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Effect of Single Fiber Pull Out Test Result on Flexural Performance of ECC

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Abstract

Study of effect of single fiber pull out test result on flexural performance of Engineered Cementitious Composite (ECC) is carried out in the present work. Cement: sand ratios of 1:0.5, 1:1, 1:1.5, and 1:2 are used in composition of ECC. Beams of 20 and 30 mm depth are tested under displacement control and four point loading arrangement. First crack strength, ultimate strength, toughness index, deflection hardening and reserved flexural strength are evaluated. Single fiber pull out test of 6 mm embedded length is carried out to evaluate frictional bond strength. An equation is suggested to evaluate ultimate flexural strength of ECC considering effect of micromechanical parameters in general and frictional bond strength in particular.

Keywords: Engineered cementitious composite; Slippage regime; Flexural performance; Micromechanical; Polypropylene fibers

Introduction

When fracture failure occurs, a high strength material need not necessarily offer higher structural strength. Rather, a tougher material and in the extreme a ductile material can lead to a higher structural strength which, in turn, can play a significant role in the seismic response of the structure. Efforts have been made in recent past to make overall performance of the structure ductile by the introduction of ductile detailing. However, ductile detailing makes the member heavily congested by the reinforcement due to which there are practical difficulties of placing and compacting of concrete. Moreover, the concrete which consumes about 85% volume in a structure still remains inherently brittle. Concrete and steel should contribute simultaneously towards ductility to maintain compatibility and integrity of the composite to enhance the overall performance of the structure. A new innovative material, which can replace ordinary concrete at some key places, can improve overall performance of the structure dramatically is Engineered Cementitious Composites (ECC) [1]. Strain hardening through multiple cracking is the key property of this smart material. Micromechanics concept is used to develop ECC which relates macroscopic properties to the microstructures of a composite and form the backbone of materials design theory. Specifically it allows systematic deliberate tailoring of fiber, matrix, and interface as well as materials optimization. Most of the investigations on ECC performance all over the world have been carried out using PVA and PE fibers of circular cross section with a typical composition employing w/c ratio and c/s ratio of 0.5 with optimized fiber volume.

Cement: sand ratio and cross section shape of the fiber are two micromechanical parameters intended in this investigation for microstructure tailoring of matrix and fiber. Polyester fibers under trade name of Recron 3S in which aster is a functional polar group, responsible for good bond with cement. Its silicon coating helps in better dispersion in matrix which is one of the essential requirements in any fiber reinforced composite. Most of the synthetic fibers available are of circular cross section whereas Recron fibers are of substantial triangular in cross section. Specific gravity and tensile strength of Recron fibers is 1.36 g/cc^3 and 1000 N/mm^2 as per manufacturer's data. Performance of any fiber reinforced composite depends upon fiber/matrix interaction, which is largely influenced by the effectiveness of bond between fibers/matrix and fiber pull-out mechanism. Relative Fiber Intrinsic Efficiency Ratio (FIER) of Recron fibers is 2.2 because of its cross section shape.

Single Fiber Pull Out Test

A method to directly assess fiber/mortar interfacial bond properties is to pull a single fiber out of its surrounding matrix. Fiber-matrix interfacial properties are important in controlling macroscopic properties of composite materials. Generally speaking, better the bond better is the composite. Increasing the bond leads to increase in both composite strength and toughness [2,3]. However, beyond certain bond strength, toughness begins to decrease due to fiber rupture. Therefore, fiber pull out rather than rupture confers a larger ductility to the fiber reinforced composite [4-6]. In addition, the phenomenon of pseudo strain hardening is strongly influenced by the maximum bridging stress, which is directly proportional to the interface bond strength [7,8].

The general profile of a single fiber pull out curve can be decomposed into three major regimes as depicted in (Figure 1) [9]. Initially a stable fiber debonding process occurs along the fiber/matrix interface. The load resisted by the fiber is then increasing up to P_a. The fiber embedded end, $l=l_e$, does not move. The debond length, l_d, increases towards $l_d=l_e$. The displacement corresponds only to elastic stretching of the debonded fiber segment and of the fiber free length. Then, the load decreases from P_a to P_b. If the load drop is significant, it reveals that the chemical bond between the fiber and the matrix has broken. This means that debonding at the interface is governed by a fracture criterion [10]. In the case of nonchemically bonded fibers, such as steel, polyester, or polypropylene fibers, P_a would be closed or equal to P_b. At point P_b, the embedded fiber end is just debonded. Finally, in the slippage regime, the fiber load is resisted by frictional forces. The

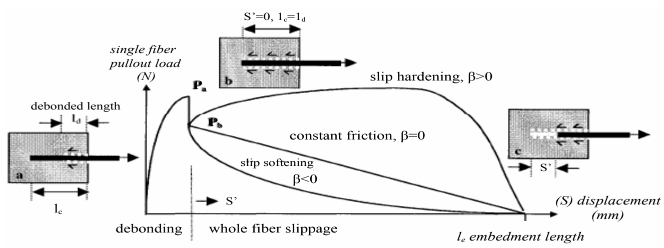

Figure 1: General profile of single fiber pull out curve.

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fiber can undergo sliding with either slip hardening, constant friction or slip softening effect, characterized by the coefficient β, which is, respectively, positive, zero, or negative [4]. Slip hardening may occur with polymer fibers, if they are less hard than surrounding matrix. They would get damaged and a jamming effect can take place inside the matrix. This leads to an increasing load resisting fiber pull out. This phenomenon can be very beneficial as long as fiber tensile strength is not exceeded. Conversely, constant friction or slip softening is often observed when the fiber hardness is higher than that of the surrounding matrix. Frictional bond strength (τ) can be computed as $p_b/\pi d_f l_e$ when full debonding of fiber takes place with a constant friction.

Preparation of Specimens and Test Set Up

Flexure test

Kamal brand 53 grade OPC, 300µ passing silica sand, W/C ratio of 0.35, 4% fiber volume fraction of Recron and 2% dose of high performance concrete super plasticizer of Glenium 51 brand based on modified polycarboxylic ether were used for the present study. Ingredients of ECC were mixed in 5 liter capacity Hobart type mixer machine. Flow table test was performed to evaluate workability of ECC in fresh state. Beams of length 500 mm, width 100 mm having depth of 20 and 30 mm were cast. Three specimens each of C: S ratio 1:0.5, 1:1, 1:1.5 and 1:2 were cast. Beams were tested with four point loading arrangement on MTS machine under displacement control at a rate of 0.005 mm per second as shown in (Figure 2). Load and displacement at the first crack and at ultimate load were recorded during the test. Load-displacement readings were automatically recorded at an interval of 1 second.

Single fiber pull out test

Moulds for pull out test were prepared for 6 mm thickness of mortar as shown in (Figure 3). Six fibers were embedded in each matrix specimen at a spacing of 2 cm. Long fibers were taken and tied to the nails provided on both sides of the mould. Cementitious matrices of C: S ratio 1: 0.5, 1:1, 1:1.5 and 1: 2 with w/c ratio of 0.35 and 0.5% Glenium 51 brand high performance super plasticizer were poured into mould and then covered with plastic for 24 hours. All the specimens were the taken out by untying the fibers and then specimens were put in the curing tank for 28 days. The extended length of fiber on one side was then cut while keeping other side as it is to facilitate proper grip in the machine. INSTRON 1121 machine of 10 KN capacity was used for testing as shown in (Figure 4).

Pull out specimens were gripped by mechanical grips and fibers were griped by pneumatic grips as shown in (Figure 5). Care was taken to ensure zero fiber free length to avoid elastic stretching of free fiber. Pull out force was applied and load was recorded with the help of 2 Kg load cell under displacement control at a rate of 3 mm/min. Load-pull out displacement graphs were plotted on plotter available with the machine as shown in (Figure 6). Results were then processed in excel software to have representative graphs. Six single fiber pull out tests were performed for each matrix out of which 3 most consistent results having variation upto 15% from the average are being considered in the present discussion.

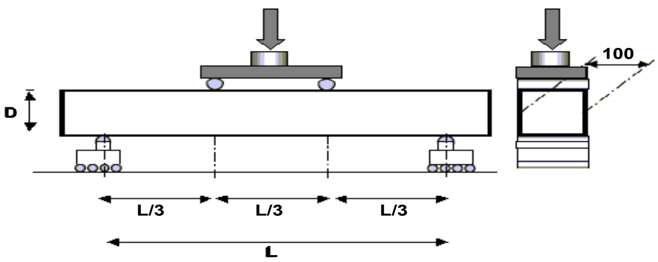

Figure 2: Four point loading set-up.

Figure 3: Pull out mould for 6 mm thickness.

Figure 4: Test set-up for pull-out test.

Figure 5: Grips for fiber and specimen.

Figure 6: Graph produced by INSTRON.

Discussion of Test Results

1. Strain hardening performance via multiple cracking in axial tension ensures strain hardening performance in flexure also but not vice versa. Experimental investigation carried out by Rathod et al. indicated strain hardening performance in the ECC in axial tension with C:S ratio of 1:0.5 and 4% fiber volume fraction [11]. In this experimental investigation, ECC with all C:S ratios indicated strain hardening performance in flexure. Average first crack strength and average ultimate strength values are indicated in Table 1. Strain hardening in flexural deformation is observed in all the specimens due to the contribution of fibers. Increase in strength after first crack is referred as reserved strength. First crack strength is considered to be the ultimate strength for ordinary concrete or normal FRC and that is taken as a reference. Any increase in strength after first crack will be as a result of subsequent multiple cracking by the fiber bridging action due to which load is getting transferred to other sections instead of being localized at a single crack unlike in normal FRC. Reserved strength shows additional load carrying capacity which represents damage tolerance of ECC material. All the beams of 20 and 30 mm depth with 1:0.5 and 1:1 C: S ratio showed multiple cracking. This validates strain hardening through multiple cracking, a unique characteristics of an ECC material. Percentage reserved strength decreases with increase in sand content in all matrices for 20 and 30 mm depth beams. C: S ratio of 1:0.5 gives the best performance. The well known size effect fact i.e. as depth of beam increases strength decreases is well validated here in all the matrices.

2. Shah and Rangan proposed the following general equation for predicting the ultimate flexural strength of the fiber reinforced composite [12]. Where f_m is the maximum strength of the plain matrix, A and B are constants which can be determined experimentally. For plain concrete, A=1 and B=0. The constant B accounts for the bond strength of the fiber and randomness of fiber distribution. Swamy et al. (1974) established values for constant A and B as 0.97 and 4.94 for ultimate flexural strength of steel fiber reinforced concretes and 0.843 and 4.25 for its first cracking strength [13]. Because of linear dependence of the ultimate flexural strength of FRC on volume fraction of fibers and their aspect ratio, it could be stated that the ultimate flexural strength generally increases with the fiber reinforcing index, defined as the product of fiber volume fraction and aspect ratio ($V_f L/d_f$).

All the micromechanical parameters including the size effect are considered in the following equation. Addition of fiber in cementitious matrix, multiply the size effect due to random orientation and distribution of fibers in the composite. To avoid size effect of plain cementitious matrix, it is preferred to substitute the strength of the same size of specimen in the equation of flexural strength of ECC which simplify the governing equation. Constants A and B are proposed in the equation for strain hardening fiber reinforced composite.

$$F_{ue} = [A\, f_m\, (1-V_f^2)] + [B\, V_f^2\, (L_f / D_f)]$$

Where,

F_{ue}=Ultimate flexural strength of ECC matrix

f_m=Ultimate flexural strength of a plain cementitious matrix of same material composition as ECC except fibers; this will elimate size effect of plain matrix.

A=1.25. A constant considered for 2 dimensional specimens i.e. where two dimensions of specimen are more than atleast 3 times the length of fiber.

V_f=Fiber volume fraction

B=g x τ where g=Snubbing coefficient (frictional pull out effect when fibers are aligned in other than the stress direction) and τ=Frictional bond strength in MPa.

L_f, D_f=Length and diameter of fiber respectively.

Snubbing coefficient is assumed to be 2 for the calculation. L_f and D_f are considered as 12.5 mm and 30 µm respectively. Actually shape of cross section of Recron 3S fiber is substantial triangular for which equivalent diameter of fiber is taken as 30 µm. Frictional bond strength values are taken from Table 2 for various matrices. Little scattering is observed between calculated and experimental values indicated in Table 3 because snubbing coefficient is not actually evaluated and is assumed to be constant for all matrices. Closer values can be achieved by evaluating g. The required flexural strength can be achieved by tailoring micromechanical parameters such as τ, g, L_f, D_f and V_f. Frictional bond strength values evaluated in this investigation helps to predict realistic flexural performance.

3. Deflection of the beam is measured under flexure, therefore, deflection hardening term may be the most appropriate to indicate enhancement in deformation after first crack up to ultimate load. It undergoes large inelastic deformation after formation of first crack. Percentage deflection hardening showed by 20 mm thick beam in a matrix having C: S ratio as 1:0.5 is 442.25%. It validates ECC material in a category of smart bendable concrete. Most of the specimens showed deflection hardening more than 100%.

4. Toughness index is used to evaluate post peak performance of the material (Table 4). Toughness index I_5 is calculated as area under load-displacement curve for 3 times first crack displacement divided by area under load-displacement curve for first crack displacement. Toughness index for plain cementitious matrix could not be represented because of

C:S Ratio	Depth of Beam (mm)	Avg. First Crack Strength (N/mm²)	Avg. Ultimate Strength (N/mm²)	Displ. At First Crack Load (mm)	Displ. At Ultimate Load (mm)	Strain Hardening
1:0.5	20	4.095	5.177	1.8541	10.0537	Yes
	30	3.553	4.277	2.0928	5.5386	Yes
1:1	20	2.554	2.834	2.3143	6.1545	Yes
	30	1.022	1.225	1.7719	4.2539	Yes
1:1.5	20	0.683	0.767	1.4041	2.2587	Yes
	30	0.563	0.604	1.4802	1.5695	No
1:2	20	0.625	0.687	1.4301	1.8057	Yes
	30	0.576	0.804	1.4473	3.1240	No

Table 1: Test results of beams in flexure.

C: S Ratio	P_{max} (N)	Bond Strength τ (N/mm²)	Average Bond Strength
1: 0.5	0.451	0.798	0.792
	0.451	0.798	
	0.441	0.780	
1: 1.0	0.441	0.780	0.746
	0.422	0.747	
	0.402	0.711	
1: 1.5	0.402	0.711	0.723
	0.392	0.694	
	0.432	0.764	
1: 2.0	0.387	0.683	0.685
	0.358	0.633	
	0.417	0.738	

Table 2: Frictional bond strength.

C: S Ratio	Depth of Beam (mm)	f_m	Ultimate Flexural Strength [Experimental] (N/mm²)	Ultimate Flexural Strength [Theoretical] (N/mm²)
1: 0.5	20	3.302	5.177	5.174
	30	2.581	4.277	4.301
1: 1	20	1.474	2.834	2.867
	30	0.184	1.225	1.232
1: 1.5	20	0.158	0.767	1.164
	30	0.288	0.604	1.326
1: 2	20	0.181	0.687	1.139
	30	0.087	0.804	1.022

Table 3: Comparison of experimental and theoretical values.

C:S Ratio	Depth of Beam (mm)	Percentage Deflection Hardening	Percentage Reserved Strength	Toughness index I_5
1:0.5	20	442.253	26.43	7.155
	30	164.652	20.38	6.937
1:1	20	165.934	10.96	5.769
	30	140.069	19.93	7.766
1:1.5	20	60.866	12.37	5.095
	30	6.033	7.22	4.195
1:2	20	26.265	9.92	4.671
	30	115.857	39.74	5.932

Table 4: Flexural performance of ECC.

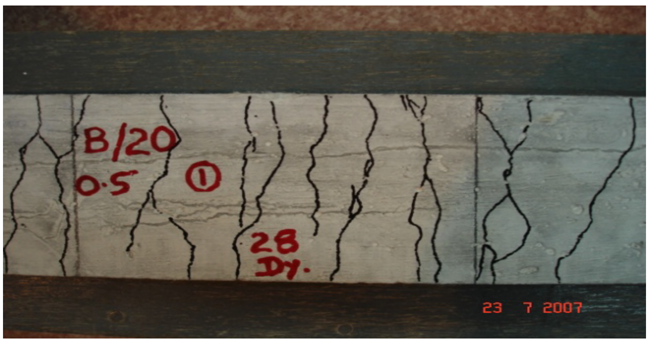

Figure 7: Multiple cracks in 20 mm beam.

catastrophic failure after first crack formation. Toughness index of any high strength concrete ranges from 1 to 2 whereas it ranges from 6 to 8 for ECC material. ECC with C: S ratio as 1:0.5 exhibited highest toughness index value.

5. Almost all the beams having 20 mm thickness exhibited multiple cracking as reflected in Figure 7. 30 mm thick beams having C: S ratio as 1:1.5, and 1:2 could not show multiple cracking due to size effect and less bond of fiber with cementitious matrix. Reduction in flexural strength is found with the increase in sand content as shown in Figure 8. It has direct relation with frictional bond strength.

6. Load-displacement curves for ECC matrix in 20 mm thick beam are shown in Figure 9. The performance showed by ECC matrices without steel reinforcement is exciting and is comparable to performance of steel reinforced concrete in which large displacement ability without unloading is exhibited due to yielding of reinforcement. This performance reveals deformation compatibility of ductile ECC material with the reinforcement without loosing integrity of the material. Such large displacement is accompanied by large spreaded damage area which gives sufficient time. After formation of first crack, the member doesn't unload immediately but exhibits inelastic deformation absorbing large energy associated with formation of other closely spaced cracks. It should be noted that this performance is only for 20 mm thick beams, which reduces with increase in beam depth which is largely reflected in load-displacement curves of all the specimens having 30 mm depth.

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Significant load drop in the curves indicating initiation of micro-crack is observed in axial tension [11], while, sudden load drop for each initiation of micro crack may not be observed because of flexural deformation mechanism.

7. Single fiber pull out tests were conducted for different matrices with 6 mm embedded length. Bridging and pull out action of 12 mm length fiber through the crack in the composite is executed to its maximum possible extent on either side of crack by 6 mm. Therefore 6 mm pull out length can be considered as an effective length in single fiber pull out test for the composite with 12 mm fiber length. Fibers were gripped in pneumatic grip and attempt was made to get zero fiber free length.

8. Load-Pull out displacement graphs were automatically plotted by INSTRON machine. The results were then processed in Microsoft Excel and graphs are plotted as shown in Figure 10. These results are taken as average of best 3 results out of 6 fibers embedded in the particular composite. Performing the pull out test is difficult task as diameter of fiber is 30 µm. As explained earlier if there is significant load drop from the maximum, it is considered to be the chemical bond. Recron 3S fibers are polyester type and hydrophobic in nature. It has no chemical bond which is confirmed from all the graphs of pull out test.

9. Complete debonding portion of load-pull out curve is linear and then it reaches to maximum pull out force which is considered for the bond strength calculation. Frictional bond strength values are given in Table 2. Bond strength increases as the C: S ratio increases. Previous study revealed that as sand content decreases, compressive strength and indirectly, the packing density increases. This effect results in more sound and stable interface around the fiber [14]. The bond strength achieved with C: S ratio as 1:0.5 is better than PE (0.5 MPa) and PP (0.1-0.3 MPa) fibers [5,15]. Calculated values of bond strength are used in the proposed equation. The results of which conform the reliability of the experiment.

10. Tensile strength of Recron 3S fibers is 1000 N/mm². Rupture of the some of the fibers takes place at 644 N/mm² strength. The strength at rupture in composite material is known as apparent tensile strength of fiber, which is always less than its actual tensile strength. As the surrounding matrix is harder than fiber, abrasion damage occurs by delaminating the layers

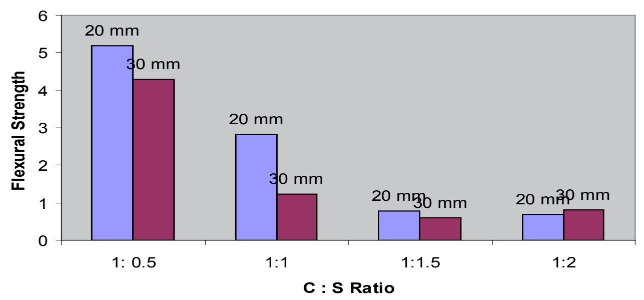

Figure 8: Flexural strength v/s C: S ratio.

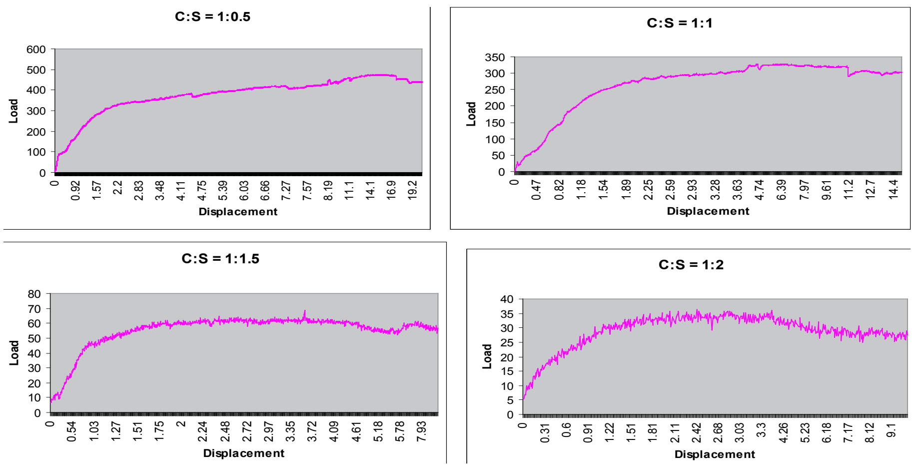

Figure 9: Load-displacement curves for 20 mm thick beam.

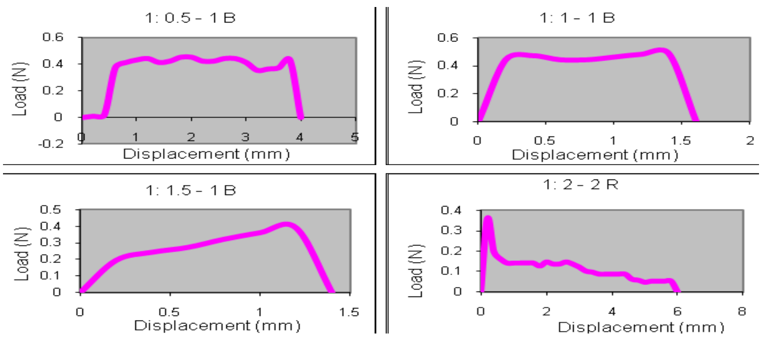

Figure 10: Load-pull out displacement curves in single fiber pull out.

through the fiber thickness. This mechanism is confirmed from the load-pullout curve very clearly. Complete pull out of fibers did not take place in the matrix with C: S ratio of 1:0.5, 1:1, 1:1.5 because after fiber gets its debonding process complete, it undergoes pull out with damage due to delamination of outer layer with the reduction in cross section which eventually resulted into rupture. This phenomenon is beneficial as it doesn't allow to unload the composite and the load resistance mechanism is enhanced. Fiber ruptures due to reduction in cross section hence before it pulls out completely the apparent tensile strength governs the mechanism. If the debonded end is viewed under microscopic lens, fiber tunnel is seen. Fiber did not rupture in the matrix with C: S ratio 1:2 due to lower bond strength. Fiber did not damage due to softer surroundings and hence resistance dropped suddenly. Frictional bond strength is calculated ignoring the β effect which is more realistic. Fibers pull out of the matrix with constant friction as seen from all the graphs, hence β value can be considered as zero.

11. Percentage deflection hardening is the phenomenon that takes place after the first crack when fibers get debonded and enhances load resistance mechanism up to the maximum load. Single fiber pull out test gives best prediction of deformation mechanism. C: S ratio of 1:0.5 gives highest bond strength hence first crack flexural strength is highest and then after debonding it pulls out about 3 mm maintaining load carrying capacity. It reflects maximum deformation by pull-out action without unloading which indicates maximum deflection hardening. Fibers do not rupture because when such large volume fraction of 4% is used, it gets fewer bonds with cementitious matrix due to interaction with each other. Deflection hardening and first crack strength in the composite with C: S ratio 1:1 is also validated by the single fiber pull out curve. Matrix with C: S ratio 1: 1.5 and 1: 2 could not undergo much deformation because fibers did not show much resistance after debonding and sudden drop could be seen in single fiber pull out curve.

Conclusions

- Although ECC is characterized by its performance in axial tension, flexural behavior should be evaluated properly as beam members behave in different manner and are used as energy absorbing element by their large inelastic deformation.
- ECC accepts challenging seismic performance and its promising deformation mechanism makes it most suitable material in key places of a structure where ductile performance is expected. Experimental results show absolutely unique and stunning performance of ECC in flexure, not seen before in any cementitious composites. The flexural performance of ECC, however, reduces with the increase in sand content.
- ECC absorbs large energy by inelastic deformation mechanism. Cement: sand ratio of 1: 0.5 is suggested for optimum performance.
- Single fiber pull out test though difficult to perform provides best means to evaluate flexural strength and understand deformation mechanism.
- Proposed equation for ultimate flexural strength holds good to predict strength. However, predication can be further improved by evaluation snubbing coefficient.

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