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Strengthening of RC beams using basalt fiber reinforced polymer with ECC

ABSTRACT

The retrofitting of concrete structures has become highly prominent with the aging and deterioration of the infrastructure. In order to cast the beams, tailored cementitious composites were infused at various layers, such as 20 and 50 mm from the bottom of the reinforced concrete beam's strain zone. The control beam and the reinforced beams' flexural behavior were compared. Damaged ECC-layered beams were repaired by applying sheets of basalt fiber. When completely wrapped with Basalt Fiber Reinforced Polymer (BFRP) sheets, the concrete specimens' compressive strength rose by 14.98% and their tensile strength by 17.14%, while the crack breadth decreased in split tensile testing. The load-carrying capacity of RC beams was increased by 8.95% and 18.76% for 20 mm and 50 mm layers, respectively, by the addition of ECC. When damaged beams were retarded using BFRP, the flexural strength significantly improved, increasing the load-carrying capacity by 8.56% and the deflection by 17.4%. Based on the study's conclusions, future infrastructure maintenance practices need to be modified to be more resilient to the issues brought on by aging infrastructure and more sustainable.

Keywords: *ECC, Polyvinyl alcohol fibre, Basalt fibre, Strengthening.*

1. INTRODUCTION

The need to upgrade concrete buildings is gradually growing in significance as infrastructure deteriorates and ages. New approaches must be used to address sustainability and safety in light of the widespread demands for infrastructure maintenance and upgrade. For reinforcing and prolonging the life of existing structures, advanced fiber reinforcement in engineered cementitious composites (ECC) is a particularly promising method. To date, fiber reinforcement has been the most effective method for imparting ductility to concrete [1]. ECC are considered a category of ultra-ductile cementitious composites incorporating fiber reinforcement [2].

Engineered cementitious composites are a significantadvancement over traditional concrete because of its improved ductility, effective crack management, and strain-hardening behavior [3]. The use of ECC as a substitute for conventional concrete in structural applications is expected to result in improved flexural and shear performance, compared to traditional RC structures [4]. ECC is an effective and promising material for improving the flexural performance of RC beams [5]. This material has the potential to greatly enhance the mechanical behavior of reinforced concrete (RC) beams when combined with fiber reinforcement, such as basalt fiber. Basalt fibres are derived from volcanic rock formations, have attracted much attention over the past few years primarily based on their excellent tensile strength, exceptional corrosion resistance, and durability [6]. Such parameters make basalt fibres an ideal candidate for retrofitting concrete structures.

With basalt fibre in retrofitting procedures, the effectiveness of the structural strength of beams will not just be improved but will also

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advocate environmental sustainability in concrete restoration. On the other hand, the basalt fibres are the more environmentally friendly type compared to synthetic fibres as it is acquired from natural raw materials with smaller energy consumption amount [7]. Moreover, they are non-toxic and not flammable and have good resistance against most environmental effects hence producing a strong and durable concrete strengthening application [8]. Previous studies show that the use of basalt fibre improves upon the load-carrying capacity, ductility, and energy absorption features of beams. Such an improvement is crucial for seismic-resistance applications or other exceptional conditions [9].

BFRP provides high tensile strength, corrosion resistance, and superior thermal stability compared to conventional steel and CFRP systems [10]. ECC contributes exceptional crack control, strain-hardening behavior, and enhanced ductility, reducing premature debonding failures [11]. The synergistic action between BFRP and ECC significantly improves flexural capacity, stiffness, and energy absorption of RC beams. Additionally, this hybrid system promotes sustainability due to the eco-friendly nature of basalt fibers and the extended service life of strengthened structures [12].

The combination of ECC with sheets of basalt fibre has a dual advantage such as while the ECC improves the crack resistance and tensile strength of the concrete, the reinforcement due to the extenuating effects of the basalt fibres on the beam's ability to carry higher loads and resist deformation gets further augmented. This hybrid finds special applications in retrofitting schemes wherein beams are damaged and deteriorated, which necessitate strengthening of both their internal and external elements to be able to restore their original structural performance[13]. Additionally, due to microcracking control within ECC, the retrofitted beams exhibit superior durability in the long run [14].

With the degradation of infrastructure globally, the need for effective retrofitting techniques is an ever-present urgency [15]. Therefore, several studies have been carried out to analyze the flexural behavior of RC beams with ECC and retrofitting potential of basalt fibres. Engineered Cementitious Composite (ECC), which possesses tensile strength significantly superior than conventional matrices, improved resistance to cracking, and extended durability, when added to basalt fibre, holds an efficient, yet sustainable strategy in enhancing the structural properties of concrete beams [16,17]. Performed a series of investigations and found that embedding ECC layers to RC beams significantly improved the flexural strength of the latter rather than comparing it with traditional concrete beams. A paralleled research work shows the parametric study on RC beams reinforced by basalt fibre fabric by[6], finding a significant improvement in the bending capacity of the beams. Results in this investigation become consistent with the past research that had proven the ability of basalt fibres to enhance the characteristics of concrete beams in terms of both flexural and tensile.Over the past few decades, the application of FRP for retrofitting structural components has gained significant popularity[18].Retrofitting reinforced concrete beams with engineered cementitious composites and basalt fibres is a promising practice that may efficiently develop both structural performance and life expectancy of deteriorating concrete infrastructure. Based on the unique mechanical properties of ECC combined with the superior tensile strength and corrosion resistance basalt fibres provide, there is a possible method for increasing the load-carrying capacity of reinforced beams and their respective resistance to cracking [19]. The conclusion Li’s work supports the future possibility of ECC and basalt fibre for retrofitting activities and their place in moving toward a more resilient infrastructure system in the more solidified world, according to[3]. In retrofitting, reinforced concrete (RC) beams are encased with basalt fibre sheets. This has proven to enhance the structural capacity of the beams in their flexural capacities and to prevent cracks in the members under applied loads [20]. Moreover, these technologies reduce the use of replacing full infrastructures, hence enabling sustainable constructions that correspond to the efforts of the world in reducing the ecologic footprint within the construction industry [8]. Thus it can be concluded that when retrofitting with ECC and basalt fibre sheets, a cost-effective and durable solution is presented for extending the service life of concrete structures in the context of infrastructure maintenance. Furthermore, the emergence of Polyvinyl Alcohol (PVA) fiber has been used with Engineering cementitious composite (ECC). PVA fiber were found to be the most suitable polymeric fibers for reinforcing the ECC [21]. The addition of basalt fibres to the ECC layers along with PVAfibres is expected to significantly improve retrofitting effectiveness since PVAfibres are known for their ability to create crack resistance and strengthen tensile properties of the concrete [22].

This paper delves into the concept of PVAfibreECC combined with basalt fibre wrapping reinforcement in enhancing uniaxial flexural enhancement and overall strengthening of RC beams. Although much has been developed regarding retrofitting techniques, knowledge about how ECC and BFRP act in combination is really very rare with regards to their structural performance in RC beams. Among the major points of concern that this research aims to consider is whether a combination of outer layers with ECC and wrapping with BFRP could offer improved load-carrying capacity, better flexural behaviour, and crack resistance of reinforced concrete beams.

2. MATERIALS AND METHODS

In the current study, M40-grade concrete was prepared as per [23, 24] incorporating Portland Pozzalano Cement (fly ash based), fine aggregates, coarse aggregates, water, super plasticizer, Polyvinyl alcohol (PVA) Fibre and Basalt Fiber Reinforced Polymer Sheets (BFRP). The properties of materials were tested as per [25, 26]and the tested values are given in Table 1. The images of PVA fiber and basalt fiber reinforced polymer sheets are shown in Figure 1 a & b respectively. The details of beams are provided in Figure 2 and the number of specimens cast for each test type are summarized in Table 2. A total of twelve cubes of concrete, all of size 150 mm × 150 mm × 150 mm, are cast for compressive strength testing. Nine control cubes and three BFRP-wrapped cubes have the compressive strength evaluated at 7 and 28 days using a compression testing machine. Six concrete cylinders were prepared also of diameter 150 mm and height 300 mm to determine the split tensile strength. The test for split tensile was performed on the cylinders after 7 days and 28 days of curing. Three of these cylinders were wrapped in BFRP for the comparative analysis. Reinforced concrete beams were cast with tailored cementitious composites (ECC) infused at different depths, specifically 20 mm and 50 mm from the bottom within the strain zone. A control beam without ECC and beams with ECC layers were prepared for comparison. All specimens were tested under flexural loading to evaluate their load–deflection behavior and failure modes. The flexural performance of the reinforced beams was compared with that of the control beam. After initial damage, the ECC-layered beams were repaired using externally bonded basalt fiber sheets and re-tested to assess performance recovery.

Table 1. Material Properties

S.No	Material	Property	Value
1.	Portland Pozzalano Cement (fly ash based)	Specific Gravity	2.88
2.	Fine Aggregate	Specific Gravity of M-Sand	2.67
		Fineness modulus	2.76
3.	Coarse Aggregate	Specific Gravity of M-Sand	2.67
		Fineness modulus	7.58
4.	Polyvinyl alcohol Fibre	Specific Gravity	1.3
		Length of fiber (mm)	18
		Diameter of fiber (µm)	38
		Aspect ratio (l/d)	474
		Tensile strength (MPa)	1600
		Modulus of elasticity (GPa)	42
5.	Basalt Fibre	Specific Surface Weight(g/m^2)	200
		Density(kg/dm^3)	2.7
		Melting Point	1350 ℃
		Thickness(mm)	0.2
6.	Superplasticizer (TEC MIX 550)	Specific Gravity	7-9
		Base	Sulphonated Naphthalene Polymers
7.	EPOXY RESIN (LY 556)	Density @ 25 ℃	1.15 - 1.2
		Viscosity @ 25 ℃	10000 - 12000
		Epoxide index	5.30 – 5.45

To achieve the maximum mid-span bending moment for evaluating flexural performance, three-point test is considered for testing of beams. For this, six beams of 1700 mm × 100 mm × 150 mm were cast with reinforcement that consisted of four 12 mm diameter steel bars, longitudinally to provide support, and ten 8 mm diameter stirrups spaced at 150 mm intervals. Among these beams, one was a control, one had ECC located at 20 mm from the bottom, and another with ECC at 50 mm from the bottom tension zone. After initial loading, the beams were retrofitted with BFRP sheets in the U-wrapping pattern. In flexural strength evaluations, a flexural testing apparatus with a maximum load of 500 kN was used. It involved the use of measurements through deflection using Linear Variable Differential Transformer (LVDT) and were observed on the Prosof-14-B software to obtain an accurate measurement.

(a)

(b)

Figure 1. (a) Polyvinyl alcohol fibre, (b) Basalt fibre sheet

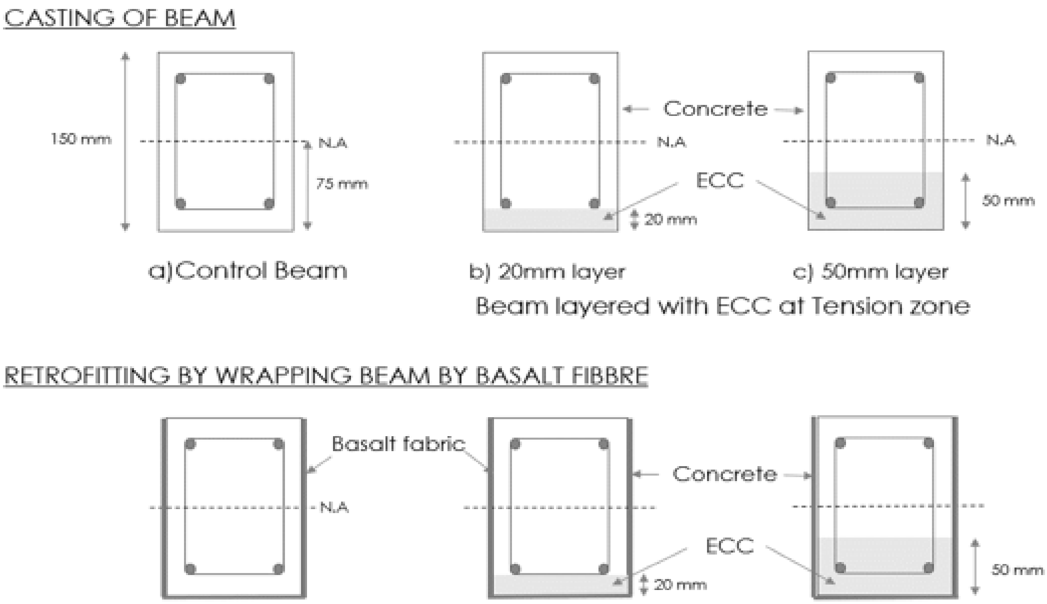

Figure 2. Details of beam

Table 2. Number of specimens tested

Sl.No.	Test Type	Specimen Designation	Number of Specimens	Notation Used
1.	Compressive Strength Test	Control Cube Specimen	9	C1, C2, C3, C4, C5, C6, C7, C8, C9
		Cube Fully wrapped with BFRP	3	C10, C11, C12
2.	Split Tensile Strength Test	Control Cylinder Specimen	6	S1, S2, S3, S4, S5, S6
		Cylinder wrapped by BFRP sheets	3	S7, S8, S9
3.	Flexural Strength Test	Control Beam	1	M0
		ECC layered at 20mm from the bottom of beam at tension zone	1	M1
		ECC layered at 50mm from the bottom of beam at tension zone	1	M2

3. RESULTS AND DISCUSSION

3.1. Compressive Strength

Compression tests were conducted on the cube specimens. In sequence, the results showed increasing strength over time. In Figure 3, at 7 days, the cube specimen achieved 53% of the target mean strength of the M40 concrete. This is normal in the fact that hydration has already started but the concrete is still in its primary stages of curing. Strength gain up to 14 days is steep and almost on 78% of the target mean strength, which translates that the concrete is getting matured well during curing. At 28 days, or the normal age at which the ultimate compressive strength of concrete is determined, the test specimen had reached 97% of the target mean strength, indicating that the mix design and cure conditions were successful in leaving the concrete just short of being entirely at full strength. Additionally, cube specimens fully wrapped by a basalt fiber reinforced polymer (BFRP) sheet indicated a good increase in strength.

Table 3. Compressive strength test results at 28 days

S.No.	Theoretical value (N/mm^2)	Experimental value (N/mm^2)	
		Control specimen	BFRP specimen
1.	48.31	46.84	53.86

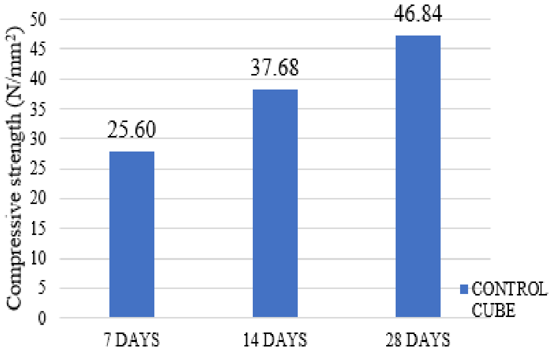

Figure 3. Compressive strength of control specimen at 7, 14 and 28 days.

From Table 3, it can be seen that wrapped specimen had an 15% gain in compressive strength at 28 days, compared to the control specimen. Therefore, this comparison proves the superiority of BFRP wrapping along with providing supplementary confinement on the concrete. Confinement delays the critical onset of crack and thus increases the load-carrying capacity within the specimen. The findings thus validate that BFRP is an appropriate reinforcement technique to be used with the intent of enhancing the toughness and performance of concrete structures.

3.2. Split Tensile Strength

The cylinder specimens that had full wrap of Basalt Fiber Reinforced Polymer (BFRP) sheets, on the other hand, showed a noticeable improvement. From Table 4, at 28 days, the split tensile strength of the BFRP-wrapped cylinders was 17.14 % higher than that of the control cube specimens.

Table 4. Split Tensile strength at 28 days

S.No.	Split Tensile strength at 28 days (N/mm^2)	
	Control specimen	BFRP specimen
1	3.5	4.1

3.3. Flexural Behavior of Beams

3.3.1. Load - Deflection Behaviour

The load versus deflection behaviour of several reinforced concrete beams is illustrated. These reinforced concrete beams are covered in BFRP sheets and have ECC layers of varying thicknesses. The comparison of similar beams is done in the following sections, with an emphasis on the effects of retrofitting techniques and ECC layering at varying thicknesses on ultimate load capacity and the corresponding deflection characteristics as shown in figures 4 to 8. Table 5 shows the load-deflection performance of beams.

Table 5. Load - deflection performance of beams

S.No	Specimen description	Load (kN)	Deflection (mm)
1	M40-Control beam	43.6	11
2	Beam layered with ECC at 20 mm from bottom at tension zone	47.5	13
3	Beam layered with ECC at 50 mm from bottom at tension zone	51.7	16
4	M40-Control beam retrofitted by basalt fabric	46.8	9
5	ECC 20 mm retrofitted	49.0	10
6	ECC 50 mm retrofitted	54.6	13

3.3.2. ECC Layering at a Distance of 20 mm from the Bottom (Tension Zone)

For the RC beam layered with ECC at a distance of 20 mm from the bottom in the tensile zone, the ultimate load increased by a relative amount of 8.95 % as compared to the control specimen but deflection increased by 17.4%. This is because of the strain-hardening nature of ECC that delays the initiation of significant cracks and failure and boosts the load-carrying capacity in the tensile zone. From the results, it can be proved to be more workable and has a greater extent of deflection before breaking. The incorporation of ECC enhanced the tensile region of the beam, which then supported heavier loads prior to yielding.

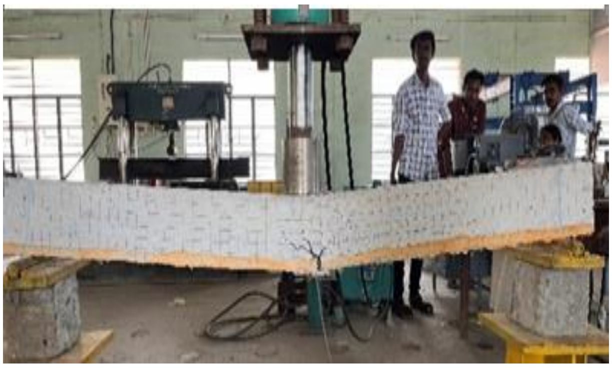

Figure 4. ECC layered at 20mm in the tension zone of beam

3.3. ECC Layering at 50 mm from the Bottom (Tension Zone)

In the tension zone, the RC beam with an ECC layer placed at 50 mm from the bottom had a more significant load capacity and deflection increase. Compared to the control specimen, the ultimate load increased by 18.76%, while the deflection increased by 45.45%. As such, ECC was indeed thicker; therefore, there is an improvement in load distribution and crack control. From the results it is clear that, in the ECC 50 mm beam, a large amount of deflection can be observed at failure. Due to a higher ECC thickness, the strain-hardening effect was more obvious, and energy absorption enhanced.

3.4. Wrapping with BFRP

The ultimate load on the RC beam wrapped in BFRP sheets compared with the control specimen was increased by 8.56%, while deflection decreased by 17.4%. After being wrapped by BFRP, the wrapping restricted the movement of the beam and terminated the further propagation of cracks, thus enhancing the strength of the section. On the contrary, the reduction in deflection signified that further addition in stiffness created the support means to cause lower ductility as compared with ECC-layered beams. Consequently, the overall structural performance of the beam wrapped with BFRP sheets was improved, considering the reduced width of the cracks. Compared with ECC-layered beams, reduced deflection indicated limited energy dissipation, and the increase in the ultimate load capacity was seen.

Figure 5. ECC layered at 50mm in the tension zone of beam

Figure 6. Control beam wrapped with BFRP sheet

3.5. Retrofitted Beam Layered with ECC at 20mm

The bottom of the tension zone is at 20 mm; here, because of ECC, a retrofitting beam has reached an ultimate load capacity that is 13% greater than the control specimen and 9.1% greater in deflection. In addition, this indicates higher ductility and flexural capacity. During this ECC layer, an improvement in crack control has occurred because of the micro-cracks that prevent the evolution of critical bigger damage. Figure 7 demonstrates the work improvements, with a larger load-bearing capacity and a higher deflection after the retrofitting of the beam than in the control beam.

3.6. Retrofitted Beam Layered with ECC at 50 mm

The ECC layer at 50 mm below the bottom edge of the tension zone had significant improvements in both load and deflection capacities compared to the control specimen. It increased by 25.23% for ultimate load, and for deflection, 17.4%, which shows that the deeper ECC layer can better resist higher loads with overall ductility improvements. Moreover, the retrofitting process managed the development of cracks efficiently, and therefore, the width of that was greatly reduced; more importantly, it improved the structural integrity. This is presented in Figure 5 as the load versus deflection curve is improved by the weight-bearing capacity and deflection capacity in the case of the retrofitted beam as opposed to the control, and this clearly demonstrates that the higher performance achieved using the 50 mm ECC layer.

Figure 7. 20 mm ECC layered retrofitted by BFRP

Figure 8. 50 mm ECC layered retrofitted by BFRP Sheet

3.7. Characteristics of Load versus Deflection

The Figures 9 shows the load - deflection characteristics of beams. The figures show notable variations in beam specimens' flexural performance.

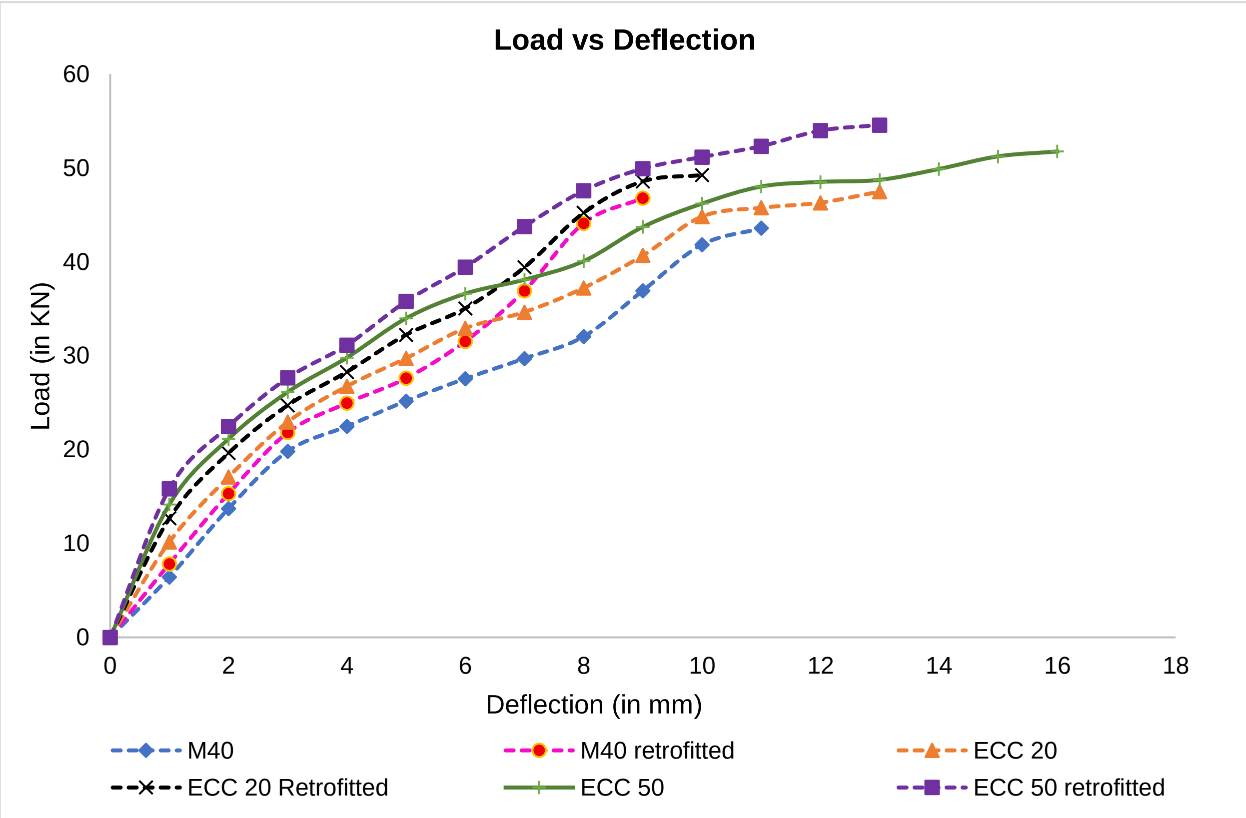

Figure 9. Load vs deflection characteristics of beams

The load–deflection curves shown in fig.9 illustrate the flexural behavior of control and retrofitted RC beams with M40 concrete, ECC 20, and ECC 50. The control M40 beam shows the lowest load-carrying capacity and stiffness, indicating early cracking and limited ductility. Retrofitting the M40 beam significantly increases both load capacity and deformation capacity, demonstrating the effectiveness of external strengthening. Beams made with ECC 20 and ECC 50 exhibit higher loads at the same deflection compared to M40, reflecting improved crack control and strain-hardening behavior of ECC. Among all specimens, ECC 50 retrofitted beams achieve the highest ultimate load and sustain larger deflections, indicating superior strength and ductility. Overall, the load-deflectioncurve confirms that higher ECC content and retrofitting synergistically enhance stiffness, load capacity, leading to a more ductile and resilient flexural response.

4. CONCLUSION

This paper discussed the feasibility of using ECC and basalt fibre for retrofitting RC beams. Experimental studies were conducted on fresh concrete as well as hardened concrete. The number of tests done in the fresh state was one single slump cone test, whereas on hardened state, compressive strength, split tensile strength, and RC beams were assessed for flexural behaviour. Control beams were compared with strengthened beams through ECC at the zone of tension in 20and 50 mm layers and also retrofitted using BFRP sheets in U-wrap configuration. The following conclusions are made:

- In the present experimental investigation, it has been shown that the application of BFRP sheets at the reinforcement of concrete elements enhances their structural capacity.
- It has been wrapped completely into concrete specimens in split tensile tests because it reduces the crack width by producing an effective increase of 14.98% compressive strength and 17.14% tensile strength.
- The ECC layer at a thickness of 20 mm and 50 mm contributes to further increases in flexural strength, amounting to 8.95% and 18.76% increase in load-carrying capacity of reinforced concrete beams through ECC.
- The ECC addition increases the load-carrying capacity of the reinforced concrete beams additionally. The measured load-carrying capacities were increased by 8.95% and 18.76% for the ECC layers at 20 and 50 mm, respectively.
- Additionally, the flexural strengths exceeded the damage limits in beams covered with BFRP sheets. Specific results for damaged beams showed a reduction in deflection by 17.4% and an increase in the load capacity by 8.56%.
- Thus, these results establish the efficiency of ECC and BFRP sheets in improving the structural behaviour of concrete components.
- These results provide several important implications for a robust and practical approach to keeping and strengthening ageing infrastructure, including improvement in strength and durability as well as minimized long-term repair costs.

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IZVOD

OJAČAVANJE ARMIRANIH GREDA KORIŠĆENJEM POLIMERA ARMIRANOG BAZALTNIM VLAKNIMA SA ECC-OM

Rekonstrukcija betonskih konstrukcija postala je veoma istaknuta sa starenjem i propadanjem infrastrukture. Da bi se grede izlivile, prilagođeni cementni kompoziti su ulivani u različite slojeve, kao što su 20 i 50 mm od dna zone naprezanja armiranobetonske grede. Upoređeno je ponašanje kontrolne grede i armiranih greda pri savijanju. Oštećene grede sa ECC slojevima su popravljene primenom ploča od bazaltnih vlakana. Kada su potpuno obmotane pločama od bazaltnih vlakana ojačanih polimera (BFRP), čvrstoća na pritisak betonskih uzoraka porasla je za 14,98%, a njihova zatezna čvrstoća za 17,14%, dok se širina pukotina smanjila pri ispitivanju zatezanja razdvajanjem. Nosivost AR greda povećana je za 8,95% i 18,76% za slojeve od 20 mm i 50 mm, respektivno, dodatkom ECC-a. Kada su oštećene grede usporene upotrebom BFRP-a, čvrstoća na savijanje se značajno poboljšala, povećavajući nosivost za 8,56% i ugib za 17,4%. Na osnovu zaključaka studije, buduće prakse održavanja infrastrukture treba izmeniti kako bi bile otpornije na probleme koje donosi starenje infrastrukture i održivije.

***Ključne reči**: ECC, polivinil alkoholna vlakna, bazaltna vlakna, ojačavanje.*

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