AN EXPERIMENTAL STUDY ON FLEXURAL STRENGTH BEHAVIOR OF LIGHTWEIGHT CONCRETE USING ECC LAYER

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ABSTRACT

This study aimed to evaluate the significant impact of an engineered cementitious composite (ECC) layer on the flexural strength behavior of lightweight concrete (LWC). Three types of beams were investigated in the study. A total of eight beams, each with dimensions of 150 mm x 150 mm x 750 mm, were cast for experimentation. This set included four LWC beams strengthened by adding ECC layers of 25 mm and 50 mm thickness to the tension zone, two beams made of lightweight concrete (LWC), another two beams made of normal weight concrete (NWC) serving as control specimens. The ECC was developed using 12-mm long polyvinyl alcohol (PVA) fiber. All beams were designed without reinforcement and tested using the third-point loading test in accordance with ASTM C78/C78M. The performance of the beams was assessed on the basis of load-deflection curves, modulus of rupture and analysis of cracking behavior. Remarkably, the addition of an ECC layer to the tension side of the LWC beam led to an increase in the ultimate loading capacity of up to 1.33 times compared to full depth LWC beams. Particularly when a 50 mm ECC layer was applied, the flexural strength of the strengthened LWC beam significantly improved, reaching a value that exceeded the flexural strength of the NWC beam while maintaining a low average density of the beam. The results of this study showed that the ECC layer can significantly improve the flexural strength of LWC beams, opening doors to innovative structural applications of lightweight concrete.

Keywords: *Lightweight concrete (LWC) beam, engineered cementitious composite (ECC) layer, strengthening, polyvinyl alcohol (PVA) fiber, flexural strength.*

1. INTRODUCTION

Concrete is an ancient building material that is valued for its remarkable strength, durability, and ease of use. It is now the second most widely used material on the planet after water. Countries with high population density, like Bangladesh, require tall buildings because of land scarcity. As construction techniques have evolved, new materials are needed. Sometimes structural engineers recommend lightweight concrete to lower the weight and cost of the structure. However, concrete also has major disadvantages, such as low tensile strength, low crack resistance, and brittle failure under tension. Moreover, lightweight concrete behaves more brittlely than normal-weight concrete with the same compressive strength because of its higher cement content and weaker lightweight aggregates (Chandra & Berntsson, 2002). The brittleness of lightweight concrete makes it more susceptible to cracking and less durable, which restricts its structural uses.

Over recent decades, (Li et al., 1995; Li, 2012; Liu et al., 2023) have developed a highly ductile type of concrete called engineering cement-based composites, or ECC. This was achieved by mixing short, randomly distributed polymer fibers into the cement base, addressing the issue of concrete's brittleness when under tension. ECC is characterized by its remarkable ductility, showing a tensile strain capacity over 3%, which is hundreds of times greater than that of normal concrete (Li et al.,2002). It tends to demonstrate strain-hardening behavior and creates a large number of microcracks, usually under 100 μm wide, when under tension (Ranade et al., 2014). Considering the benefits mentioned above, ECC has been effectively used in various infrastructure projects to enhance their service life, resilience, and strength. This includes applications like coupling beams in tall buildings, dam repair, and seismic dampers in bridges, among others (Lepech et al.,2006; Kojima et al.,2004; Qian et al.,2013).

In lab experiments, various tests were conducted to assess the performance of ECC structural components. These tests revealed that using ECC improved the structural performance (Li et al.,1994; Ma et al.,2018). While many investigations on the flexural behavior of ECC structural elements have been conducted, only a few have focused on RC beams reinforced with ECC, which may be more cost-effective and feasible in real-world applications (Qin et al., 2020). (Khan et al.,2016) studied the flexural behavior of high-strength concrete beams reinforced with ECC and found that adding an ECC layer could increase the beam's load capacity. Similarly, (Qiao et al.,2019) examined the flexural behavior of ECC-RC composite beams and observed that these composite beams had higher ductility, load capacity, and damage resistance than regular reinforced concrete beams.

The previous review work shows that some studies have investigated the use of ECC to improve the flexural behavior of RC beams with conventional concrete and achieved good research results. However, the research is insufficient when it comes to strengthening lightweight concrete (Batran et al., 2021). Adding an ECC layer to LWC beams can help minimize the brittleness of LWC without significantly increasing the concrete unit weight. Moreover, the use of optimized low-density ECC as a reinforcing layer in the beam can lead to more sustainable and resilient structures while maintaining a low average density of the composite structures (Batran et al., 2022). Previous studies on LWC used various kinds of light-weight aggregates with different strengths, such as expanded clay, shale, or lightweight synthetic aggregates. But there is a lack of research in this domain while using brick aggregates in the production of lightweight concrete. In Bangladesh, where there is an abundance of brick production, brick aggregates are typically used in the production of lightweight concrete.

In this paper, the flexural behaviors of LWC beams strengthened with ECC under flexural loads were experimentally studied and compared with those of ordinary LWC and NWC beams. Various ECC layer thicknesses were used at tension zones to investigate the flexural performance of strengthened beams as well as control beams. Based on the experimental results, the load-deflection curve, cracking behavior, failure mode, and load capacity of all tested beams were examined.

2. METHODOLOGY

The purpose of this experimental study is to determine concrete's flexural strength using simple beam. After obtaining the required materials, the needed material tests are carried out, and then the mix design step is carried out in order to attain the target compressive strength. After that, every beam is cast, and a 28-day curing period is followed. The next step involves inspecting and analysing the beams' flexural strength. The flow chart of the experimental program in Figure 1 depicts the approaches used to conduct the investigation.

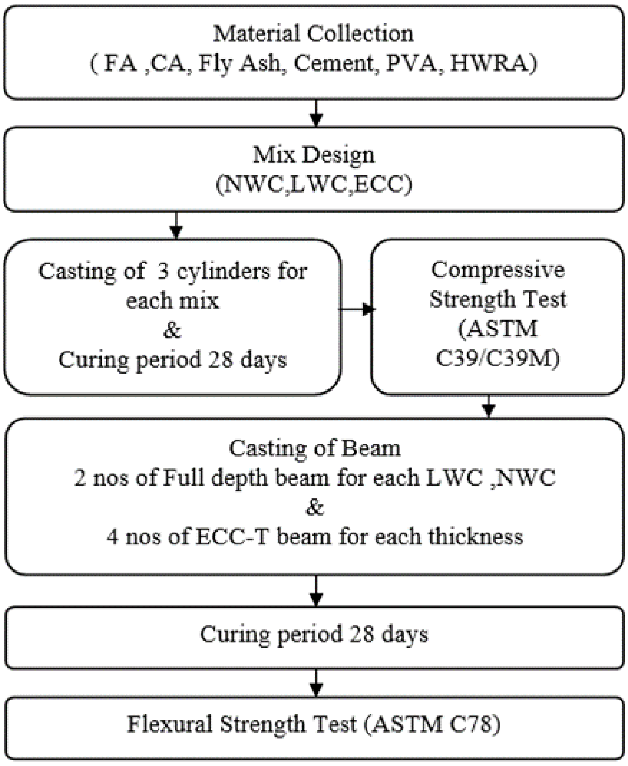


Figure 1: Flow Chart of Experimental Program

3. Test Matrix

Eight unreinforced beams were tested in this study. The tested beams are detailed in table 1 as follows: Four beams of lightweight concrete (LWC) and normal weight concrete (NWC), four beams made of lightweight concrete and reinforced with ECC at the bottom side (ECC-T). For strengthening, two different ECC layer thicknesses were used: 25 mm and 50 mm. The LWC beam strengthened by the addition of ECC layers, is denoted as ECC-T_1 and ECC-T_2, correspondingly.

Table 1: Mixture proportions of NWC & LWC mixtures

Beam ID	**No of Beams**	**ECC layer (mm)**	**Beam Dimension**		
			Length (mm)	**Width (mm)**	**Height (mm)**
LWC	2	0	750	150	150
NWC	2	0			
ECC-T_1	2	25			
ECC-T_2	2	50			

4. Properties of Material

In this study, three mixtures were developed: LWC, NWC, and ECC. Sieve analysis for coarse aggregates and fine aggregates and is performed according to ASTM C136/C136-01. Specific gravity and absorption capacity test is performed following ASTM C127 and ASTM C29 is followed for measuring unit weight of the aggregate. The following is a description of materials used in the mixtures:

a. The NWC mixture was developed with stone chips as coarse aggregates and fine aggregates with specific gravity of 2.71 and 2.63, respectively, and water absorption of 1% and 1.01%, respectively. The density of the developed NWC mixture was 2340.5 kg/m^3.
b. The LWC mixture was developed with brick chips as coarse aggregates and fine aggregates with specific gravity of 2.25 and 2.63, respectively, and water absorption of 16.83% and 1.01%, respectively. The density of the developed NWC mixture was 1922.8 kg/m^3. Figure 2 depicts a fine aggregate sieve analysis graph and the FM of fine aggregate was 2.62.

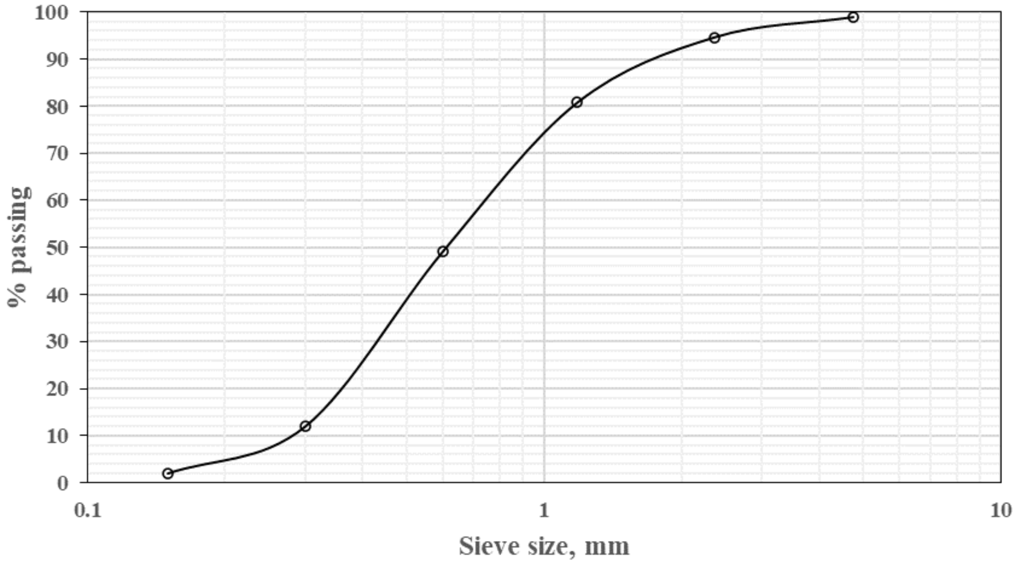


Figure 2: Sieve analysis of fine aggregate

c. The ECC mixture was also produced consisting of Ordinary Portland Cement with specific gravity 3.15, Class F fly ash with specific gravity 2.24. The ECC mixture was reinforced with 12 mm PVA fibers. A Master Polyheed 8650 product was used as a High Range Water Reducing Admixture (HRWRA) to increase the workability of ECC mixtures. The density of the developed ECC mixture was 2026 kg/m^3. Figure 3 shows the material used in this work.

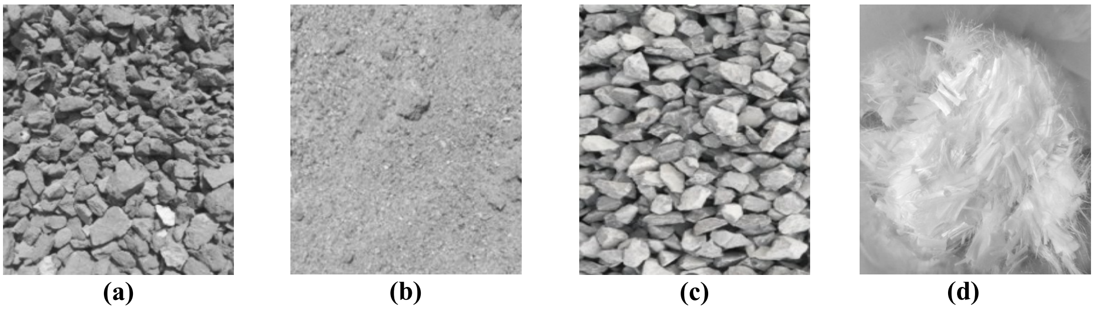


Figure 3: (a) Brick Chips (b) Sand (c) Stone Chips (d) PVA Fiber

5. Mixture Proportion

The table 2 describes the mix designs for normal weight concrete (NWC) and lightweight concrete (LWC). The intended compressive strengths for NWC and LWC are 25 MPa and 21 MPa, respectively.

Table 2: Mixture proportions of NWC & LWC mixtures

Mixture	Cement	Sand	Coarse Aggregate	w/c
NWC	1	1.72	2.41	0.49
LWC	1	1.89	2.60	0.47

The trial mix for ECC was initiated following the specified proportions outlined by Shuxin Wang and Victor C. Li, 2007 in table 3, aiming to achieve a compressive strength of 38 MPa.

Table 3: Mixture proportions of ECC mixtures

Cement	Sand	Fly Ash/c	w/c	w/cm*	%PVA fiber by volume	HRWRA %
1	0.80	1.20	0.53	0.24	2	3

*cm is cementitious material (cement + fly ash)

6. Mixing Procedure

Conventional mixing procedures were used for normal weight concrete (NWC) and lightweight concrete mixtures (LWC). A mixer was used to prepare the ECC mixture for this investigation. Before the mixing process began, each of the ingredients that made up the ECC mixture was weighed separately. The solid ingredients, which included fly ash, sand, and cement, were first mixed for about a minute. Then, before adding HRWRA to the mixer, water was added and mixed for a further three minutes. Once a consistent mixture was reached, fiber was added. The resulting fresh mixture exhibited good flowability and could be easily cast into molds without requiring vibration (Wang and Li, 2007).

7. Fabrication of Specimen

The beams were 150 mm x 150 mm x 750 mm, following the specifications of ASTM C31. According to this code, to better understand how the beams bend and fail, a beam size of 150 mm x 150 mm with a span length of 600 mm was selected. Figure 4 shows the side of the strengthened beam. The mixes were progressively cast for the control beams (LWC and NWC) to a depth of 150 mm. For strengthened beams ECC-T, after setting up the LWC layer, the ECC layer was placed in the beam.

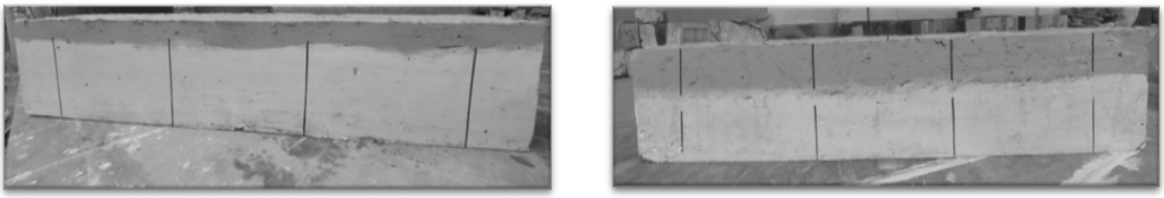


Figure 4: Side view of 25 mm & 50 mm ECC Layer beams

8. Test Setup

The main purpose of the flexural strength test is to measure the ability of a beam to resist bending and let the beam fail at flexure in order to find the modulus of rupture. As a result, there is no reinforcement in the beams. Figure 5 shows the Schematic of Flexural Testing Apparatus for Third-Point Loading Method. This method is used in this investigation as per ASTM C78.

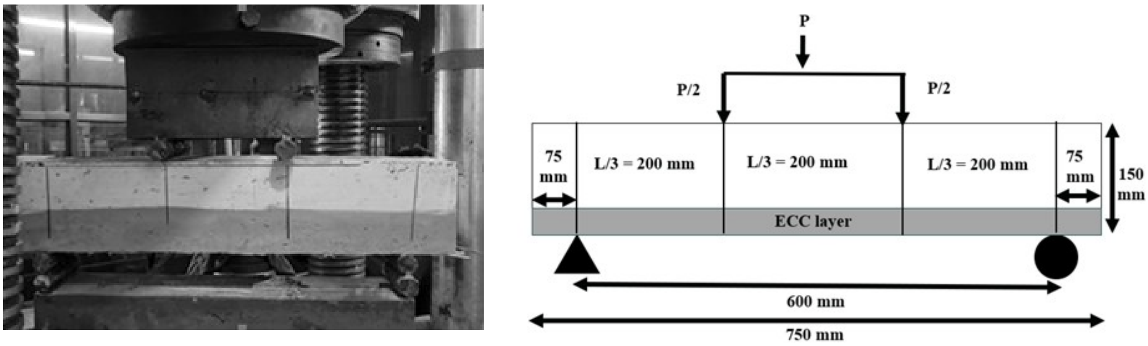


Figure 5: The experimental setup prepared in this study.

9. RESULT & DISCUSSION

In the experiment on lightweight concrete, ECC layers with 25 mm and 50 mm thicknesses applied on the side of the beam that experiences tension. Load-deflection and modulus of rupture of all beams were studied. ECC layers' effects on the cracking behavior of LWC beams are also investigated. Additionally, a load capacity comparison of LWC, NWC, and ECC-T beams was done as well.

10. Load-Deflection Curves

Figure 6 illustrates, the bending-induced deflection of all the tested beams. Since concrete is prone to weakness under tension, there is a rapid escalation in deflection for LWC and NWC as the beam approaches failure when subjected to bending. However, the ECC-T1 and ECC-T2 beams showed high initial stiffness in the early stage of loading. By adding ECC layer in the tension zone, the beams improved their resistance to bending and delayed the formation of cracks.

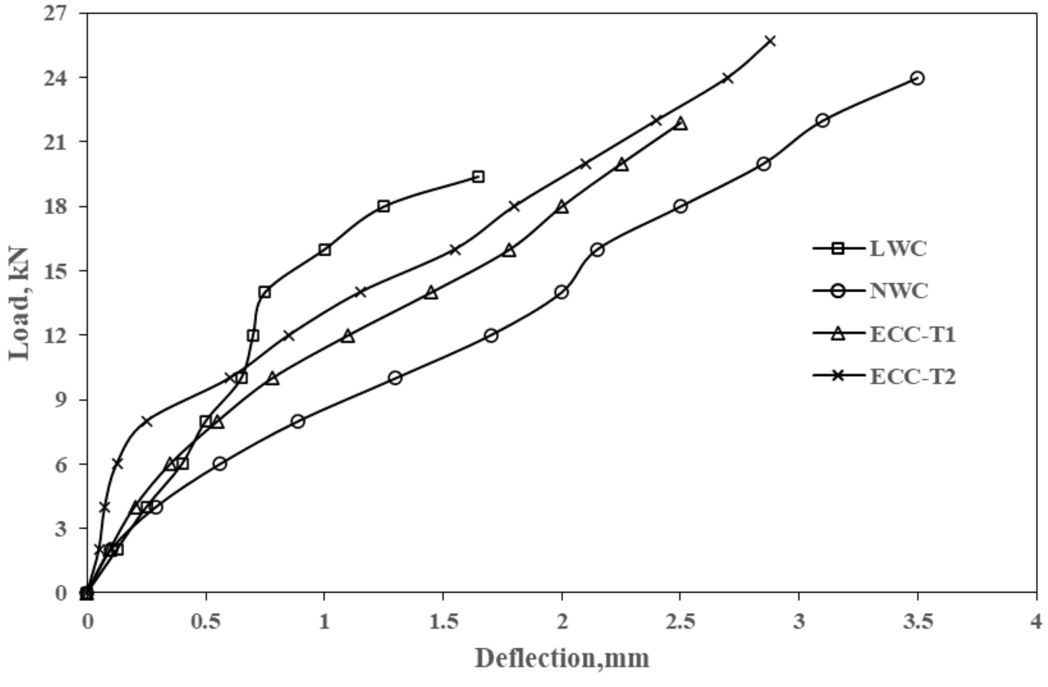


Figure 6: Load-deflection curves of all the tested beams

The comparison above suggests that using ECC layer at the tension side improves the flexural strength of LWC beams. This is because ECC has a greater capacity to withstand tension compared to lightweight concrete.

11. Effects of ECC Layer

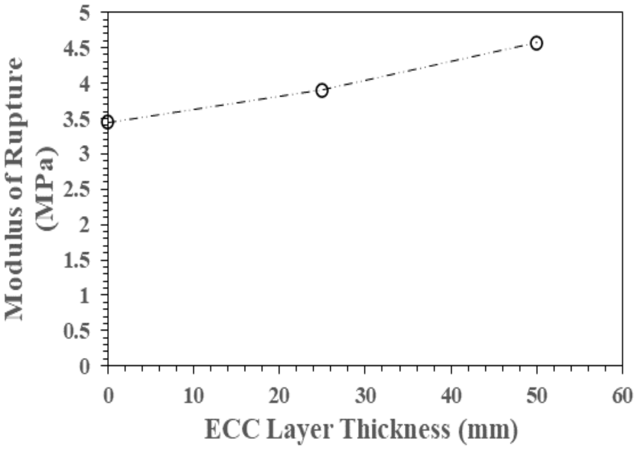


Figure 7: Modulus of rupture vs ECC layer thickness

As shown in Figure 7, the modulus of rupture is enhanced by the ECC layer in the tension zone. Compared to the control lightweight concrete, the modulus of rupture rises by 13.04% and 32.2% for ECC layer thicknesses of 25 mm and 50 mm respectively.

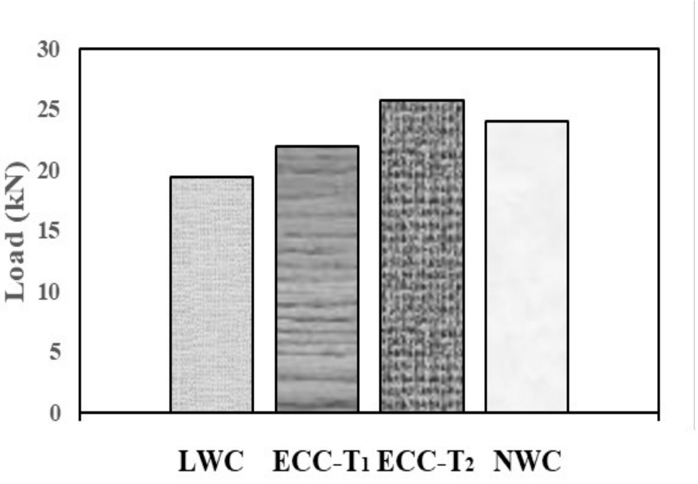


Figure 8: Load capacity of all tested beams

In the above figure 8, the LWC beams with ECC layer in the tension zone have 1.13- and 1.33-times higher load capacity than ordinary LWC beam. The ECC-T beam with 50 mm ECC layer thickness also had 1.07 times more load capacity than the normal weight concrete beam. thickness of 50 mm.

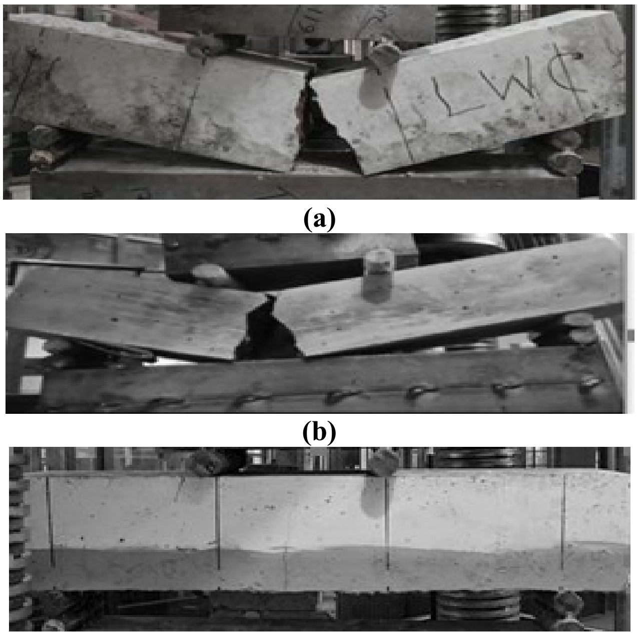
Table 4: Result of all tested beams

Beam ID	ECC layer thickness (mm)	Failure load (kN)	Maximum deflection (mm)	Modulus of rupture MPa	Density (kg/m^3)
LWC	-	19.40	1.65	3.45	1922.80
NWC	-	24.00	3.10	4.27	2340.50
ECC-T$_1$	25	21.90	2.40	3.90	1940.10
ECC-T$_2$	50	25.70	2.85	4.57	1968.50

Table 4 represents result of all tested beams tested in third-point loading (ASTM C78). Overall, it is seen that ECC-T$_2$ has performed better than normal weight beams and lightweight beams while maintaining low average density of concrete.

12. Failure Mode & Cracking Behaviour of All Tested Beams

As shown in figure 9, all the beams are failed in flexure and fracture occurred inside the middle third of the beam. But ECC-T beams resisted cracking better and avoided the quick and sudden collapse because of the PVA fibers that slowed down and limited the crack development.



(a)

(b)

(c)

Figure 9: Crack pattern (a) LWC beam (b) NWC beam (c) ECC-T beam

13.CONCLUSIONS

The following findings can be derived from the experimental investigations undertaken in this study:

- Providing an ECC layer in the tension area demonstrates a greater enhancement in flexural strength of lightweight concrete.
- The load capacity of lightweight concrete increase 1.07 times and 1.33 time due to use of 25mm and 50mm ECC layer.
- When compared to the load capacity of normal weight concrete, the beam’s load capacity which is strengthened using 50mm ECC layer reaches a value 1.07 times higher than the value of NWC. In the meantime, the density of lightweight concrete increases up to 2.3%.
- The failure of lightweight and normal weight concrete beams was catastrophic. In contrast, strengthened beams showed better crack resistance, preventing rapid and brittle breakdown due to the use of ECC layer in tension zone.

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