



ORIGINAL ARTICLE

Reinforcing concrete with jute fiber: a holistic approach to mechanical performance, thermal insulation and carbon footprint reduction

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Abstract: The concrete, thus, as a modern-day building material, sustains serious challenges in the area of environmental and mechanical limitations. This investigation concentrates on the viability of jute fiber as a sustainable reinforcement stuff. For jute fiber-reinforced concrete (JFRC) composites, a complex explorative sequence was developed to examine mechanical characteristics such as split tensile strength, compressive strength, flexural strength, modulus of elasticity, and durability tests, for example, water absorption, chloride penetration resistance, water permeability, and thermal conductivity. The investigation went further to evaluate the embodied carbon of JFRC in order to appraise its environmental sustainability. Results show that adding jute fiber by a volume fraction of between 0.25 and 0.5% makes noticeable enhancements to mechanical characteristics. On the other hand, a larger fiber content (>0.5%) and longer fibers (17.5 mm) were also found to increase porosity and water absorption, adversely affecting durability. The study brings out the identification of optimum fiber length (12.5 mm) and content dictating mechanical action against durability. Jute fiber integration substantially reduces concrete's embodied carbon, making it an eco-friendly building alternative. This research generates an important understanding of natural fibers within concrete, opening a route to developing low-carbon, high-performance building materials.

Keywords: natural fiber, concrete, durability, sustainability, mechanical properties, embodied carbon

1 Introduction

Concrete is one of the most admired substances which has been used for its durability, availability, affordability, and high compressive strength [1]. This manmade paraphernalia can be transferred to various shapes and has high thermal insulation and fire and electric conductivity, giving it high acceptance worldwide. Besides these advantages, concrete is made from readily available and cheap materials all around the globe. Thereafter, its origination during the Roman epoch, its uses in many sectors have continued to grow [2]. The rapidly automated and developed world increases the need for concrete enormously [3,4]. Despite the advantages of concrete, its low fracture strain capacity, poor resistance to fissure development, weakness in terms of ductility, resistance to breaking, and vulnerability to low tension restrict its use [5–9]. Ordinary Portland Cement is a pivotal ingredient for manufacturing construction materials, about 0.8 to 1 kg of greenhouse gases emitted to the environment due to the manufacture of 1 Kg of OPC. Cement industries are liable for almost 8% of

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global carbon emission [4,10,11] Furthermore, in contemporary practices, various waste materials are being incorporated into concrete, significantly aiding in the creation of a sustainable environment [12–14] In the past few decades, sustainability issues and the increasing cost of artificial materials have led to a significant focus on organic fibers as a replacement reinforcement in polymer compounds, generating significant curiosity among many professionals in the field [15–19].

There are three major categories of fibers. For example, 1) synthetic or manufactured fibers 2) repurposed textiles, and 3) organic textiles. When differentiated with organic plant-based threads, the qualities of artificial yarns, such as steel, glass, and polymer fibers, are better, but steel fiber also poses a significant effect on corrosion [20]. However, compared to manufactured fibers, natural yarns are garnering greater study attention because of their inexpensive cost, internal curing process, lightweight nature, and little carbon impact [21–24]. Besides, greenhouse gases are produced when petroleum-based yarn is used to make the composites, although cellulosic fiber-based compounds may reduce this issue [25,26]. Based on their place of origin, innate fibers are often divided into triple groups: plant, animal, and mineral. Because they are readily available worldwide, plant-based yarns are generally accepted among other groups. The bast, petal, seed, grain, and wood are among the plant elements from which plant fiber can be extracted [27]. Natural fiber has emerged as the go-to reinforcing material in terms of both durability and biodegradability, since it is harmless and environmentally benign [28,29]. Jute is an organic fiber obtained from the *Corchorus* herb. This plant-based thread is elongated, supple, and lustrous, and it may be swung into robust, bumpy strings. Following cotton, this fiber ranks as the second most prevalent organic thread. Considering that jute fibers are biological engineering resources, they may be an affordable and environmentally friendly construction resource [16,30,31]. When it comes to fiber reinforcement, jute is the most popular, readily available, and reasonably priced substance. 14–20% hemicellulose, 70% cellulose, and 7% microfiber make up jute fiber (JF) [32,33]. It was also discovered that the annexing of coconut, roselle, hemp, sisal, sugarcane bagasse, and jute to concrete mixtures ameliorates concrete's tensile and compressive aptitude [34,35]. Jute's high specific qualities, inexpensive price, simplicity of supplies, and environmentally friendly composition make it an extremely significant biodegradable natural fiber [36]. In order to satisfy high strength, many admixtures and supplementary materials are applied in the concrete mix, but these stuffs often accelerate shrinkage during the primary periods and, subsequently, the cracking aptitude and the arete of persistence. To mitigate these problems, researchers incorporate fibers with concrete, which can decrease the shrinkage tremendously [37]. Jute fiber has a high water absorption capacity, which increases its capability to reduce crack width and uphold internal curing [38–40].

Numerous investigations have been handled to identify the mechanical phenomenon of jute fiber-fortified concrete [19,41–43]. The JFRC was studied such that with fiber fractions of 0.1-0.4% by volume and of lengths 20 & 25 mm, compressive strength was observed to uphold by 7% and splitting tensile strength to improve by 25%. More than this, a remarkable enhancement of shrinkage crack resistance was witnessed with jute fibers, minimizing up to about 61% of the crack region and about 62% of the optimum crack breadth, confirming the plausible applicability of jute yarn as an eco-friendly substance for the erection industry in arid zones [8]. According to another finding of the investigation, the use of Jute Fiber Reinforced Concrete Composites (JFRCC) with low fiber lengths-10-15 mm and very low fiber extent (0.1-0.25%) produces profound ameliorations in compressive, tensile, and flexural strengths, with tensile strength gaining as much as 35%. In contrast, longer fibers (20-25 mm) and a higher fiber content (>0.25%) triggered a fall in mechanical properties ascribed to an uneven distribution of fibers and greater porosity [44]. The study on jute fiber-reinforced compressed earth composites (JRCECs) showed that 0.5% of jute fiber at a normal amount of moisture caused a very substantial enhancement in tensile and compressive increasing tensile strength three times and compressive strength two times in comparison to unreinforced samples. Saturated and subsequently dried jute fibers, due to fiber degradation, swelling, and contraction, had inferior mechanical properties, yet they did help increase the post-failure remanent compressive strength in comparison to the contradicting samples. Whereas JRCECs at innate moisture contained the maximal average tensile and compressive strength, contrasting works indicated soggy jute yarns failed in improved tensile load than parched fibers, pointing at further investigation needed to clarify the discrepancies [45]. Tariq et al. [46] scavenged that the features of concrete, like flexural and compressive strength, are considerably enhanced in the presence of polypropylene, jute, and coir fibers, together with steel bars, with coir fibers

providing a good interfacial bond owing to their rough surface. Besides the previous enhancements, adding fibers also modified the shattering mechanism in fabricated concrete beams from the restraint support failure to central-span failure, thereby enhancing the structural performance. According to economic research, steel-reinforced concrete constructions may be made more affordable while preserving or enhancing their mechanical qualities by utilizing jute fiber polypropylene threads wrapped around steel bars

In most previous works, mainly the mechanical and thermal features of jute fiber-fabricated concrete were analyzed, but there was no such evidence about embodied carbon, rapid chloride penetration test (RCPT), heat insulation, and permeability of JFRC. Rapid chloride penetration and permeability of water are indications of durability and also indicate the life span of jute fiber-reinforced concrete, which is an immense apprehension to techies. Hence, this study mainly focused on chloride penetration through jute fiber-reinforced concrete composites, durability, environmental significance, and other mechanical and physical properties.

2 Materials and Methods

The motive of this current project is to highlight how jute fiber contributes to the durability and strength of the main construction component, which is concrete. Determining the ideal proportion of jute fiber required for efficient property enhancement was suggested.

2.1 Materials

For concrete preparation, OPC was implemented. Domar sand (**Fig. 1**) was exploited as dusty aggregate, and broken rocks with a nominal size of 20 mm were used as coarse aggregate. The origin of the Domar sand is the northern region of Bangladesh, specifically Panchagarh. After being cleaned three times to remove dust and salt, the sand was oven-dried for twenty-four hours at 110 degrees Celsius. Following drying, sieving was done according to ASTM D6913 [47]. The sieving was done by using an IRC sieve, and the shaking was done by a mechanical shaking machine.

To make the jute fiber-reinforced concrete, unprocessed raw jute, known as "Tusha Pat", was utilized as a jute yarn source. From the local market, the raw jute fiber has been purchased and brought to the laboratory of Rajshai University of Science and Technology, Rajshai. Tusha Pat is a golden-colored, 1.0–2.0 m long fiber shown in **Fig. 1**. The jute fiber was cut into two different pieces of about 12.5 mm and 17.5 mm in length for our experiment and used in the concrete.



Fig. 1. Domar sand and jute fiber

2.2 Concrete Mixtures

Several specimens containing various jute fiber percentages with two different lengths were made for this specific experimental project, and several testing procedures were used. Each of the mixes had its respective specimen cast. Concrete beams were cast for the flexural strength test, and cylindrical specimens were cast for other strength and durability tests. Compressive strength was done for curing days 7, 14, and 28 days. Remainder tests for hardened concrete were done only after 28 days of curing. The curing of the sample was conducted following ASTM C192/C192M–19 [48]. A well-defined

mixing procedure ensured uniform fiber distribution within the concrete matrix. The fibers were then added slowly to the concrete mix while stirring continuously to prevent clumping and to achieve uniform dispersion. No particular imaging techniques were used for the quantitative measure of fiber dispersion (i.e., X-ray, SEM, digital image processing). Rather, a simple visual inspection of fresh and hardened concrete samples was performed to look for clustering or uneven distribution of the fibers. **Table 1** breaks down the specific parameters that were analyzed in the study, which assists in clarifying the scope of research. Specimens were cast for every test, and nine distinct concrete mixtures were made. **Table 2** breaks down the variable parameters of the mixes.

Table 1. Parameter of this study

Constant Parameters	Variable parameters
Type of cement: Portland cement (PC)	Jute fiber as volume fractions of concrete - 0, 0.25, 0.5, 0.75, 1
Water/binder ratio: 0.45	Length of jute fiber- 12.5 mm, 17.5 mm
Binder: Fine aggregate: Coarse aggregate - 1:2:3	
Maximum size of coarse aggregate: 20 mm	
Sample type: Cylindrical, concrete beam	
Curing days: 7, 14, 28 days	

Table 2. Mix Proportions with Varying Jute Fiber Content and Length in Concrete

Mix	Fiber Content as volume fractions of concrete (%)	Fiber Length (mm)
Mix 1	0	
Mix 2	0.25	12.5
Mix 3	0.5	12.5
Mix 4	0.75	12.5
Mix 5	1	12.5
Mix 6	0.25	17.5
Mix 7	0.5	17.5
Mix 8	0.75	17.5
Mix 9	1	17.5

2.3 Fresh Properties of Concrete

Concrete workability evaluates how fresh concrete behaves from mixing to compaction. Freshly mixed concrete with varying amounts of jute fibers by volume fractions was implemented in the slump assessment by conforming to ASTM C143/C143M– 09 [49].

2.4 Hardened Concrete Properties

2.4.1 Compressive Strength



Fig. 2. Compressive strength test

For compressive strength testing, 81 cylindrical concrete specimens were produced. These samples corresponded to nine different concrete mixes with variations in jute fiber content and fiber length, as shown in Table 2. Each mix underwent testing at curing periods of 7, 14, and 28 days. Three specimens were prepared for each mix–curing duration combination, and the average of these three was taken to assess how jute fiber reinforcement influenced compressive performance. Each (cylindrical specimen) is (of 100 mm dia. and 200 mm) in (height). The compressive strength evaluation was conducted as illustrated in **Fig. 2**, while all appraisals were managed in conferring with ASTM C39/C39M–21 [50] by following the standard procedure for measuring concrete compressive strength.

2.4.2 Split Tensile Strength Test

Fig. 3 Twenty-seven concrete cylinders with varying jute fiber contents and lengths, as outlined in Table 2, were prepared to evaluate their split tensile strength characteristics. Each specimen had dimensions of 200 mm in length and 100 mm in width. The experiments aimed to assess how jute fiber affected the tensile strength of the specimens after a 28-day curing duration. To ensure accurate measurement of the tensile behavior of concrete, all procedures and curing intervals followed the guidelines specified in ASTM C496/C496M-17 [51]. The setup used for tensile strength testing is illustrated in **Fig. 3**.



Fig. 3. Split tensile strength test



Fig. 4. Flexural strength test

2.4.3 Flexural Strength Test

A set of 18 concrete beams with differing lengths and proportions of jute fibers were cast for flexural strength tests. The dimensions for each beam were 100mm x 100mm x 500mm. In the flexure test, two specimens were cast for each specimen, and the average of these two was taken. The post-cure jute fiber performance on the flexural behavior of concrete was examined after a curing period of 28 days. It is noteworthy that all procedures were done according to ASTM C78/C78M–21 [52], thus standardizing the evaluation of the material's structural performance. **Fig. 4** demonstrated how a concrete member failed when the flexural strength was determined.

2.4.4 Water Absorption Test

According to ASTM C642-21[53] guidelines, concrete water absorption is tested by measuring the mass increase that occurs after the material is submerged in water. For this test, the specimen needs to be dried before being submerged in a controlled environment. The dry weight of the specimen is then divided by this value. This test is one of the main ways to gauge how long concrete will last and how resistant it is to moisture. It is also one of the primary methods of measuring concrete's moisture resistance and durability over time.

2.4.5 Modulus of Elasticity

Concrete's elastic modulus was evaluated in accordance with ASTM C469/C469M-22 [54] using a device that measures the deformation of materials subjected to compressive forces. The setup involved applying a load using a universal testing machine on cylindrical concrete samples, where both stress and strain values were recorded. The modulus was calculated using the initial linear segment of the stress-strain curve to evaluate the material's rigidity and potential for structural application.

2.4.6 Rapid Chloride Penetration Test

A number of cylindrical concrete samples, each with dimensions of 100 mm in diameter and 200 mm in height, were produced and cured for each mix type. Following casting, the specimens were demolded and water-cured for 28 days at a temperature of approximately 23°C. The cylindrical samples' midsection was sawed to create 50 mm thick slices, which served as specimen preparation for the Rapid Chloride Permeability Test (RCPT). Based on ASTM C1202 [55], all slices were vacuum-saturated before testing to minimize variability. During the RCPT, the specimens were sandwiched between two acrylic cells, one filled with 3.0N NaOH and the other with 0.52N NaCl solution. The testing apparatus is shown in **Fig. 5**, illustrating the experimental setup. Over the course of six hours, a 60-V power source was delivered across the cells, and the current that resulted was measured and noted. The overall charge that passed through the specimen was then calculated.

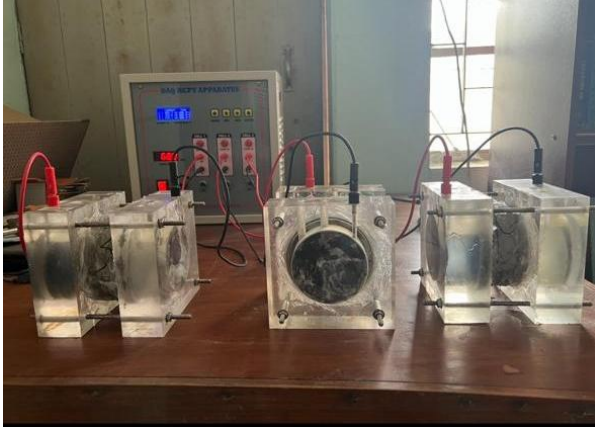


Fig. 5. Experimental set-up of RCPT apparatus



Fig. 6. Permeability testing machine

2.4.6 Water Permeability Test

Water permeability was tested as per IS:3085 -1965 [56]. In this method, concrete exemplars (100 mm dia. and 200 mm height) were equipped and placed in a water penetration cell. The permeability machine, mentioned in **Fig. 6** had a couple of specific regulators. The air pressure regulator was set to 5 kg/cm², and the water reservoir tube was filled to 75%, ensuring visibility through a glass tube. The specimen was secured in the cell with its cast surface perpendicular to the test surface. The water-releasing knob and air valve were partially opened, with the motor maintaining 5 kg/cm² air pressure. This pressure forced water to penetrate the concrete. The pressure was maintained for two hours before releasing it and removing the specimen from the cell. Then the specimen was split using a compression testing machine, where the highest depth of water penetration was marked and measured. A deeper water penetration indicated lower durability. The results were compared with other concrete samples to evaluate relative durability, providing insights into the potential durability of different concrete types.

2.4.7 Thermal Conductivity Test



Fig. 7. Setup for a thermal conductivity test

Concrete samples of 150 mm × 150 mm × 50 mm dimensions were examined for thermal conductivity in accordance with ASTM C177 [57]. The specimens were desiccated in an oven at 50 °C for 5–14 days until their mass became constant. Afterward, they were positioned in airtight plastic bags and were still left to desiccate prior to testing with the final instrument. The testing environment maintained a temperature of 25 ± 3 °C and a relative humidity of 60 ± 10%. A device for measuring heat flow was fitted with hot and no-plates and measured thermal conductivity every minute for 300 minutes. Mean sample temperatures were assumed to be 20 °C, with ΔT = 10 °C. An insulating ring made of wool was placed to reduce heat loss. The setup is shown in **Fig. 7**. The following equation was used to test the thermal conductivity.

$$\lambda = \frac{QS}{A(dT)} \quad (1)$$

where Q is the heat flux in watts, S is the specimen thickness in m, A is the active surface area, and dT is the temperature difference at degree Celsius.

2.5 Assessment of Sustainability

2.5.1 Embodied Carbon

Every construction component has an ecological footprint, which is manifested in the greenhouse gases that are released into the atmosphere. Selecting building materials involves several procedures, such as procurement, transportation, production, and placement. The significant dependence on finite energy resources during these procedures adds to the greenhouse gas emissions linked to construction undertakings. Carbon emissions linked to materials prior to their application in construction activities are referred to as embodied carbon. Although the amount of energy used varies depending on the material, it is always considerable per kilogram generated during industrial manufacturing processes [58]. The EC reckons of each mixture was determined using the literary texts that were accessible in order to assess the sustainability of concrete. The EC factors of each material were identified using the literature, and using the respective embodied carbon coefficients, the embodied carbon for all mix ratios with different jute fiber contents was determined [59]. **Table 3** contains the EC factors. The total EC of the concrete mix is determined through the summation of the embodied carbon contributions from each individual material used in the mix, as shown in the following formula:

$$EC_i = \sum_{i=0}^n \text{Amount of Material}_i \times \text{Embodied Carbon Factor}_i \quad (2)$$

Where i represents each material component in a mixture of concrete components (cement, fine aggregate, coarse aggregate, water, and jute fiber). Amount of material is in kg/m³, Embodied Carbon Factor is in kg CO₂ per kg of the material. This calculation provides the total embodied carbon in kg CO₂ per cubic meter of concrete. Each material's contribution is calculated by multiplying the amount of the material used by its corresponding embodied carbon factor. The total embodied carbon is then determined by summing the individual contributions of all materials in the mix.

Table 3: Embodied Carbon Value of RCC Components

Material	EC factors, CO ₂ kg/kg
Coarse Aggregate	0.0408 [12]
Fine Aggregate	0.0139 [12]
Water	0 [13]
Portland cement	0.93 [14]
Jute fiber	0.566 [15]

3. Results and Discussion

3.1 Slump

The influence of varying amounts of jute fiber on the slump values of composites using 12.5 mm and 17.5 mm fibers is illustrated in **Fig. 8**. The slump tends to reduce as the fiber content increases, independent of fiber length, which is a trend exhibited consistently. This can be attributed to the jute

fiber's thin cross-section and large surface-to-volume ratio [60]. Furthermore, the moisture-retaining nature of jute, due to its hydrophilic character, helps to lessen slump [61]. Nevertheless, the slump value is significantly reduced if fibers are incorporated, and this effect is more noticeable for shorter fibers (12.5 mm) than for longer fibers (17.5 mm). The variation in slump values between the two fiber lengths suggests that, when used at the same percentage, the workability of jute fiber concrete is somewhat less affected by longer fibers than by shorter fibers. The reason for this is that shorter fibers tend to increase the entrapped air in the concrete, and higher air content generally reduces slump more significantly [62]. This underlines how crucial it is to optimize fiber content, which must lead to adequate workability and the targeted mechanical properties.

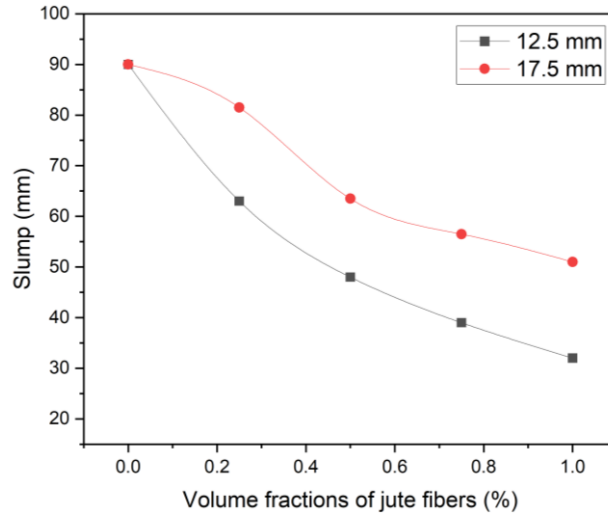


Fig. 8. Effect of volume and length of jute fiber on the slump of fresh concrete.

3.2 Compressive Strength

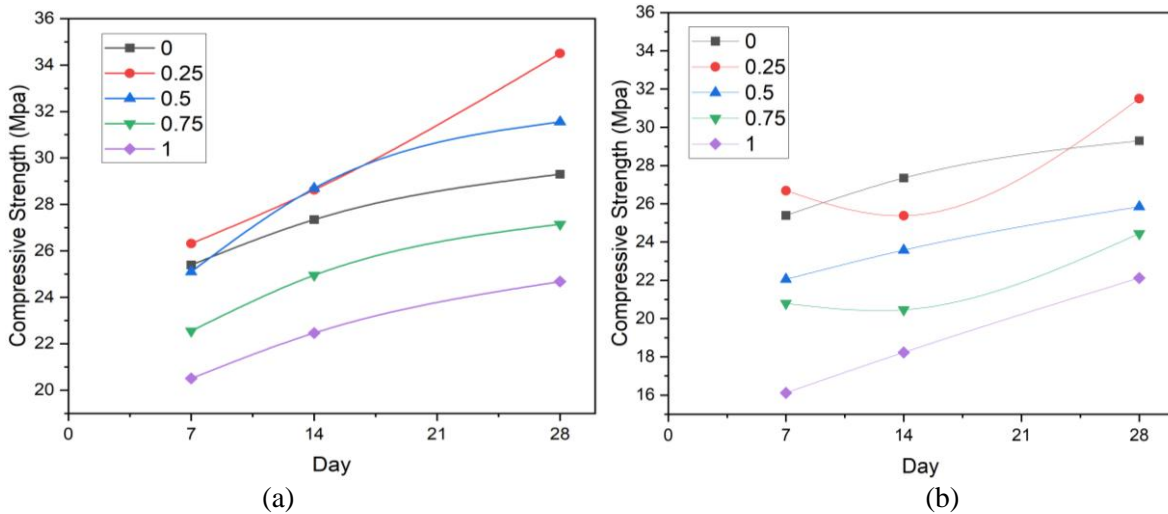


Fig. 9. Compressive strength of concrete blended with various proportions of jute fiber for a) the fiber length of 12.5 mm and b) the fiber length of 17.5 mm.

Fig. 9 illustrates and contrasts the concrete's resistance to compression, incorporating different dosages of jute fiber at varying levels within the 12.5 mm and 17.5 mm fiber lengths. The results of compressive strength measured after 7, 14, and 28 days of curing are displayed for each fiber type. For 12.5 mm fibers, 0.25% of jute gives maximum compressive strength; however, 0.5% is superior to 0%. As for 17.5 mm fibers, the presence of 0.25% increases their strength slightly, while 0.5% and above does reduce its strength and reveals diminishing returns. This is because adding fiber at a smaller volume firmly joins the composite's constituent parts, forming a solid and unified bond [63]. Additional fiber percentage increases result in more voids in the concrete, which lowers the ability of the concrete to withstand compression [64]. The sharpest drop occurs at 1% jute fiber, showing that an increased

number of longer fibers deteriorates the efficiency of the material. When looking at the two figures, it can be seen that the 12.5 mm fibers perform better in overall strength than the 17.5 mm fibers. The reason behind this may be that 17.5 mm fibers are attributed to increased fiber clustering and inadequate bonding with the cement matrix. Longer fibers tend to overlap, creating voids that weaken the concrete structure and hinder uniform dispersion, which ultimately leads to poor stress transfer efficiency, reducing overall mechanical performance. A comparable pattern was likewise observed in the research carried out by T. Zhang & others [65]. 0.25% consistently provides the optimum percentage for both fiber lengths in terms of the reinforcement of the matrix and material properties. The data shows a clear trend: Compressive strength increases with moderate amounts of fiber, but is significantly reduced on either side of an optimal percentage, particularly with longer fibers.

3.3 Flexure Strength

The flexural tensile strength is an important test for concrete against bending action. For both fiber lengths, a rise in modulus of rupture was noted at moderate fiber dosages, with a decrease in modulus of rupture occurring with all higher fiber contents, as illustrated in **Fig. 10**. The highest flexural strength value was revealed as the significantly lower level at 12.5 mm with 0.5% fiber content, describing a reasonable degree of reinforcement filling in the matrix within the material. Nevertheless, the modulus of rupture significantly decreases at larger percentages, most likely as a result of fiber concentration or inadequate bonding [66]. Likewise, in the case of 17.5 mm fibers, the other trend for flexural strength shows a maximum of 0.5% but decreases at higher percentages. The maximum values of flexural strength are obtained with 12.5 mm fiber at respective fiber percentages, while the lowest values of flexural strength are observed at 1% for both fiber lengths. To sum up, the other 12.5 mm fiber length with 0.5% dosage is less than all other cases than plain concrete, and compared with the larger length of the fiber, flexure length was also found to be decreased. As reported in research conducted by M. Zakaria et al., concrete's flexural strength will decrease when the fiber length increases beyond 10 mm [67].

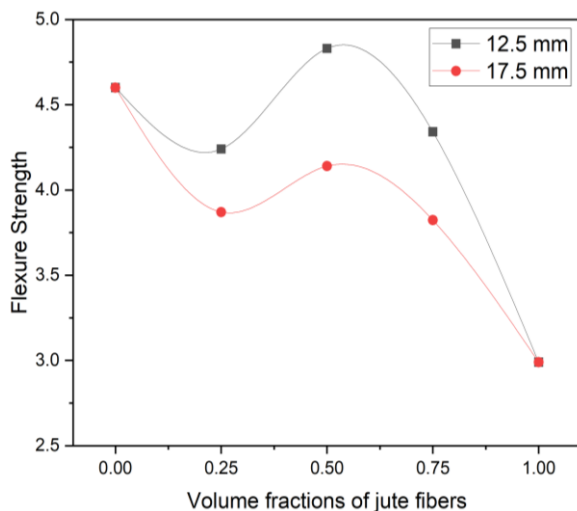


Fig. 10. Flexure strength of concrete blended with various proportions of jute fiber

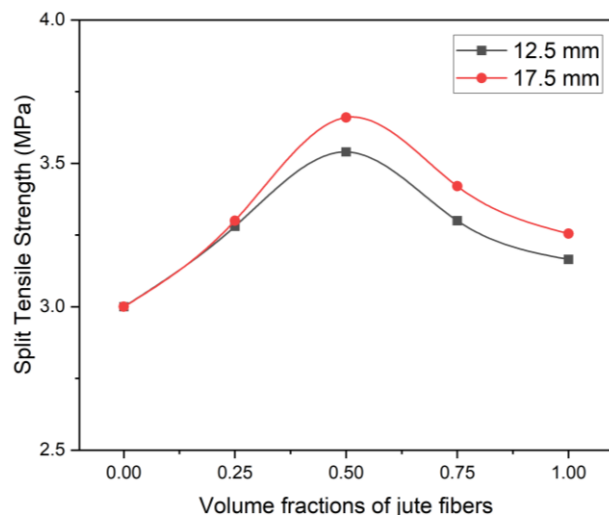


Fig. 11. Split tensile strength of concrete blended with various proportions of jute fiber

3.4 Split Tensile Strength

The relationship between split tensile strength and varying amounts of jute fiber for both 12.5 mm and 17.5 mm fiber lengths is presented in **Fig. 11**. It is quite apparent the split tensile strength increases until the optimum percentage of jute fiber; however, starts to decrease with the increase of jute fibers. For both fiber lengths, the maximum tensile strength peaks at the same 0.5% fiber content, indicating the optimal reinforcing effect. A similar result was conducted by J. Ahmed & others [68]. The strength diminishes after this percentage. This is because the jute fiber's distribution shifts from scattered to well-distributed and eventually to overcrowded as its content got higher, resulting in an initial improvement followed by a decline in the concrete's tensile strength [69]. The results show the highest

split tensile strength for 12.5 mm fibers at the optimum fiber content and indicate that longer fibers provide better enhancement of tensile performance. On the other hand, 12.5 mm fibers followed a similar trend, though lower strength values were observed at all percentages. Despite 17.5 mm fibers being the strongest in their tensile properties, a moderate fiber content always shows the greatest improvement in tensile properties, reaffirming that appropriately increased matrices may have a significant reinforcement improvement in fiber-reinforced composites.

3.5 Water Absorption

The moisture absorption characteristics of jute fiber-enhanced concrete, relative to its volume and incorporating different jute fiber proportions (0%, 0.25%, 0.5%, 0.75%, and 1%), are shown in **Fig. 12** for two separate fiber lengths (10 mm and 20 mm). For both lengths, water absorption steadily rises as the quantity of jute fibers increases. This occurs because higher fiber inclusion creates more voids in the concrete, which raises the concrete's capacity to absorb water [65,70]. The absorbance values were lowest at 0% fiber. 17.5 mm fibers have the greatest water absorption of 12.5 mm fibers, indicating that greater fiber length results in greater water uptake. This is because longer fibers were able to form more capillary channels that allow for greater water absorption. Hence, these results indicate that jute fibers can enhance the structural performance of concrete while elevating the uptake of water, with longer fibers being a larger contributor to moisture uptake. The data shows, however, how critical it is to balance both the fiber percentage and the length to achieve strength without sacrificing durability under wet conditions.

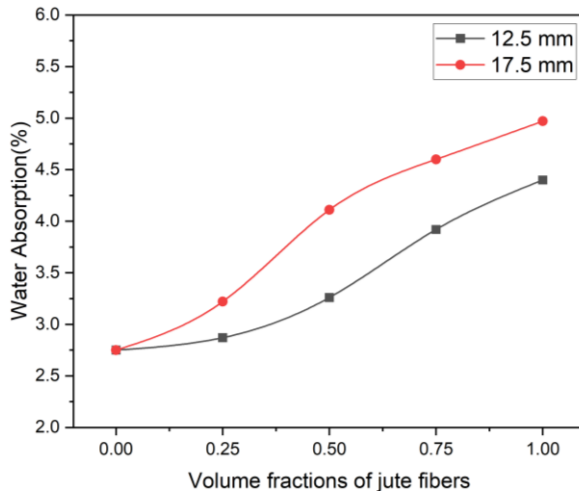


Fig. 12. Water absorption of concrete blended with various proportions of jute fiber

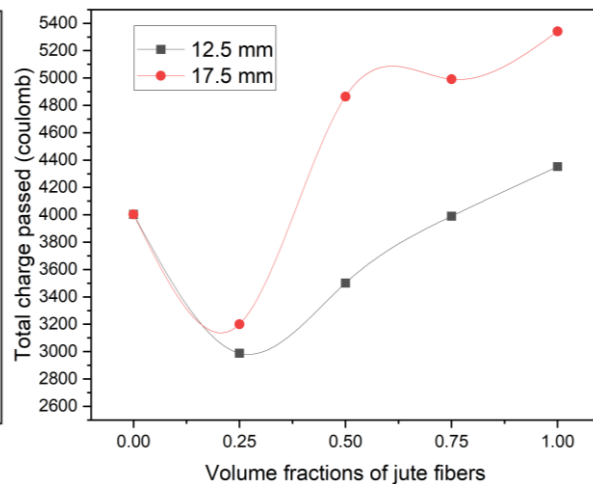


Fig. 13. Total charge passed in rapid chloride penetration test of concrete blended with various proportions of jute fiber

3.6 Rapid Chloride Penetration Test (RCPT)

During the Rapid Chloride Penetration Test (RCPT), the total electrical charge passed (measured in coulombs) for jute fiber-reinforced concrete with two fiber lengths (12.5 mm and 17.5 mm) and various fiber percentages is displayed in **Fig. 13**. It is generally noticed that incorporating jute fibers into the concrete matrix results in a pattern of increased permeability to chloride ions, which is demonstrated by the increased total charge passed. This indicates a reduction in chloride penetration, as evidenced by the decrease in total charge passed at 0.25% fiber content concerning 0% fiber content. However, beyond a certain point, as the fiber percentage increases this charge passed increases, which suggests higher susceptibility towards chloride ion ingress. The primary reason behind this trend is at low fiber content (0.25%), jute fibers help improve matrix integrity, reducing permeability and chloride ingress. However, at higher contents ($\geq 0.5\%$), fiber clustering and increased voids create pathways for chloride ions, increasing permeability. The microchannels formed by poorly bonded fibers facilitate ion movement, explaining the observed rise in chloride penetration at higher dosages. A similar study was conducted that introduced natural fibers such as jute, sisal, and coir significantly raises chloride ion ingress in concrete [71]. It was consistently observed that 17.5 mm fibers had a higher penetration

across both 12.5 mm and 17.5 mm fiber types, and the total charge passed was greater for the 17.5 mm compared with the 12.5 mm at the corresponding percentage of fiber content. A peak is observed for 1% fiber content and 17.5 mm fibers; greater fiber volumes in the mix enhance chloride ion movement when longer fibers are used, thus reducing the durability of concrete. To sum up, the inclusion of jute fibers initially enhances chloride resistance in low proportions, and in higher proportions, permeability increases. The fiber content and fiber length should thus be optimized to achieve a balanced improvement of mechanical properties and resistance to chloride ion ingress.

3.7 Modulus of Elasticity (MOE)

The connection between the modulus of elasticity (MOE) and the amount of jute fiber incorporated into concrete is demonstrated in **Fig. 14** for two fiber lengths: 12.5 mm and 17.5 mm. It becomes evident that the MOE for both fiber lengths increased with 0.25% fiber content, but later on, gradually declines as the fiber percentage continues to increase. MOE for the 12.5 mm fiber also peaks at 0.25%, suggesting enhanced elasticity stemming from the reinforcing action of the shorter fibers. The 17.5 mm fiber also shows a maximum MOE at 0.25% but the value is lower than the 12.5 mm fiber. A gradual reduction in MOE is observed as the fiber content increases beyond 0.25%, especially with fiber lengths of 17.5 mm and 12.5 mm, in which the lowest recorded values are seen at a fiber content of 1%. In contrast, the highest reduction is achieved with the 17.5 mm fiber, indicating the greater disruption of the matrix of concrete at elevated volumes for longer fibers. To summarize, the 12.5 mm fiber has a little bit better overall performance throughout the percentages. The fact that jute fiber length generally lowers the elasticity of jute fiber geopolymer concrete is further supported by a recent study conducted in 2024 [72]. According to numerous studies, using longer fibers in greater volumes tends to generate more internal voids and weaken the interfacial bond among the fibers, aggregates, and cementitious matrix.[73]. The relation between MOE and CS of the specimens of jute-reinforced concrete is depicted in **Fig. 15**.

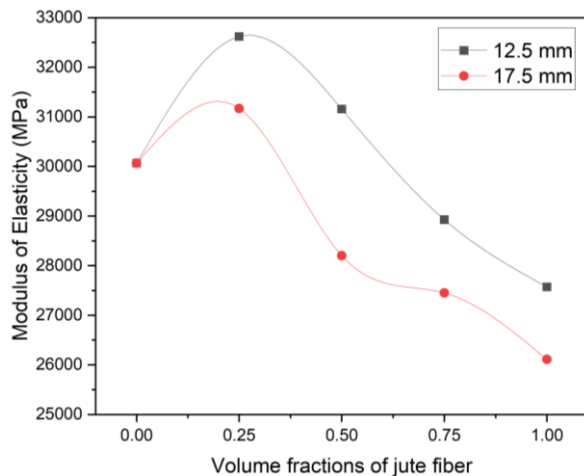


Fig. 14. Modulus of elasticity (MOE) of concrete blended with various proportions of jute fiber

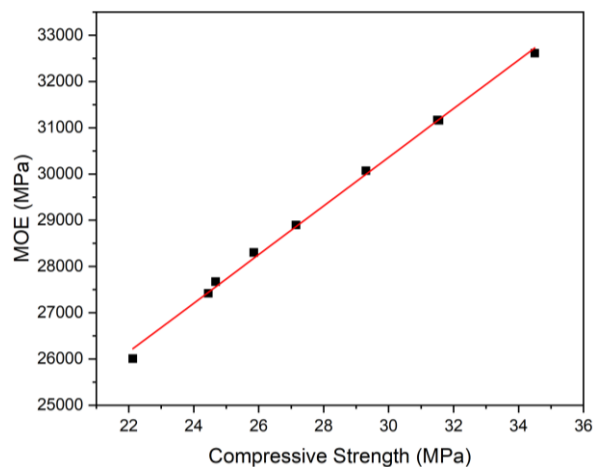


Fig. 15. Relation between modulus of elasticity with compressive strength in jute fiber concrete

3.8 Water Permeability Test

The penetration depth corresponding to the jute fiber volume fraction was an increasing function at both fiber lengths (12.5 mm and 17.5 mm), as illustrated in **Fig. 16**. The penetration depth increases with the rise in jute fiber content from 0% to 1% for both fiber lengths. At 12.5 mm fiber length, the penetration depth increases by 37.6 % (17.8 mm – 24.5 mm). For the 17.5 mm fibers, the depth rises from 17.8 mm to 28.3 mm, infers an increase of 59%. This indicates that longer fibers give higher water permeability. Fiber volume and length correlate with permeability. The steepest increase is in between 0.25% and 0.5% fiber volume, especially for the longer fiber length (17.5 mm). This is probably due to fiber-generated microchannels in the concrete [74], which enhances the water infiltration. Longer fibers are likely to create more interconnected voids within the concrete structure, which increases porosity and therefore permeability.

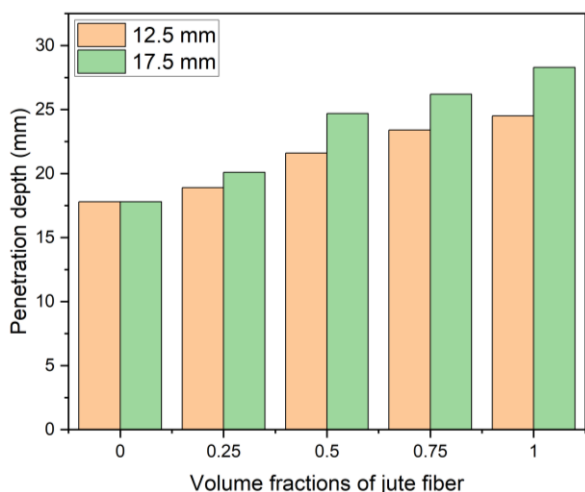


Fig. 16. Total water penetration depth in water permeability test of concrete blended with various proportions of jute fiber

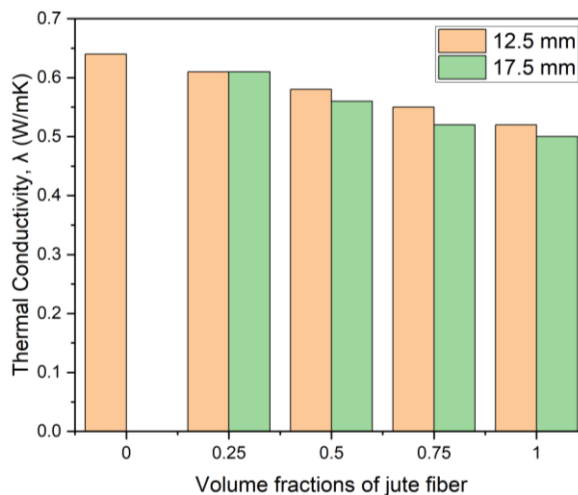


Fig. 17. Thermal conductivity test of concrete blended with various proportions of jute fiber

3.9 Thermal Conductivity Test

The findings from the thermal conductivity test for various proportions of jute fiber for two different lengths are illustrated in **Fig. 17**. Thermal conductivity tends to decline as jute fiber content increases, demonstrating jute fiber's insulating properties. This reduction is due to the fibers of jute forming air pockets that limit the transfer of heat. For 12.5 mm fibers, λ follows a decreasing trend, decreasing from 0.64 W/mK (0% fiber) to 0.52 W/mK (1% fiber), 18.75% decrease, whereas for 17.5 mm fibers, λ decreases from 0.64 W/mK to 0.50 W/mK, 21.88% reduction. That means longer fiber shows better performance of thermal insulation. This is because longer fiber traps more air, which affects poor thermal conductivity. Interestingly, for 0.25% volume fractions, thermal conductivity showed independent results irrespective of jute fiber length.

3.10 Embodied Carbon (EC)

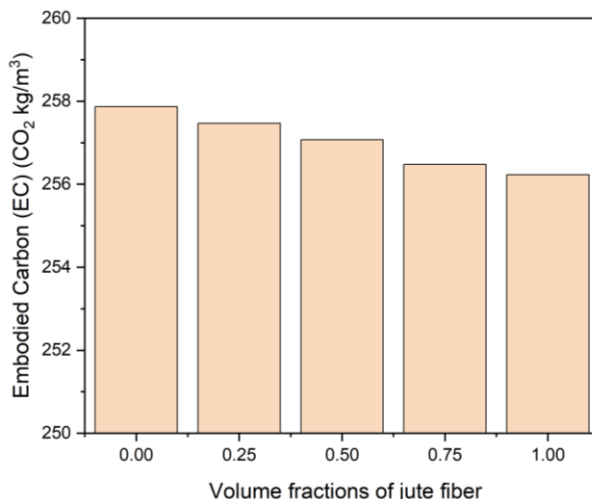


Fig. 18. Embodied carbon for various proportions of jute fiber.

The embodied carbon (EC) values also exhibit a gradual reduction with higher fiber inclusion, as described in **Fig. 18**, with fiber content of 0% to 1%, EC decreased from 257.87 kg CO₂/m³ to 256.23 kg CO₂/m³ (0.64% reduction). This indicates that including jute fiber in concrete reduces its embodied carbon. This trend further enforces the observation of decreasing embodied carbon values with increasing fiber contents, suggesting that jute, as a natural fiber and its composites, could be a sustainable choice for green housing. The reduction is probably because the natural, renewable property of jute partially substitutes high-carbon materials such as cement in the concrete mix. Moreover, the

lower overall density of fiber-reinforced concrete may reduce the volume of material required, further contributing to the drop in EC. The reduction in itself might seem small, but it can be significant when applied to large-scale concrete production.

5 Conclusions

This research evaluates the viability of jute yarn as a green supplementary material in construction, establishing jute's significance in terms of its mechanical characteristics, imperishability, and reliability of concrete from an environmental perspective. The tentative outcomes show that the inclusion of jute fiber in concrete microscopically improves mechanical phenomena, such as flexural, compressive, and split tensile strength, by incorporating 0.25% to 0.5% volume fractions. However, a higher fiber content (>0.5%) exceeding 17.5 mm length made the porosity higher, the water absorption higher, and also increased the chloride penetration along with the deterioration of durability performance. This condition leads to the trade-off between mechanical improvement and durability degradation, necessitating accurate fiber proportioning in actual applications. To address this, researchers emphasize the importance of optimizing fiber dosage and employing techniques such as fiber pre-treatment, SCM incorporation, and chemical modifications to balance strength enhancement with durability preservation. Finally, it is testimony to reduced thermal conductivity as high as 21.88%, thereby confirming better insulation ability. The embodied carbon furthermore decreases with the accrual in jute fiber amount, proving the environmental promise of JFRC and presenting itself as efficient low-carbon concrete compared to conventional ones.

In this research, a shorter-term evaluation was carried out, but longer-term evaluations, such as 90 or 180 days, may give additional information on aging effects and the long-term durability of construction materials incorporated with jute fiber. This present experiment was limited to early-age durability; however, in future experiments, additional curing durations will be carried out to deliver a better understanding of the everlasting achievement of this material, and the regional variations in material production could influence EC values due to differences in energy sources, manufacturing practices, and transportation distances.

The whole research bridges a significant gap in knowledge on mechanical, durability, thermal, and environmental characterization of JFRC to provide an overall assessment of performance. The results, therefore, pave the way to further research on JFRC for long-term behavior and application performance, with the role of advancing sustainable construction practices worldwide being complemented very well by jute fibers. This presents a great deal of interest for engineers and researchers who want to invent eco-friendly high-performance building materials for resilient infrastructure development.

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CRedit authorship contribution statement

Anwar Hossain: Formal analysis, Investigation, Writing –Experimental program & Results, Writing – review & editing. **Mehedi Hashan Riad:** Conceptualization, Supervision, Formal analysis, Investigation, Writing – original draft.

Conflicts of Interest

The authors declare that they have no conflicts of interest to report regarding the present study.

Data Availability Statement

Some or all data, models, or codes that support the findings of this study are available from the corresponding author upon reasonable request.

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