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Enhancing the performance of ECC through chemically treated Jute fibre reinforcement

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Abstract

In this comprehensive study, the potential of chemically treated jute fibres as a reinforcement in Engineered Cementitious Composite (ECC) is thoroughly investigated. The alkali treatment process significantly enhances the interaction between these fibres and the cement matrix, resulting in substantial improvements in the mechanical properties of the concrete. Various parameters, such as direct tensile strength of the fibre, compressive strength, flexural strength, direct tensile strength of ECC, modulus of rupture, modulus of elasticity, bond strength between ECC and concrete, and bond strength between ECC and steel, are meticulously evaluated for both treated and untreated jute fibres integrated into the concrete. The research underscores the critical importance of maintaining an optimal fibre content, typically around 1.5%, to achieve a well-balanced mix design that ensures optimal composite performance. The study places strong emphasis on the adoption of sustainable and eco-friendly construction practices by incorporating biodegradable materials. Furthermore, it highlights the pivotal roles played by aspect ratio and interfacial bonding in influencing the stiffness, strength, and overall durability of the concrete. Ultimately, this research contributes valuable insights that advance the field of composite materials and encourage the adoption of sustainable construction approaches.

Keywords : Chemical treatment, ECC, Jute fibre, Mechanical properties

1. Introduction

In recent years, researchers have increasingly recognized the value of natural fibres as reinforcements in cement composites [1]. These fibres can be derived from various parts of plants, including stems, roots, leaves, seeds, and fruits. Among the available natural fibres, jute stands out as a notable choice due to its robust tensile strength and widespread availability [2-4]. However, researchers also consider other natural fibres like sisal, hemp, coir, banana, bamboo, ramie, and cotton due to their affordability and ease of extraction from renewable resources. Using natural fibres for reinforcement offers several advantages over traditional engineering fibres like carbon, glass, and minerals [5]. These advantages include their lightweight nature, remarkable flexibility, minimal impact on processing machinery wear, optimal aspect ratio, and high specific modulus. Moreover, these natural fibres are eco-friendly and biodegradable, setting them apart from conventional engineering fibres [6].

Engineered Cementitious Composite (ECC) represents a unique category of concrete that distinguishes itself by substituting coarse aggregates with fibres [7]. The maximum allowable fibre dosage in ECC is typically limited to 2% [8]. Until recently, synthetic fibres have been the predominant choice for ECC applications, while the use of natural fibres remains largely uncharted territory. Natural fibres have not been widely adopted in ECC due to concerns about their degradability over time. To address this limitation, a crucial step involves chemical treatment [9]. This treatment process effectively removes undesirable materials from natural fibres, enhancing their strength and making them more suitable for integration into the cement matrix [10]. The outcome is a reinforced material that not only retains the environmental benefits of natural fibres but also offers increased strength, a promising avenue for sustainable and durable construction materials [11].

In the specific case of jute fibres, they are typically subjected to alkali treatment (NaOH) to enhance surface cleanliness and expose more cellulose, thereby increasing interaction sites. This treatment approach aids in the removal of impurities and promotes a better fibre-matrix interaction. Additionally, natural fibres possess unique attributes related to their high moisture absorption, which is closely linked to interfacial adhesion and absorption [12]. Surface treatment procedures play a pivotal role in this context by generating an adhesive layer on the fibre cell wall, mitigating the elevated moisture absorption observed in the fibres' natural state [13]. These inherent characteristics carry implications for the utility of natural fibres in applications like fabrics and reinforcements in cementitious composites.

Incorporating chemically treated jute fibres into ECC is a significant step forward [14]. Extensive research has been conducted to integrate synthetic fibres into ECC; however, the untapped potential of natural fibres, hindered by their inherent hydrophilicity and biodegradability, has sparked renewed interest [15]. This study signifies a pivotal shift, advocating the incorporation of natural fibres into ECC, contending that with appropriate chemical treatments, natural fibres exhibit performance on par with their synthetic counterparts.[16,17]

2. Materials and methods

2.1 Cement

In the research study, Ordinary Portland Pozzolana cement (43 Grade) that conformed to IS: 8112-1989 [18] was used as the primary material for the experimental program. The properties of the cement are given in Table.1

Table 1 Properties of OPC cement.

Physical test	Results obtained	IS: 8112-1989 Specifications
Fineness (retained on 90-μm sieve)	8.3	10 maximum
Normal consistency	34%	–
Soundness Test (Le Chatelier method)	8 mm	10 mm maximum
Vicat time of setting (min)		
Initial	75	30 minimum
Final	470	600 maximum
Compressive strength (MPa)		
3 days	22.1	22.0 minimum
7 days	33.9	33.0 minimum
28 days	45.7	43.0 minimum
Specific gravity (Le Chatlier's flask)	3.15	–

2.2 Fine Aggregate

Natural river sand was used for the study. The sand was initially dried to remove any moisture content present. The sand was subjected to sieve analysis and specific gravity tests as per IS 383: 1970 [19]. Fine aggregate was classified as Zone III. The properties of the fine aggregate are given below in Table.2 and the fineness modulus graph are represented in Figure.1

Table 2 Properties of aggregates.

Physical Characteristics	Values of Fine aggregates	Values of Coarse aggregates
Fineness modulus	2.20	6.95
Specific gravity	2.82	2.78
SSD absorption (%)	0.83	1.09
Void (%)	35.7	37.4
Unit weight (kg/m3)	1680	1610

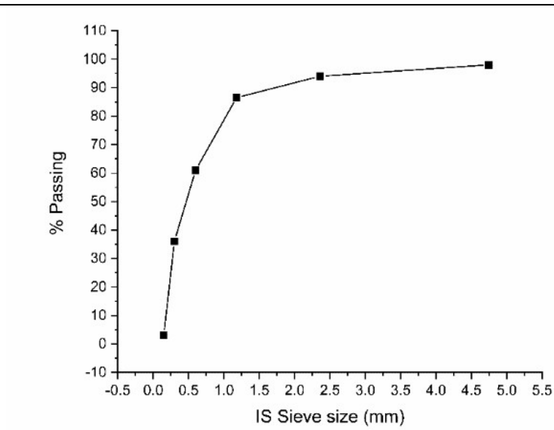

Figure 1 Fineness Modulus of Fine Aggregate after Sieve Analysis.

2.3 Sodium Hydroxide (NaOH)

Sodium hydroxide pellets were purchased from Erode Scientific and Chemicals Private Ltd. Lab grade. Sodium hydroxide was opted for the research purpose.

2.4 Jute Fibre

Jute fibres were obtained from Fibre Region Private Ltd in Coimbatore. The fibres were chopped into smaller fragments of length 10mm so as to add in the cement matrix [20]. The fibres were washed with water at room temperature to remove external impurities [21]. After wetting, the jute fibres were air-dried for 48 hours at 25°C before being placed in an oven. This step aimed to eliminate the initial moisture from the fibre surfaces. The residual moisture was further eliminated by subjecting the fibres to an oven temperature of 80°C for 72 hours [22]. The properties of the Jute fibre are given below in Table 3.

Table 3 Properties of Jute Fibre.

Properties	Values
Density	1.5 g/cm^3
Tensile strength	393-773 Mpa
Elastic modulus	10-30 Gpa
Lignin %	12–13
Hemi cellulose %	11.89
Cellulose %	61–71
Water soluble materials %	1.2
Pectin %	0.38
Waxes %	0.3
Aspect Ratio	100

2.5 Superplasticizer

For this experimental program, CONPLAST 430 was used as the superplasticizer. The dosage of the superplasticizer was determined through the V-funnel test. The recommended dosage after the test was found to be 1% [23].

2.6 Alkaline Solution

Approximately 35 grams of Sodium Hydroxide Pellets were added to 100ml of distilled water. The mixture was then placed on a magnetic stirrer and stirred for about 3 hours at 30°C. Jute fibres were soaked in a 5% (w/v) aqueous alkaline (NaOH) solution for 1 hour at 25°C. After the treatment, the jute fibres were washed 3-4 times with distilled water to remove any traces of NaOH from the surface. Subsequently, the jute fibres were neutralized by adding an acetic acid solution to achieve a pH of 7. The NaOH-treated jute fibres were then vacuum-dried at 80°C for 72 hours [24].

2.7 Mix Design

In adherence to the guidelines outlined in IS 10262:2019 [25], multiple mix proportions were formulated and are presented in Table 4. Control represents control mix, UTJ represents untreated jute and TJ represents treated jute with their proportions mentioned alongside. The upper limit for the inclusion of jute fibres was set at approximately 2%. The design of the mixture was tailored for M30 grade concrete, with a water-cement ratio of 0.44. In a departure from convention, jute fibres were utilized to replace the coarse aggregates. Both treated and untreated jute fibres, each measuring 10 mm in length, were introduced as substitutes for coarse aggregates. Varying proportions of these fibres, specifically 0.00%, 0.50%, 1.00%, 1.50%, and 2.00% of the concrete volume, were incorporated to assess the impact of fibre volume on the concrete's hardened properties. The specimens underwent a curing period spanning approximately 28 days, during which time their mechanical characteristics were meticulously ascertained.

Table 4 Mix Design of Treated and Untreated Sisal fibre in concrete.

Mix	Fibre Fractions (%)	Cement	Fine aggregate	Coarse aggregate	Water	Super plasticizer Dosage (%)
Control	0	1	1.6	2.78	0.44	1%
UTJ1	0.5	1	1.6	2.28	0.44	1%
UTJ2	1	1	1.6	1.78	0.44	1%
UTJ3	1.5	1	1.6	1.28	0.44	1%
UTJ4	2	1	1.6	0.78	0.44	1%
TJ1	0.5	1	1.6	2.28	0.44	1%
TJ2	1	1	1.6	1.78	0.44	1%
TJ3	1.5	1	1.6	1.28	0.44	1%
TJ4	2	1	1.6	0.78	0.44	1%

3. Results and discussion

3.1 Field Emission Scanning Electron Microscope (FESEM)

The jute fibre employed in the research underwent FESEM analysis both prior to and following a chemical treatment. The captured images in Figure 2 unequivocally reveal that the chemical treatment induced discernible changes in the fibre's surface morphology. Notably, this treatment effectively eliminated the protein layer, along with undesirable wax and other contaminants, consequently rendering the fibre more amenable to integration within the cement matrix. This integration in turn helps in achieving better mechanical properties of concrete [26,27].

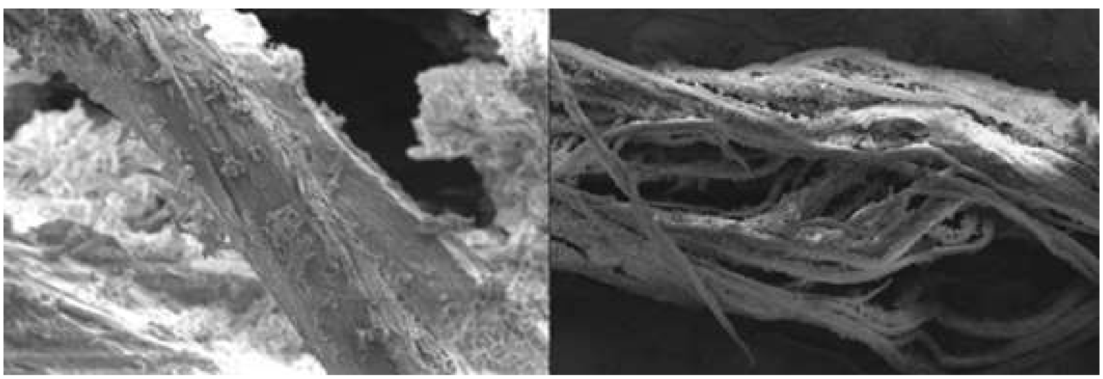

Figure 2 SEM images of fibre before and after the chemical treatment.

3.2 Direct Tensile Strength of fibre

To determine the tensile strength of the fibres after the chemical treatment, direct tensile strength tests were conducted at the Centre for Testing at PSG Tech. The Zwick Roell Z010 equipment was employed for these tests, with a test speed set at 100 mm/min. A total of 10 fibre samples, both treated and untreated jute, were tested to obtain the results. The final reading was determined as the average of these samples. The samples, with a length of 130 mm, were prepared to match the gauge length of the sample holder. The grip-to-grip separation at the initial position was maintained at 75 mm. The testing environment was controlled at a temperature of 25°C. The results of the test are shown in the Table 5.

Table 5 Tensile Strength of Fibres.

Specimen	Tensile Strength (MPa)										
	1	2	3	4	5	6	7	8	9	10	Average
Untreated Jute	12.98	12.47	13.15	12.56	11.97	13.42	12.33	13.67	12.97	12.37	12.79
Treated Jute	19.55	19.75	18.94	19.74	19.05	18.63	18.36	19.54	19.31	19.22	19.21

The tensile strength of the treated jute fibres increased by 50.19% on an average scale after the chemical treatment. Particularly in specimen 3 the strength gain was about 58%, while the least strength gain was noticed in specimen 6 at 38%. The reason being removal of protein matter and other unwanted materials.

3.3 Compressive Strength

To determine the compressive strength of the cement mortar, the process involved casting the concrete into steel moulds shaped like cubes measuring 70.7 x 70.7 x 70.7 mm as per IS: 4031 Part 6 [28]. 27 cubes were cast for each mix and the average of the three was considered. Once the cement mortar had set, the cubes were removed from the moulds and subjected to a curing period lasting approximately 28 days. Throughout the curing process, the pH of the curing tank was regularly monitored. Following the completion of curing, the cubes underwent compressive testing using a Universal Compression Testing Machine with a capacity of 200 tonnes. The compressive strength results are presented in Figure.3.

Chemically treated jute fibres in cement mortar demonstrated a slightly higher average strength of 33.21 MPa compared to untreated jute fibre concrete at 33.08 MPa, attributed to the removal of undesirable elements and the enhanced organization and structure of the fibres, leading to improved binding with the concrete.

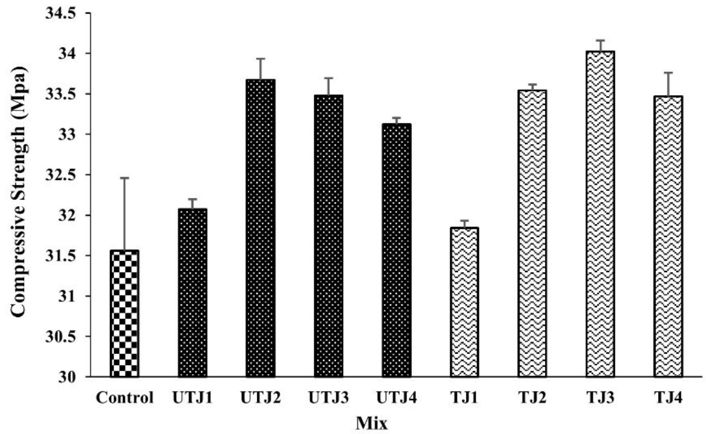

Figure 3 Compressive Strength of Control, Untreated and Treated Jute Fibre Mixes.

The TJ3 variant demonstrated the highest strength at approximately 33.48 MPa, marking a significant 7.73% improvement over the control mix, while exceeding 1.5% volume of fibres in UTJ4 and TJ4 led to a slight strength decrease of about 1.07% and 1.61%, respectively, attributed to higher fibre content relative to cement in the concrete mix. The primary factor behind the strength increase is the enhanced bonding between the treated fibres within the matrix and the cement composite. This improved bonding effectively holds the concrete together, thereby significantly enhancing its overall strength.

3.4 Direct Tensile Strength of ECC

The direct tensile strength of cement mortar with treated and untreated jute fibres were determined by casting the specimen in the shape of dog bone in accordance to ASTM D3039 [29]. The dimensions of the specimen are 330 mm x 60 mm x 30 mm.

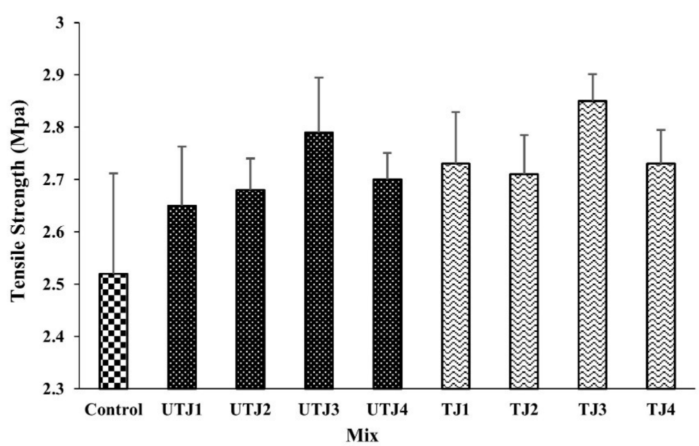

Figure 4 Direct Tensile Strength of Control, Untreated and Treated Jute Fibre Mixes.

For each mix 3 specimens were cast and the average value was considered and showed in Figure 4. The mean split tensile strength of the samples was found to be 2.72 MPa. TJ3 exhibited the highest split tensile strength where as the control mix without any fibres exhibited split tensile strength of about 2.52 Mpa. The coefficient of variation (CV) of 2.17% was seen in the results, indicates the relative variability in the data, showcasing a moderate level of dispersion. Comparing the control mix with TJ3, TJ3 exhibited 13.09 % increase in the split tensile strength. The rise in strength can be attributed to the C-O bond, also referred to as the cellulose bond, within the natural fibres. This bond undergoes stretching, leading to increased crystallinity, thereby significantly bolstering the overall strength in the treated fibres. In contrast to the untreated fibres, the treated fibres demonstrated notably higher levels of tensile strength, representing another contributing factor to the strength increase.

3.5 Modulus of Rupture

Modulus of rupture can be determined on hardened concrete prisms of standard size 25 mm x 60 mm x 350 mm after 28 days of curing as per ASTM C 1018-97 [30]. The specimen was placed in the flexure testing machine, and load was applied to the upper most surface of the prism. Load is applied without shock and increased continuously until the specimen fails.

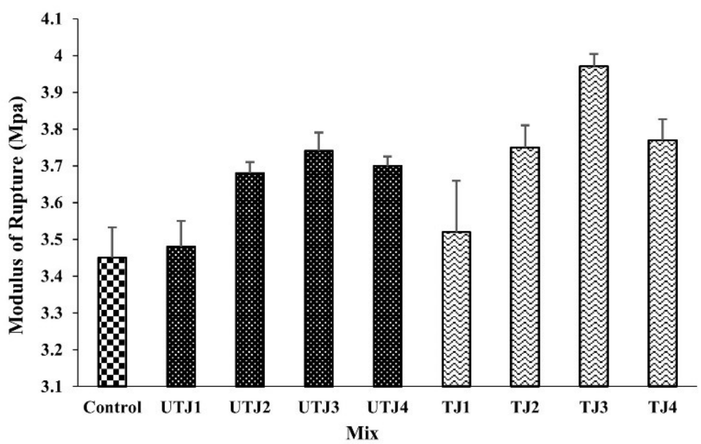

Figure 5 Modulus of Rupture of Control, Untreated and Treated Jute Fibre Mixes.

For each mix 3 specimens were cast and the values are showed in Figure 5. The mean Modulus of Rupture across all samples is 3.68 MPa, with TJ3 exhibiting the highest value at 3.97 MPa, indicating notable strength enhancement, while the control mix shows a Modulus of Rupture of 3.45 MPa. The percentage increase in Modulus of Rupture for treated samples compared to the control mix ranges from 1.74% to 15.07%, with TJ3 demonstrating the most substantial improvement, and a coefficient of variation of 5.13% suggests a moderate level of data variability among the results. The gain in strength observed in the treated fibres can be attributed to their enhanced binding properties, which, in turn, enable them to effectively restrain the concrete matrix from rupturing beyond a certain limit.

3.6 Modulus of Elasticity

The deformation patterns of concrete, crucial for assessing mechanical response and potential fractures under stress, are intricately linked to its composition and grade, with the elastic moduli, influenced by diverse chemical phases and microstructure, playing a vital role, as exemplified by the calculated modulus of elasticity in an M30 grade concrete mixture. This calculation involved subjecting cylindrical specimens, measuring 150mm in diameter and 300mm in height, to compression tests following the IS: 516-1959 standard [31]. To precisely assess deformation, a compressometer was utilized to measure alterations occurring within these cylindrical specimens and the values are showed in Figure 6. These meticulous evaluations offer a comprehensive understanding of the material's mechanical behavior, elasticity, and susceptibility to fractures.

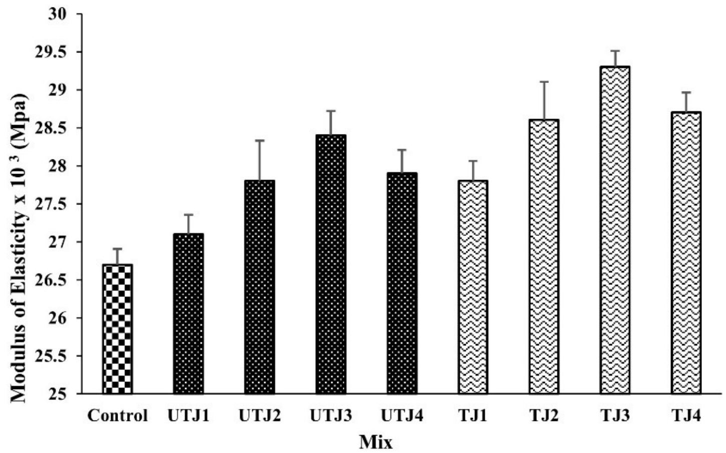

Figure 6 Modulus of Elasticity of Control, Untreated and Treated Jute Fibre Mixes.

From a statistical perspective, the mean Modulus of Elasticity across all samples is 28.04 x 10^3 Mpa, with a standard deviation of approximately 0.72 x 10^3 Mpa. The data indicates a progressive increase in Modulus of Elasticity with the incorporation of treated jute fibres, with TJ3 exhibiting the highest value at 29.3 x 10^3 Mpa. The CV stands at 2.57%, suggesting a moderate level of data variability. This analysis underscores the positive impact of jute fibre treatment on the material's elasticity and mechanical properties, as well as the consistency of results across the tested samples. The increase in strength observed in treated fibres is attributable to the enhanced binding capacity within the concrete matrix, stemming from enhanced fibre characteristics, thereby limiting rupture under stress and contributing to the overall structural integrity.

3.7 Bond Strength between ECC and Concrete interface

Cubes with dimensions of 150 x 150 x 150 mm are the recommended specimens for conducting bond tests on ECC and Concrete Interface. A bond test assesses an adhesive's ability to maintain contact with a surface or material while subjected to stress, or its ability to effectively bind two materials under stress conditions. This evaluation involves subjecting the bond to progressively increasing or constant force until it ultimately fails.

Upon completion of the mixing process, a fresh, workable, and cohesive mixture was poured into moulds for each specimen, followed by vibration on a vibrating table. Subsequently, the specimens were covered with lids and left to set for 24 hours before demoulding. These specimens were then placed in a curing chamber with a consistent temperature of 23°C and a relative humidity of 100%, where they remained until the testing day [32]. The results are discussed in Table 6.

Table 6 Bond Strength between ECC and Concrete.

Specimen	UTJ1	UTJ2	UTJ3	UTJ4	TJ1	TJ2	TJ3	TJ4
Bond Strength between ECC and Steel (kN)	62.1	65.4	66.9	66.3	63.4	67.8	70.5	69.7

ECC and Concrete Interface showed strengths ranging from 62.1 kN to 70.5 kN. Among the samples TJ3 exhibited the maximum strength of 70.5 kN. The significant bonding between the optimum dosage of fibres in ECC and the concrete matrix helped the specimen to achieve higher in TJ3 but when the dosage exceeded the optimum limit the fibre ratio increased causing the strength to rupture due to the inadequacy of the cement mortar.

3.8 Bond Strength between ECC and Steel

Cubes with dimensions of 80 mm x 80 mm x 80 mm serve as the recommended specimens for conducting bond tests between ECC and steel, in accordance with IS 2770 (Part 1)-1967 standards. This bond test is a crucial evaluation of steel's ability to maintain contact with ECC. During the specimen's casting, a steel rod was inserted within the ECC mix, and the specimen underwent a 28-day curing period. Subsequently, the bond between ECC and steel was tested using a Universal Testing Machine (UTM), continuing until bond failure occurred. To precisely measure the displacement of steel reinforcement, a deflectometer was employed [33] and the vales are showed in Table 7.

Table 7 Bond Strength between ECC and Steel.

Specimen	Control Mix	UTJ1	UTJ2	UTJ3	UTJ4	TJ1	TJ2	TJ3	TJ4
Bond Strength between ECC and Steel (kN)	20.3	20.7	21.4	22.4	21.9	21.4	23.4	25.7	25.4

The test results lead to the conclusion that the specimens incorporating treated jute fibres within the cement matrix outperformed the untreated jute cement matrices [34]. Specifically, in comparison to the control mix, the TJ3 specimen demonstrated a remarkable strength increase of approximately 26.6%. This significant enhancement can be primarily attributed to the improved surface morphology, which facilitated better adhesion of the steel within the cement matrix, ultimately resulting in higher strength [35].

4. Conclusion

In summary, the research outcomes underscore the substantial benefits of incorporating chemically treated jute fibres within cement matrices. The treatment process effectively removed unwanted elements, such as proteins and wax, rendering the fibres more compatible with cement. This enhancement resulted in notable improvements across various mechanical properties. Treated jute fibres demonstrated a remarkable 33.42% increase in tensile strength, leading to stronger and more resilient composites. Compressive strength saw a modest but positive improvement, primarily attributed to the removal of undesirable elements and enhanced fibre arrangement. Furthermore, the direct tensile strength of ECC displayed a significant 13.09% boost in split tensile strength with treated fibres, and the modulus of rupture exhibited a substantial increase, with TJ3 leading at 15.07%. The modulus of elasticity also showed an upward trend with the inclusion of treated jute fibres, with TJ3 recording the highest value. Additionally, bond strength tests between ECC and Concrete Interface revealed robust adhesion, while bond strength between ECC and steel displayed a notable 26.6% increase, emphasizing the pivotal role of improved surface morphology and enhanced adhesion. These findings collectively highlight the effectiveness of jute fibre treatment in enhancing the mechanical properties and durability of cementitious materials, showcasing the potential for more sustainable and eco-friendly construction solutions.

5. Acknowledgement

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6. Conflicts of Interest

The authors declare no conflict of interest.

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