ECC AND ITS APPLICATION FOR STRENGTHENING OF MASONRY BEAMS

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ABSTRACT. Engineer Cementitious Composite (ECC) is a mortar based composite reinforced with polymeric fibers and exhibits strain-hardening characteristic through the process of multiple micro-cracking. In this study, two types of polymeric fibers (i.e., polyvinyl alcohol (PVA) fibers and polyester (Poly) fibers) were used for making of ECC. The uniaxial compressive, uniaxial tensile, and four-point bending tests were carried out to characterize the mechanical behavior of PVA-ECC and Poly-ECC with same mix proportions. The compressive, tensile and flexural stress-strain responses of ECC are plotted. Moreover, the effectiveness of precast engineered cementitious composite (ECC) sheets for strengthening of masonry beams by bonding them on tension face as well as both on tension and compression faces like sandwich beam have been investigated. Two types of bonding materials have been used, i.e., epoxy and cement mortar for bonding the ECC sheets with masonry beam. The masonry beams were tested for four-point bending and loaded monotonically up to failure. Experimental flexural response has been predicted for tension strengthened as well as sandwich beams. The present study results reveal that the application of precast ECC increases the strength and deformability of masonry beams and hence demonstrate its effectiveness as strengthening element for masonry structures.

Keywords: Engineer Cementitious Composite (ECC); Flexural strength; Masonry beams; Polyester fiber; PVA fiber; Stress-strain response

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INTRODUCTION

In India, brick masonry with concrete elements are extensively used in the construction of multi-storey dwellings. Apart from heritage structures many of them are mainly constructed with brick masonry. The strength and ductility of these brittle brick masonry structures are limited. Hence many of the brick masonry (Concrete and/ or clay brick) structures collapsed during 2001 Gujarat and 2005 North Kashmir earthquakes. Since the steel as strengthening materials are corrodible, conventional strengthening patterns are not showing durable performance and long life. Usage of non-corrodible, high strength and high ductile materials for strengthening of brick masonry structures seem to be a potential solution for the above-mentioned problems. Numerous strengthening materials such as metallic or polymeric grid, engineer cementitious composite (ECC), textile-reinforced mortars (TRM), and fiber-reinforced polymer (FRP) are used for strengthening purpose nevertheless ECC has gained increasing popularity in the construction field because of its valuable properties such as high tensile strength, and non-corrodible characteristics. ECC is cement based composite which contains discontinuous short polymeric fibers featuring high ductility and strain hardening behavior based upon micromechanics. ECC can be developed with a variety of polymeric fibers such as polyvinyl alcohol (PVA), polyethylene fiber (PE), and polyester fibers [1]. Most investigations so far, have been carried out on polyvinyl alcohol (PVA) and polyethylene (PE) fibers for making of ECC. There is a difference in basic micromechanics of these two fibers. The PE fibers are hydrophobic in nature and do not make any bond with cement matrix but PVA fibers are hydrophilic and makes bond with cement matrix [2]. Most of the researchers [3-7] had used oiled PVA fibers (oil coating to the surface of fibers) because unoiled PVA fibers may be ruptured in a cementitious matrix due to the strong chemical bonding to cement hydrates [8]. As a result, it is difficult to put ECC into large scale practical applications. It is worth studying on the low-cost ECC. Polyester fiber is another alternative which can be used for producing ECC and its cost is relatively lower, about 1/4th that of PVA fibers. Polyester fibers are hydrophobic and hydrophilic in nature which develop the very good bond strength between fiber and cementitious matrix [9].

Some research works [9-13] have been conducted on the use of polyester fibers for making ECC. Rathod and Patodi [9], conducted the experimental study on interface tailoring of polyester fiber in ECC matrix against pullout and have concluded that polyester fibers do not require any extra treatment such as oiling agent or plasma treatment to enhance the performance of ECC. Ahamed et al. [10] studied the flexural behavior of ECC beams made up of polyester fibers and have investigated material properties of polyester-ECC. Singh et al. [11] studied the flexural response of masonry beams with polyester-ECC as bed joint in place of cement mortar and concluded that masonry beams with ECC as bed joint could be used as a structural beam. Singh et al. [12] have shown the comparative response of masonry beams with PVA-ECC and Poly-ECC as bed joints. Authors [12] concluded that masonry beams with PVA-ECC as bed joints exhibit better performance, and the load carrying capacity is found to be 1.5 times of that of masonry beam with Poly-ECC as bed joint.

Most of these past studies indicate that there are limited studies on the use of polyester fibers for making of ECC. The aim of the present paper is to determine the mechanical properties such as compressive strength, tensile strength, split tensile strength, and flexural strength of Poly-ECC. Moreover, the application of polyester-ECC for the strengthening of masonry beams in flexure have been investigated.

EXPERIMENTAL DETAILS

Materials and mix design

ECC generally consists of mixtures of cement, silica-sand, Fly-ash, water, super-plasticizer, and polymeric fibers to reinforce the mix. In this study, Portland pozzolana cement (PPC) as binder, micro silica sand with an average grain size of 100 μm, and class F fly-ash (pozzocrete-63) was used to prepare the ECC. The material properties of Portland pozzolana cement explained by Singh et al. [14] is used. Glenium Sky 8777 provided by BASF India Ltd. was used as the super plasticizer. The present study used two types of polymeric fibers such as polyester fibers of triangular shape and polyvinyl alcohol (PVA) fibers. The material properties of polymeric fibers are given in Table 1. The mix proportion of ECC has been presented in Table 2.

Table 1 Materials properties of polymeric fibers

PROPERTIES	POLYESTER FIBER	PVA FIBER
Fiber diameter (mm)	0.025-0.035	0.04
Fiber length (mm)	12	8
Tensile Strength (MPa)	480	1600
Elongation (%)	30	-
Rupture strain (%)	-	7
Manufacturer	Reliance, India	Kuraray & Co., Japan

Table 2 Mix proportion of ECC in kg/m^3

CEMENT	SILICA SAND	FLY-ASH	WATER	SUPER PLASTICIZER	FIBER
620	620	620	290	8.5	26

Mixing process and specimen preparations

Hobart mixer was used to prepare the ECC. The mixing process is completed in the three steps.

Step 1: Water and super plasticizer are added and thoroughly mixed using Hobart mortar mixer.

Step 2: Silica sand is then added and is mixed for around 2 minutes. Then Fly-ash is added and the mixing process is continued.

Step 3: Further cement is added and mixed about 5 minutes. Fibers are then added slowly. The entire process takes around 20-25 minutes. In this mixing method, cement is added in the step #3 because entire process will take around 20-25 minutes, since cement would attain its initial setting time in this period.

After mixing the ECC, cubes of size 150 × 150 × 150 mm and 70.7 × 70.7 × 70.7 mm, cylinders of size 150 × 300 mm and 100 × 200 mm, tensile coupons of size 310 × 75 × 13 mm, and rectangular prisms of size 100 × 100 × 500 mm were cast. A thin layer of release agent was spread on the interiors of the moulds using a clean brush and then a paste of ECC was poured into the mould. Specimens were left in the mould inside the moist room (temperature 27 ± 3°C and relative humidity 65%) for a period of 24 hours. The specimens were removed from the mould and placed inside the curing tank at temperature of 27 ± 3°C for 28 days. ECC specimens were divided into two categories i.e., PVA-ECC and Poly-ECC as differentiated with type of the fibers inclusion.

Compressive strength

Five cylindrical specimens (150 × 300 mm) and ten cube (150 × 150 × 150 mm and 70.7 × 70.7 × 70.7 mm) specimens, were tested in Compression Testing Machine (CTM) of capacity 2000 kN after 28 days. Cylindrical and cube specimens were tested as per ASTM C39 [15] and IS 516:1959 [16], respectively. Compressive strength was measured by placing the specimens in the contact of bearing surface of the CTM and the load was applied at the rate of 2-5 N/mm^2 per minute until failure occurs. The compressive strength was calculated by dividing the maximum load applied to the specimen during the test by cross sectional area. The modulus of elasticity and Poisson's ratio of cylindrical specimens were calculated as per ASTM C469 [17].

The results of compressive strength, strain at peak stress, failure strain, and modulus of elasticity are presented in Table 3. The failure strain is defined throughout this paper as the strain corresponding to stress equal to 80 % of the peak stress in the post peak region. This definition of the failure strain is arbitrary in the sense that after reaching the peak stress, a sudden drop in stress value is observed with small increment in the strain. Thereafter, strain is increasing with higher rate due to crushing of ECC. The average compressive strength of cube (150 mm), cylinder, and small cube (70.7 mm) specimens is observed to be 54.05, 45.12, and 61.74 MPa, respectively for PVA-ECC whereas it is found to be 46.25, 38.55, 50.88 MPa, respectively for Poly-ECC. The compressive strengths of cylinder (150 × 300 mm), and small cube (70.7 × 70.7 × 70.7 mm) are observed to be 0.83 and 1.14 times of compressive strength of standard cube (150 × 150 × 150 mm), respectively for PVA-ECC whereas they are observed to be 0.83 and 1.10 times of compressive strength for Poly-ECC. The compressive strength of PVA-ECC is found 1.17 times of the compressive strength of Poly-ECC. The compressive axial stress-strain response of the cylindrical specimens of ECC (PVA-ECC and Poly-ECC) is shown in Figure 1. It is seen that, initially both the curves are linear up to about half of the peak stress after which it becomes nonlinear accompanied by a sudden drop in the stress is observed after peak load.

Table 3 Experimental results of compressive strength and split tensile strength tests

ECC TYPES	CUBE[A]	CUBE[B]	CYLINDER, 150 × 300 MM					CYLINDER, 100 × 200 MM
	Comp. Strength, MPa	Comp. Strength, MPa	Comp. Strength, MPa	Peak Comp. Strain, mm/mm	Failure Strain[c], mm/mm	Comp. Modulus, GPa	Poisson's Ratio	Split tensile strength, MPa
Poly-ECC	46.25	50.88	38.55	0.0030	0.0031	16.85	0.164	3.81
PVA-ECC	54.05	61.74	45.12	0.0032	0.0033	22.24	0.172	4.24

Cube[a] = size of cube is 150 × 150 × 150 mm
Cube[b] = size of cube is 70.7 × 70.7 × 70.7 mm
Failure Strain[c] = strain corresponding to the stress equal to 80% of the peak stress in the post peak region.

Split tensile strength

The split tensile strength of ECC was measured through testing of five cylindrical specimens (100 × 200 mm) of each category as per IS 5816-1999 [18] and BS 1881-part 117 [19]. The split tensile strength can be calculated using Equation 1. In this equation, f_{ct} is split tensile strength, P is the load applied to the specimen, and l, d are length and diameter of the specimen, respectively. The results of split tensile strength of ECC are presented in Table 3.

$$f_{ct} = \frac{2P}{\pi dl} \tag{1}$$

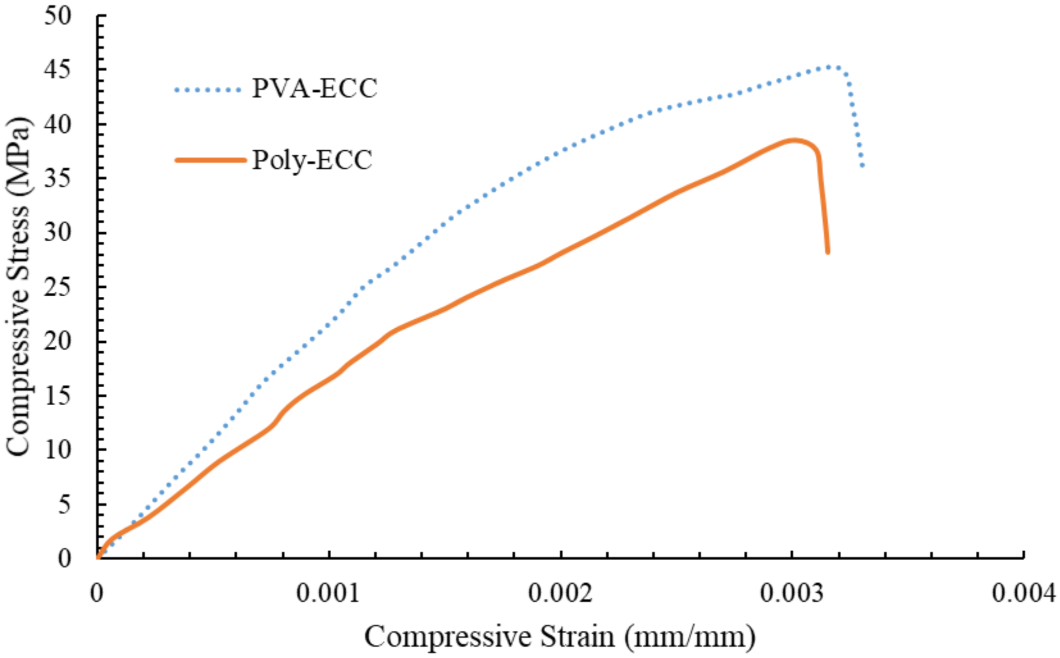

Figure 1 Compressive stress-strain response of ECC cylinder specimens

Tensile strength

Five specimens of ECC coupons of each category were tested in automated deformation controlled hydraulic Universal Testing Machine (UTM) of capacity 100 kN and the load was applied at displacement control rate of 0.5 mm/min. The size of coupons was 310 × 75 × 13 mm and gauge length was maintained as 200 mm. The tensile stress-strain response of ECC coupons were measured by the UTM. The results of tensile strength of ECC coupons are presented in Table 4.

Table 4 Experimental results of tensile strength of ECC coupons

PROPERTIES	POLY-ECC	PVA-ECC
Tensile Strength, MPa	2.51	4.78
Peak Strain, %	0.04	0.20
Rupture Strain, %	2.40	2.80
Young’s Modulus, GPa	8.20	9.60

The average tensile stress-strain response of the ECC coupons is presented in Figure 2. It is seen that PVA-ECC has higher tensile strength in comparison to the Poly-ECC. The tensile strength of PVA-ECC is about 2 times of tensile strength of Poly-ECC. After the first crack, the tensile stress is increased in PVA-ECC due to bridging action of cement and fibers bonding whereas in Poly-ECC, small drop in stress is observed after the first crack and then, stress increases due to strain hardening. The reason behind this significant strength in PVA-

ECC i.e., PVA fiber which has higher tensile strength and stronger bonding with cement matrix in comparison to Polyester fibers.

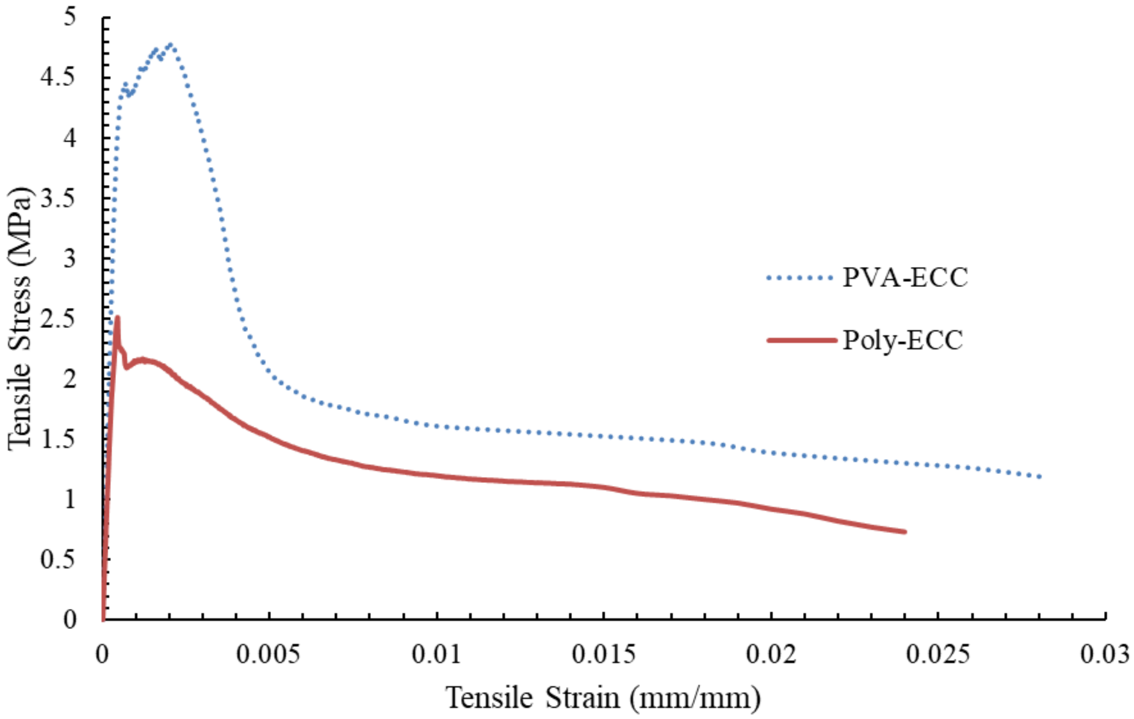

Figure 2 Average tensile stress-strain response of ECC coupons

Bending test

Four-point bending tests were performed on the five rectangular prism specimens of each category on servo hydraulic actuator of capacity 200 kN as per ASTM D790 [20]. The load was applied on the prisms at the displacement control rate of 0.5 mm/min. The results of the four-point bending test of ECC prisms are presented in Table 5. The average flexural strength of PVA-ECC and Poly-ECC is observed to be 9.49 and 8.52 MPa, respectively. The flexural stress-strain response of the ECC prism is presented in Figure 3. PVA-ECC prism has shown more flexural stress in comparison to Poly-ECC. The flexural strength of PVA-ECC prism is found to be 1.11 times of the flexural strength of Poly-ECC prism.

Table 5 Experimental results of bending test of ECC prism

PROPERTIES	POLY-ECC	PVA-ECC
Flexural Strength, MPa	8.52	9.49
Peak Strain, %	1.59	1.68
Failure Strain, %	1.60	1.73
Flexural Modulus, MPa	98.74	83.15

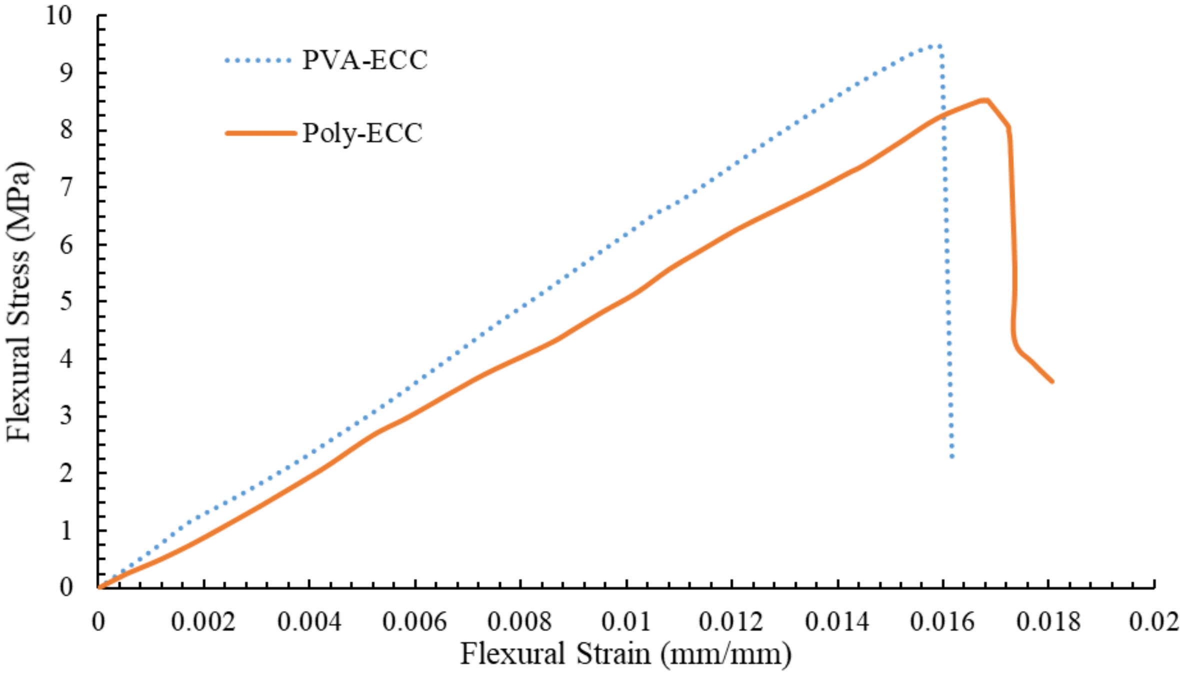

Figure 3 Flexural stress-strain response of ECC prism

APPLICATION OF ECC FOR STRENGTHENING OF MASONRY BEAMS

Flexural response of masonry beams strengthened with ECC sheet

This section demonstrates the effectiveness of precast ECC sheet for strengthening of masonry beams by bonding them on tension face as well as both on the tension and compression faces like a sandwich beam. Two types of bonding materials have been used, i.e., epoxy and cement mortar for bonding the ECC sheet with masonry beam.

Specimen preparation

A total of 11 burnt-clay brick masonry beams of 230 mm (width) × 110 mm (depth) cross-section and 860 mm length were cast. The masonry beams have nine brick units with eight mortar joints, each of approximately 20 mm thickness. Out of the 11 beams, 4 beams were strengthened on the bottom (tension face) with ECC sheet of 35 mm thickness and 4 beams were strengthened on both sides (compression and tension faces) like a sandwich beam with ECC sheet of 35 mm thickness. The other three beams acted as control beams (i.e., unstrengthened). Two types of bonding materials were used for strengthening purpose i.e., epoxy and cement mortar. The thickness of epoxy and cement mortar was maintained approximately 1 mm and 8 mm, respectively. Portland pozzolana cement and local river sand were used in the mix proportion of 1:3 (cement: sand) for the casting of masonry beams. Polyester-ECC was used for casting of ECC sheets. The beams were cured for 28 days before testing. In addition to the masonry beams, two numbers of ECC sheets of size 860 mm (length) × 230 mm (width) × 35 mm (depth) were also tested under 4-point flexural loading to predict the flexural response of ECC sheets.

Installation of ECC sheets on masonry beams

Installation of ECC sheets on the faces of masonry beams was executed using two types of bonding agents resulting in two sets of strengthened beams; (i) tension strengthened; and (ii) sandwich beams. In tension strengthened beam, the bonding agent epoxy/cement mortar was applied on tension face and ECC strip of 35 mm thickness was bonded to the tension face. In the case of sandwich beam, tension as well as compression faces was levelled and applied with specific bonding agent, i.e., epoxy/cement mortar before bonding ECC strip on both the faces. After bonding the ECC strips, the beam specimens were left for curing for 28 days.

Test setup

All beams were tested under four-point loading using servo hydraulic actuator of capacity 200 kN and subjected to monotonic load till failure. The vertical deflection was measured by linear variable differential transducers kept at soffit of the beam at the mid-span. The beams were subjected to a ramp loading at a displacement control rate of 0.05 mm per sec till failure. The schematic of 4-point loading arrangement for beams is shown in Figure 4. This arrangement of 4-point loading ensured desired flexural failure in the test beam.

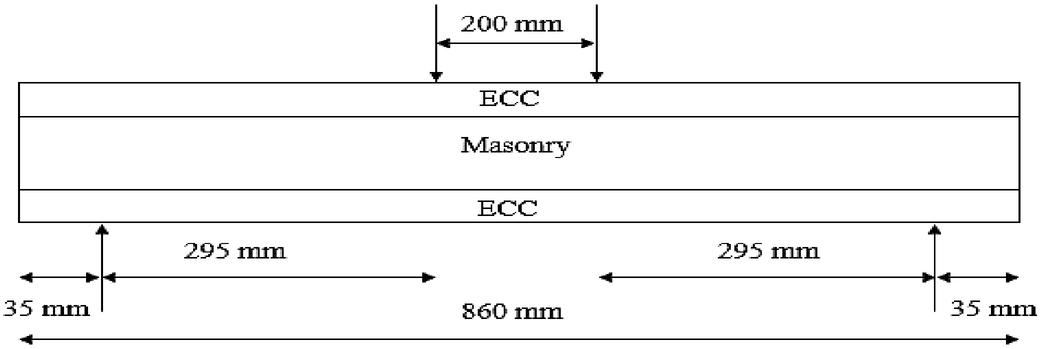

Figure 4 Schematic loading arrangement for beams

Results and discussion

Table 6 depicts the average experimental test results along with the descriptions of beams used in this study. As shown in Figure 5, the control beam, i.e., the beam without external strengthening, failed due to rupture of brick units at an average failure load of 2.18 kN. The tension cracks initiated from the bottom tip of left side of loading point and propagated towards the top of the beam. The sudden failure of the control masonry beams was observed. The tension strengthened beam (ET) with epoxy as bonding agent shows higher flexural strength approximately two times of the corresponding beam (CT) with cement mortar as bonding agent. The delamination was the mode of failure in tension strengthened masonry beam with cement mortar as bonding agent as shown in Figure 6. In sandwich beams with epoxy as bonding agent, cracks originated in the flexure zone from the bottom and propagated towards the end as shown in Figure 7. While in sandwich beams with cement mortar as bonding agent, a vertical crack developed near the left side of loading point due to stress concentration and led to flexural failure of the beam as shown in Figure 8. Experimental responses in the form of load versus deflection have been presented in Figure 9. It is shown that the load-carrying capacity and stiffness of ECC strengthened masonry beams has improved significantly.

Table 6 Experimental results of masonry beams strengthened with ECC sheet

BEAM DESIGNATION	BEAM DESCRIPTION	EXPERIMENTAL		P_{SB}/P_{CB^*}	$\delta_{SB}/\delta_{CB^{**}}$
		Peak load (kN)	Mid-span deflection (mm)		
M	Masonry control beam of depth 110 mm	2.18	0.99	-	-
ECC	ECC control beam of depth 35 mm	0.65	2.66	-	-
ET	Epoxy bonded tension strengthened beam with ECC thickness 35 mm on tension face	7.70	2.80	3.53	2.83
CT	Cement mortar bonded tension strengthened beam with ECC thickness 35 mm on tension face	3.90	2.30	1.79	2.32
ECT	Epoxy bonded Sandwich beam with ECC thickness 35 mm on both faces	11.25	2.23	5.16	2.25
CCT	Cement mortar bonded Sandwich beam with ECC thickness 35 mm on both faces	9.58	2.32	4.39	2.34

* P_{SB} = Load carrying capacity of strengthened masonry beam
* P_{CB} = Load carrying capacity of control masonry beam
**δ_{SB} = Mid-span deflection of strengthened masonry beam
**δ_{CB} = Mid-span displacement of control masonry beam

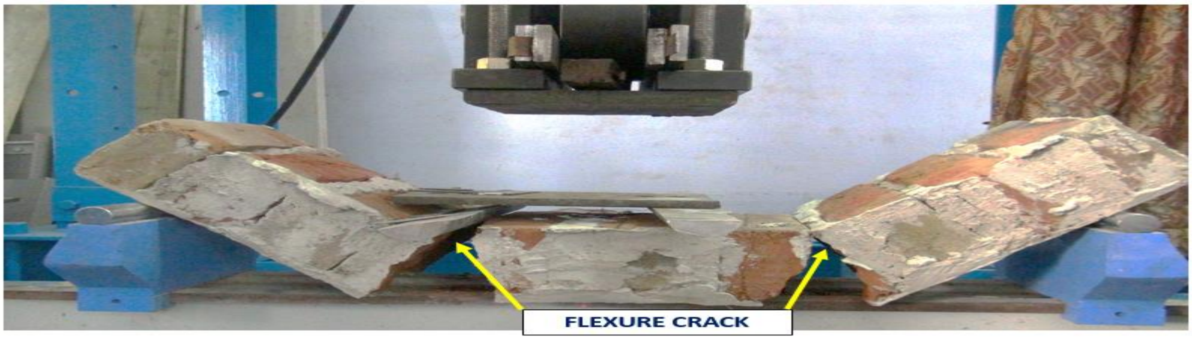

Figure 5 Failure of control masonry beam

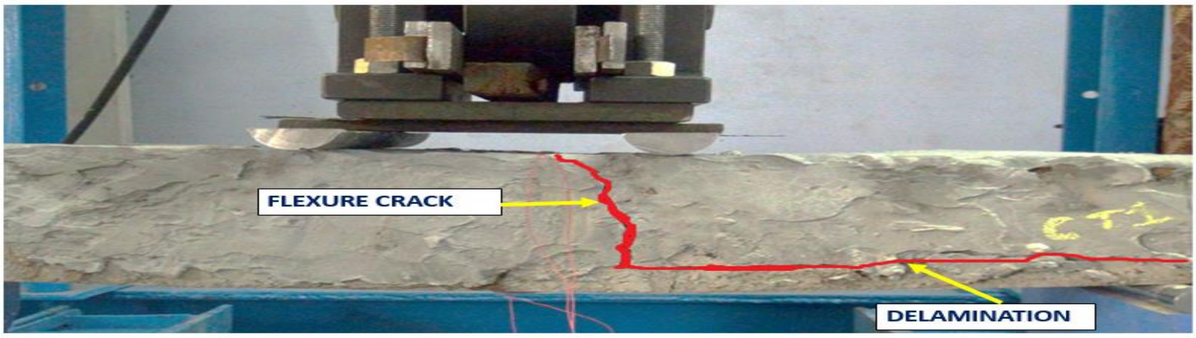

Figure 6 Delamination of tension strengthened masonry beam with cement mortar as bonding agent

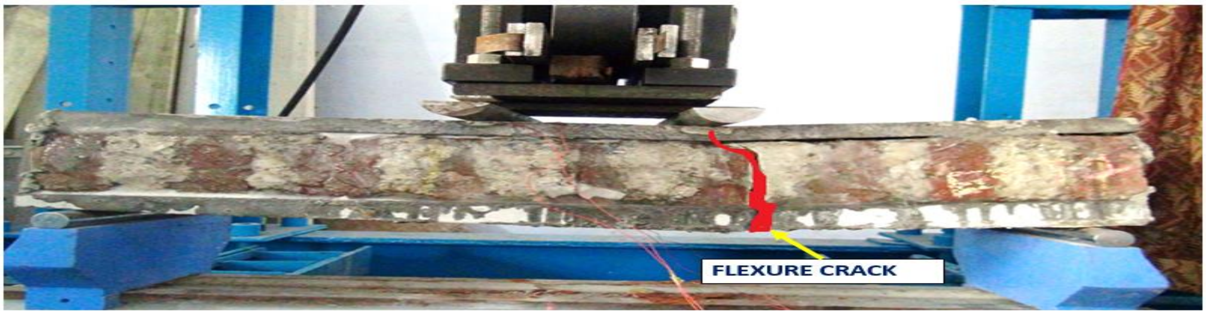

Figure 7 Failure of sandwich beam with epoxy as bonding agent

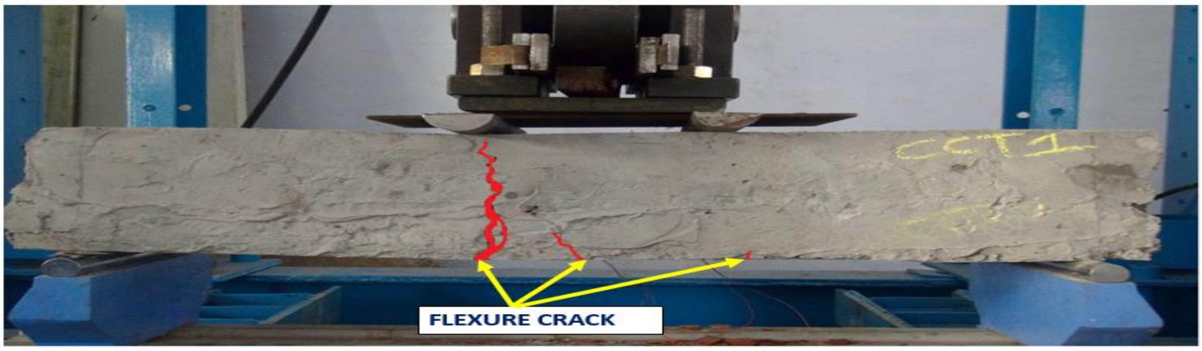

Figure 8 Failure of sandwich beam with cement mortar as bonding agent

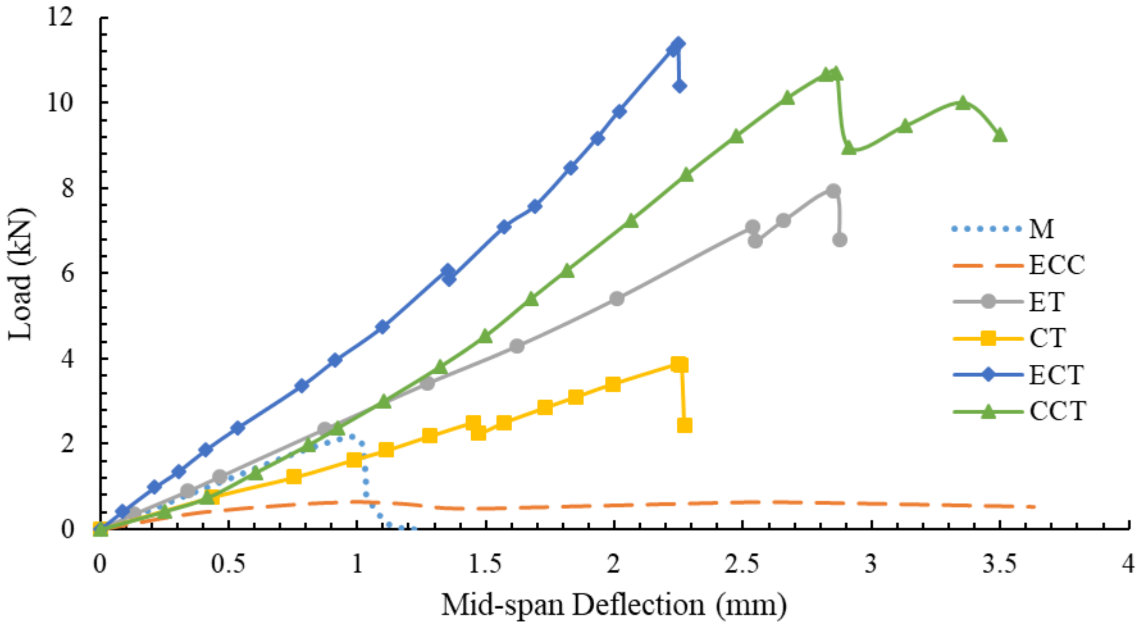

Figure 9 Load-deflection response of control and strengthened masonry beams

CONCLUDING REMARKS

The following concluding remarks are made based on the results presented in this study.

i. The compressive, tensile, and flexural strength of PVA-ECC are respectively found to be 1.14, 2, and 1.11 times of compressive, tensile and flexural strength of Poly-ECC.

ii. Epoxy is observed to be better bonding agent over cement mortar especially for sandwich beams with respect to the load capacity, flexural stiffness, and deformability.

iii. Epoxy bonded beams have higher flexural load carrying capacity compared to the cement mortar bonded beams.

iv. Load carrying capacity of epoxy bonded sandwich beam with ECC sheet is found to be about 5 times of that of unstrengthened masonry beam.

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