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Structural Performance and Early Age Crack Resistance of High Strength Concrete Beams Reinforced with Borassus Fibers

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Abstract

This study investigates the structural performance and crack resistance of high-strength concrete (HSC) reinforced with Borassus fibers as a sustainable alternative to steel fibers. Concrete's brittleness and low tensile strength can lead to premature cracking, reducing durability and performance. While fibers can mitigate these issues, the effectiveness of different fiber types is not well established. Borassus fibers, derived from the Palmyra palm, offer environmental benefits and high tensile strength, potentially enhancing crack resistance. The research evaluates treated and untreated Borassus fibers in HSC using a four-point bending test. Beams (150 mm × 200 mm × 750 mm) were cured for 7 days, with crack measurements taken using a crack gauge detector. Results indicate that fiber-reinforced concrete significantly outperforms the control mix in load capacity, crack resistance, stiffness, and energy absorption. The ultimate load capacity increased by 38% with steel fibers (SF) and 46% with treated Borassus fibers (TBF), while untreated Borassus fibers (UBF) showed a slight decrease. First crack loads improved by 37% (SF), 46% (UBF), and 53% (TBF) over the control. TBF exhibited the most refined crack patterns, achieving a reduction in crack depth and width by 30% and 76%, respectively. increasing by 99% from 57 kN/mm (control) to 114 kN/mm, and the highest energy absorption at 1824 kN.mm.

Key words: Fiber-Reinforced Concrete (FRC), Borassus Fibers, Steel Fibers (SF), Load Capacity, Crack Resistance

1 Introduction

Concrete is a widely used construction material due to its durability and availability, but it is prone to cracking, which can compromise structural integrity (Ahmad et al., 2022; Lakhiar et al., 2018). High-strength concrete (HSC) offers superior mechanical properties compared to conventional concrete, making it suitable for demanding applications like high-rise buildings and long-span bridges (ACI Committee 363, 2011). However, HSC is more brittle and susceptible to cracks, which can reduce its durability, especially in harsh environments (Hadi & Elbasha, 2007). In recent years, researchers have focused on improving the toughness of conventional concrete by incorporating dispersed fibers into composite concrete mixtures. This technique has been successful in mitigating the formation, spread, and coalescence of early-age cracks, which addresses the brittleness issue of traditional concrete. Integrating fibers into the concrete matrix enhances its energy absorption, toughness, and resistance to premature cracking, thus serving as an effective method for crack arrest (Farooqi & Ali, 2018; Zhou et al., 2020).

Fiber Reinforced Concrete (FRC) is a type of concrete that includes fibrous materials as reinforcement. These fibers can be natural or synthetic, and they are used to improve the properties of the concrete, especially in terms of tensile strength, crack resistance, and durability (Abdelsamie et al., 2021; Yan et al., 2016). The incorporation of fibers into concrete enhances its mechanical performance, including increased resistance to cracking, impact, and thermal stress (Elgharbawy, 2023). Fiber reinforcement in beams mitigates these issues by enhancing the beam's toughness, ductility, and energy absorption capacity. The use of fibers reduces crack width, delays crack propagation, and increases the load-carrying capacity of beams, making them more resilient to dynamic and impact loads (Köksal et al., 2022; Singh et al., 2023). The early age crack resistance of fiber-reinforced concrete (FRC) is crucial for ensuring structural durability and longevity (Kang et al., 2023).

Steel fibers have been widely studied for their ability to enhance concrete's mechanical properties, including tensile strength, ductility, and crack resistance (Augustino et al., 2022). These fibers function as crack arrestors, reducing the formation and propagation of both microcracks and macro-cracks, thereby mitigating early age thermal and shrinkage cracking (Bakhshi et al., 2014). Steel fibers, while effective, contribute to environmental pollution and are prone to corrosion, leading to maintenance challenges (Kaaria et al., 2023). This has prompted interest in sustainable alternatives like natural fibers, which offer similar crack-resistance benefits while reducing environmental impact.

Borassus fibers, also known as Palm fibers and derived from the Palmyra palm tree, are gaining attention as a sustainable, eco-friendly, and cost-effective natural reinforcement for concrete, offering a promising alternative for enhancing the crack resistance of high-strength concrete. (Alhijazi et al., 2020; Jamik et al., 2017). These fibers possess high tensile strength and good adhesion to concrete, helping to bridge and arrest crack formation, improving both durability and load-carrying capacity (Sivaraja & Pillai, 2010). The use of Borassus fibers in structural elements, particularly beams, can enhance their resistance to cracking and deformation, leading to longer-lasting structures (Rajkohila et al., 2024)

Research indicates that the inclusion of steel fibers significantly increases flexural strength, impact resistance, and fatigue performance in reinforced concrete beams making them ideal for high-stress applications such as bridges and industrial structures. Hooked-end steel fibers, in particular, improve post-cracking behavior by bridging cracks and enhancing stress transfer across fractured sections (Hussain et al., 2022). Studies have demonstrated that steel fiber-reinforced concrete (SFRC) beams exhibit higher first-crack loads and improved toughness compared to conventional reinforced concrete beams. The study by Kan et al. (2022) utilized numerical simulations to analyze the crack propagation process in SFRC beams subjected to four-point bending, demonstrating that increasing the fiber content and length improves flexural performance. Steel Fiber Reinforced Concrete beams under cyclic loading reveals that steel fibers effectively arrest cracks and enhance ductility, particularly at volume fractions of up to 2%. Finite element analysis has further validated these findings, showing that SFRC beams exhibit superior resistance to crack formation and propagation compared to conventional reinforced concrete beams (Ranjbaran et al., 2018; Zhicheng & Nordin, 2022).

A study by Bittner & Oettel (2022) investigated the application of bamboo fibers in ultra-high performance concrete (UHPC) beams, finding that the fibers significantly improved flexural behavior and post-crack performance. Similarly, a study by Nwankwo & Ede (2020) examined the flexural strengthening of reinforced concrete beams using kenaf fiber-reinforced polymer laminates, demonstrating a 77.9% increase in ultimate load capacity and reduced beam deflections5. These studies highlight the potential of natural fibers as sustainable alternatives to synthetic reinforcements, offering improved crack resistance and load-bearing capacity while reducing environmental impact.

Borassus fibers enhance tensile, compression, and flexural strength in composite materials, with treated fibers showing superior durability and bonding. Flexural tests confirm their crack resistance (Priya et al., 2017). Incorporating Borassus fibers into the concrete used for beams can enhance their tensile strength and toughness, making them more resilient to various types of stress and deformation. This can lead to longer-lasting and more durable structures (Doko et al., 2018).

Steel fiber-reinforced concrete (SFRC) has been widely studied for enhancing beam load-bearing capacity and crack resistance, with optimal steel fiber volumes (1.5-2%) significantly improving flexural behavior due to fiber bridging (Kan et al., 2022; Ranjbaran et al., 2018). However, concerns about cost and environmental impact drive interest in natural fibers, which offer eco-friendly alternatives but generally exhibit lower mechanical performance (Bittner & Oettel, 2022; Nwankwo & Ede, 2020). Borassus fibers, in particular, show promise for improving tensile strength and crack resistance when treated, but limited studies have explored their use in load-bearing beams or compared treated versus untreated fibers (Doko et al., 2018). Most research focuses on general concrete properties rather than structural applications, leaving a gap in understanding Borassus fiber efficacy relative to steel fibers. This study addresses this gap by experimentally evaluating the flexural performance and crack resistance of beams reinforced with treated and untreated Borassus fibers, steel fibers, and plain concrete, offering insights into their comparative structural benefits.

2 Materials and Methodology

2.1 Materials

The Borassus fibers were obtained from South Sudan from Borassus palm trees leaves. Borassus fibers with a diameter an average diameter of 0.2mm and 0.18mm for untreated and treated respectively and an ultimate tensile strength of 541 MPa (treated) and 496 MPa (untreated) were used. Steel fibers were extracted from 0.75 mm diameter galvanized soft steel wire sourced locally in Kenya. steel fibers with an ultimate tensile strength of 358 MPa were used. CEM II/B-P 42.5N Portland pozzolana cement produced in Kenya to KS-EAS 18 and conforming to European standard EN 197 was used for all tests. Coarse aggregate was crushed stones of maximum aggregate size 12.5 mm with a specific gravity of 2.48 and bulk density of 1,542 kg/m³, and fine aggregate was river sand obtained from a local supplier and conforming to ASTM C33/ C33M (ASTM C33/ C33M, 2008) with a specific gravity of 2.40, fineness modulus of 2.92, and bulk density of 1,629 kg/m³. The superplasticizer (SP) used for workability enhancement was a high range water reducer Sika Viscocrete 20HE KE obtained locally from Sika (Kenya) Limited.

2.2 Formwork preparation and beam fabrication

For the beam preparation, wooden formworks were fabricated to cast beams of standard dimensions: 150 mm width, 200 mm depth, and 750 mm length. The inner surfaces of the formworks were smeared with grease oil to prevent adhesion to the concrete. Steel reinforcement bars were cut, bent, and arranged according to the design specifications. The reinforcement included 2T12 bars at the bottom, 2T10 bars at the top, and T6 shear links at 140 mm c/c to ensure proper structural integrity.

2.3 Material characterization

Reinforcement bar samples were prepared according to ASTM A370 (2020), with a length of 600 mm and a gauge length of 360 mm. Tensile testing was performed using a universal testing machine (UTM), applying a tensile load at a constant strain rate as specified. Mechanical properties such as yield strength, ultimate tensile strength, and elongation at fracture were determined. After fracture, the final gauge length was measured to calculate percentage elongation.

2.4 Concrete mix design

The concrete mix design was based on the optimal mix identified through mechanical property analysis in earlier stages of the study. The mixes were prepared using different fiber contents: 1.5% steel fibers, 0.5% untreated Borassus fibers, and 1.5% treated Borassus fibers. The control mix served as a baseline for comparison with fiber-reinforced concrete. The mix proportions are shown in table 2.1 below.

Table 2.1: Concrete mix proportions in 1 m^3 of concrete.

Mix	Coarse aggregate (kg)	Fine aggregate (kg)	Cement (kg)	Water (kg)	Fiber (kg)
1 (control)	1049	576	457	160	0
2-1 (1.5% SF)	1049	576	457	160	2.29
2-2 (0.5% UBF)	1049	576	457	160	4.57
2-3 (1.5% TBF)	1049	576	457	160	6.89

Where Control- conventional concrete without fibers, SF- Steel fibers, UBF- Untreated Borassus fibers, TBF- Treated Borassus fibers

2.5 Concrete mixing

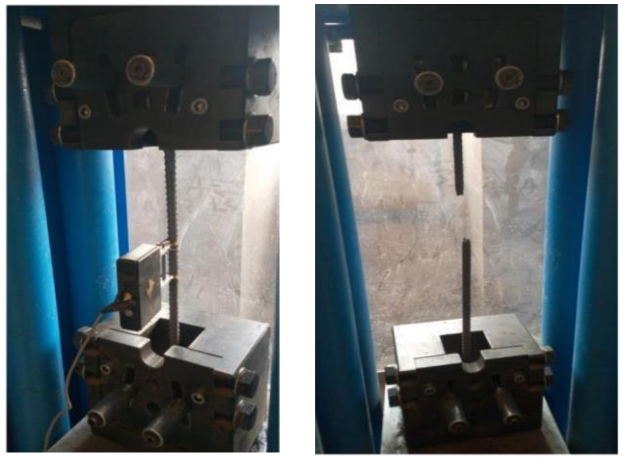
The mixing was carried out using a rotating drum mixer. Water and part of the SP was added to the mixer first and were mixed to spread the SP in the mix water. Cement was then added and mixing was carried until a uniform paste was obtained. Fine aggregate was added next and mixing continued to create a uniform mortar. Fibers were then added and mixing was continued to produce uniform consistency. Finally, aggregates were added starting with aggregated passing 9.5 mm and retained on 5 mm sieve, and later aggregates passing 12.5 mm sieve and retained on 9.5 mm sieve. Each addition was followed by mixing to uniform consistency. SP was added as necessary to maintain a workable mix. poured into the prepared formwork, vibrated for proper compaction, and then subjected to controlled curing in water for 7 days before further testing.

2.6 Preparation and curing of test samples

A total of 12 beams was prepared to be tested after 7 days of curing. The beams measured 150 mm × 200 mm × 750 mm. Three samples from each mix were prepared and average value was taken for consideration.

2.7 Tensile test on reinforcement bars

Reinforcement bar samples were selected according to ASTM A370 (2020), with a length of 600mm and a gauge length of 360mm. A universal testing machine (UTM) was used for tensile testing, applying a constant strain rate of 0.5 mm/min during the elastic phase, with the option to increase the rate after yielding. The UTM recorded force and elongation, and key parameters like yield strength, ultimate tensile strength, and elongation at fracture were obtained. After testing, the broken specimen was removed, and the final gauge length was remeasured. The test setup is shown in figure 2.1 below.



(a) *(b)*

Figure 2.1: Tensile strength testing of reinforcement steel bars set up (a) set up before the test, (b) sample after failure

2.8 Test on Beams

The structural performance and early-age crack resistance of the beams were evaluated using a four-point bending test per BS EN 12390-5:2009. The four-point bending setup applied two symmetrical loads at one-third spans. The beams were simply supported on 600 mm-spaced supports, following BS EN 1992-1-1:2004 (Eurocode 2). A 50-ton load jack applied the force, while an LVDT measured deflections. Load was applied in 2 stock unit increments until the first crack appeared, then reduced to 1 stock unit for accurate recording. The load was gradually increased to determine the first crack load and maximum load capacity. Deflections at different intervals were recorded using a data logger. Cracks were visually observed, and crack depth was measured using a Pundit L 200 crack gauge detector. Crack spacing, width, and propagation were analyzed to assess failure mechanisms and fiber effects on crack resistance. Figure 2.2 illustrates the test setup.

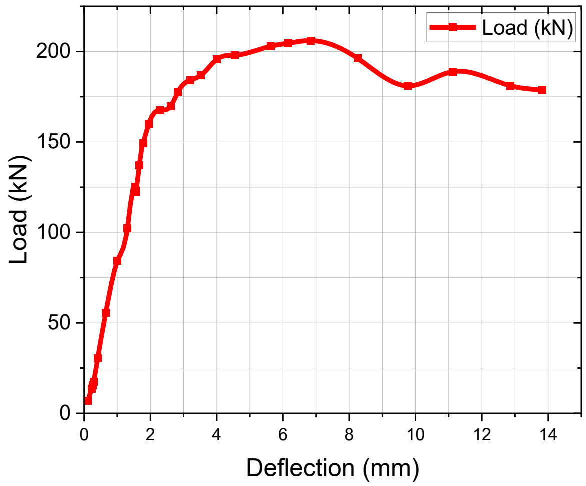
Figure 2.2: Beam test setup

3 Results and discussions

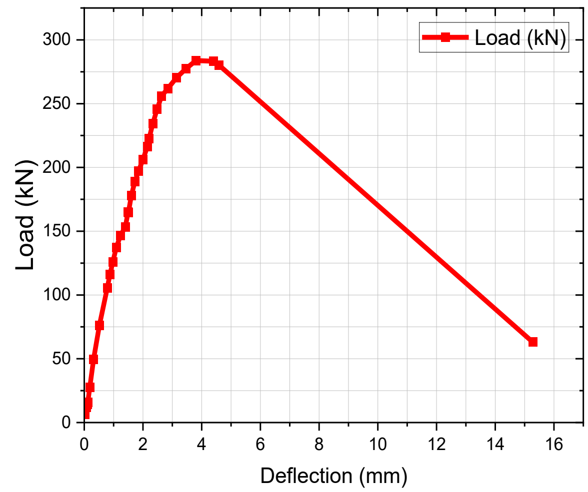
3.1 Load Bearing Capacity

3.1.1 Ultimate Capacity

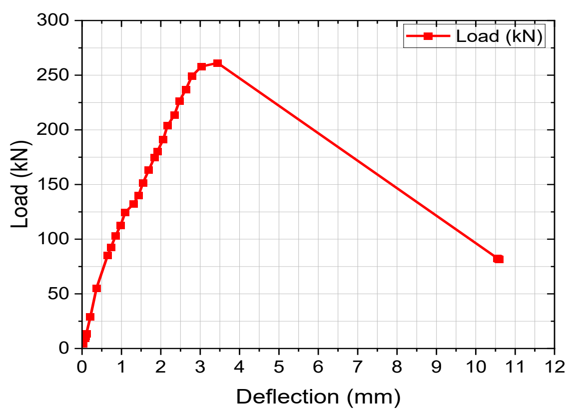
Figure 3.1 (a) to (d) illustrates the structural differences between fiber-reinforced concrete and the control mix. The control beam carried a load of 206 N, while fiber-reinforced beams exhibited higher capacities: 283 N for steel fibers (SF), 201 N for untreated Borassus fibers (UBF), and 300 N for treated Borassus fibers (TBF). Compared to the control, SF increased load capacity by 38%, UBF showed a slight decrease of 2.7%, and TBF achieved the highest increase of 46%. This indicates that fiber reinforcement enhances flexural resistance, with TBF performing the best. The superior performance of TBF over SF and UBF is due to improved bonding with the cement matrix, which enhances load transfer, crack resistance, and overall structural integrity.



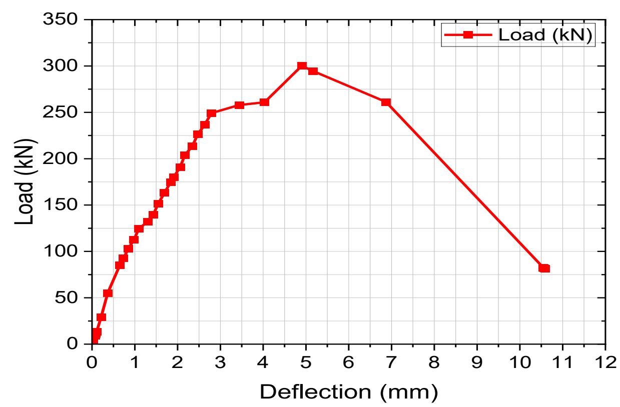
(a) Control mix.



(b) Steel fiber reinforcement.



(c) Untreated Borassus fiber reinforcement.



(d) Treated Borassus fiber reinforcement.

Figure 3.1:Compressive strength (a) Steel fiber reinforcement, (b) untreated Borassusfiber reinforcement, (c) treated Borassus fiber reinforcement, (d) Optimal fiber reinforcement with control.

3.1.2 First crack load

Figure 3.2 shows the graph for first crack load. The results for the first crack load demonstrate the impact of different fiber types on concrete's resistance to cracking. The control mix, without fibers, has the lowest first crack load at 56 kN due to its brittle nature. Steel fibers (SF) significantly improve this to 76 kN (37% increase), enhancing crack resistance through high tensile strength and stress redistribution. Untreated Borassus fibers (UBF) further increase the first crack load to 81 kN (46% improvement), acting as stress absorbers within the cement matrix. The highest first crack load is achieved with treated Borassus fibers (TBF) at 85 kN (53% increase), as treatment enhances fiber-matrix bonding, improving stress transfer and energy absorption. These findings highlight how fiber reinforcement enhances concrete toughness and tensile strength, with steel fibers providing high stiffness and natural fibersespecially treated ones, offering flexibility and superior bonding

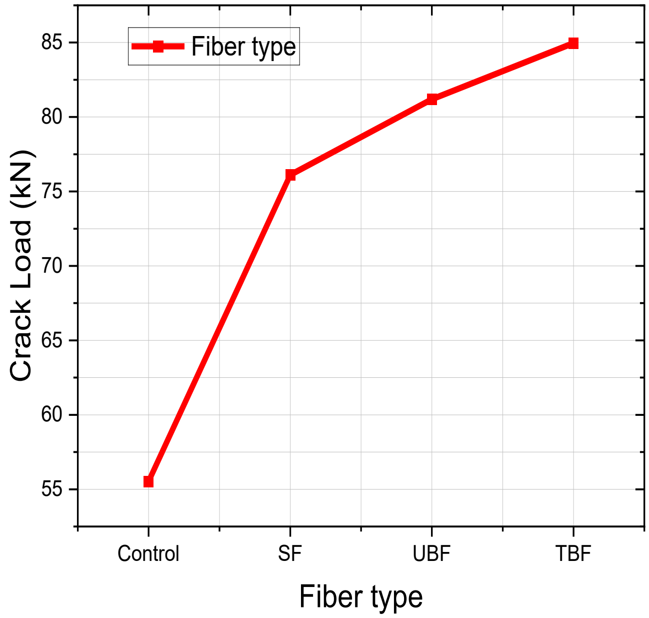


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Figure 3.2: Splitting tensile strength

3.2 Early age crack behavior

3.2.1 Crack patterns and distributions

Figure 3.3 (a)–(d) illustrates crack propagation and patterns in the tested beams. Most beams failed due to shear cracks, influenced by a mix of shear and flexural cracks. Control beams exhibited wide, abrupt shear cracks, indicating low crack resistance and sudden failure. Beams with 1.5% steel fibers (SF) showed narrower, more distributed cracks due to the fibers' crack-bridging ability, leading to gradual failure. Beams with 0.5% untreated Borassus fibers (UBF) displayed mixed crack patterns but had limited performance due to weaker bonding. In contrast, 1.5% treated Borassus fibers (TBF) resulted in finer, slower-propagating cracks, enhancing ductility and shear resistance. Overall, fibers, especially steel and treated Borassus fibers, significantly improved crack resistance, with treated fibers demonstrating the best performance.

(a) Control mix.

(b) Steel fiber reinforcement (1.5%).

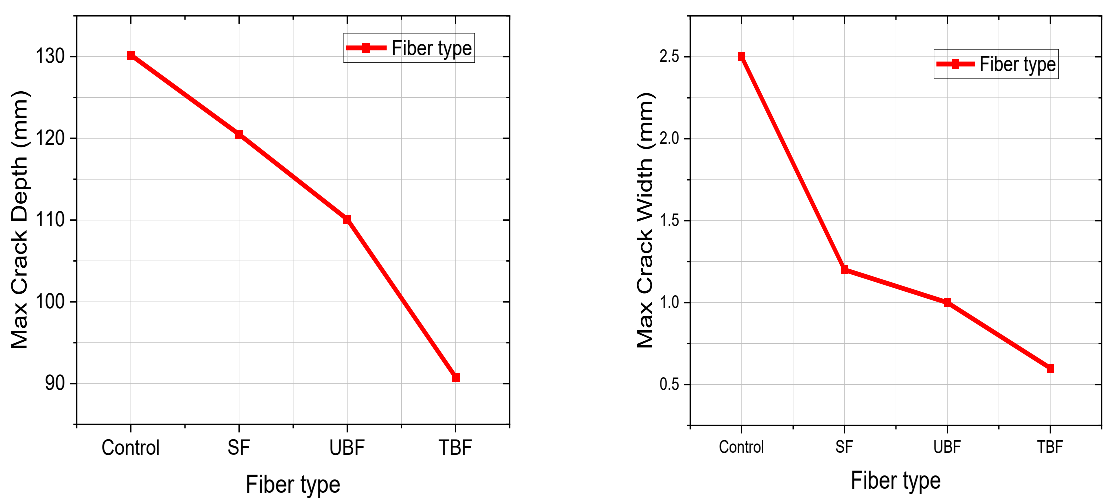
(c) Untreated Borassus fiber reinforcement (0.5%).

(d) Treated Borassus fiber reinforcement (1.5%).

Figure 3.3: Crack patterns for various beams.

3.2.2 Maximum crack width and crack depth

Figure 3.4 (a) and (b) show the crack depth and width results for the control and fiber-reinforced beams. The inclusion of fibers significantly improves crack resistance, with fiber type and treatment playing a key role. The control mix, without fibers, had the highest crack depth (130 mm) and width (2.5 mm). Steel fibers (SF) reduced the crack depth to 121 mm and width to 1.2 mm, a 7.5% and 52% improvement, respectively. Untreated Borassus fibers (UBF) performed even better, reducing crack depth to 110 mm and width to 1.0 mm, a 15% and 60% improvement. Treated Borassus fibers (TBF) showed the best results, with crack depth of 91 mm and width of 0.6 mm, achieving a 30% reduction in depth and 76% reduction in width, due to improved fiber-matrix bonding



(a) Maximum crack depth.

(b) Maximum crack width.

Figure 3.4: Maximum crack depth and width

3.3 Deflection and stiffness

3.3.1 Load-deflection behavior

The load-deflection behavior of the beams, as shown in Figures 4-12 (a) to (d), demonstrates how different concrete types respond to increasing loads. The control mix exhibited a gradual deflection increase, with a sharp rise after 125 kN, reaching 14 mm at 206 kN, and failure primarily due to shear. The steel fiber (SF)-reinforced beam showed low initial deflection, increasing to 4.6 mm at 284 kN, and then linearly to 15.2 mm after peak load, with a combined shear and flexure failure mode. The untreated Borassus fiber (UBF) beam had a maximum deflection of 3.5 mm at 260 kN, failing mainly by shear. The treated Borassus fiber (TBF) beam had the highest peak load of 300 kN with 4.9 mm deflection, and a combined shear and flexure failure mode. Steel fibers enhanced ductility, allowing greater deflection before failure, while Borassus fibers were less ductile, limiting deflection.

3.3.2 Initial Stiffness

The control beam's initial stiffness is 57 kN/mm, with the SF beam at 102 kN/mm, UBF at 74 kN/mm, and TBF at 114 kN/mm. The SF beam shows an increase of 79.5% in stiffness, indicating better resistance to early deflections. The UBF beam improves stiffness by 30% over the control but is less effective due to weaker bonding. The TBF beam has the highest initial stiffness, 99% greater than the control, due to the stronger bond between treated fibers and the matrix.

3.3.3 Energy absorption and toughness

Energy absorption is assessed from the area under the load-deflection curve. The control beam absorbs 1038 kN.mm, with rapid failure after peak load. The SF beam absorbs 1528 kN.mm, enhancing toughness through better stress distribution and delayed cracking. The UBF beam absorbs 1056 kN.mm, showing moderate energy absorption due to weaker bonding. The TBF beam absorbs the most energy at 1824 kN.mm, benefiting from better crack resistance and energy dissipation, though its deflection extension is not as much as SF

4 Conclusion and Recommendation

4.1 Conclusions

- Fiber reinforcement enhances concrete beam performance, improving load-bearing capacity, crack resistance, stiffness, and energy absorption, with treated Borassus fibers (TBF) performing better than untreated fibers (UBF).
- TBF outperformed steel fibers (SF) in first crack load improvement (53%) and showed superior crack control, reducing crack width by 76% and depth by 30%, demonstrating its effectiveness as a sustainable reinforcement.
- Stiffness and energy absorption were highest with TBF, increasing stiffness by 99% and reaching an energy absorption value of 1824 kN.mm, emphasizing the importance of fiber treatment for durability and structural efficiency

4.2 Recommendation

- The study demonstrates that treated Borassus fibers significantly enhance crack resistance, stiffness, and energy absorption in concrete beams. It is recommended that Borassus fiber treatment be standardized for use in structural applications, particularly in regions prioritizing eco-friendly and cost-effective reinforcement solutions**.**
- Compare the cost-effectiveness of treated Borassus fibers to other reinforcement materials.

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