

EFFECTIVENESS OF ECC FOR REPAIR OF DISTRESSED RC BEAMS

A Thesis Report submitted in the partial fulfillment for the award of the degree of

MASTER OF ENGINEERING

IN

STRUCTURES

Submitted By

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DECLARATION

I, SAURABH CHANDEL, hereby declare that this thesis entitled "EFFECTIVENESS OF ECC FOR REPAIR OF DISTRESSED RC BEAMS" in fulfillment of the requirements for the award of the Degree of **Master of Engineering in Structural Engineering** and submitted in the Civil Engineering Department, Thapar Institute of Engineering & Technology, Patiala is an authentic record of my work carried out during a period from January 2019 to August 2019 under the supervision of **Dr. Shruti Sharma, Associate Professor and Dr. Heaven Singh, Assistant Professor** Department of Civil Engineering, TIET, Patiala.

The research reports and the results presented in this thesis have not been submitted in parts or in full to any other University or Institute for the award of any degree or diploma.

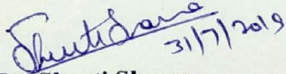
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This is to certify that above statement made by the student concerned is correct and true to the best of my knowledge and belief.


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ABSTRACT

As the demand for economic infrastructure increases worldwide, there is a greater need to cater for the rehabilitation of concrete structures that are damaged by continuous wear and environmental conditions. Rehabilitation and repair constitutes an important stage in the life cycle of most reinforced concrete and precast structures as it contributes to maintaining serviceability and further extending their operational phase.

In this study ECC called Engineered Cementitious Composite which belongs to class of high performance fiber reinforced cement based composite that exhibits strain hardening and multiple cracking behavior under tension and flexure. Several experiments have been performed by researchers to assess the potential use of ECC as a repair mortar using bonded overlay technique. For this purpose seven beams were cast and two beams were loaded to get the ultimate load carrying capacity, then the remaining five beams were stressed to 70 % of the ultimate load. The cracked concrete was removed and surface was prepared to place a layer of overlay mixes having PVA and steel fibers in varying fiber volume fraction and ultimately the repaired overlays were checked for their effectiveness in increasing the capacity of beam under flexural loading and also the bond adequacy was also determined.

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

The purpose of this thesis is to study and evaluate the behavior of ECC called Engineered Cementitious Composite as a repair material to distressed RC beams. ECC refers to the category of fiber reinforced ultra ductile composites exhibiting specific material and physical properties (Li, 1998). It has unique tensile strain capacity, crack width and resistance (Li, 1992). Its micromechanical design approach allows tailoring a flexible material that has structural applications (Fukuyama et al., 2000). ECC research is still underway so as to get a material which can cater the brittle failure problems of concrete. ECC also has strain hardening properties which can be a solution to the durability issues in conventional concrete.

In present study the bonded overlay of ECC was used as a repair for the already distressed RC beams under various stress levels. The beams were subjected to a determined stress level after getting the ultimate load for control beams and then the deteriorated portion of concrete was removed and was replaced by ECC as a repair material. Various types of ECC mixes using different fibers (PVA and steel fibers) were prepared and checked for their strength. These mixes were used to repair the distressed concrete beams, then their performance was compared with control beams as well as their original behavior. So for bonded overlay to have a monolithic behavior the effective bonding between the repair and the concrete substrate is essential. The bond strength for durability of repair should also be adequate. There is always a chance of debonding between the two, so to minimize the debonding probability the bond strength need to be studied.

1.2 PROBLEM STATEMENT

Environmental conditions and wear & tear leads to the deterioration of concrete structures worldwide. In order that these concrete structures continue to perform their intended functions and also to extend their life, the damaged structures are rehabilitated and repaired (Lim, (1997). Every year large amount of funds are allocated for the rehabilitation of distressed structures. But the inadequate durability of the available repair patches only adds to the inefficient investment and adds to the already diminished budget for maintenance of infrastructure.

Normally high compressive strength concrete is widely used as repair patch but the high strength concrete has inherent brittleness with them which results in uneconomical design. Also the brittleness number increases as the strength increases thereby limiting their application to high stress zones. This brittle failure results in low strain of around 0.01 %. To improve this behavior, Fiber Reinforced Concrete was made using short discrete fibers in concrete matrix which bridges the crack and inhibits their propagation leading to increased ductility and higher strains. FRC's were developed in 1970's but at that time only steel and glass fibers were employed in mixes. But due to their higher fiber content, special

processing techniques and restricted application to precast members there was need to switch to a composite such that it satisfies the (a) flexible processing, (b) moderate volume fraction and (c) high performance this could have only be possible by introducing fibers by applying micromechanics tailoring approach with only 2% fibers by volume and material was referred as Engineered Cementitious Composite (ECC) (Li, 1998).

1.3 ENGINEERED CEMENTITIOUS COMPOSITE (ECC) AND IT'S BEHAVIOR

As of material constituents, ingredients of ECC are same as that of (FRC) which contains water, cement, fine aggregate, fibers and the chemical admixtures except the coarse aggregate which may affect their tensile behavior. Typically ECC has a w/c ratio equal to or less than 0.5. But unlike FRC, high volume of fibers is not used in ECC. Generally to attain a composite optimization leading to formation of composite having excellent performance could have had only be possible with moderate fiber volume fraction. ECC deploys pseudo strain hardening properties having low fiber volume fraction of 2 % or less based on micro mechanical models which is based on fracture and deformation mechanics (Kanda et al., 2000).

Failures which are observed due to tension loading are:

- a. Brittle
- b. Quasi brittle
- c. Strain hardening.

As shown in Fig 1.1 Curve A represents the brittle failure which is observed in hardened cement paste having a sudden stress drop with tensile strain of 0.01 %. Quasi-brittle failure (Curve B) has a linear stress-strain part having softening tail beyond first crack. Whereas the stress strain hardening Curve C, it shows large deformations with strain values of much higher order in comparison of brittle and quasi-brittle material.

This transition of quasi-brittle to strain hardening failure is due to steady state cracking caused by extension of matrix cracking due to fiber bridging. To understand strain hardening property of ECC when compared to tension softening tail of FRC, load bearing and energy absorption ; two fundamental purposes of fibers bridging needs to be distinguished. Stress-strain plots can be modeled to understand crack behavior which characterizes the average force which leads to increase in crack width under tension. Strain hardening is due to large energy and bridging strength (σ_{cu}) within the matrix. Also the basic requirement of multiple cracking is that the cracking strength of matrix should not be more than maximum bridging stress (σ_{cu}) which is so called strength criterion. And second is the crack propagation mode which is described as energy criterion (Li, 2003).

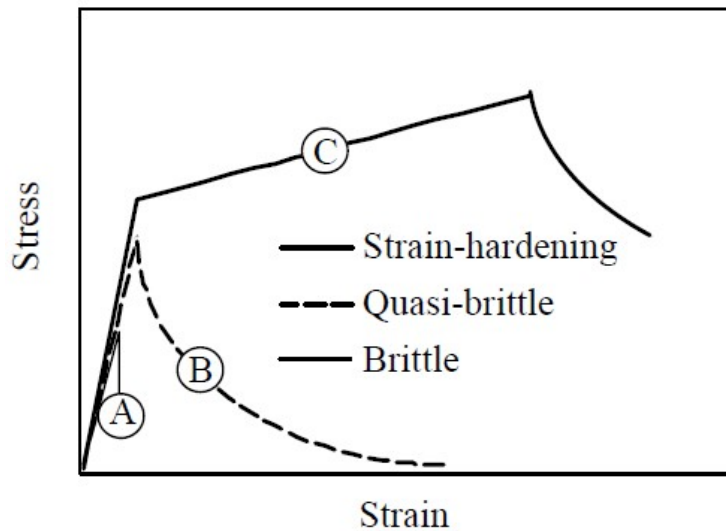


Fig 1.1 Failure Modes Observed in Cementitious Materials (Li, 2003)

1.3.1 Micromechanics

Micromechanics deals with the crack bridging property of fibers. Exceptional ductility of ECC is because of its composite tailoring. For example, fibers are characterized by their length, elastic modulus, diameter, fiber volume and their strength. The cementitious matrix is characterized by its properties such as elastic modulus and fracture toughness. Interface, more precisely which can be called as Fiber-matrix interface parameters i.e. chemical and frictional bonds of fiber and cementitious matrix are also to be considered. So the micromechanics involve the analysis of bond strength and fiber, and matrix and interface interaction with each other under specified loading condition. Therefore ECC is the composite having tensile strain capacity with strain levels of 1-8% (Ma et al., 2015) depending upon the requirement, generally two times than that of concrete. The multiple cracks having small openings is among its superiority.

Due to presence of relatively lower fiber volume and also the chopped nature of fiber the mixing procedure is similar to normal concrete. Various fibers can be used in ECC but they have to obey the rules based on micromechanics consideration (Li, 1998) which implies the fiber, matrix and interface properties should be in correct combination so as to represent the unique behavior of ECCs.

1.4 DIFFERENCE BETWEEN ECC AND FRC

On the basis of material requirements, same ingredients as that of FRC are utilized in ECC but unlike FRCs, large amount of fibers are not utilized in ECC. FRCs employ fibers in higher volume fraction whereas ECC generally uses 2% or less by volume of fibers. The fundamental difference between FRC and ECC is the strain hardening property of ECC instead of tension softening after the initial crack. In FRC the crack continues to widen with increasing load due to fiber pull out resulting in decrease in stress carrying capacity but in ECC there is rise in stress after the first cracking and also increase in strain

is observed (Zhang et al., 2016). And this strain hardening tension softening is seen after certain strain is achieved, thus the stress strain plot represents a shape of a ductile metal. Compressive strain of ECC is almost the double to those of FRC's (0.4 – 0.65 %) (Zhang et al., 2016). But the main difference between ECC and FRC is due the ductile nature of ECC and that too with small amount of fiber volume (< 2 %) and the reason for this is the composite tailoring. This tailoring process modifies the micromechanical (fiber-matrix-interface) which imparts ECC its attendant properties.

1.5 APPLICATION OF ECC

On the basis of their performance characteristics their application is divided into three broad categories as a repair material. The first application is for the provision of safe infrastructure accommodating higher mechanical loads which means it has ability to absorb high levels of energy. The second application is use of ECC as a construction material. Third use includes durable infrastructure capable of catering environmental loading and severe conditions. This includes the ECC application as a repair to already distressed structures including dams, sewer lines and bridge decks.

Some renowned application includes:

- (i) Casting in situ ECC link slab of bridge decks (Lepech and Li, 2009)
- (ii) Retrofitting of Mitaka Dam in Japan (Kunieda and Rokugo, 2006)
- (iii) Sprayed UHTCC tunnel linings in South Korea (Fischer et al., 2004)
- (iv) Repairing of Irrigation channel in Japan (Inaguma et al., 2006)
- (v) ECC damper in Tokyo and Yokohama buildings (Kanda et al., 2005)



Fig 1.2 Retrofitting of Mitaka Dam by spraying ECC layer (Kunieda and Rokugo, 2006)



Fig 1.3 Concrete retaining wall before (left) and after (right) (Rokugo et al., 2005)

1.6 ORGANIZATION OF THESIS

This study aims to investigate the effectiveness of different repair mix to strengthen the already stressed beams with ECC having different proportions of PVA and steel fibers.

This work has been organized as follows:

Chapter 1: This chapter deals with the introduction and history of ECC.

Chapter 2: Literature work has been reviewed in this chapter.

Chapter 3: This chapter comprises of detailed experimental program. Material properties and experimental procedure is discussed in detail.

Chapter 4: This chapter discusses the results of various test and properties of the work carried out.

Chapter 5: It details the conclusion of tests and study carried out.

CHAPTER 2

LITERATURE REVIEW

2.1 GENERAL

Different studies have been done by different researchers on the micro-mechanics of fiber bridging, mechanical properties and repair with ECC.

The review has been divided into following categories:

- (a) Based on micro-mechanics.
- (b) Based on mechanical properties.
- (c) Based on repair and retrofit.

2.2 REVIEW BASED ON MICRO-MECHANICS

Table 2.1 Lists the studies on the micro-mechanics, fiber length and fiber volume fraction which are engaged in preparation of ECC

Name of Author	Year	Name of Paper	Properties studied
Fukuyama et al.	2000	Ductile Engineered Cementitious Composite Elements for Seismic structural applications.	Fiber Volume Fraction
Li, V.	1998	ECC- Tailored Composites through micromechanical modeling.	Fiber bridging. Critical fiber volume fraction.

The details of the above mentioned papers are discussed below.

Li, (1998) studied the various properties of FRC, their characteristics and the types of FRC based on fiber volume fraction. According to past studies High Fiber Volume fraction composites which had 3-10% of fibers require special processing methods in order to accommodate high volume of fibers in them. Further, in thin sheets products incorporating higher fiber volume, there may be a difficulty in placing the main reinforcement.

Along with improved mechanical and strength properties the high cost, anisotropy and associated weight is always a concern. Hence, composite optimization can lead to composite having excellent performance having moderate fiber volume which can also meet the characteristics of FRC.

Hence in order to have link between the constituent parameter and composite properties, they developed micromechanics. He reviewed the micromechanics-based approaches to engineer a FRC exhibiting pseudo strain hardening with low fiber volume of 2% or lower called Engineered Cementitious composites (ECC). In fiber composites, after the first cracking there is always fiber bridging that occurs over the crack. Further on extension of crack, the bridging zone also extends which leads to increase in bridging stress. When the bridging stress becomes equivalent to the applied load, the crack gets flatten so as to maintain same stress level called steady state cracking stress. It is now in steady state cracking mode, which extends without increase in load and at this stage tensile load is independent of crack length.

Fukuyama et al., (2000) reviewed material technology involving ECC design using micromechanical principles and focused on developing elements for seismic applications having high performance. ECC development was based on fiber bridging micromechanics and matrix crack extension. Under tensile loading the pseudo strain hardening was accomplished with randomly oriented short fiber in cementitious matrix when fibers were in excess of critical fiber volume fraction V_f^{cr} .

It was concluded that in order to get a composite having high strain capacity the fiber volume fraction should be greater than V_f^{cr} i.e. critical fiber volume fraction. To achieve pseudo strain hardening with minimum amount of fiber the aim should be at low V_f^{cr} . Below this critical value the strain in composite was almost the same as that of cement matrix; also the fiber fraction much above the critical value does not increase the strain value. The reason for the high strain capacity is clarified by the stress strain curve. When the specimen is loaded and the first crack occurs further when the load is continuously applied, the increased load is taken by the bridging fiber leading to occurrence of cracks elsewhere. This multiple cracking occurs till the maximum load σ_0 is reached- resulting in pseudo strain hardening behavior of the composite.

2.3 REVIEW BASED ON MECHANICAL PROPERTIES.

Table 2.2 Following are the recent works on mechanical properties of ECC

Name of Author	Year	Name of Paper	Material used	Properties studied
Kan et al.	2019	Effect of fineness and calcium content of fly ash on the mechanical properties of Engineered Cementitious Composites (ECC)	PVA fiber, methyl-cellulose thickener, four classes of fly ash.	Compressive strength
Guan et al.	2018	Flexural properties of ECC-composite beam	OPC, PVA- fiber	Tensile strength, flexure strength

Kandasamy and Krishnaraja.	2018	Flexural Performance of Hybrid Engineered Cementitious Composite Layered Reinforced Concrete Beams	OPC 53, Class F fly-ash, PVA and steel fiber.	Split tensile strength, flexural behavior, compressive and bond strength.
Esakkideepan and Pooraniya.	2017	Strengthening of PCC Beam Using ECC	OPC 53 grade cement, Fly-ash, silica sand, PVA fiber	Flexural behavior of repaired beam.
Munjal and Singh.	2016	Mechanical Properties of PVA and Polyester Fibers Based Engineered Cementitious Composites	PPC, PVA and polyester fiber.	Split tensile strength, four point bending test, compressive strength.
Abbas and Khan.	2016	Flexural behavior of high-strength concrete beams reinforced with a strain hardening cement-based composite layer	PVA and steel fiber.	Flexural behavior, compressive strength
Li and Li.	2016	Behavior of ECC/Concrete layered repair system under drying shrinkage condition.	PVA fiber, Fly-ash, SFRC.	Drying shrinkage of ECC repair.
Zhang et al.	2016	Flexural performance of layered ECC-concrete composite beam.	PVA fiber, ordinary Portland cement.	Flexural behavior of ECC layered beam.
Singh and Sivasubramaniam.	2013	Flexural response of ECC strengthened reinforced concrete beams	OPC, Class F Fly-ash and PVA fiber.	Flexural strength.

Anwar. A, et al.	2009	ECC for repair of initially cracked concrete beams.	Polyethylene fibers, CFRP sheets, epoxy.	Retrofitting of already damaged beam.
Lepech, M. and Li, V.	2009	Application of ECC for bridge deck link slabs.	PVA-ECC	Retrofitting of bridge deck.
Kunieda et al.	2005	Patching repair with ECC on cracked concrete surface.	PE-ECC	Patch repair of slabs.
Li and Wang.	2005	Polyvinyl alcohol fiber reinforced engineered cementitious composites: material design and performances	Class F Fly-ash and PVA fiber.	Tensile strength, flexural strength and compressive strength.
Kanda et al.	2000	Repair and retrofit with engineered cementitious composites	PE-ECC and FRC overlays.	Bond strength of repair material.

The detailed review of above mentioned works are discussed below.

Li and Wang, (2005) summarized the properties of PVA-ECC such as tensile behavior, bending response and compressive strength. In their mix they used the water to binder ratio as 0.24. Mix proportion for M45 grade PVA-ECC as given in Table 2.3 was used. Fiber volume fraction used was 2% and large aggregates were not used for preparing the mix. Maximum grain size of silica sand was 250 μ m.

Table 2.3 PVA-ECC mix proportions (kg/m³) (Li and Wang, 2005)

Cement	Sand	Class F Fly-Ash	Water	Super plasticizer	PVA Fiber
583	467	700	298	19	26

For measuring compressive strength cylindrical specimen of size 75 X 150 mm was used. Initially the strength was increased till 14 days but after that the rate of increase of strength was much slower for next 8 months. Two point bending was used to measure the flexural behavior. Beam of size 304.8 mm X 76.2 mm X 12.7 mm was casted with test length of 101.6 x 76.2 x 101.6 mm. Bending stress and deformation plot of beam after 24 hours and 90 days showed a increase in bending stress at the end of 90 days and also the deformation measured was more at the end on 90 days as compared with 24 hours deformation.

Singh and Sivasubramanium, (2013) tested four beams having ECC layer provided in tension zone. In all, six beams of M30 grade concrete were cast, of which three were over-reinforced while other three were under-reinforced. In each sets, two beams were then employed with ECC layer of 50 and 70 mm respectively, while the third beam in each set acted as control beam. Poly-Vinyl-Alcohol fibers as polymeric fiber with volume fraction of 2% were used. ECC layers in two stages were cast, in first stage ECC layer was poured for the desired thickness and then after 24 hours concrete was poured onto the ECC layer with no reinforcement or bonding agent at the interface. The beam was subjected to two-point loading using a 1000 KN capacity load frame. The loading spans were kept 400 mm & 520 mm for strengthened beams and control beams respectively, 70 mm overhangs were left from both the ends.

Response of under-reinforced layered beam (Fig 2.1): Overall beam length was 1300 mm and of size 100 mm x 200mm. The failure occurred due to flexural tension and the beams showed no micro cracks. The failure was governed by ordinary flexural cracks at the tension side. Beams having ECC layers were observed to be capable of bearing higher loads than the RC beams. The normalized load carrying capacities of beams with 70 mm and 50 mm ECC layer were 8.31 and 5.37 times more than that of the control beam. 70 mm ECC layer beam was more effective in providing ductility than 50 mm ECC layer.

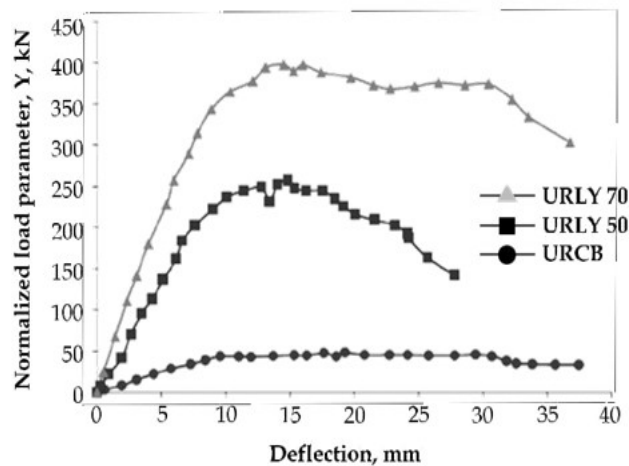


Figure 2.1 Response of under-reinforced layered beam (Singh and Sivasubramanium, 2013)

URLY stands for under reinforced layered beam and the numeric value represents the thickness of ECC layer in mm.

Over-reinforced layered beam: All the over-reinforced beams were having 3 #12 mm dia rebars as main longitudinal reinforcement. In addition, vertical stirrups were provided as (8 mm diameter @ 40 mm spacing) to ensure that beam failed in flexural compression. The failure of all over-reinforced beams occurred in flexural compression due to concrete crushing. It was observed that all beams strengthened with ECC layers were capable of taking more loads than the control beams. The normalized load carrying capacities of ORLY 70 and ORLY 50 were 8.45 and 5.71 times more than that of the control beam, respectively. Further, it could also be observed that the ECC layers improved the ductility of over-reinforced beam along with increasing load.

Abbas and Khan, (2016) to study the flexural behavior ECC layer around the tension steel was used. For control purpose high-strength concrete beams were used, also 1.5 % by volume of steel fibers were used to study structural behavior. Composite layer covered the main steel with thickness of 25 mm leaving behind the concrete cover. Researchers used Poly-Vinyl Alcohol (PVA) and steel fibers to prepare the mix.

Three beams i.e. control beam other having composite layer and the third beam had 1.5% by volume of steel fibers were employed. Beam size was 1200 mm x 250 mm x 150 mm. Yielding of tension steel occurred in high strength control beam before it was crushed having lower deflection than B2. Initially both beams showed linear behavior but after first crack the linearity deviated. So it was concluded that composite layer increased the ductility by undergoing more deflection and also higher load carrying capacity. Load-deflection plot of all the three beams are shown in Fig 2.2. Beam having 1.5 % steel fibers exhibited higher load carrying capacity and deformation than the other two. Load deflection curve of beam having steel fibers revealed the softening tail. Load drop was observed on comparing with control beam and the beam having PVA fibers. The results indicated that after the development of cracks, strain was developed in tension steel due to which the bars were yielded and lead to compressive failure of concrete. By adding steel fibers post crack energy absorption was increased significantly because of fiber bridging. Also the beams in which no fiber was provided had lower crack load as compared to beams which were cast with ECC layer having PVA or steel fibers.

Compressive strength test and elastic modulus for ECC were measured from cylinders having 100 x 200 mm size with and without fibers. Stress-strain plot indicated that fibers increased the compressive strength and elastic modulus. Specimens with fibers represented ductility whereas the cylinders having no fibers were crushed completely.

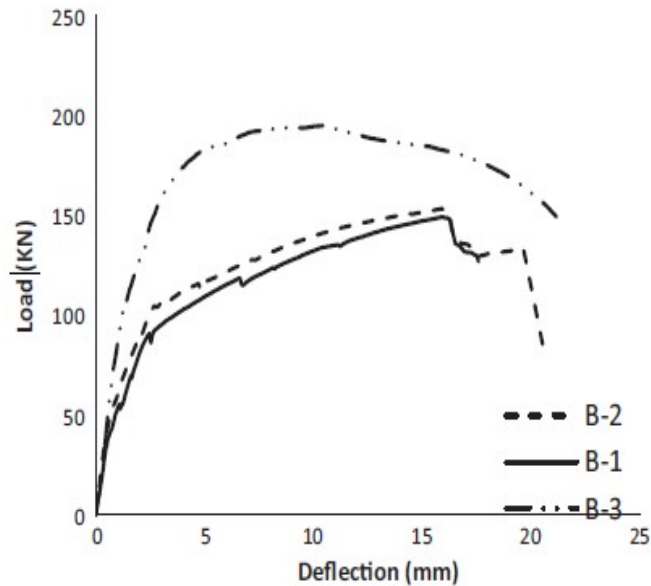


Figure 2.2 Load-deflection curves (Abbas and Khan, 2016)

B-1 control beam, B-2 composite having PVA fiber and B-3 composite having steel fibers.

Munjal and Singh, (2016) examined the use of polyester PE and PVA fibers in concrete to study the mechanical properties of ECC. Basic micromechanical difference between the two fibers was studied. PPC, silica sand having average size of $100\mu\text{m}$ and Class F flyash for preparation of mix were used. Cement, sand and Fly Ash were proportioned in 1:1:1 by weight having 290 kg/m^3 of water. 2 % by volume of fibers were used.

Four point bending test on five rectangular beams on UTM of 200 kN capacity at 0.5 mm/min was conducted. Average flexural strength of PVA was 9.49 MPa and Poly-ECC was 8.52 MPa. The stress-strain curve for ECC beam is shown Fig 2.3. PVA-ECC beam had shown higher flexural stress as compared to PE-ECC. Flexural strength of PVA-ECC beam was 1.11 times than that of Poly-ECC beam and concluded that PVA fiber was hydrophilic and PE used fibers were hydrophobic thus making poor bond with the cement matrix. Five cylinders having diameter and height as 150 and 300 mm and 5 cubes 150 mm size and 70.5 mm size respectively were loaded under CTM. Average compressive strength of 150 mm cube was 50.04 MPa, cylindrical sample 45.12 MPa and cube of lesser dimension had strength of 61.74 MPa for PVA-ECC fiber and that for Poly-ECC fiber they were recorded as 46.25, 38.55, 50.88 MPa. The comparison of the test results are illustrated in Fig. 2.4. In cylindrical specimen initially the cracks occurred at the top and then extended to the bottom with increasing load and get widened.

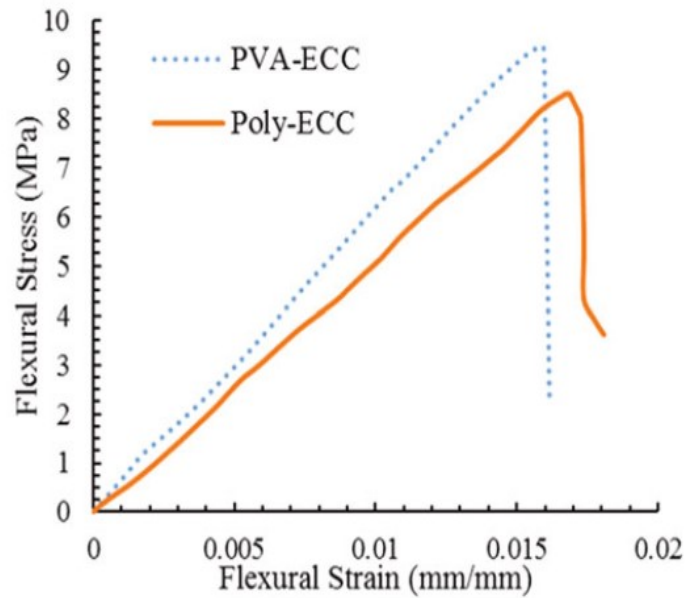


Figure 2.3 Flexural Stress and Strain Response for ECC beam (Munjal and Singh, 2016)

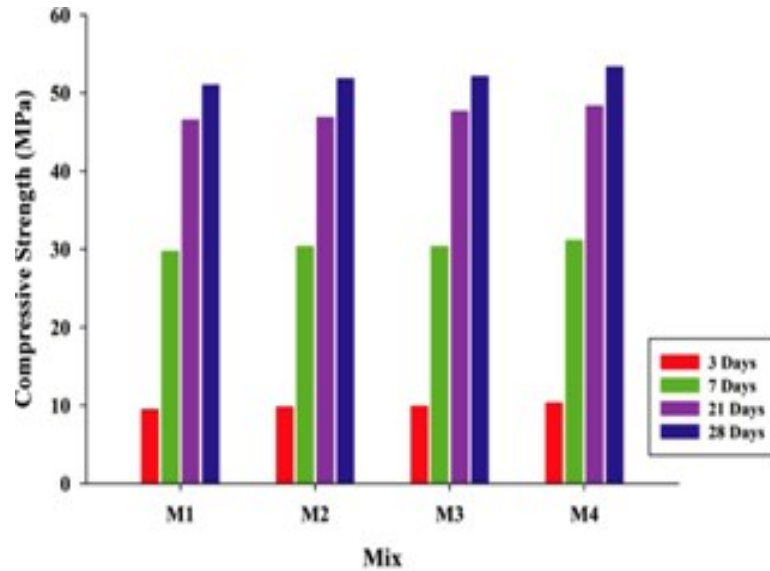


Figure 2.4 Compressive strength of ECC mix (Munjal and Singh, 2016)

Guan et al., (2018) studied how the fully bonded ECC layer with normal concrete increases the load carrying capacity and longer cracks present in concrete leads to localized cracking in ECC layer. To prevent penetration of cracks in ECC layer plastic was employed between the two, to break the bond. Also, a mesh of fiber was also employed in ECC layer; so they studied effects of ECC on bonding and reinforcing on the bending of composite beam.

Two point loading was conducted on $15 \times 50 \times 350$ mm specimens. For measurement of deflection LVDT and UTM at 0.5 mm/min loading rate were used. At failure the midpoint deflection was 20.5 mm. Much higher first crack strength of 7.7 MPa and flexural strength of 14.7 MPa were recorded.

In beginning, the midspan deflection increased linearly and due to cracking of ECC and yielding of r/f steel there was force drop at the end followed by even more deflection.

The type of bonding between the two layers governs the loading capacity and deflection whether the fiber mesh is placed or not in the ECC layer. Because of high tensile strength and ductile nature, it carried higher loads after concrete gets cracked. The unbonded composite beam had higher post crack energy absorption capacity because of ECC layer deformation. The unbonded ECC cover can be considered as an external strengthening reinforcement. There was distribution of longitudinal strain over the ECC cover because of interface slip, thus higher deflections were observed.

Kandasamy and Krishnaraja, (2018) experimentally investigated the flexural behavior of ECC and hybrid ECC layers around the tension reinforcement consisting different percentages of fiber volume fraction. For examining various behaviors, hybridization was done. Four mixes designated as M1, M2, M3 and M4 were used. M1 was prepared by fiber volume fraction of 2% and used as reference mix. The rest of mixes were prepared by hybridization of PVA fiber and steel fiber; in M2 mix PVA volume fraction was 1.35% and steel fiber fraction was 0.65%. Mix M3 has steel and PVA fiber fraction as 1 % and Mix M4 has only steel fibers. All the mixes had super plasticizer and water binder ratio as 1% and 0.35 % respectively.

Four point loading for 1800 mm span on a beam of 2000 mm x 100 mm x 150 mm was used. ECC layer of thickness 30 mm was placed at tension zone and after one-hour normal concrete was poured. All beams behaved similarly under flexure and the first cracks appeared within the yield stage. Load deflection curves (Fig 2.5) of layered ECC beams were wider than the conventional concrete due to higher ductility. ECC with PVA volume fraction of 0.65% and 1.35% steel (M3) showed better results.

Set of three cubes of size 70.7 mm size were at 3, 7, 21 and 28 days according to IS 4031- Part 6 :1988 employes to have the compressive strength. 28 days compressive strength was 51 MPa, 51.8Pa, 52.1MPa and 53.2MPa for mixes M1 to M4. The 3 day strength of respective mixes were 18.4%, 18.8%, 18.9% and 19.5%. This showed that steel hybridization didn't increase the compressive strength of mixes and because of fiber bridging it depicted the ductile nature.

Comparison of bond strength of control specimen and the bonding of conventional concrete and ECC mixes is represented in Fig 2.6 after 3, 7 and 28 days. Because of steel and PVA fibers there was a rise observed in strength. The reason for increased strength was fiber bridging and also from the failure surface fibers were observed at interface whereas in control specimen only aggregates were present. Mono PVA fiber mix exhibited the highest strength gain.

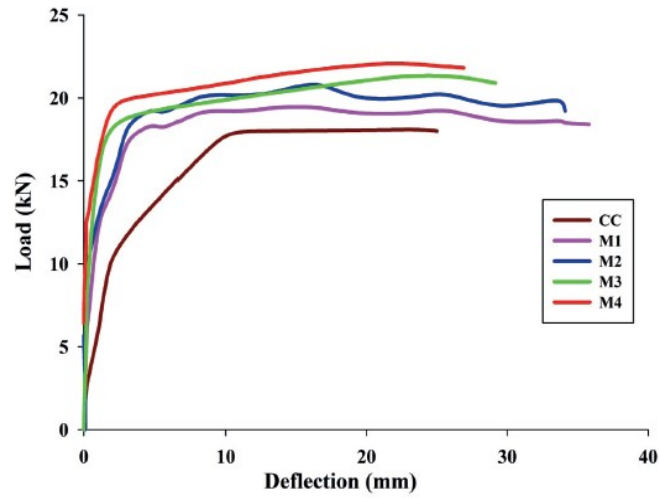


Figure 2.5 Load deflection curve of various beams (Kandasamy and Krishnaraja, 2018)

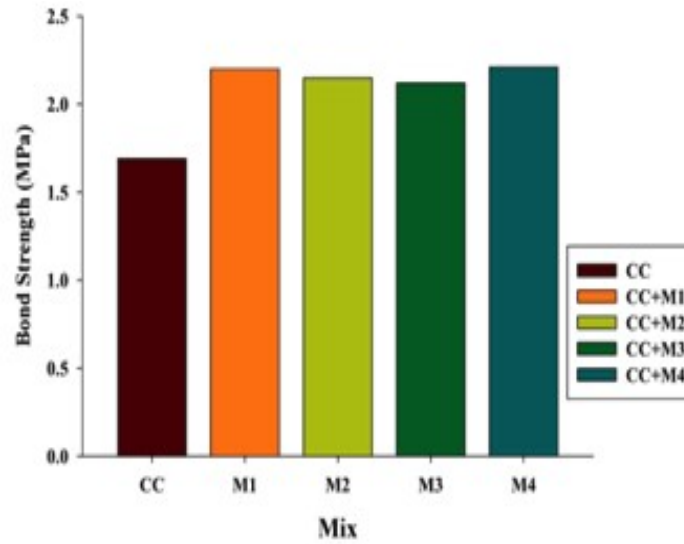


Figure 2.6 Bond strength of different mixes (Kandasamy and Krishnaraja, 2018)

Kan et al., (2019) examined the effect of different flyash on properties of ECC. For investigations four kinds of FA was employed and PVA fiber volume fraction of 2% was used to make ECC mixes. Table 2.4 represents mix proportions of ECC.

Table 2.4 Mix proportions of ECC (kg/m^3) (Kan et al., 2019)

Cement	Sand	FA	Water	MC	Fiber
346.33	346.33	808.10	346.33	1.88	24.29

MC: thickener (Methyl Cellulose)

For determining the compressive strength of ECC set of 50 mm size cube for each mix was tested. Fall in compressive strength of cube was observed with the fineness of FA because FA replacement with low calcium content resulted in less calcium available for hydration to occur which reduced the strength.

2.4 REVIEW BASED ON ECC AS REPAIR AND RETROFITTING

Kanda et al., (2000) they studied the bond of repair material with the concrete substrate. They studied the two failure modes which can occur in repair i.e. (a) Delamination and (b) Spalling. They used three repair materials, concrete, ECC and FRC which were used as overlays. Polyethylene fibers (PE-ECC) having 38micron diameter were used in 1-2% fiber volume fraction.

Fig 2.7 shows the simulated repair system which was subjected to four point loading, in order to represent a interface defect horizontal initial notch in form of smooth tape was introduced b/w the concrete and overlay. Joint was introduced in base concrete below notch to have severe loading case.

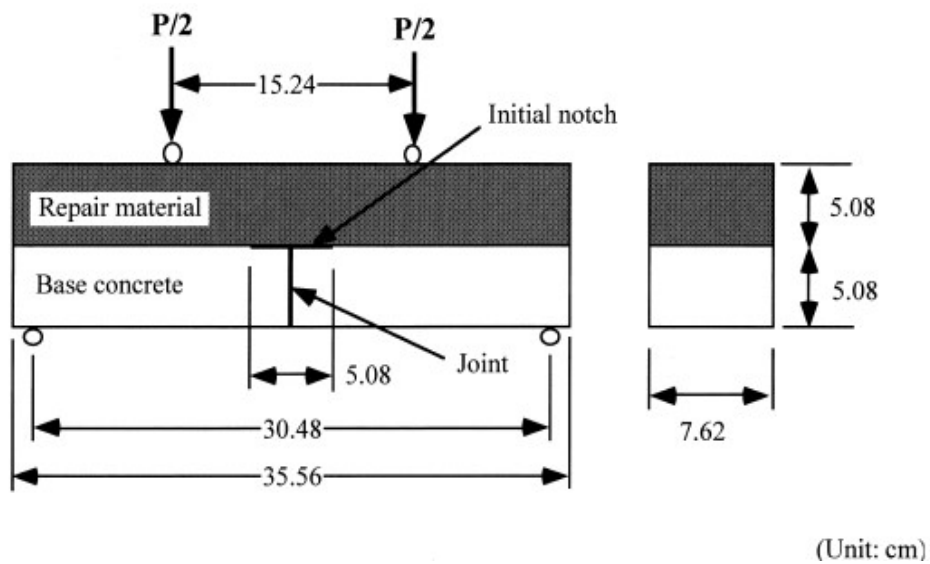


Fig 2.7 Simulated repair system (Kanda, et al., 2000)

Spalling of the repair material was observed in specimens with concrete and FRC with very small amount of delamination. In case of concrete repair material the specimen broke into two halves with immediate load drop followed by kink out. There was fiber bridging due to steel fibers in spalled cracks and load drop was observed for FRC repair. For the ECC repair sample, an interface crack extension, and re-initiation of crack interface events occurred as the load increases. Resulting in pattern of kink-out micro cracks in the ECC.

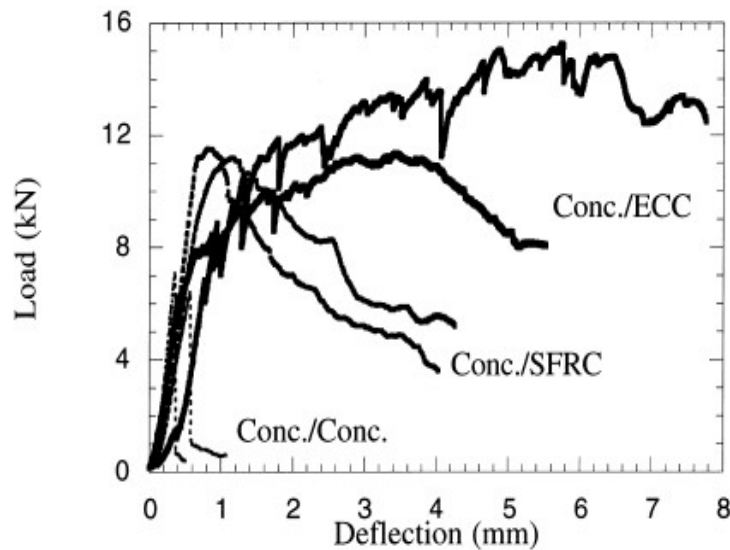


Fig 2.8 Load-deflection curves of repaired systems (Kanda et al., 2000)

Kunieda et al., (2005) investigated the effect of patch repair system, for this purpose ECC layer of 30 mm thickness was placed on concrete substrate. Polyethylene fibers at 1.5% fiber volume fraction was used to make the ECC mix. Diameter of fiber is 12×10^{-3} and 12 mm length.

Two beams of cross section 100 mm x 100 mm and length as 400 mm were placed side by side with zero clearance between them to represent an artificial crack. Also to study the effect of bonding between substrate and repair some specimens were made partially unbonded by placing 50 mm wide tape. Two point loading was used to test the specimens. Distance between the load was 100 mm i.e. 50 mm on either side of beams at interface. Specimen configuration is shown in Fig 2.9. From load-displacement curve it was observed that most of samples failed after a deflection of 2-3 mm, also there was no effect of unbonded region on load-displacement curve. From load-strain curve it was noted that strains were distributed to larger ECC area contributing to deformation without being transferred to substrate.

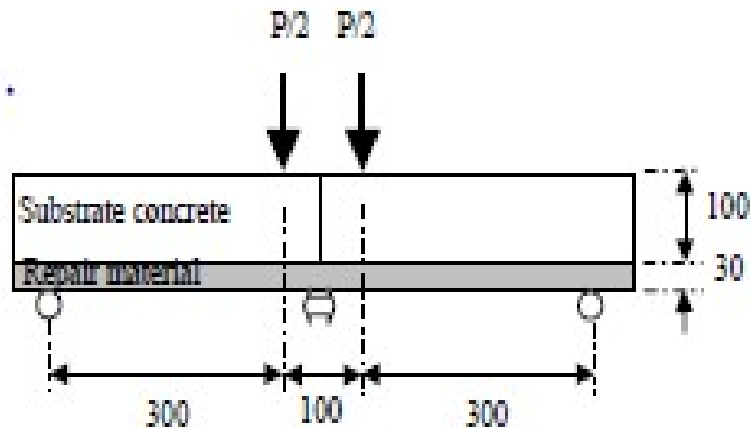


Fig 2.9 Specimen configuration (Kunieda et al., 2005)

Anwar et al., (2009) retrofitted the already damaged concrete beams. They prepared 21 conventional concrete beams having pre defined cracks and retrofitted with ECC and combination of ECC with CFRP. For conducting the cracks, separators were placed at the time of casting in the moulds. Table 2.5 shows the mix proportion of and ECC resp. ECC was in the form of ready mix powder incorporating Polyethylene fibers having length of 12.7 mm and 38 micron diameter with tensile strength of 190 MPa.

Table 2.5 ECC mix proportions (kg/m³) (Anwar et al., 2009)

Ready mix powder	Water	Fiber by volume (%)	Super plasticizer
1562	350	2	16.9

Twenty one control beams of length 400 mm and 100 mm x 100 mm cross section were subjected to two point loading with test length of 300 mm. Casting of Concrete/ECC beams were carried out in two stages; firstly, the free space was left in moulds while casting the plain concrete and after curing for 28 days ECC of varying thicknesses were added to fill the space in moulds. There were seven different types of specimen. Group 1A and Group 2A represent original and deteriorated samples. A represents that method for repair is by the use of ECC and B denotes the sample where CFRP sheets were used with ECC. As there were large number of specimens prepared so the description of those specimens can be referred from concerned article.

ECC alone was found to be more effective. For ECC alone, ECC was applied around 100 mm at base and was extended to full crack depth and showed an increase in section capacity 220 % higher than damaged state for target beam. Application of ECC layers up to longer distance and different thicknesses showed improvement in flexural performance. Also ECC acted as a bridge in transferring the forces to the other side of crack. The section capacity for beams with varying ECC thicknesses was more than target specimen and also higher than damaged specimen. The same was also repeated with CFRP sheets at the soffit of beam. Application of CFRP sheet increased the energy absorption until failure leading to small deflection with high load carrying capacity.

Control and target specimen failed purely in flexure. Common repair adopted showed that crack started from same place of existing crack. Spalling of local ECC with flexure crack signified that bond between ECC and substrate cannot withstand tensile stresses. But the samples with ECC and epoxy showed no spalling of ECC layer.

Lepech and Li, (2009) worked on retrofitting of bridge using ECC link slabs instead of expansion joints. For this purpose they designed the ECC link slab and also due to high strain capacity of ECC, the reinforcement ratio was adjusted accordingly. An ECC link slab of size 5.5 x 20.25 m having a thickness of 225 mm was investigated. Static load testing was carried out on link slab, the instrumentation focused on two parameters i.e. slab under static load – end rotation and the strain on slab. For the purpose of static

load two 6-axle trucks were employed. From the FEM analysis and the measured end rotations of the girder validated the assumptions made during use of ECC that is ductility. Also the link slab performance didn't change for next two years. The strains measured from the transducers were also less than the tensile strain capacity (2% at design time) making it to absorb the strains

Li and Li, (2016) suggested a material to inhibit the drying shrinkage of repair. They focused on repair material which is durable. Concrete, steel fiber reinforced concrete (SFRC) and ECC were used where concrete and SFRC were considered as control. Poly-vinyl-alcohol fibers used in ECC having 12 mm length and 39 micron diameter. The composition for concrete and SFRC was kept same the only difference was that 1 % of steel fibers were used in SFRC. For ECC 2 % of PVA fibers were used and also the w/c ratio used was 0.53.

Layered repair system was investigated for all three materials. Concrete substrate of dimension 1560 x 100 x 100 mm was initially cast and moisture cured for 28 days and left for drying till 60 days to allow for any potential shrinkage. After that a repair layer of 60 mm was placed. Fig 2.10 represents the layered repair system. Two dial gages were placed to record the interfacial vertical separation at the ends as a function of drying time. Also microscopes were used to measure the delamination crack which was measured on daily basis. From shrinkage strain plot it was observed that ECC had highest value as there was no aggregate and high cement proportion whereas SFRC was having value lowest because of steel fibers.

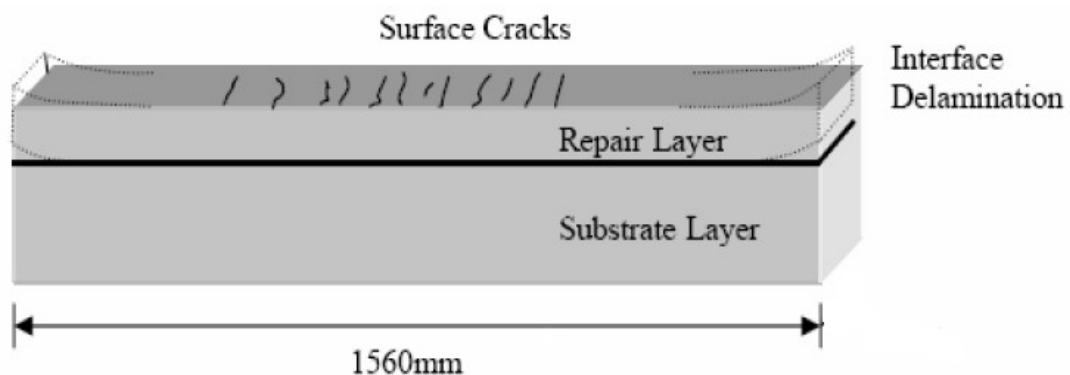


Fig 2.10 Layered repair system. (Li and Li, 2016)

Concrete and SFRC showed 4 and 3 cracks resp. Width of crack for SFRC was less than that of concrete because of fiber bridging across the crack. In contrast ECC mix showed 76 micro cracks but the maximum crack width was of 60 microns which showed that restrained shrinkage crack width of ECC is independent of dimensions and is material property and thus ECC is expected to exhibit tight crack width even on large scale repair application.

Zhang et al., (2016) investigated the flexural behavior of composite beam with two varying thicknesses of ECC layer i.e. 25 and 50 mm. Set of three beams were tested under flexural loading. Mix proportions for ECC used by weight of cement were cement:water:sand 1:0.32:0.4 with 1.7% by volume of PVA fibers.

Two different ECC layered specimens were cast having thickness 25 mm and 50 mm. ECC layer was first cast then after 24 hours concrete was laid so that aggregates of concrete shouldn't mix with ECC and were subjected to four point bending. Flexural stress –deflection plot are shown in Fig 2.11. It was observed that on adding a ECC layer of 25 mm the average flexural strength risen to 5.2 MPa from 4.4 MPa for control concrete beam. Similarly for beam of 50 mm ECC layer the strength increased to 6.3 MPa. So they concluded that ECC layer increases the flexural strength, also it imparts significant ductility to the member.

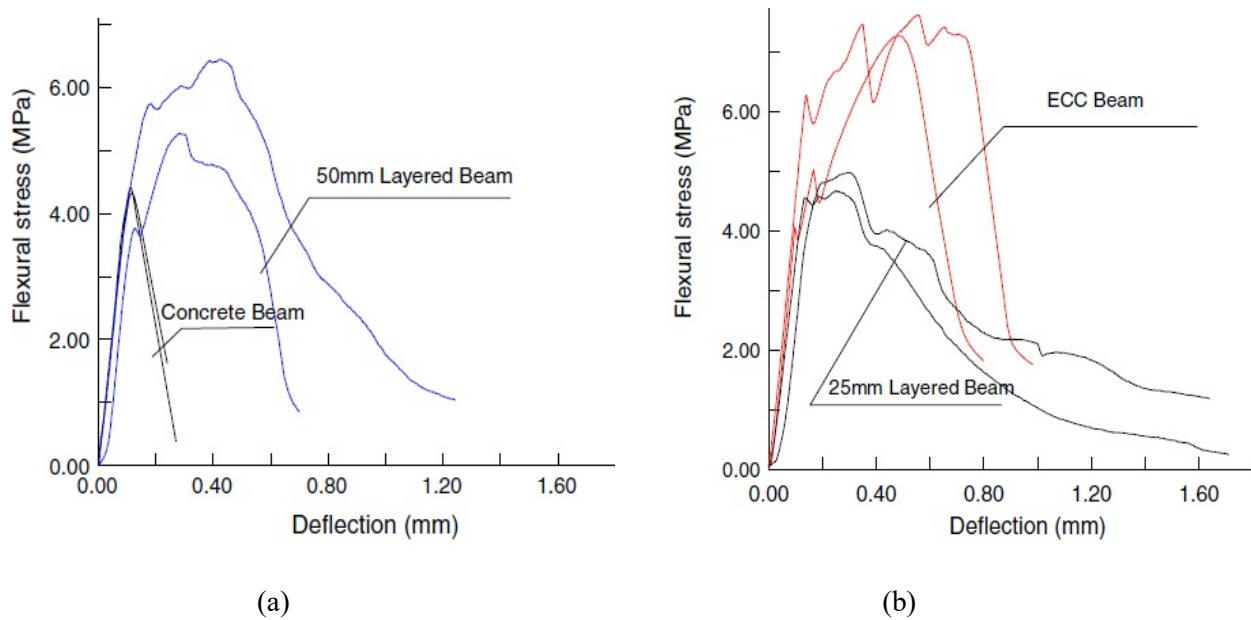


Fig 2.11 Flexural stress-deflection curves (a) 50 mm ECC layer beams (b) 25 mm ECC layered and whole ECC beams (Zhang et al., 2016)

Esakkideepan and Pooraniya, (2017) studied flexural behavior of PCC beams and PCC beams strengthened with ECC. PCC beams were of grade M30 having the 28 days strength as 31.62 MPa. Length and diameter of PVA used were 12 mm and 0.04 mm with tension strength of 1600 MPa. Ten beams of size 100 x 200 x 700 mm to be subjected to two point loading were cast. ECC layers of different width and thicknesses were casted. For loading setup 50 mm overhangs were left on both the ends. After comparing the results of PCC and strengthened beams they concluded that ECC strengthening upgraded the flexural strength of PCC beams.

CHAPTER 3

EXPERIMENTAL PROGRAM AND METHODOLOGY

3.1 INTRODUCTION

Experimental approaches and the material considered to achieve the required objective of the thesis are described in this section. The materials and equipments utilized are discussed. The experimental procedure adopted in testing is also discussed in detail.

3.2 TEST PROGRAM AND METHODOLOGY

The test program is devised so as to find the properties of materials used for casting RC beams and the ECC repair mix, then the behavior of repaired beams. This test program has been divided into following steps:

1. Determining the basic properties of all the constituent materials i.e. cement, fine aggregate, coarse aggregate, silica fume and flyash used as per Indian Standards.
2. Casting of seven RC beams with dimension 130 mm x 230 mm x 1000 mm of M 25 grade concrete.
3. Design of ECC mixes using steel and PVA fibers in four different proportions.
4. Casting of four different ECC mixes which were to be used as a repair material for the beams and evaluating the compressive strength, flexural strength and flowability.
5. Testing of RC (control) beams under mid point loading to get ultimate load of control beam.
6. Remaining six beams were stressed to 70% of failure load.
7. Preparation of distressed beams for ECC repair.
8. Repairing the beams with ECC and micro-concrete available in market.
9. The ECC repaired beams are loaded to investigate the flexural behavior of all different repair mix with the concrete substrate and check the effectiveness of repair.

3.3 MATERIALS

Cement, fine aggregate, coarse aggregate, silica fume, fly ash, super plasticizer, epoxy, steel bars, steel fibers, PVA fibers, micro concrete were used for designing and casting of ECC repair mix mortars used for repairing whose properties and specifications are mentioned as under:

3.3.1 Cement

Cement acts as a binding agent which sets and hardens on addition of water causing the hydration reaction and resulting in the C-S-H (Calcium Silicate Hydrate) gel formation around the constituent particles and acts as a cohesive link between them thus binding them together. There are also various other binding materials having considerable binding properties but cement is considered necessary to initiate hydration, without which even other pozzolans do not show any binding property. OPC 43 Grade

Cement was used in this study. Physical properties and chemical composition of cement are given in Table 3.1.

Table 3.1 Physical Properties of Cement used

Properties	Value	IS 8112:1989 Specifications
Grade	OPC-43	OPC-43
Specific Gravity	3.14	3.10-3.25
Initial Setting Time	150 minutes	30 minutes, minimum
Final Setting Time	385 minutes	600 minutes, maximum
Normal consistency	30 %	-

3.3.2 Fine Aggregates

IS: 383-1970 divided it into four grading zones i.e. Zone I to IV. Natural river sand belonging to Zone II collected from local supplier in Patiala was used. Table 3.2 shows the sieve analysis of fine aggregates.

Table 3.2 Sieve Analysis of Fine Aggregates

IS-Sieve (mm)	Wt. Retained (gm)	Cumulative Wt. Retained	Cumulative % retained	Cumulative % passing
10	0	0	0	100
4.75	28	28	2.8	97.2
2.36	186.5	214.5	21.45	78.55
1.18	177.5	392	39.2	60.80
600 μ m	130	522	52.2	47.80
300 μ m	291	813	81.3	47.80
150 μ m	138	951	95.1	18.70
Pan	49	1000	$\Sigma C= 292.05$	4.90

Fineness modulus = 2.92

3.3.3 Coarse Aggregate

Coarse Aggregates are retained on 4.75 mm IS sieve which are formed either by natural disintegration or by crushing of gravels and rocks. IS: 383-1970 recommends the quality standard of aggregate to be strong, hard, durable and clear from veins. Also flaky and elongated aggregates should be avoided. Properties of coarse aggregate used are given in Table 3.3. Table 3.4 and Table 3.5 represent the sieve analysis of 10 mm and 20 mm aggregate.

Table 3.3 Coarse Aggregates properties

Characteristics	Value	
Color	Grey	
Shape	Angular	
Maximum size	20mm	10mm
Specific gravity	2.705	2.695

Table 3.4 Sieve analysis of Coarse Aggregate (10 mm)

IS- Sieve (mm)	Wt. Retained (gm)	% age Retained	Cumulative retained (gm)	Cumulative % Retained
20	0	0	0	0
10	379	18.950	379	18.950
4.75	1442.5	72.125	1821.5	91.075
Pan	178.5	8.925	2000	
			Σ	110.025

Fineness modulus = 6.10025 \approx 6.10

Table 3.5 Sieve Analysis of coarse Aggregate (20 mm)

IS- Sieve (mm)	Wt. Retained	% age Retained	Cumulative retained (gm)	Cumulative % Retained
20	160	3.20	160	3.20
10	4410	88.20	4570	91.40
4.75	360	7.20	4930	98.60
Pan	70	1.40	5000	
			Σ	193.2

Fineness modulus = 6.932

3.3.4 Fly Ash

Fly-Ash is considered as an important ingredient which imparts long term strength to the concrete due to more amount of unhydrated cementitious material which is used at later stages of hydration. The chemical composition of flyash is given in Table 3.6 below.

Table 3.6 Chemical composition of Fly-Ash

Constituents	Percentage (%)
Al ₂ O ₃	39.95
SiO ₂	57.40
Mgo	0.33
Na ₂ O	0.10
K ₂ O	0.85
FeO	1.05
CaO	0.32

3.3.5 Silica Fume

Silica fume is a pozzolanic admixture also called micro silica is by-product of silicon and is in form of very fine powder having spherical particles. When used in concrete due to its high percent of silica content it imparts high compressive strength and bond strength. Composition of silica fume is given in Table 3.7.

Table 3.7 Chemical composition of Silica Fume

Constituents	Percentage (%)
SiO ₂	99.78
Na ₂ O	0.07
K ₂ O	0.01
FeO	0.14
MgO	0.11

3.3.6 Super Plasticizer

In order to get a workable mix and to reduce the water content AURAMIX 200 of Fosroc Chemicals (India) Pvt. Ltd. was used as water reducing agent. Auramix 200 complies with IS: 9103, BS: 5075 and ASTM-C494

Advantages of Auramix 200:

1. Increased durability
2. Better resistance to aggressive atmospheric conditions.
3. Low viscosity.
4. Reduced shrinkage and creep.

Table 3.8 Properties of Auramix 200 (Fosroc Chemicals (India) Pvt. Ltd.)

Appearance	Yellowish to brown liquid
pH	Minimum 6
Chloride content	Nil
Alkali content	Typically less than 1g Na ₂ O equivalent / liter of admixture.
Specific Gravity	1.03 – 1.07

3.3.7 Water

It is an important ingredient of concrete which act as a binding agent when added to matrix. On addition of water cement undergoes the hydration reaction which is responsible for strength of cement. Generally potable water should be used mixing and curing. Thus the water used should be free from silt, oil and organic matter. Tap water was employed for both curing and casting.

3.3.8 Reinforcing Steel

HYSD steel bars of grade Fe-500 (Tata Tiscon) of 8, 10, 20 mm diameter were used. For tension reinforcement 12 mm diameter and for compression reinforcement 10mm diameter bars were used. 8mm bars were used as shear reinforcement.

3.3.9 Steel Fibers

Steel fibers which were used to make the different ECC mixes as repair were obtained from Stewols India (P) Ltd (Fig. 3.1). Steel fibers were used to impart strength and ductility. There are different configurations of fibers available like round and crimped, flat and crimped, hooked ends etc. In this study round and crimped steel fibers were used. Table 3.9 represents the various properties of fibers as provided by the supplier as per ASTM A 820M standards.

Table 3.9 Properties of Steel fibers (Stewols India (P) Ltd)

Property	Value
Tensile strength	1100 (MPa)
Diameter	0.45 (mm)
Length	12.5 (mm)
Aspect ratio	27.7

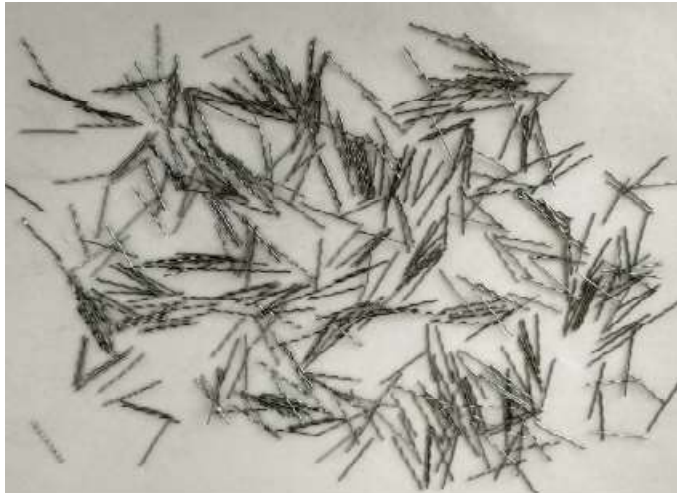


Fig 3.1 Crimped Steel fibers (Stewols India (P) Ltd)

3.3.10 Epoxy

Epoxy is used at the interface where it is required to have desirable bond between any two substances. In this investigation epoxy was applied to the chipped surface prior placing the repair material. For this purpose Dr. Fixit 211 bonding agent was used which is recommended to make bond between old and new concrete. It comes in two parts resin and a hardener which are mixed in 1:1 ratio. Properties of epoxy are given in Table 3.10.

Table 3.10 Properties of Epoxy used (Dr. Fixit 211)

Property	Value
Mix Density	1120 kg/m ³
Color	Grey
Pot life @ 30° C	± 30 - 40 minutes.
Tensile strength at 7 days	10.4 N/mm ²

3.3.11 PVA (Poly-Vinyl-Alcohol) fibers

PVA fibers to be used to prepare ECC mixes were obtained from The Yarn Guru India Inc. They were selected because of their high ductility, superior crack-fighting properties and high modulus of elasticity. Generally they are available in various dimensions. Properties of fiber are given in Table 3.11 as provided by the supplier. PVA fibers are shown in Fig 3.2

Table 3.11 Properties of PVA fibers (The Yarn Guru India Inc)

Fiber type	Bunchy monofilaments
Density	1.3 kg/cm ³
Formula	(CH ₂ CHOH) _n
Length	12mm
Fiber elongation	4-9 %
Tensile Strength	880-1600 MPa



Fig 3.2 PVA fibers (The Yarn Guru India Inc)

3.3.12 Micro-Concrete

For comparing the performance of ECC as repair mix one RC beam was also repaired with micro-concrete available in market. Dr. Fixit Micro Concrete was used which is flowable mortar for repair of damaged concrete members. Properties of micro concrete are given in Table 3.12 as provided by the supplier.

Table 3.12 Properties of micro concrete (Dr. Fixit)

Properties	Values
Compressive strength	30 N/mm ² 3 days
	50 N/mm ² 7 days
	60 N/mm ² 28 days

Flexural strength	6 N/mm ²
Tensile strength	2.5 N/mm ²
Water absorption after 24 hours	0.2 %

3.4 DESIGN CONCRETE MIX

M 25 concrete grade was used and designed according to IS: 10262-2009 using the properties of different materials. Water/binder ratio used was 0.45. Six cubes were casted and set of 3 cubes each was tested at the curing age of 7 days and 28 days. Average compressive strength of cubes at 7 and 28 days were obtained as 23 MPa and 34 MPa respectively.

3.5 MIX PROPORTIONS OF ECC

In order to repair the distressed beams four ECC repair mortar mixes were prepared having no coarse aggregate and one distressed conventional beam was repaired using Dr. Fixit micro concrete. For all four repair mixes hybridization of PVA and Steel fibers were done with varying fiber volume fraction. Mix proportions for the mortar mix by volume are given in Table 3.13. Fibers were added in percentage by volume of the total mix to be prepared. For ECC mix sand retaining on 600 µm was used.

Initially the maximum fiber volume fraction for ECC was kept as 2 % by the total volume of mix having water/binder ratio as 0.45. But on mixing the PVA fibers the mix was not workable and lumpy mix was segregation was also observed. Hence the mix was rejected and various trials were done to achieve a workable mix which can easily fill in cracks by varying the water/binder and super plasticizer content.

Finally four mixes were finalized having maximum fiber fraction of 1.2%. Mix M1 consists only of PVA fiber having 1.2% by volume of fibers, mix M2 consists PVA and steel fibers having fiber volume fraction of 0.8 % and 0.4 % respectively. Mix M3 had 0.8 % volume fraction of steel fibers and 0.4 % PVA fiber fraction whereas mix M4 only had 1.2 % steel fiber fraction. The fiber volume fraction, water/binder ratio and super plasticizer values by weight for all the four mixes are given in Table 3.14.

Table 3.13 Mix proportion of ECC repair mortar

Cement	Sand	Fly-Ash	Silica Fume
1	0.5	0.2	0.1

Table 3.14 Mix designation and their specifications (by weight)

Mix	PVA Fiber Volume Fraction (%)	Steel Volume (%)	Fiber Fraction	water/binder Ratio	Super plasticizer (%)
M1	1.2	--		0.40	0.8
M2	0.8	0.4		0.40	0.6
M3	0.4	0.8		0.35	0.6
M4	--	1.2		0.30	0.6

3.6 RCC BEAM DESIGN AND CASTING

In this investigation the beam was designed as per Limit State Method (IS-456: 2000) of as an under reinforced section of following 130 mm x 230 mm x 1000 mm The beam was reinforced with 2 # 12 mm diameter bars on tension side and 2 bars of 10mm diameter on compression side. 2 legged 8 mm diameter bars were employed as vertical stirrups @100 mm c/c. Longitudinal and cross sectional details of beam are shown in Fig 3.3.

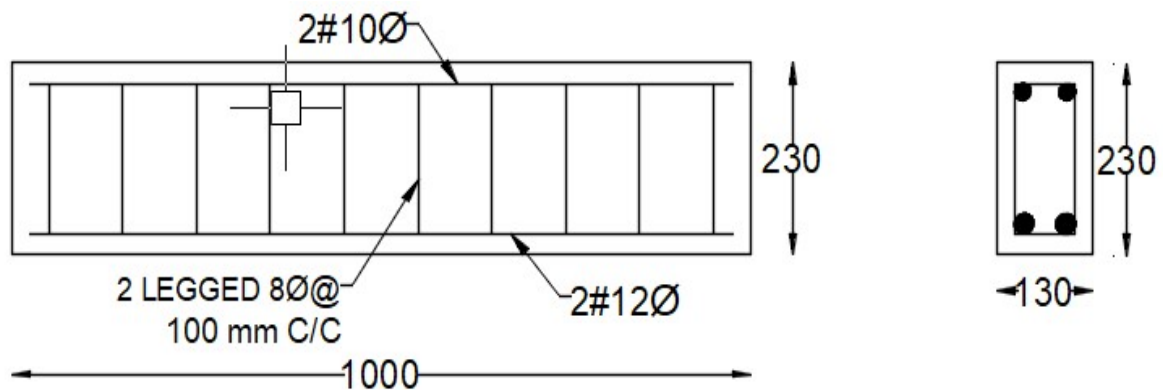


Fig 3.3 Longitudinal and cross sectional view of concrete beam

Beams which were to be repaired with overlay once they are damaged were casted in moulds of cross-section 230 x 130 mm and having a length of 1000 mm. 7 beams were cast in steel moulds two were control beams and damaged completely and rest 5 were repaired with four ECC mixes and micro-concrete. Before casting, the moulds were oiled so that they can be easily demoulded. Cover blocks of 25mm were placed so that the reinforcing cage can be placed in position. All constituents were weighed in designed proportions and were mixed in mechanical mixer and the mix was placed in the moulds. Needle vibrator was used for compaction to completely fill the mould. Beams were removed from the

moulds after a period of 24 hours and were cured for 28 days by covering them with jute bags which were watered daily. Fig 3.4 (a) and 3.4 (b) shows images the mould before and after casting.



(a)



(b)

Fig 3.4 (a) and (b) Mould before and after casting

Beams were centrally loaded in flexure (Fig 3.5) in UTM of 1000 kN capacity. Beams were white washed prior to their testing. All beams were tested as simply supported members having a test length of 850 mm in flexure after leaving the overhangs of 75 mm from both the ends and loading rate was kept as 0.1 kN/sec. For determining the midspan deflection dial gauge at the soffit of the beam was placed.

Once the ultimate load of control beam was obtained, rest of the beams were investigated for their flexural performance after using five different repair materials. The remaining five beams were distressed to 70 % of ultimate load using same testing arrangement. The cracks were visually observed and were marked in order to carry the chipping along them. These 5 beams were further subjected to repair using four ECC mixes and one micro-concrete as explained in section 3.8.



Fig 3.5 Test setup for single point loading

3.7 PREPARATION OF ECC MIXES AND TESTING

ECC mixes which were to be used as overlay were first checked for their mechanical properties i.e. compressive strength and flexural strength. For determining the compressive strength of all four different mixes, cubes of size 70.6 mm as per ASTM C 109 - 93 were cast. Total 9 cubes of each mix were cast for measuring strength at 3, 7 and 28 days.

Similarly since the RC beams to be used in flexural loading were to be repaired, the flexural strength of ECC mixes were also measured. Beams of size 40 mm x 40 mm x 160 mm as per (ASTM C 348 – 02) were cast. Set of 3 beams for all four mixes were prepared and were subjected to mid point loading in UTM at 7 and 28 days. For flexural strength of ECC mixes, beams were loaded centrally at midspan having a test length of 120 mm after leaving the overhangs of 20 mm on both the sides. Beams were loaded till their failure and the corresponding load was noted. Fig 3.6 shows the test setup for flexural strength of ECC.



Fig 3.6 Mid point loading setup for ECC mix

For mixing mortar, all the constituent materials were weighed in given proportion and were first thoroughly mixed dry. Then the fibers were added to the dry mix. Later on the water already added with required and fixed dosage of super plasticizer was poured to get the desired plastic mortar and mixed for 3-4 minutes so as to obtain the uniform dispersion of fibers. The prepared mix was then placed in the moulds and was compacted for two minutes by clamping them so that the air voids are removed. After moulding, the moulds were kept at room temperature for 24 hours and then they were demoulded and kept for respective period of curing. Fig 3.7 shows the mixing of PVA fibers.



Fig 3.7 Mixing of PVA fibers in laboratory

3.7.1 Measurement of Slump flow value

All the four mortar mixes with varying fiber volume fraction were checked for their workability in order to prepare a mortar which can be used as a repair material for cracks and can easily fill the cracks. For this purpose, slump value for all four mortars were prepared as per BIS 4031 (Part 7) – 1988. Formula to calculate the slump value is given in equation.

$$Slump = \frac{(D_{avg} - D_o)}{D_o} \times 100 \quad (3.1)$$

Where D_{avg} = average base diameter.

D_o = original base diameter.

In order to get the slump value, flow table was used. For this purpose after the mix was prepared it was immediately transferred to the mould in two layers and was tamped for 25 times with the rod after that the mould was removed and 25 blows were given to the table.

3.7.2 Compressive strength of ECC mixes

For determining the compressive strength of ECC mixes, three cubes for each curing period as mentioned in section 3.7 were tested on UTM and were loaded on their side faces without any packing between the specimen and the loading platen of machine. The load was increased gradually from zero.

3.7.3 Flexural Strength of ECC mixes

In order to get flexural strength of ECC mixes, beams thus prepared were loaded under midpoint loading for a test length of 120 mm leaving overhangs of 20 mm on both sides. Load was applied until their failure and the corresponding load was noted. Fig 3.6 represents the test setup for flexural strength of ECC mix.

3.8 PREPARATION OF BEAMS FOR REPAIR

Four beams which were to be repaired using ECC and micro-concrete were subjected to 70 % of ultimate load, further the cracked portion of concrete was removed entirely and then prepared so that the overlay of ECC mix could be placed. Placing of ECC overlay was carried out in following 3 steps:

Step1. Chipping of damaged concrete.

In this step all 5 beams distressed up to 70 % of ultimate load were chipped off to a depth of 25 mm on both the faces and the bottom face so that the stirrups were exposed. Chipping was carried out by removing the loose and cracked surfaces of concrete with the help of chisel and a hammer. Fig 3.8 shows the chipped off portion of the beams exposing the vertical stirrups and the reinforcement.



Fig 3.8 Chipped beam

Step 2. Cleaning of chipped beam

After chipping off the concrete cover, beams were cleaned to make it free from loose grits and dust with the help of wire brush. The excess of dust was removed with water at pressure. The beams were air dried for 2 hours after cleaning. In order that the repair material can make a strong bond with the concrete substrate, epoxy was applied. For preparing epoxy the base and hardener were mixed in equal proportions and was applied with help of brush so that repair ECC mix and micro-concrete could further be placed. The epoxy was used to ensure firm bond between the old concrete and new repair mortar.

Fig 3.9 (a) and (b) shows the cleaning of specimens with wire brush and water. Fig 3.10 shows the beam after application of epoxy to its surface.



Fig 3.9 (a). Removal of dust with wire brush



Fig 3.9 (b) Cleaning of beam with water under pressure

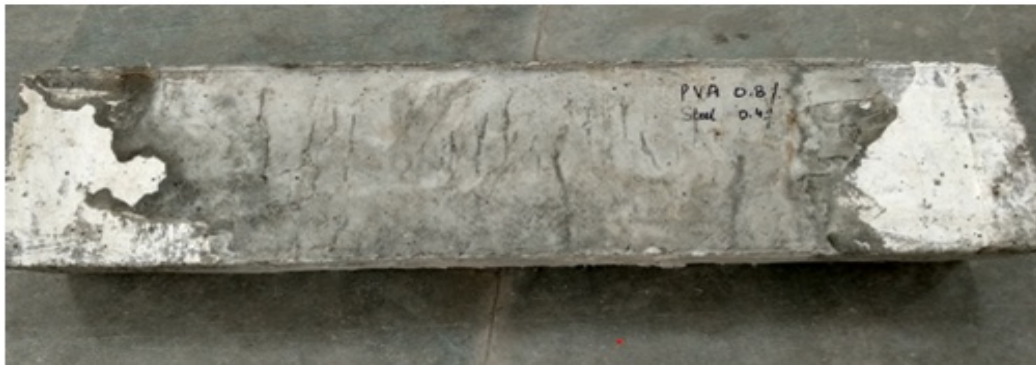


Fig 3.10 Damaged beam after application of epoxy

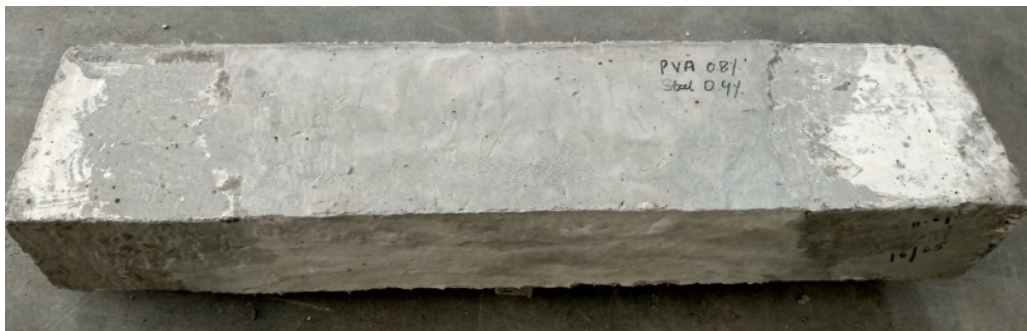
Step 3. Placing of Repair ECC mix and micro-concrete

After the application of epoxy to the exposed surface of the beam specimens they were air dried for 2-3 hours so as to obtain a sticky surface. In order to place the ECC overlay beam specimens were again put in the moulds and respective ECC mixes were hand mixed in exact proportions as discussed earlier and were placed into the moulds with the help of trowel. They were vibrated on table vibrator so that the mix fills all the spaces of moulds and also to remove the air voids. They were de-moulded after 24 hours. They were covered with jute bags for curing period of 28 days.

After placing repair mix and curing them for 28 days, beam specimens were air dried. Before loading them again the surface of all the specimens was smoothed and the extra repair layer on all the surfaces of beam was removed with the help of grinder so as to flush the surface of concrete substrate and the ECC layer. They were then white washed to facilitate marking of the cracks at the time of loading. Fig 3.11 shows the repaired beam with ECC after 28 days curing and surface finished for further test.



(a)



(b)

Fig 3.11 (a) Repaired beam at time of 28 day curing (b) surface finished repaired beam

The five repaired beams are now ready to be tested in flexural loading to investigate the performance of ECC mixes as repair material for concrete beams.

3.9 CLOSING REMARK

This chapter outlines and discusses the test program and methodology followed for the research work. The details of materials used in the work are also outlined.

CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 INTRODUCTION

Results of experimental investigation are discussed in this section. In present investigation ECC mixes as a overlay to repair the damaged RC beams and their efficiency is examined. For this purpose all the four types of ECC mix as discussed in previous section were checked for their compressive strength and flexural strength properties. Two control beams were tested till ultimate load value under mid point loading and remaining 5 beams were stressed to 70% value of ultimate load and further repaired with designed ECC mixes. After placing the repair layer they were checked for their effectiveness in strengthening the beams and investigate the efficiency of ECC as repair material.

4.2 TESTING METHODOLOGY

Firstly the ECC mortar mixes were cast and their slump flow value, compressive and flexural strength were obtained. After that two control beams were loaded till failure so as they get failed in flexure and the corresponding load-deflection plot was recorded.

Rest 5 beams were stressed to 70 % of the ultimate load value so as to get the flexural cracks and further chipping could be carried along them such that the reinforcement was exposed. After that they were repaired with four ECC mixes and a micro concrete. They were then cured for 28 days and were again tested in flexure to check the efficiency of ECC as repair material.

4.3 FRESH PROPERTIES OF ECC MIXES

The procedure to calculate the slump is mentioned in previous section. After the 25 blows the diameter of settled mix was calculated in both the directions. Table 4.1 shows the slump value of all four mortar mixes calculated as in equation 3.1.

Mix with 1.2 % steel fiber reported the highest workability as compared to other mixes. Mix M1 having 1.2 % by volume of PVA fiber reported minimum slump value, this may be due to the polymeric fibers which absorbs the water forming lumps. It was concluded that on increasing the PVA fibers the workability of mortar decreased. Hence, in the mixes with PVA fibers, water/binder ratio was reduced to 0.40 from 0.45 and super plasticizer was decreased from 1.2 % to 1 % for mix M1 having 1.2% by volume of PVA fiber.

Table 4.1 Slump of ECC mixes

Mix ID	Slump value
M1	89
M2	95
M3	100
M4	118

4.4 HARDENED PROPERTIES OF ECC MIX

4.4.1 Compressive strength of ECC

For calculating the strengths at end of respective curing period for all cube sets the maximum value of load carried by each specimen was divided by the cross sectional area of cube. Final strength is calculated by taking average of each set and was expressed to the nearest of 0.5 N/mm². Fig 4.1 and Table 4.2 represents the average compressive strengths of all the four mixes (M1, M2, M3 and M4) at 3, 7 and 28 days of curing. Fig 4.2 shows linear comparison of maximum value at end of each curing period.

Table 4.2 Compressive Strength of ECC mortar (MPa)

Mix ID	3 Days	7 Days	28 Days
Control mortar	--	19	24
M1	22.5	27	37
M2	29	34.5	44.5
M3	38	40	53
M4	40	46.5	59

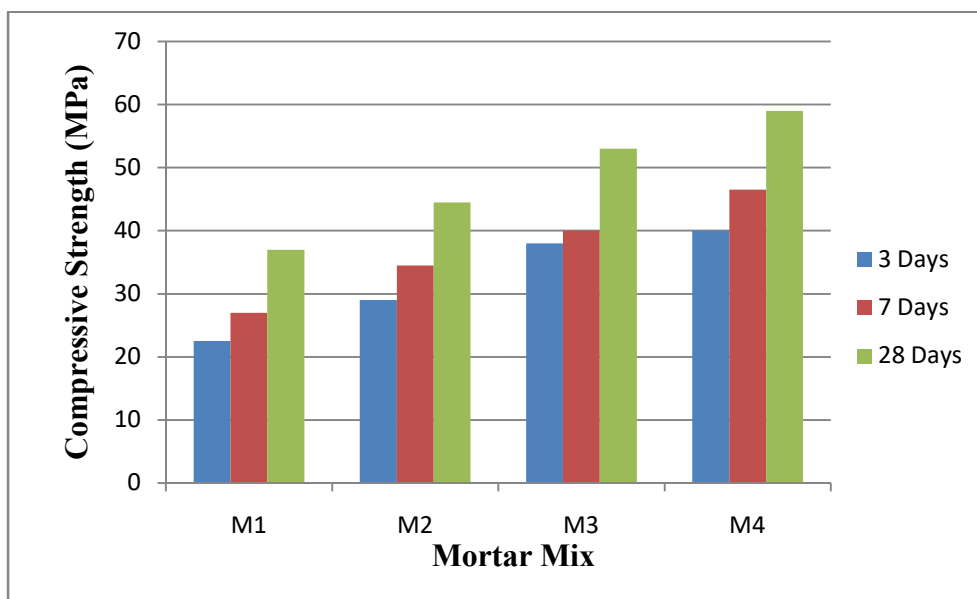


Fig 4.1 Compressive Strength of ECC mixes at 3, 7 and 28 days

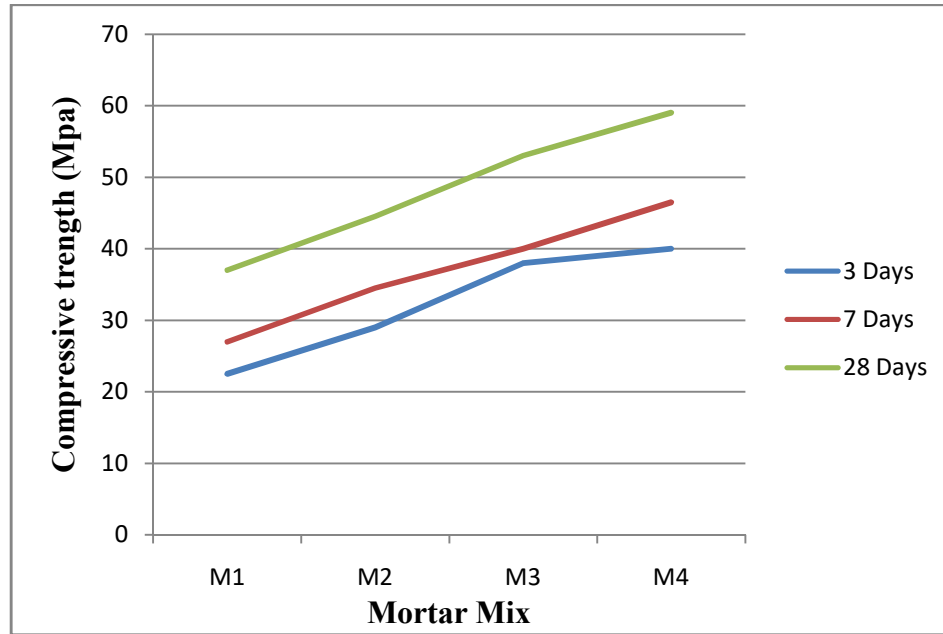


Fig 4.2 Strength comparison of ECC mixes

From compressive strength test results at each respective curing period it was observed that there was rise in strength as the volume fraction of ECC was increased.

- It is observed that ECC mixes reported larger 28 days compressive strength in comparison to cement mortar cubes without any fiber by 54 %, 85 %, 120 % and 145.8 % increase for mixes M1, M2, M3 and M4.
- An increase in strength is observed as the volume of steel fibers in ECC mixes increased. Mix having 1.2 % of PVA fiber volume fraction reported lowest compressive strength whereas the mix having 1.2 % steel fiber fraction showed the highest gain in compressive strength for all curing periods.
- At 3 days of curing an increase of 28.8 %, 68 % and 77.7 % is observed for mixes M2, M3 and M4 having steel fibers in comparison to ECC mix having only PVA fibers.
- At 7 days curing an increase of 27.7 %, 48 % and 72 % is observed in comparison to ECC mix having only PVA fibers.
- At 28 days percentage increase in compressive strength with increase in steel fiber volume is observed as 20.2 %, 43 % and 59.4 % for mixes M2, M3 and M4 as compared to mix M1.
- In all mixes, the 28 days compressive strength was greater than the 28 days compressive strength of concrete used in RC beams by 12 %, 34 %, 60 % and 78.8 % increase in strength for mixes M1, M2, M3 and M4. Hence they can be very efficiently suggested to be used as repair and strengthening material for RC beams as overlay.

- The reason that steel fiber composites reported higher strength than PVA fiber is due to their high tensile strength and better bridging property across crack than the PVA fiber.

4.3.2 Flexural strength

ECC beam specimens were loaded centrally in UTM having test span of 120 mm. Table 4.3 represents the flexural strengths of ECC mortar beams at 7 days and 28 days of curing. Fig 4.3 shows the bar graph comparing the flexural strengths of all four mixes.

The following results are reported by flexural strength test:

- The flexural strength of all the ECC mixes increases from 7 days of curing to 28 days curing.
- Percentage increase in flexural strength after 28 days curing in comparison with 7 days curing is 37.7 %, 16.6 %, 35.5 % and 18 % for mixes M1, M2, M3 and M4 respectively.
- The highest flexural strength is recorded for ECC mix M2 having 0.8 % by volume of PVA fibers and 0.4 % by volume of steel fibers.
- Strength values at 28 days curing for mixes M1, M3 and M4 are 16.14 %, 11.8 % and 3.6 % less than that of M2.

Table 4.3 Flexural Strength of ECC mix (MPa)

Mix ID	7 Days	28 Days
M1	9.8	13.5
M2	13.8	16.1
M3	10.48	14.2
M4	12.72	15.52

Beam used to determine the flexural strength at the time of failure is shown in Fig 4.4.

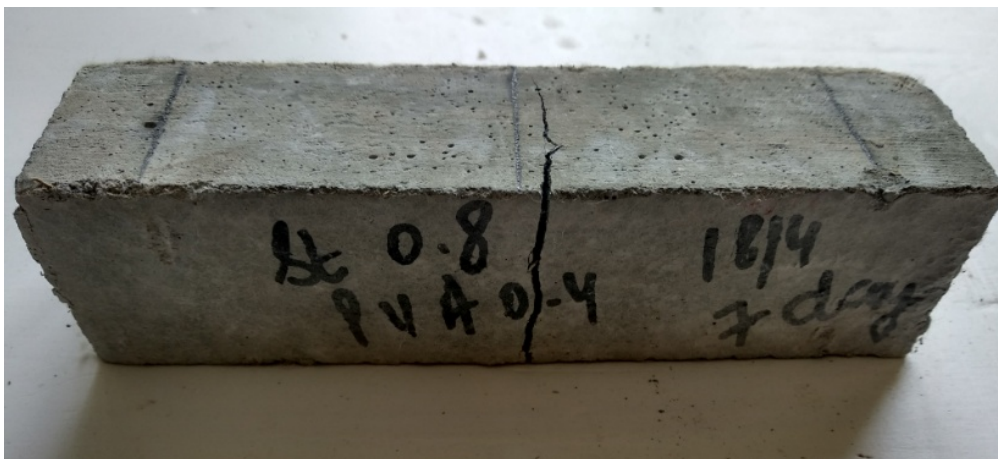


Fig 4.3 Beam after flexural failure

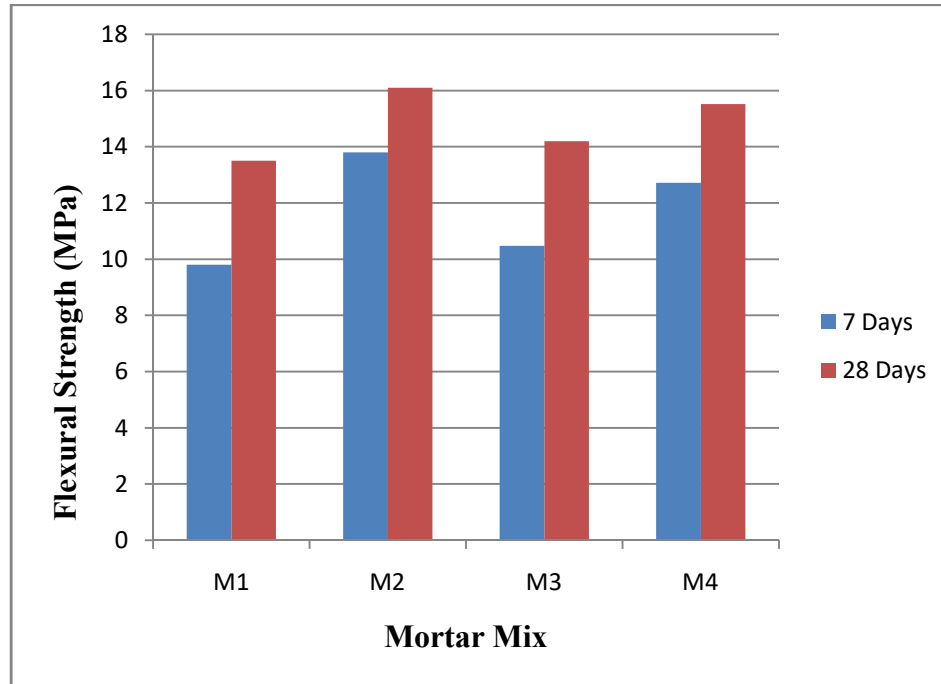


Fig 4.4 Comparison of Flexural strengths

4.5 CONTROL RC BEAMS

After 28 days of curing two control beams were air cured for 24 hours and then they were subjected to mid point bending. As the loading was gradually increased linear plot was obtained between load and deflection with initially flat curve at lower load values. First crack in control beam CB1 was observed at 37 kN whereas in CB2 it occurred at 39 kN. As the load increased, the multiple flexural cracks were observed in central bottom part which propagated further with increasing load. Finally the control beam CB1 failed at the ultimate load of 130 kN and CB2 failed at a load of 134 kN. Load deflection curve for both the beams CB1 and CB2 and their average is shown in Fig 4.5 and Fig 4.6. The observed cracking pattern in control beam is shown in Fig 4.7 and the following conclusion is drawn:

- The cracks initiated as flexural cracks in the middle at the bottom and propagated towards the upper part of the beam under the loading point.
- Initially the deflection increased slowly with the increasing load but later as the load increased the deflection was drastically increased.
- The control beam finally reported an ultimate deflection of 3.128 mm and 2.83 mm for control beam CB1 and CB2 respectively.

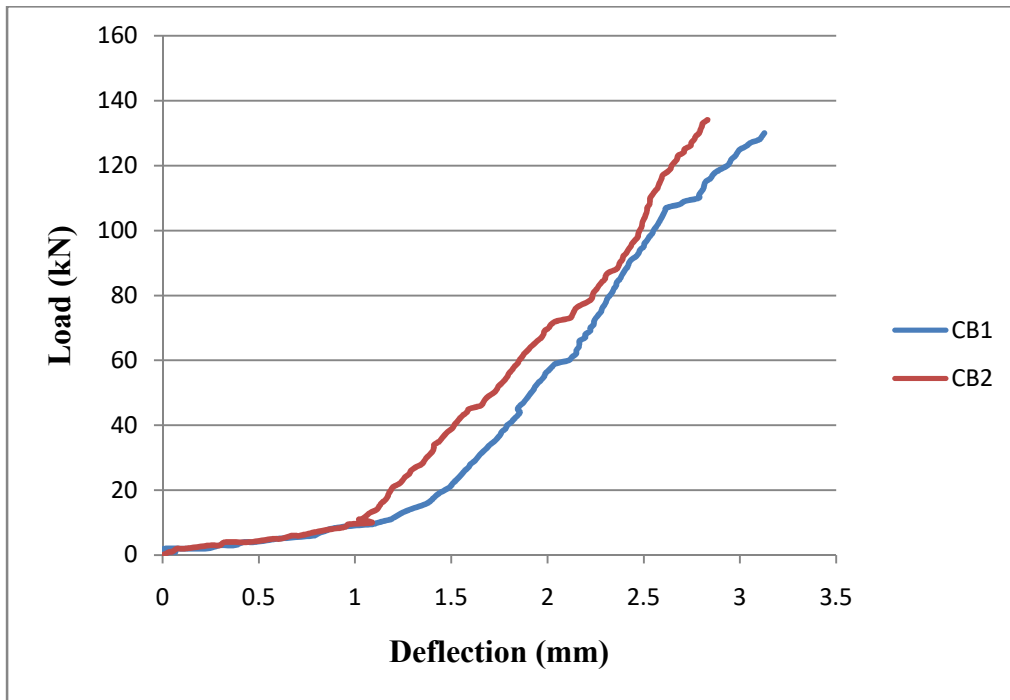


Fig 4.5 Load-deflection curve of control beams

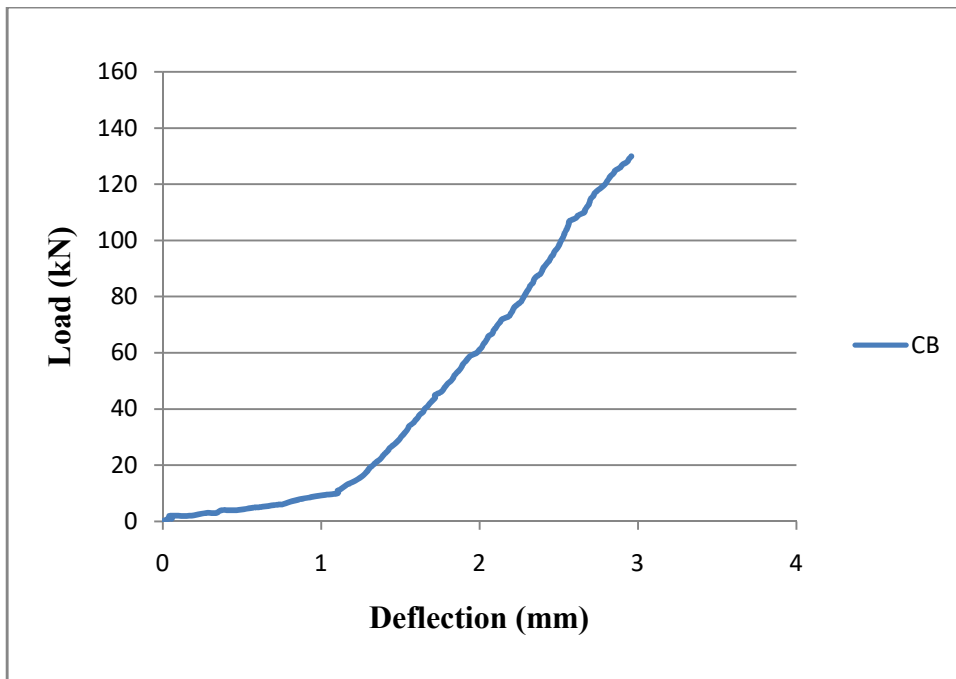


Fig 4.6 Average plot of load-deflection for beam CB1 and CB2

In Fig 4.7 flexural cracks can be seen in the central portion of beam originated from the bottom and propagated to the top where the load was being applied.

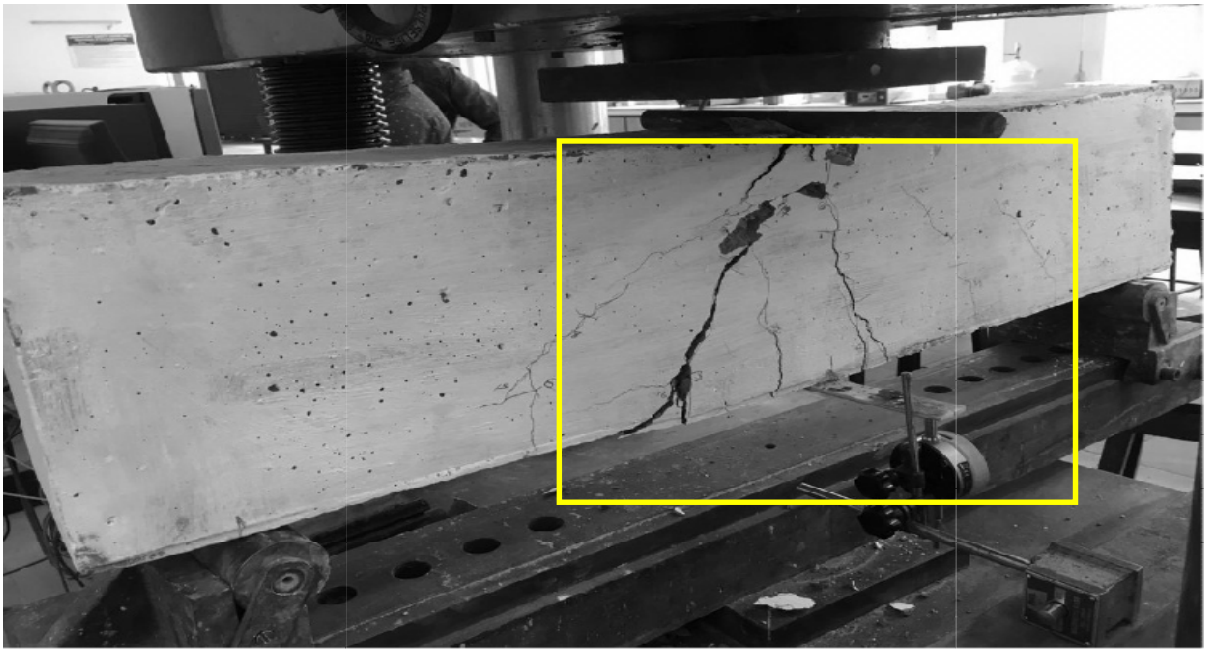


Fig 4.7 Control beam at the time of failure

4.6 BEAMS REPAIRED WITH ECC MIXES

4.6.1 Beam repaired with micro-concrete

Beam repaired with an overlay of Dr. Fixit micro concrete when loaded to 70 % of ultimate load of RC beam showed the following results:

- It is observed that there is rise in ultimate load carrying capacity in comparison to RC beam. It reported an increase of 2.65 % in ultimate load value.
- First crack was observed at 40 kN which is almost same as that of RC beam (39 kN).
- Load deflection graph shown in Fig 4.8 it is observed that initially the load-deflection plot was flat up to a load value of 10 kN, after that deflection varied linearly with increasing load.
- It can be observed from the graph that after certain load value (115 kN) area under the curve started increasing which represents the energy absorption characteristic of repair mortar.
- At the ultimate load value the failure of beam was only due to flexural cracks only (Fig 4.9), no failure due to debonding or spalling along the interface of substrate concrete and overlay was observed highlighting good bonding of old substrate and new material and their cohesiveness in carrying loads.

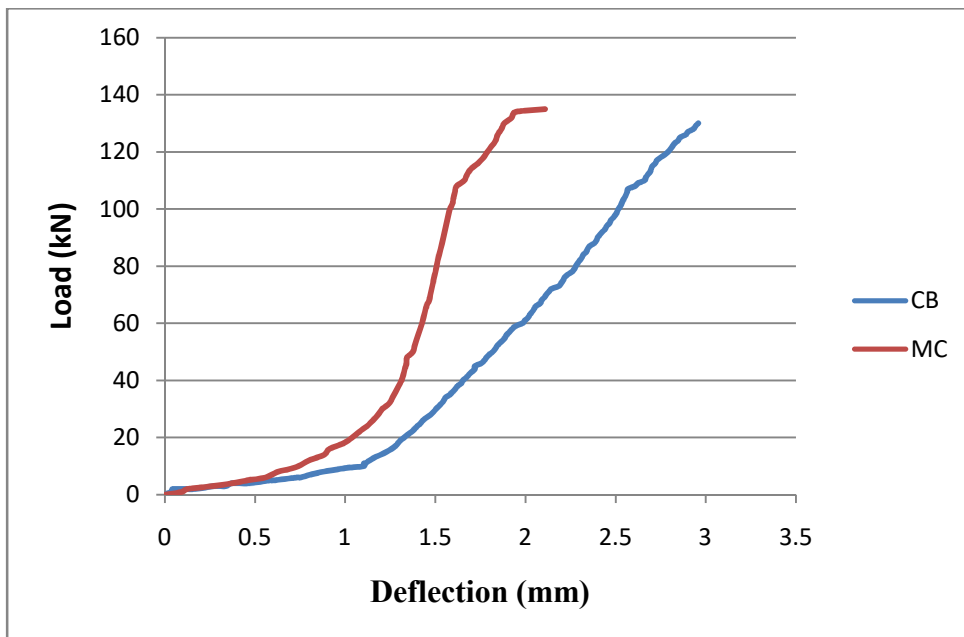


Fig 4.8 Load-deflection comparison of CB and Mix M4 repaired beam



Fig 4.9 Cracking pattern of beam repaired with Micro Concrete

4.6.2 Beam repaired with mix M1

Beam repaired with mix M1 having only PVA fibers as 1.2 % of total volume in RC beams stressed to 70% of ultimate load is shown in Fig 4.10.

- It is observed that there is rise in ultimate load carrying capacity of repaired beam as compared to control beam from 132 kN to 146 kN which is 10.6 % higher than the control beam.
- But there is no significant increase in overall midspan deflection observed in beam repaired with mix M1.
- Also from the cracking behavior the first crack was observed at 36 kN (Fig 4.11) in comparison to 39 kN for control beam.
- The ultimate failure is due to flexural cracks only originating in the middle portion.

- No failure due to the delamination of the concrete and repair material is observed highlighting good bonding interface between the old concrete and repair mix.
- An increase in the load carrying capacity with a minor increase in ductility was observed as the area under the load deflection curve increase slightly when repaired with M1 ECC mix containing 1.2 % PVA fibers.

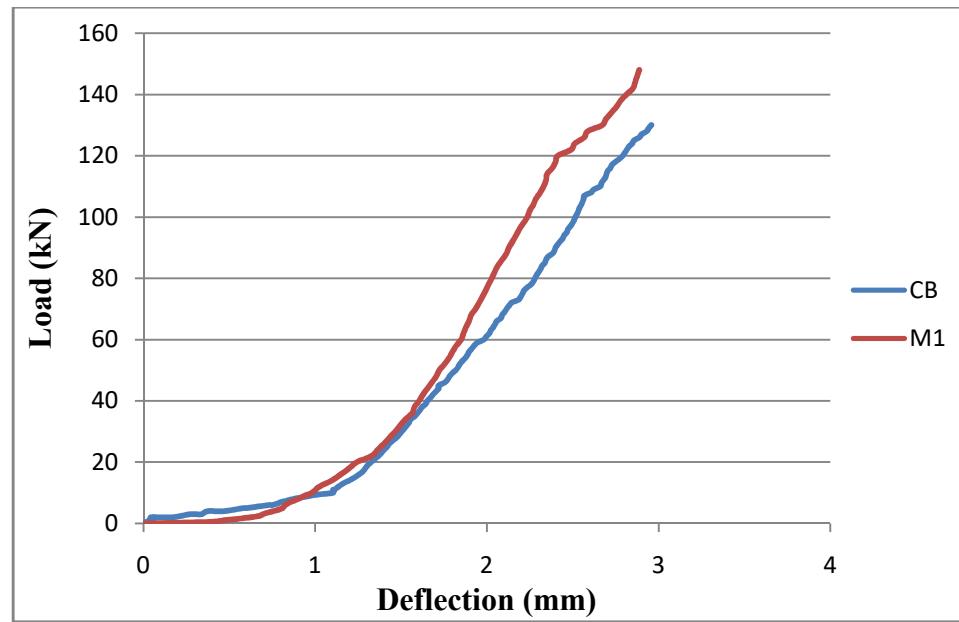


Fig 4.10 Load-deflection comparison of CB and beam repaired with M1



Fig 4.11 Cracking pattern of beam repaired with M1

4.6.3 Beam repaired with mix M2

Beam repaired with mix M2 when loaded at the Midspan following observations are made:

- The ultimate load at which the beam failed is noted as 140.5 kN with a slight increase of 6.5 % in comparison with the control beam.
- First crack occurred at a load of 54 kN which is 39 kN for control beam, also spalling of repair along the interface is observed at a load of 103 kN but the ultimate failure of beam is only due to flexural crack which originated almost from the central part of beam soffit and propagated to the top at the failure as shown in Fig 4.13.
- Although the increase in load carrying capacity was not much higher but the area under the curve was observed to be increasing with the increasing load representing the strain hardening region and the ductile behavior of the repair mortar.

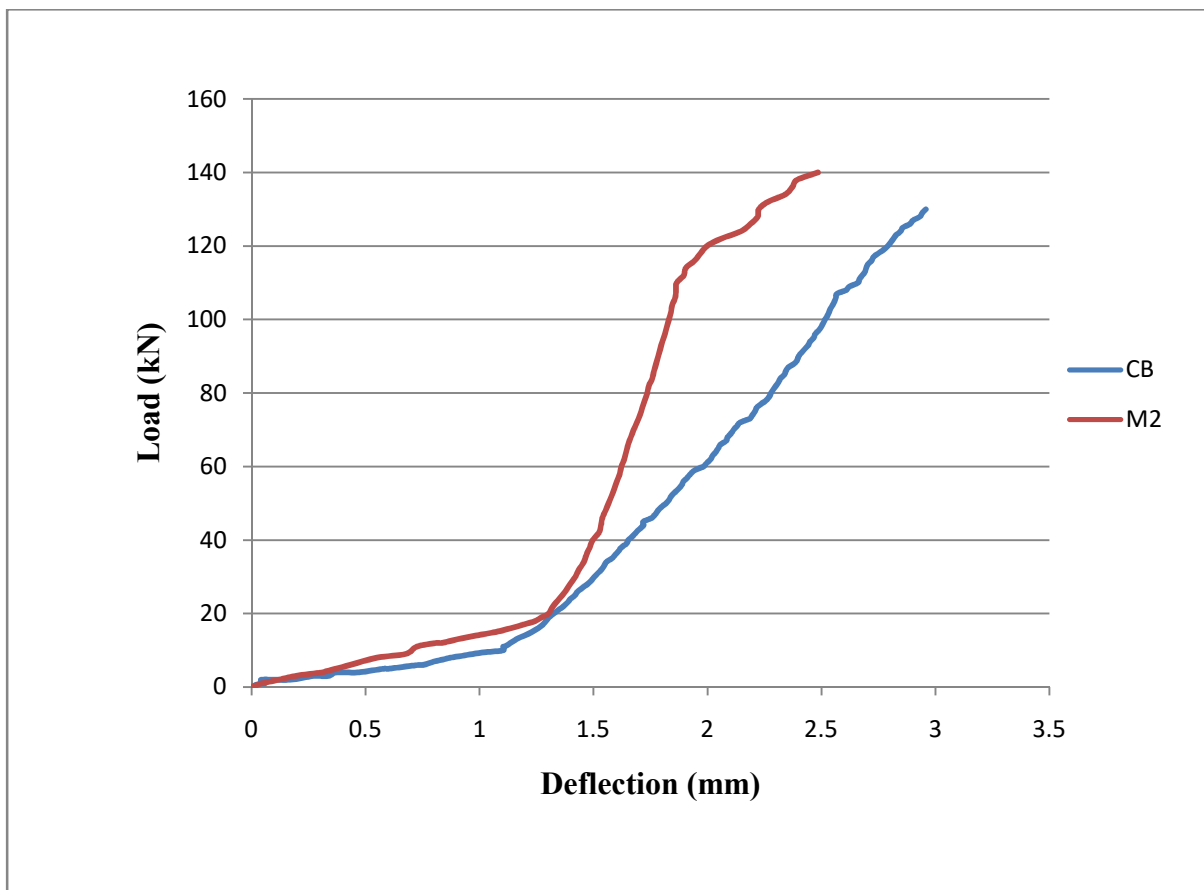


Fig 4.12 Load-deflection comparison of CB and M2 repaired beam

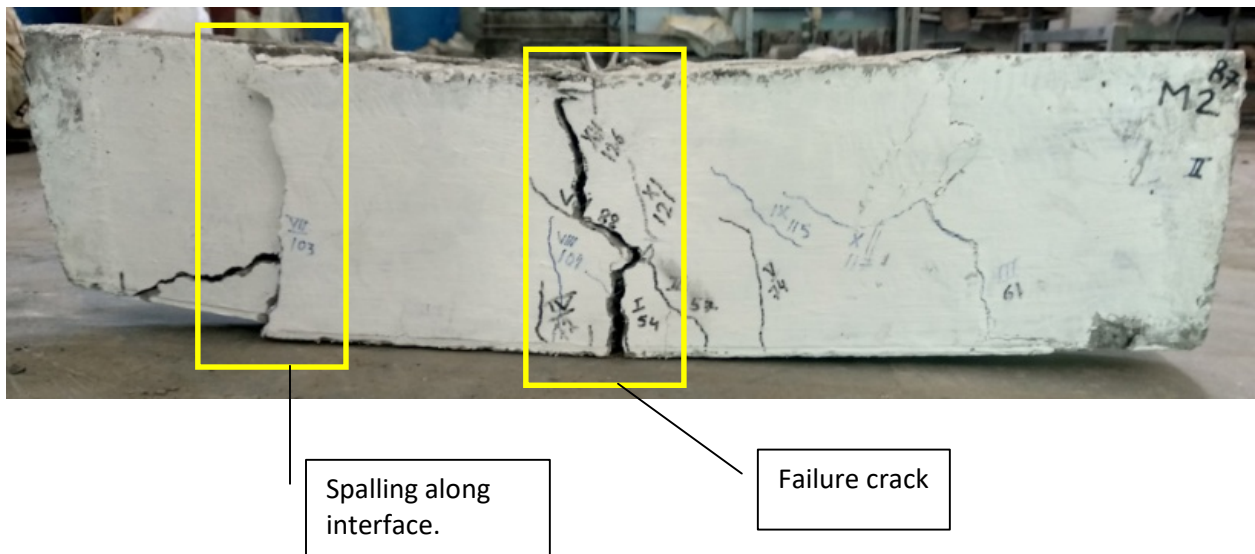


Fig 4.13 Cracking pattern of beam repaired with M2

4.6.4 Beam repaired with mix M3

Distressed beam when repaired with M3 overlays following observations are made:

- Linear plot between load and deflection was obtained for mix M3. The first crack was observed at a load of 44 kN which is higher than that of control beam.
- Ultimate load carrying capacity is observed as 148.8 kN which 12.7 % higher in comparison with control beam.
- From load deflection curve it is evident that there is increase in the ductility of the beam as the area under the curve is increased with increasing load with higher deflection than the control beam.
- After a load of 138 kN sudden increase in deflection is observed highlighting the strain hardening region.
- Beam repaired with mix M3 having 0.8 % of steel and 0.4 % of PVA fibers by volume reported an increase in load carrying capacity and also showed the strain hardening and the ductile behavior of ECC mix.

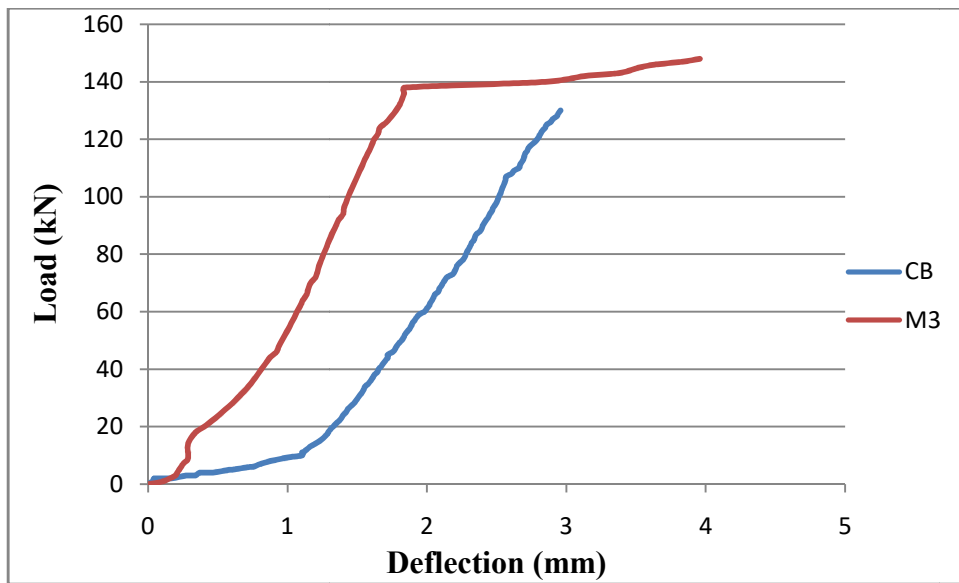


Fig 4.14 Load-deflection comparison of CB and beam repaired with M3

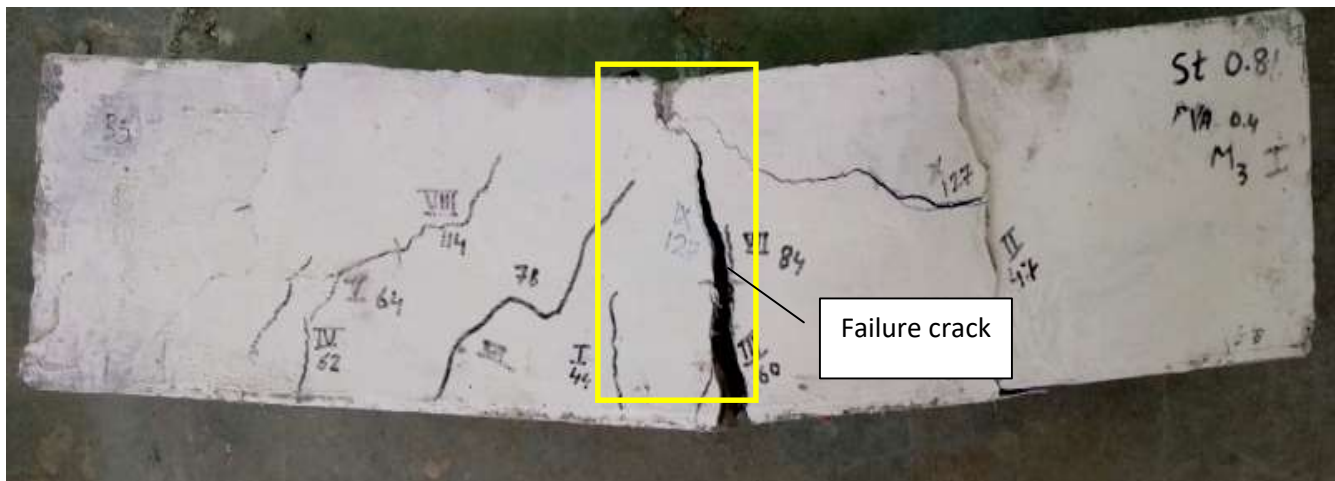


Fig 4.15 cracking pattern of beam repaired with M3

4.6.5 Beam repaired with mix M4

ECC mix M4 having 1.2 % by volume of steel fibers when used as overlay showed the following results:

- The first crack is observed at a load of 42 kN which is slightly higher than the control beam.
- Ultimate load carried by the repaired beam is 151.6 kN with 14.8 % increase in ultimate load value compared to control beam.
- Initially the plot between load and deflection is flat but there is sudden increase in the deformation representing the increase in ductility and strain hardening region.
- Mix having 1.2 % by volume of steel fibers increased the efficiency of RC beams and signified the ductile nature of the repair mix.

- Increased area under the curve represents the higher energy absorption characteristic of the beam.

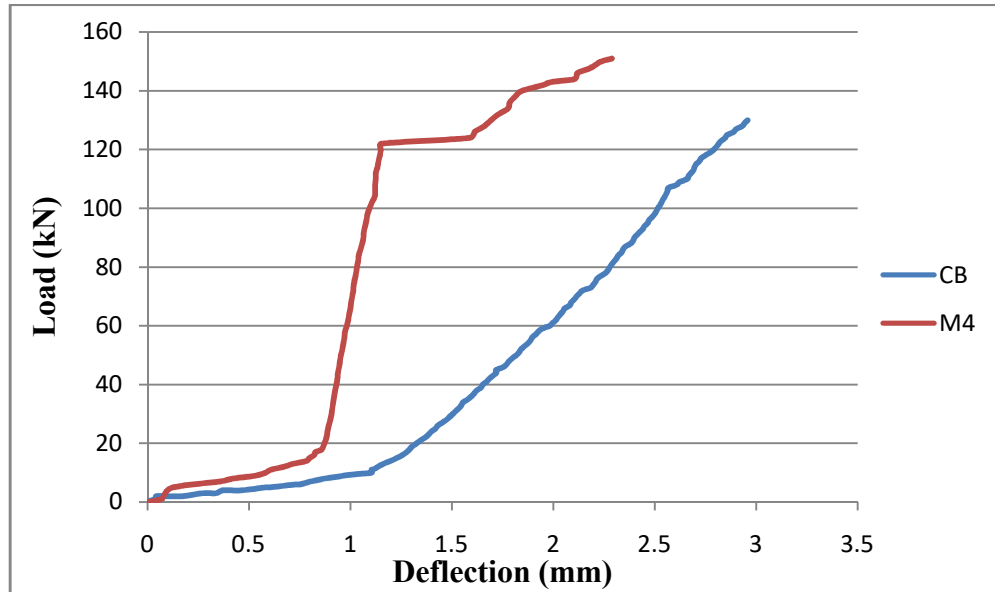


Fig 4.16 Load-deflection comparison of CB and beam repaired M4



Fig 4.17 Cracking pattern of beam repaired with Mix M4

4.7 COMPARISON OF ALL REPAIRED BEAMS

Load-deflection curves for all the distressed beams after their repair is shown in Fig 4.18. On comparing the results based on load values shown in table 4.4 are:

Table 4.4 Comparison of all repaired RC beams

Mix ID	First crack load (kN)	Ultimate load (kN)	% age increase in ultimate load.
Control Beam	39	132	
Micro concrete	40	135.5	2.65
M1	36	146	10.6
M2	54	140.5	6.5
M3	44	148.8	12.7
M4	42	151.6	14.85

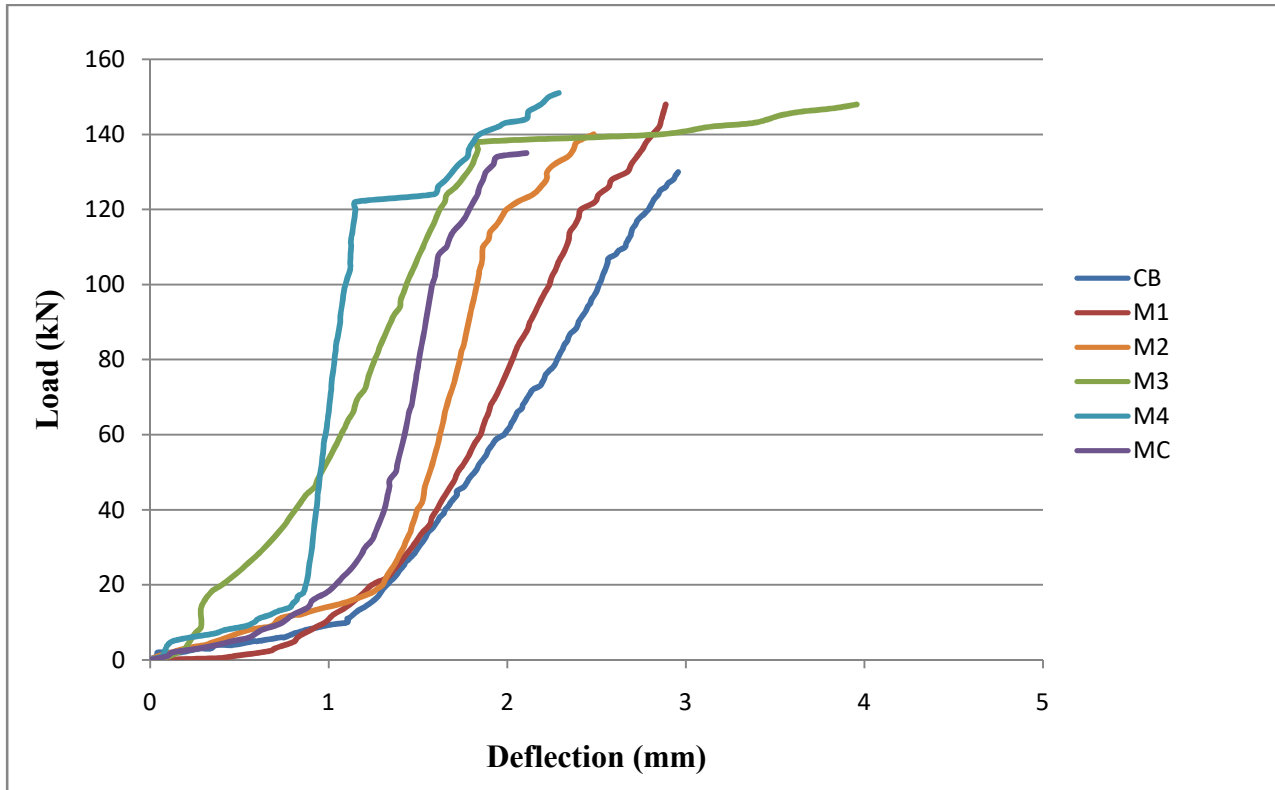


Fig 4.18 Load deflection curve of all repaired beams and control beam

- The first crack for control RC beam is observed at load of 39 kN whereas for all the repair mixes the first crack appeared at load of 40 kN, 36 kN, 54 kN, 44 kN and 42 kN for micro-concrete, M1, M2, M3 and M4 ECC repaired beams respectively which is higher in all the cases. It points towards the crack bridging capability of fibers used for repair.
- Highest first crack load is reported for M2 mix having 0.8 % PVA and 0.4 % steel fibers by 30 % increase in comparison to control RC beam.
- Ultimate load carrying capacity for control and ECC repaired beams are 132 kN, 135.5 kN, 146 kN, 140.5 kN, 148.8 kN and 151.6 kN for RC control beams, micro-concrete, M1, M2, M3 and M4 mix respectively. Highest value being recorded for beam with 1.2 % steel fibers.
- Percentage increase in the load carrying capacity by repairing with micro-concrete and ECC mixes as an overlay is observed as 2.65 %, 10.6 %, 6.5%, 12.7% and 14.85 % respectively in comparison with the control beam. This point towards the effectiveness of repairing highly distressed beams in flexure using PVA and steel.
- Beams repaired with PVA fibers reported large first crack load and ultimate load carrying capacity in comparison to control and micro-concrete.

- Beam repaired with steel fibers reported the enhancement in load carrying capacity, increased ductility and energy absorption capacity as indicated by increase in the area under the load deflection curve and increase in strain hardening region.
- All ECC mixes having different fiber volume fractions when used as a repair material, strengthened the RC beams, improved ultimate load carrying, ductility and energy absorption capacities.

CHAPTER 5

CONCLUSIONS

The aim of this thesis was to evaluate the effectiveness of ECC as repair material to strengthen the distressed concrete beams. The results of repaired beams were compared with that of the control beams.

- having varying volume fraction of PVA and steel fibers reported larger compressive strength at all curing periods in comparison with cement mortar cubes having no fibers.
- 28 days compressive strength of all ECC mixes is higher than the characteristic compressive strength of concrete used for casting RC beams with M25 grade concrete.
- As the volume fraction of steel fibers increases in ECC mixes, an increase in compressive strength is observed because of high tensile strength and better bridging property across crack obtained with steel fibers.
- ECC mixes reported higher 28 days flexural strengths in comparison to 7 days curing compressive strength.
- Initial cracks in case of ECC repaired beams appeared at greater load values in comparison to the control RC beams highlighting the efficiency of ECC mixes in repair.
- When the distressed beams are repaired with an overlay of all the 4 ECC mixes and the micro-concrete the ultimate load carrying capacity is increased for all RC beams.
- ECC and micro-concrete increased the effectiveness of distressed beams in carrying higher loads than in conventional conditions.
- Beam repaired with steel fibers reported the enhancement in load carrying capacity, increased ductility and energy absorption capacity as indicated by increase in the area under the load deflection curve and increase in strain hardening region.
- All ECC mixes having different fiber volume fractions when used as a repair material strengthened the RC beams, improved ultimate load carrying, ductility and energy absorption capacities.
- At higher loads with larger area under the curve exhibited the traces of ductility.
- At the time of failure of repaired beams the ultimate failure is only due to flexural cracks in central region and no failure is due to the delamination or spalling of overlay at the interface of old concrete and repair layer which highlights the adequate bond between the repair and old concrete substrate.

Finally it is concluded that ECC mixes with varying volume fraction of fibers (PVA and steel) can be very efficiently suggested to be used as repair and strengthening material for RC beams as overlay as

repaired beams reported higher load carrying capacity than control beams. This can be attributed to their crack bridging property and multiple cracking behavior under flexure. The strain hardening and ductile behavior exhibited by the ECC mixes can also be used in construction and repair of structural members to which increases the energy absorption thus imparting ductility to the RC member.

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