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Enhancing concrete flexural behaviour with euphorbia tortilis cactus: Sustainable additive for improved load-carrying capacity and ductility

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This study delves into the flexural behavior of concrete beams incorporating Euphorbia tortilis cactus (ETC) as an environmentally friendly additive. Six sets of reinforced concrete beams with varying compositions, including ETC and reference concrete, were subjected to two-point load tests. The results revealed several critical findings. All tested beams exhibited a flexural mode of failure, indicating a ductile response. ETC-incorporated beams displayed superior load-carrying capacity, with initial crack loads increasing by up to 47.9%. ETC beams exhibited lower crack widths, reduced deformations, and enhanced stiffness. The stiffness gradient relative to the ultimate load demonstrated the improved resistance of ETC beams. Energy absorption was significantly higher in ETC beams, signifying their capacity to withstand energy fluctuations. ETC fibers effectively prevented pull-out failures. Overall, ETC-enhanced concrete beams exhibited enhanced performance, highlighting their potential for sustainable construction.

Keywords: Bio-additive, Bio-concrete, Cactus, Deflection, Flexural beam

1 Introduction

The construction industry has seen an increased demand for the restoration, enhancement, and modernization of concrete structures in recent years[1]. Several factors contribute to this trend, such as environmental degradation, design deficiencies, substandard construction techniques, insufficient maintenance, changes in building codes, increased loads, and seismic risks[2-5]. According to IS 456:2000, a significant portion of reinforced concrete structures in India is primarily designed for gravity loads, leaving them susceptible to seismic damage[6]. In the event of a strong earthquake, these structures may undergo inelastic deformation, necessitating ductility, and energy dissipation for structural integrity[7]. Gravity-loaded structures require strengthening measures to enhance their strength, stiffness, and ductility to address this vulnerability[8]. One commonly employed method for increasing the strength of reinforced concrete (RC) beams is known as additives[9]. This technique results in a flexural beam with improved axial strength, bending capacity, and stiffness when compared to their original counterparts[10].

Ali *et al*. studied corroded steel and concrete-filled double-skin tubular members. ECC enhances CFDST's performance against corrosion, with potential in marine environments[11]. Corrosion impacts stiffness, ductility, and energy absorption more than ultimate strength, with ECC outperforming NC. Existing codes lack corrosion impact considerations, prompting a theoretical stiffness analysis and comparison with EC4, AIJ, BS5400, and AISC[12]. Sathishkumar *et al*. investigated the flexural behavior of concrete-filled double-skinaluminium alloy tubular members. 10 beams tested, validated FE models, parametric study, Eurocode 4-based design methodology proposed[13,14]. Accornero *et al*.[15] Investigated the flexural behavior of steel fiber-reinforced concrete beams explained using a cohesive softening model, incorporating reinforcement and fiber slippage effects. Parameters NP and NW govern the composite response and match experimental data[16]. LiZ *et al*.[17] explore the flexural behavior of RC-BFRC beams, offering formulas validated by experiments, demonstrating improved performance compared to RC beams, with insights from a parametric analysis. Li Cexamined UHPC's effectiveness in retrofitting shear-deficient HSC beams, significantly enhancing shear and flexural performance, with steel ratio affecting failure

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modes[18]. Durairaj *et al*. explore the flexural behavior of sustainable RCC beams with a smart mortar layer, enhancing sustainability by sensing and inferring damage through electrical resistivity changes[20]. It demonstrates a linear relationship between load and electrical resistance change, with increased resistivity changes in brass fiber-added mortar layers compared to hybrid layers[21]. This approach offers a promising method for structural health monitoring and damage detection in concrete beams[22]. Hasan *et al*. investigate GFRP-reinforced geopolymer concrete T-beams[23]. Geopolymer concrete's behavior differs from OPC, affecting failure modes. Predictive equations like ACI 440 2R-17 overestimate capacity and underestimate deflection[24]. Fattouh *et al*. examine the impact of steel fiber and silica fume on compressive strength and flexural behavior of road pavement slabs under different curing conditions[25]. Rabi *et al*. investigate the behavior of stainless-steel reinforced concrete (SSRC) beams to enhance concrete structure durability [26]. It assesses performance measures and examines design standards' applicability, including recently developed methods tailored for SSRC. Compressive strength and flexural load-bearing capacity were significantly improved with these additives[27], offering potential benefits for concrete durability and performance in marine environments[28]. Sifan *et al*. studied the flexural behavior of concrete-infilled hollow flange cold-formed steel (CF-HFCFS) beams with lightweight normal and high-strength concrete[29]. A numerical analysis and simplified design approach were developed, enhancing our understanding of these complex structural members[30]. Shen *et al*.[31] experimented using compression-yielding (CY) blocks to enhance the ductility of FRP bar-reinforced concrete beams. Numerical analysis reveals improved ductility by changing the failure mode from brittle to ductile, and the effects of material properties and CY block geometry were examined[32].Wang *et al*. evaluate the flexural behavior of GFRP bar-reinforced seawater-sea sand concrete beams, considering parameters like reinforcement ratio, stirrup ratio, prestress level, and shear span ratio[33]. Results show that prestress level significantly influences cracking load, and various factors affect the ultimate load and failure modes. Existing calculation models[34,35]for FRP bar-reinforced concrete beams yield different estimations, and further research is needed for prestressed GFRP bar-reinforced SWSSC beams. Sryh *et al*. investigate the long-term flexural behavior of recycled aggregate concrete (RAC) beams with varying levels of recycled aggregate[36]. Results show reduced strength and increased deflection in RAC beams compared to normal concrete (NC). Eurocode 2 underestimates deflections in RAC beams, highlighting the need to modify the tension stiffening factor β[37]. Madan *et al*. studied the use of GFRP sheets in OPC and HVFA concrete slabs, comparing their flexural behavior to steel-reinforced slabs[38,39]. Experimental and numerical results support GFRP as a sustainable alternative for reinforcement in concrete structures. Subramanian *et al*. investigate the flexural behavior of geopolymer concrete beams reinforced with BFRP/GFRP and steel rebars, including the effect of adhesively bonded BFRP/GFRP stirrups[40]. Results show differences in failure modes[41], deflection, and crack behavior, highlighting the performance of FRP bars in geopolymer concrete. Zhang *et al*. conducted a numerical study on layered UHPC-NC beams[42], revealing the significance of interfacial bonding and cost-effectiveness[43], making these beams a viable and economical choice with exceptional mechanical performance. Zhao *et al*. evaluates the impact of vibration time on steel fiber distribution and flexural behavior in SFRC[44]. Vibration duration affects fiber settling and segregation, influencing flexural strength and performance. An optimal vibration time should align with SFRC's flowability for improved results[45].YildizEl *et al*. explore the use of recycled waste steel wires (RWSWs) from car tire wastes as an additive in reinforced concrete beams[46]. RWSWs enhance mechanical properties and are recommended at a 2% dosage for improved bending performance[47]. A predictive equation for hybrid beam capacity is provided. Piatek *et al*. investigate RC beams strengthened with CFRP strips, considering anchoring, tensioning, and prestressing levels[48,49]. Tensioned CFRP strips significantly enhance cracking, yielding, and ultimate moments, with an optimal prestressing level identified as 60% of CFRP tensile strength. Sun *et al*. investigate the flexural behavior of steel-basalt fiber composite bar (SBFCB)-reinforced concrete beams[50]. Results show that SBFCB-reinforced beams have good ductility, and calculated ultimate bearing capacities align well with measured values. A maximum strain limit of 0.75 times the ultimate strain is recommended to prevent brittle failure[51]. Omar *et al*. concluded a numerical modelling approach using XFEM-CZM to predict the debonding failure in externally CFRP-strengthened concrete beams, achieving good agreement with experiments[52, 53]. Accurate results are expected with concrete-specific fracture energy values. Kumar *et al*. investigate the flexural behavior of geopolymer concrete beams with varying percentages of waste glass powder (WGP) as fine aggregate[54]. The RGPC beams with 50% WGP exhibited improved cracking resistance, serviceability, ductility, and load-carrying capacity compared to reference beams. Qin *et al*. examine the flexural behavior of ECC-reinforced concrete composite beams, considering ECC layer thickness and shape[55]. ECC-RC composite beams exhibit superior ductility, energy absorption, and crack control compared to RC beams, with U-shaped ECC layers showing the best performance[56]. Formulas for predicting the flexural capacity of ECC-RC composite beams are derived. A novel wood-concrete flooring system was tested through bending experiments, proving its high load-bearing capacity, minimal deflection, and suitability for various building types, meeting strength and stiffness requirements with eco-friendly construction by Martín-Gutiérrez *et al*[57].

In previous research articles[1-70], few authors have made investigations on concrete with cactus, and most of them with cement mortar. This research aims to investigate the flexural behavior of concrete beams incorporating Euphorbia tortilis cactus (ETC) as an environmentally friendly additive. The study evaluates the load-carrying capacity, ductility, energy absorption, and stiffness of ETC-enhanced beams in comparison to conventional concrete beams. Six sets of reinforced concrete beams were tested under static loading. These included reference concrete and ETC-incorporated beams of different compositions. The study conducted two-point load tests, using a loading frame and strain gauges to measure deflection. It analyzed load-deflection behavior, stiffness, ductility, and energy absorption to assess the performance of ETC beams. The research shows the greater load-carrying capacity and improved ductility of ETC-enhanced concrete beams, demonstrating their potential for sustainable construction practices.

2 Materials and Methods

The cement sample, tested in accordance with IS: 12269 - 2013 standards, demonstrated robust performance in key physical properties[59]. The cement's fineness, measured at 327 m^2/kg, surpassed the required 300 m^2/kg threshold, ensuring a fine particle size distribution essential for workability. The normal consistency, though unspecified, holds significance for workability and was found to be 30.5%[60]. Setting time is a crucial factor in construction, and the cement excelled in this aspect. The initial setting occurred at 34 minutes, slightly exceeding the 30-minute minimum, while the final setting time was well within the 600-minute limit, making it suitable for various applications[61]. The cement exhibited excellent soundness, with a Le-chatelier expansion of 3.5 mm, far below the 10.0 mm limit. The auto-clave expansion, vital for cement stability, registered at just 0.07%, well below the 0.8% threshold, indicating no detrimental expansion under high pressure[62]. Compressive strength results were robust, exceeding minimum requirements. At 3 days, the strength reached 28.87 MPa, surpassing the 27.0 MPa minimum. After 7 days, it increased to 38.91 MPa, exceeding the required 37.0 MPa, and at 21 days, it reached 54.66 MPa, comfortably surpassing the 53.0 MPa minimum[63]. This underscores the cement's suitability for construction, meeting IS: 12269 - 2013 standards. In the aggregate analysis, fine aggregate passed through a 4.75mm sieve, had a fineness modulus of 3.225, and 0.6% water absorption. Bulking of sand was noted, with a maximum bulking of 22.8% at 4% water content. The specific gravity was 2.6, and it had a void ratio of 0.55. Bulk density was 1770 kg/m^3, providing insights into mass per unit volume[64]. The coarse aggregate, with 20mm particles, exhibited a fineness modulus of 7.3, 0.5% water absorption, and a specific gravity of 2.76. Mechanical properties included a 7% crushing value, 24% abrasion value, and 20% aggregate impact value, with flakiness and elongation indices of 19% and 17%, indicating resistance to crushing, wear, and impact. In the realm of sustainable construction, organic additives are replacing synthetic ones. Euphorbia tortilis cactus extract, abundant in western Tamil Nadu, offers an eco-friendly alternative. Extract properties were analyzed, and it was added to water in concentrations ranging from 1% to 9%. A crude fat test revealed 5.2% of polysaccharides and 1.9% of proteins in the cactus extract. Water constituted 92.85% of its composition[65]. These properties underscore the potential of Euphorbia tortilis cactus extract as a sustainable additive, aligning with the industry's shift towards eco-conscious construction practices.

3 Results and Discussions

3.1 Experimental study

A loading frame was used to study the load-carrying capacity and load-deflection behaviour of reinforced concrete beams under two-point loads. A reinforced concrete beam measuring 1000 mm in length and having a cross-section of 150 mm x 200 mm will be cast for optimum ETC (9%) and tested as part of the experimental programme. The beam's actual length is kept constant at 1000mm. The beam's under-reinforced section was created to withstand a minimum ultimate load of 4000 kN. Fig. 1 (a-b) displays the specifics of the reinforcement that was supplied. As tensile reinforcement, the beam has two numbers of 12mm diameter HYSD bars at the bottom. As hanger bars, two additional 8 mm diameter bars were positioned at the top[66]. Stirrups with a 6mm diameter were employed at a 160mm center-to-center distance to hold the reinforcements and serve as shear reinforcements. In total, 2 numbers (1 reference concrete, and another one with optimum ETC) of reinforced concrete beams have been cast and kept in water for curing for 28days. The specimen was securely positioned on the loading frame for testing[67]. To ensure the vertical axial load application, a loading frame was employed. This frame facilitated the imposition of a constant axial load of 50 kN, which was expertly transmitted through steel rollers supported by steel plates, strategically positioned between the hydraulic jack and the column head. The magnitude of the vertical load, set at 50 kN, was chosen based on a design compression value that corresponds to 0.30 of the RC axial resistance, as determined through prior analysis.

3.2. Experimental results and discussion

This section elaborates in greater depth on the flexural behaviour of the beams under static loading. Six sets of RC beams (two concrete references of M 20 and M 25, two (M 20 and M 25) with ETC9, and another two (ETC9 of M 20 and M 25 with AFRP sheets) with effective lengths of 1200mm and cross-sections of 100x170mm were cast; a two-point load test was conducted on an ETC Concrete beam as was indicated[68]. Until it achieves the ultimate load, the beam is gradually loaded. A strain gauge placed in the specimen's middle is used to measure the deflection of the center of the beam at each load increment. The load increment is maintained at 10kN. For each beam, the load corresponding to the initial crack load is also given. The load-deflection values of the ETC9% beam and reference concrete are shown in Table 1. During the investigation, the load at the first crack, corresponding deflection, ultimate load, and maximum deflection are noted for each beam. All of the tested beams failed in a flexural mode rather than a brittle mode. It was discovered that the aggregates, ETC had a strong bond. Additionally, ETC and AFRP concrete beam samples displayed less deformations at

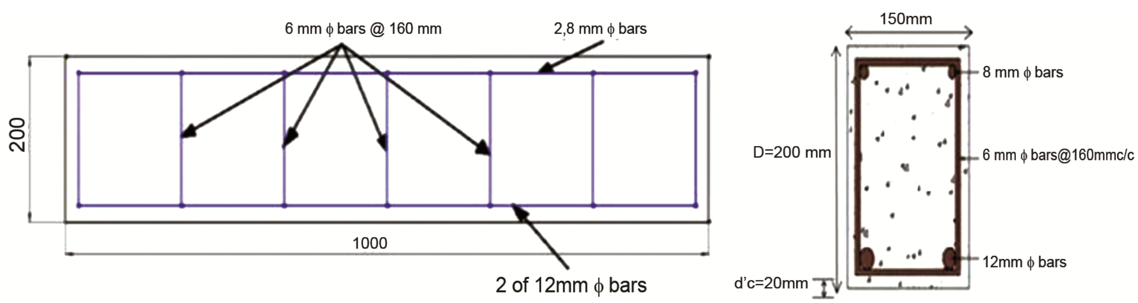

Fig. 1 — a) Longitudinal view of the beam, and b) Cross-sectional view of the beam.

Table 1 — Test results of Flexural Concrete beam.

Particulars	M20 Grade		M25 Grade	
	Reference Concrete	Cactus concrete (ETC9)	Reference Concrete	Cactus concrete (ETC9)
First crack load (kN)	12.5	30.20	25	33.71
Deflection at yield load (Δ_{crack})	1.38	1.19	1.07	1.10
Ultimate load (kN)	60.5	85	70	94.5
Deflection at Ultimate load (Δ_{ulti})	2.91	2.14	2.57	1.72
Stiffness (kN/mm)	20.79	39.72	23.64	54.94
Ductility factor (Δ_{ulti} / Δ_{crack})	2.11	1.79	2.40	1.57
Energy absorption (kN-mm)	169	160	179	165

all load levels, lower crack widths, a minor improvement in stiffness, and improved ultimate load-carrying capacity. The initial crack load of the ETC beam is 30.20kN and the Ultimate load is 85kN.

3.2.1 Structural load-deflection of beam

Euphorbia tortilis cactus was added to two beam specimens that were produced in the concrete according to nominal designs M 20 and M 25. A loading frame and a two-point loading system are used to conduct the test. The center deflection is measured and the load is applied in increments of 2.5kN. It takes up the test setup for testing beams with a two-point loading process. Figure 2 where depicts the test setup for beam testing, where Fig. 3 depicts the load-deflection curve for M 20 concrete beams (ETC0 & ETC9), and Fig. 4 also displays the load-deflection curve for M 25 concrete beams (ETC0 & ETC9). Initially, the beam demonstrates a linear relationship between the applied load and deflection, remaining free of cracks until the mid-span area reaches the cracking moment, marking the occurrence of the first crack. The formation of a crack results in a reduction in the beam's moment of inertia, leading to a decrease in the beam's overall stiffness. Subsequently, the beam enters the post-cracked phase. During this phase, while the reinforcing bars are presumed to bear the entire tensile force, the concrete possesses the capacity to transmit tension through the bond between the reinforcing bars and itself. This contribution of concrete in transmitting tensile stress, which gradually alters the beam's stiffness from the point of cracking to the point of yielding, is recognized as the tension-stiffening effect in reinforced concrete. Once the reinforcing bars yield, there is a substantial decline in the beam's stiffness. This stage is known as the post-yielded phase, primarily governed by the behavior of the reinforcing bars. In this phase, the beam continues to support additional loads as a result of the reinforcement bars hardening until it reaches its maximum moment capacity, depicted as the peak point.

As depicted in the illustration, it is evident that Beam ETC9 displayed a lower cracking moment in comparison to Beam ETC0, although the former had higher compressive strengths than the latter. This contrasts with the typical behavior observed in regular reinforced beams, where the cracking moment tends to increase with higher compressive strength. Notably, prior research has indicated that ETC9

Fig. 2 — Flexural cracks formation and propagation during the experiment.

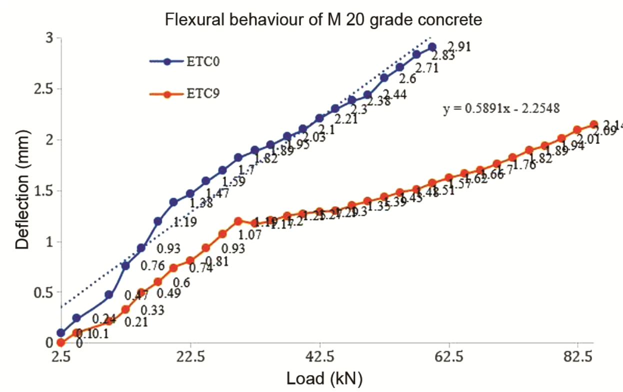

Fig. 3 — Deflection value of the flexural concrete beam (M 20 grade).

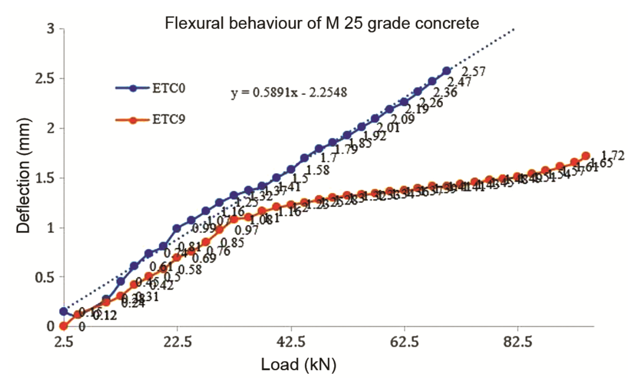

Fig. 4 — Deflection value of the flexural concrete beam (M 25 grade).

boasts a greater flexural strength than ETC0, even when their compressive strengths are similar, which should logically result in a higher cracking moment. This unusual phenomenon regarding cracking resistance has not been documented in previous studies that investigated the flexural performance of ETC9 beams. The reduction in cracking resistance can be attributed to the exceptionally high drying shrinkage exhibited by the beam. It is a well-established fact that drying shrinkage can lead to a decrease in the cracking moment of reinforced concrete structures due to the emergence of shrinkage restraint stresses induced by shrinkage strain. Furthermore, beams with a substantial ETC content, when subjected to ambient curing conditions, have been documented to exhibit considerably higher levels of shrinkage compared to ETC0. Consequently, the pronounced shrinkage-induced cracks and strain may be the underlying reasons for the observed decrease in the cracking moment [69].

Figures 3 & 4 plots the load versus mid-span deflection curve for the tested ETC0 and ETC9 flexural beams for comparison and better representation. It is evident from the load-deflection sample that ETC9 flexural beams have increased load-carrying capacity with less deformation than conventional concrete beams. The deflection evaluated in the ETC9 flexural beam exposed to two asymmetric concentrated loads is given in Table 1. When the internal steel yields, the ETC that is bonded into the concrete materials carries the extra tensile force, increasing the load-carrying capacity. Figures 3 & 4 clearly shows that the ETC9 concrete beam carries a higher load while deforming excessively compared to the nominal concrete beam. The failure pattern of the ETC9 beam is shown in Fig. 2. From the results, it is evident that the specimens with ETC provide better load-carrying capacity among all the beams[70]. It is followed by ETC reinforced beam specimen. Among all the specimens, ETC9 produces less flexural results when compared to the conventional beam. According to the results of this study, ETC9 concrete flexural beams outperformed reference concrete. As shown in Figs 3 & 4, the relationship between the load (x) and deflections (y) can be calculated as y = 0.5891x-2.2548. A workability model has been created using experimental results and regression analysis. The R-square value is almost equal to the one in Figs 3 & 4, indicating a strong correlation between the regression and test data.

3.2.2 Stiffness

For additional endorsements, the stiffness was also considered as a comparable parameter resisting the loads against ETC and collapse alongside deflections. According to Table 1 and Fig. 5, the conventional concrete mix required 12.5kN and 25 kN for the first crack load as the improvised concrete mix required 30.20 kN and 33.71 kN with corresponding ultimate loads for total failure at 60.5kN and 70kN as discussed previously for M20 and M25 respectively. The stiffness in terms of the maximum mid-span sagging was found to be 20.79mm for conventional beams against an ultimate load of 60.5kN and the same for the improvised concrete mix was 39.72mm against 85kN for M20 grade. Also, the stiffness in terms of the maximum mid-span sagging was found to be 23.64mm for conventional beams against an ultimate load of 70kN and the same for the improvised concrete mix was 54.94mm against 94.5kN for M25 grade. Hence the relative deflection gradient corresponding to the relative increase in ultimate load for the improvised concrete mix was found to be 0.17mm/kN. This means that the improvised concrete mix has shown its resistance by stiffness at a positive gradient of 0.17 mm for every 1 kN addition of loads concerning the total collapse due to cracking. In contrast, the ETC9 beams with cactus showed higher stiffness in the post-cracked stage due to the ability to transfer the tensile force at cracks and better control of shrinkage cracks and strain.

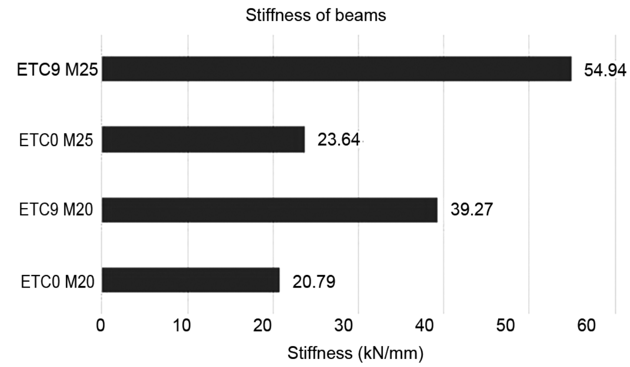

Fig. 5 — Stiffness of the flexural concrete beam.

Only vertical flexural fractures developed in all tested beams; no inclined cracks developed, even in the shear spans, as Fig. 2 illustrates. Approximately seven cracks were evenly spaced over the flexural span of each beam, with plain ETC0 and ETC9 having an average crack spacing of 90 mm. The plain ETC9 beam's crack growth and patterns were, for the most part, nearly exact replicas of the reinforced ETC beams documented cracking behaviour in the literature. In comparison to the standard ETC0 beams, all of the ETC9 beams containing cacti displayed lesser crack widths and slower crack progression. The number of cracks is unaffected by the addition of cacti; however, the width and rate of crack formation are reduced. This is mostly because, as was covered in the earlier sections, cacti help to improve the tensile behaviour of concrete. The conventional concrete for its mid-span deflection at 2.91 mm corresponding to an ultimate failure load of 60.55 kN was projected for an ultimate load of 85 kN as 2.14 mm whereas for the same 85 kN, the improvised concrete mix has shown only 2.14 mm for M20 grade concrete. The conventional concrete for its mid-span deflection at 2.57 mm corresponding to an ultimate failure load of 70 kN was projected for an ultimate load of 94.5 kN as 1.72 mm for M 25 grade concrete. Hence by the stiffness criterion, the relative durability with resistance for external loading has also been confirmed for the improvised concrete mix for its significant edge over the conventional concrete mix.

3.2.3 Ductility factor

Technically ductility would mean the mechanical property related to the plasticity of any material getting deformed under loading before the total fracture or collision occurs with an ultimate loading. For quantification, purpose ductility is taken as the ratio of maximum deflection to the first yield deformation of the beam specimens tested. The graphical representation of the ductility factor is presented in Fig. 6. Accordingly, the ductility factor for the conventional concrete was found to be 2.11 against that for ETC (M20) at 1.79 and the conventional concrete (M25) was found to be 2.40 against that for ETC9 at 1.57. That is the improvised concrete mix has shown a relative percentage increase in the resistivity to plastic deformations by 15.17% and 34.58% which again proves the efficacy of the improvised concrete mix over the conventional concrete mix M20 and M25 respectively. The experimental results have shown that cactus in the beam can reduce the brittleness of the failure mode of ETC beams.

3.2.4 Energy Absorption

Loading of any structure leads to the absorption of certain energy by the specimen tested for load vs. deflection in deciding the critical loading condition for first cracking, and ultimate collision with maximum deflection is expressed in force units of a moment as kN-mm. Figure 7 depicts the energy absorption of flexural concrete beams with and without ETC. For the present investigation, the conventional concrete mix exhibited an energy absorption level of 160 kN-mm whereas ETC registered 176 kN-mm which is nearly 70% more ability to withstand energy absorption fluctuation by the improvised concrete mix over the conventional one.

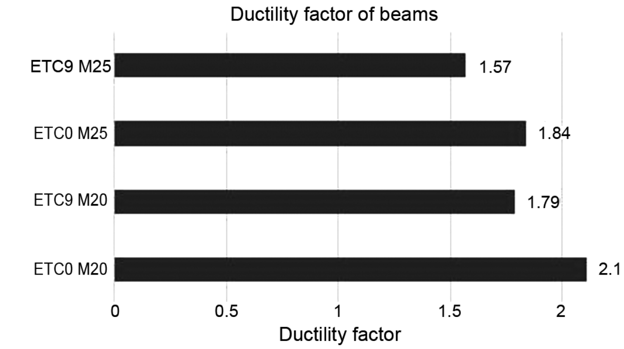

Fig. 6 — Ductility factor of the flexural concrete beam.

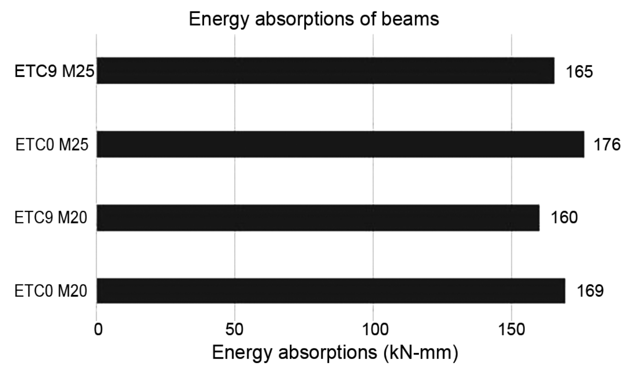

Fig. 7 — Energy absorption of the flexural concrete beam.

3.4.5 Load-carrying capacity

Studies on flexural beams are carried out, and the load-carrying capacity of the beam using ETC is compared with the control beam. A comparison of the load-carrying capacity of ETC0 and ETC9 is given in Table 1. The ultimate load-carrying capacity for the ETC9 beam is 50kN which is 1.33 times more than that of the beams cast with conventional concrete. The reinforced concrete beams ETC9 show better performance in the load-carrying capacity as well as an increase in the initial crack load. The initial crack load of ETC9 beam1 and ETC9 beam2 has increased by 47.9% and 30% respectively which is 1.9 and 1.3 times respectively more than that of the control specimen. According to this finding out, cactus fibres offer enough embedded length to prevent a pull-out failure. Therefore, an increase in fibre length of more than 35 mm did not result in an improvement in the load-carrying capacity of the ETC beams; on the contrary, it caused negative consequences such fibre balling, which caused the load-carrying capacity to drop. According to the experimental results, ETC-incorporated beams have better ultimate deflection, ultimate load, yield deflection, and yield load than standard concrete beams without ETC addition.

4 Conclusions

In this study, the flexural behavior of concrete beams incorporating Euphorbia tortilis cactus (ETC) was thoroughly investigated. ETC concrete beams exhibited superior performance compared to conventional concrete beams. Notable findings include:

- ETC concrete beams, particularly ETC9, demonstrated a significant increase in load-carrying capacity, with the ultimate load reaching 1.33 times that of conventional concrete beams. This substantial improvement highlights the effectiveness of ETC in enhancing the structural strength of concrete elements.
- ETC beams exhibited remarkable cracking resistance, as evidenced by a substantial increase in the initial crack load. ETC9 beams showed an impressive 1.9 times increase in initial crack load compared to control specimens. This enhanced cracking resistance is crucial for the durability and longevity of concrete structures.
- ETC9 beams displayed greater stiffness, improved control of shrinkage cracks, and strain, leading to a more robust and resilient structural response. The ability of ETC to mitigate shrinkage-induced cracks and strain is a promising feature for concrete elements. The cactus fibers embedded in ETC provided adequate length to prevent pull-out failure. This is a critical factor in ensuring the structural integrity of reinforced concrete elements.
- ETC-incorporated beams exhibited superior ultimate deflection, ultimate load, yield deflection, and yield load compared to standard concrete beams. These improvements highlight the potential of ETC as an effective additive to enhance the overall performance of concrete structures. These findings underscore the potential of ETC as a valuable additive for improving the mechanical properties and durability of concrete structures, offering a more sustainable construction material. The use of cactus fibers in concrete can contribute to eco-friendly and resilient building solutions.

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