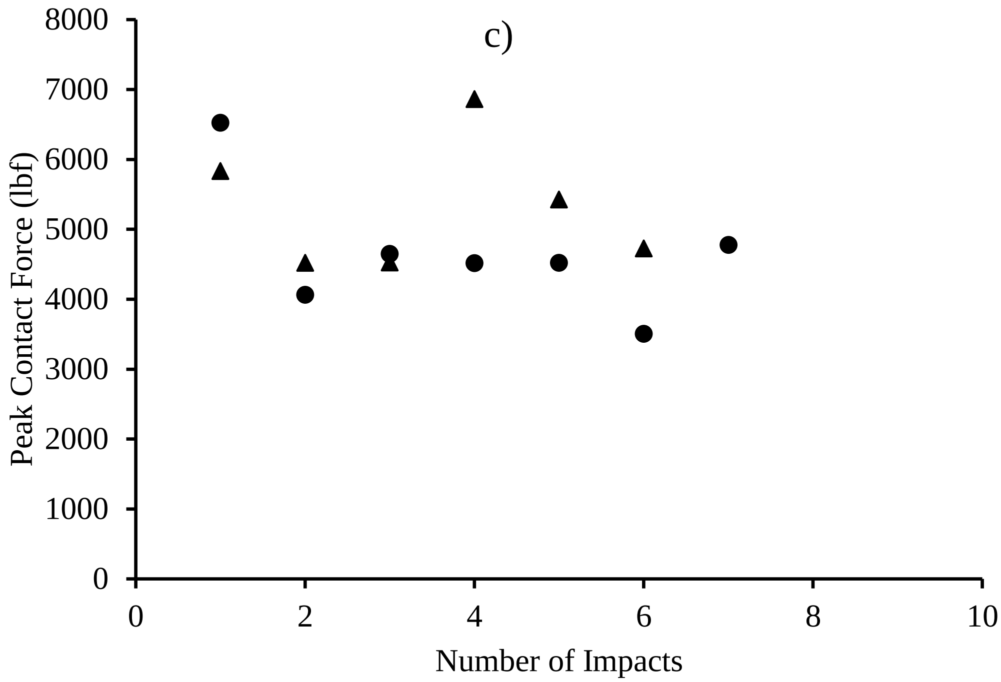


Figure 16 Peak contact force under multiple impact for drop height of a) 22 in b) 30 in and c) 38 in

It is observed that the peak contact force remains constant through the test for each drop height. The visual observation of the panels shows that the panel develops fine multiple cracks on the tension side. The crack pattern for the drop height of 22 in is shown in Figure 17. In the figure, it can be seen that with each impact, more cracks are developed and are distributed throughout the tension face. The constant peak contact force suggests the load carrying capacity of the materials does not drop and the cracked sample still holds same load bearing capacity as a virgin sample. The sample survived the impacts without spalling of the specimen, suggesting ECC structures can remain intact even after repetitive impact and can maintain the integrity of the structure.

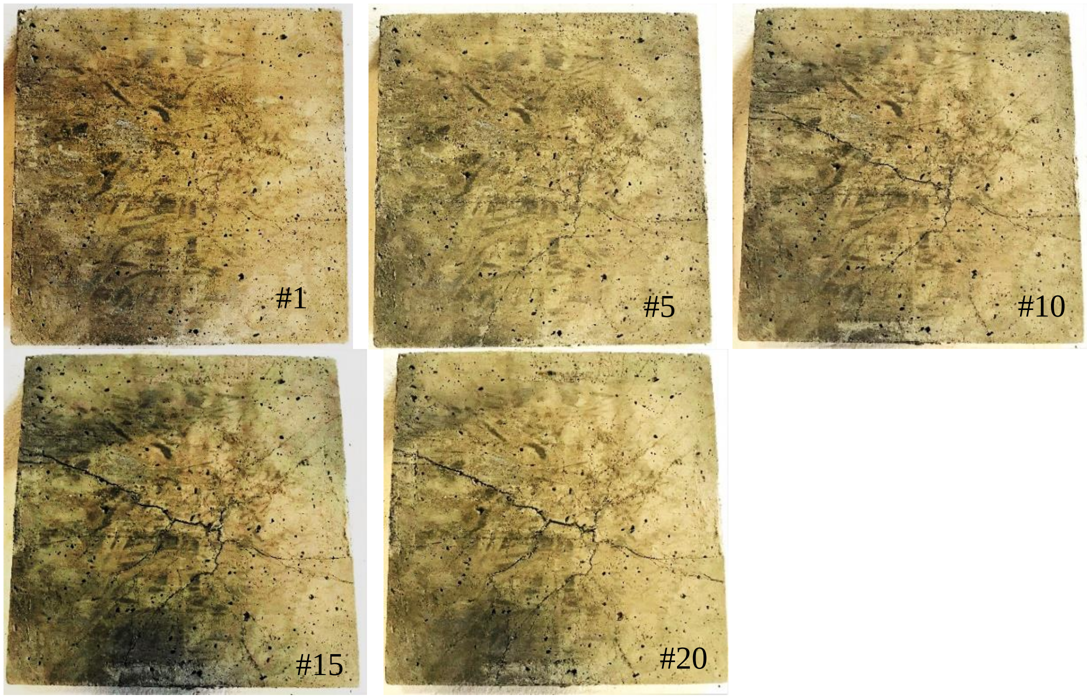


Figure 17 Crack Development in ECC panel after each impact as indicated for drop height of 22 in

The performance of ECC panel was then compared with R/C panel under multiple impacts for impact resistance behavior. An intermediate drop height of 30 in was selected for the comparison test. Figure 18 shows the load capacity of R/C panel in each impact. The test statistics of ECC and R/C panel specimens for drop height of 30 in during first impact is shown in Table 6. The performance of the R/C panel was found to be relatively poor compare the ECC panel tested at the same height (Figure 16 (b)) as R/C panel failed after less than 7 impacts. As per the visual inspection R/C panel experienced severe damage during first impact compare to ECC specimens. The visual observation was verified by maximum deflection presented in Table 6 for R/C panel which was higher than that of ECC panel because the deflection and damage in R/C was localized whereas in ECC it was well distributed to wider area. ECC panel had comparatively lower compressive strength of 4336 psi and was unreinforced (reinforced by fibers only) but still had a better impact resistance behavior and load carrying capacity than higher strength R/C panel.

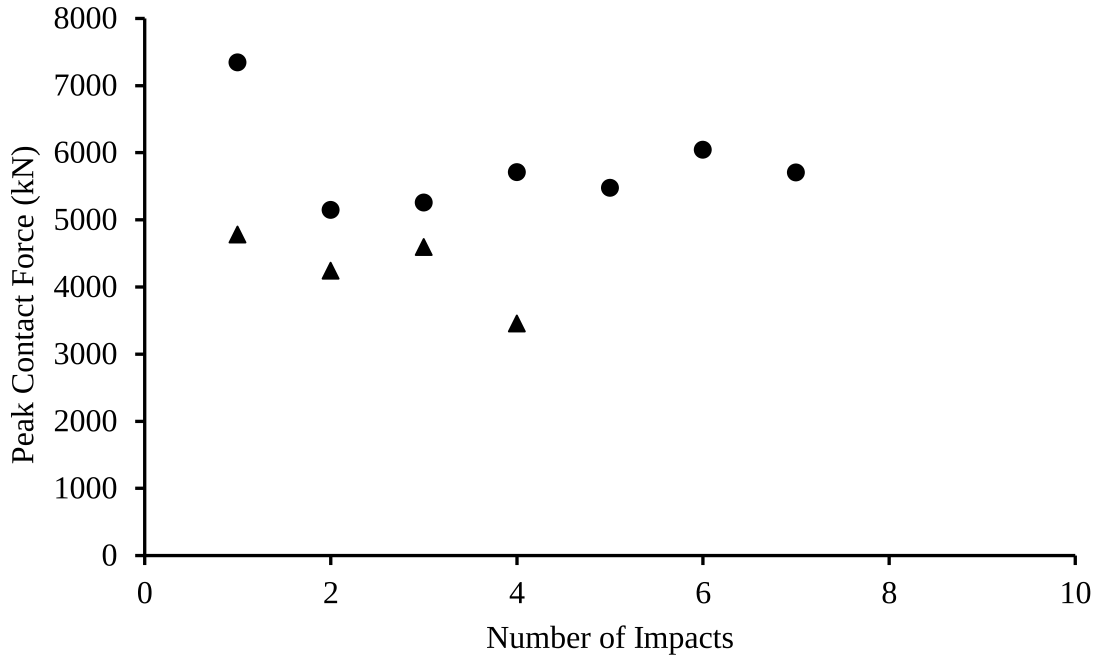


Figure 18 Peak contact force under multiple impact for drop height of 22 in on R/C panel

Table 6 Test Statistics for ECC and R/C panel during first impact

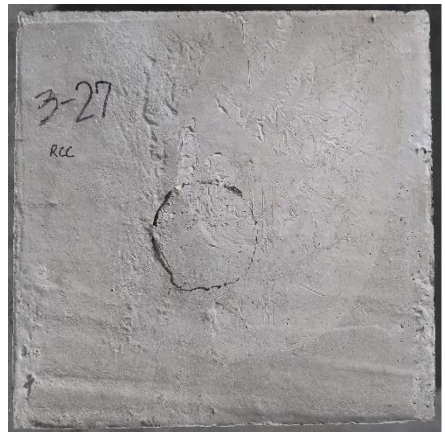
Specimen Type	Sample	Peak Contact Force (lbf)	Max Displacement (in)
ECC	1	4748	0.012
	2	4959	0.015
	Average	4853.5 ± 149.2	0.014±0.002
R/C	1	4781	0.023
	2	7346	0.026
	Average	6063.5 ± 1813	0.025±0.002

The energy absorbed by the ECC specimens and R/C specimens was computed and presented in Table 8. The energy absorbed by the specimens during impact was considered to be the total loss of kinetic energy of drop weight assembly between time of impact to rebound. As already mentioned the ECC specimens sustained higher number of impact compared to R/C specimens as shown in Table 8. ECC specimens (reinforced with fibers only) showed similar energy absorption capacity compare to R/C specimens per impact due same kinetic energy of the drop-weight assembly corresponding to similar drop height. However, the total energy absorbed by ECC specimens is much higher compared to that of R/C structure after multiple. ECC can take more number of impact before failure and thus absorbs more impact energy while improving the damage tolerance and maintaining the structural integrity.

Table 7 Energy absorption in ECC and R/C panel specimens

Specimen Type	Sample	Number of Impact for failure	Average Energy Absorbed per Impact (foot-pound)	Total Energy Absorbed (foot-pound)
ECC	1	9	56.52±6.6	508.68
	2	10	60.753±1.28	607.28
R/C	1	4	60.07±2.88	240.27
	2	7	56.6±4.91	396.14

The damage pattern of ECC specimen and R/C specimen at failure is shown in Figure 19. It can be seen that the R/C sample failed with larger crack width and spalling of concrete from the surface resulting in severe loss of structural integrity. On the other hand, damage pattern on ECC specimens shows fine microcracks across the tension face with no signs of spalling of concrete. This result demonstrates ECC has the superior impact resistance to sustain multiple impacts while maintaining structural integrity and damage tolerance.



a) b)

c) d)

Figure 19 Damage of ECC panel after 10 impacts (a. Compression face and c. Tension face) and R/C panel after 7 impacts (b. Compression face and d. Tension face)

This suggests that the newly developed ECC mixture is suitable for proposed application in crash barriers structures. The newly developed ECC material is shown to have high impact resistance and absorb higher amount of energy during collision thus improving the safety performance of concrete barriers compare to regular concrete. Also, the constant load bearing capacity of ECC under repetitive impact loading and fine cracks suggests that the barriers will remain intact even after several collision and maintains structural integrity. It may not require repair after occasion impacts and could potentially reduce the maintenance cost.

Long-term environmental conditioned test

The specimens for long-term environmental conditioned sample are exposed to chloride solution and hot water at 60^{o} C and will be tested for tension and impact loading at 1, 2, 3, and 4 months.

CONCLUSIONS

The purpose of this research was to employ ECC technology in design of concrete crash barriers, to improve the impact resistance and reduce the damage to vehicle and passengers during vehicle-barrier collisions. For which, ductile ECC using local ingredients like domestic PVA fibers and river sand was developed with high impact resistance and energy absorption capacity. Tailoring of the ECC with local ingredients was possible through micromechanics design principle which required the basic understanding of the relation between material macroscopic properties and material microstructures. It allowed the new ECC to have desirable tensile ductility under pseudo-static (10^{-5} s^{-1}) and high rate roading (10^{-1} s^{-1}). Examining the performance of newly developed ECC panel and R/C panel under impact loading, ECC was considered superior and suitability for purposed application in the crash barrier.

- The test results revealed that domestically manufactured PVA fibers with no surface coating and locally available river sand could be successfully used to develop ECC mixture with desired tensile performance. Adjustment of the matrix composition and use of high content fly ash were deemed necessary to achieve the high tensile ductility.

- Newly developed ECC mixture showed the average compressive strength of 4336 psi, the tensile strength of 342.3 psi, tensile strain capacity of 2.58 % and flexural strength of 1457.6 psi.

- Under tension, the average first cracking strength and average ultimate tensile strength of dogbone specimen increased by 67% and 29% respectively as the strain rate was increased from 10^{-4} to 10^{-1} s^{-1}. However, the average tensile strain capacity decreases slightly from 2.57% at 10^{-4} s^{-1} to 1.88% at 10^{-1} s^{-1}. The tension test results confirmed that the newly developed ECC mixture does not lose tensile ductile even under high rate loadings.

- The result of flexural test was in resemblance with the tensile test results. The flexural strength of the ECC increased from 1457.6 psi to 1979.8 psi for strain rate increase from 10^{-4} s^{-1} to 10^{-1} s^{-1} respectively. The newly developed material shows minimal rate dependency and maintained the desirable ductile behavior under high strain rate loadings.

- Drop weight impact test results indicated the load caring capacity of ECC panel specimen does not drop under multiple impacts ECC showed the well distributed fine cracking without any signs of spalling at failure. The composite was able to absorb the significantly higher amount of energy during impact without significant damage.

- Comparing the performance of ECC with R/C panel showed that the ECC has superior behavior under impact loading. ECC was able to dissipate more energy, have higher damage tolerance and maintain the structural integrity.

RECOMMENDATIONS

This research confirms that the ECC material can be retailored incorporating the local ingredients to achieve impact resistance behavior. ECC mixture developed from this research showed high damage tolerance, and high energy dissipation capacity, so it can be considered suitable for the proposed application. If incorporated in design of concrete barrier it will improve the impact resistance and energy absorption capacity of the structure. Additionally, the newly developed ECC mixture is also considered suitable for other transportation infrastructures that are prone to impact damage, such as exterior girders of highway overpass bridges, bridge piers, and runway pavement of airports, ect.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

ASTM	American society for Testing and Materials
ECC	Engineered Cementitious Composites
FA	Fly Ash
FA/C	Fly Ash to Cement ratio
ft	foot (feet)
in	inch
kHz	kilo Hertz
LADOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
LVDT	Linear Variable Differential Transformer
lb.	pound(s)
MAS	Maximum Aggregate Size
MTS	Material Testing System
psi	pound per square inch
PVA	Poly-vinyl Alcohol
R/C	Reinforced Concrete

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