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Green reinforcement: exploring bamboo's potential in sustainable concrete construction

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ABSTRACT

Steel and cement production emits CO_2, spurring research for alternatives. Concrete materials are studied for shortages and enhancement. Construction, especially steel structures, will grow, but costs and shortages loom. Developing countries face steel scarcity and higher costs. Researchers explore natural or synthetic fiber replacements for steel, with bamboo showing promise. This study examines bamboo, with and without epoxy coating, as a steel substitute. Bamboo can replace steel in small or non-critical structures. The article explores bamboo's properties and behavior in reinforced concrete. Treating bamboo is vital for bond strength and flexural behavior under static loads. Three coatings are tested: natural, epoxy-coated, and epoxy with sand-coated bamboo. Twelve slab specimens are tested per Indian standards against steel-reinforced concrete slabs. The study evaluates bond strength, flexural behavior, and crack resistance using ultrasonic pulse velocity tests. Epoxy and sand-coated bamboo show significant improvement in bond strength, flexural performance, and concrete quality.

Keywords: Natural bamboo; treated bamboo; bond strength; flexural performance; ultra-sonic test.

1. INTRODUCTION

In cement composite matrices, bamboo emerges as a promising alternative to steel reinforcement, offering both affordability and environmental sustainability. With its low cost and renewable nature, bamboo presents a viable option for enhancing structural integrity. Its impressive mechanical strength, boasting a tension of approximately 370 MPa, further solidifies its suitability for construction applications [1]. Throughout history, bamboo has been a staple building material, particularly in underdeveloped regions where it's commonly used for hut-style constructions. Its utilization as reinforcement in cement matrices was recognized as early as the turn of the twentieth century [2]. Recent studies investigating the interaction between soil and geogrids have highlighted the superiority of bamboo grids over polymer geo-grids in terms of pull-out resistance. These experiments reveal that bamboo grids, readily available locally and boasting eco-friendliness and cost-efficiency, are particularly effective for slope stabilization. Consequently, many impoverished nations have embraced this technology [3].

Concrete is used to expand the bamboo column at its lower end. The concrete enters the bamboo for around 400 mm and reaches outside the column for more than 600 mm. The bamboo culm is held upside-down while the concrete is poured into it. Formwork is being employed, which consists of a length of PVC tubing wrapped around the bamboo. This answer is noteworthy since it is straightforward and sensible, and it is based on a thorough examination of the issue [4]. The importance of rethinking bamboo scaffold installation and design, as well as the efficient use of structural bamboo and safer bamboo scaffolds. The findings from four full-scale scaffolds that were constructed, tested, and ultimately failed in order to assess the bamboo columns' axial buckling behavior and pinpoint common failure modes, are given [5].

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The impact of age and diameter on the compressive strength of bamboo. The fiber density of the sclerenchyma tissues of two bamboo species, was examined with a scanning electronic microscope. The compressive strengths of the tissues ranged from 47.1 to 62.7 N/mm^2 and 37.8 to 61.9 N/mm^2, respectively [6]. It was also found that when the outside diameter grew, the strength drastically decreased. The upper portion of the bamboo has more tightly packed sclerenchyma fibers, which gives the bamboo additional strength. The word "bamboo" describes a densely growing kind of plant [7].

It is important to use caution while constructing beams since shear and crushing failures are frequent occurrences. Also mentioned was bamboo's benefit compared to other natural building products due to its quick growth rate—up to 25m in just 6 months [8]. Bamboo to be the best material out of all the readily accessible local indigenous options. In this study, the mechanical characteristics of bamboo were especially studied in relation to bamboo in concrete, and it was demonstrated that a bamboo-reinforced concrete beam had an enhanced maximum load of 400% when compared to unreinforced concrete [9]. To highlight the excellent features of bamboo, another deceptive comparison is made between the strength of bamboo per weight and the strength of steel per weight. Because the reinforcing in reinforced concrete only makes up a minor portion of the weight, this comparison is deceptive [10]. Steel is superior to bamboo in another manner because it is more ductile. Unlike steel, which behaves ductilely after yielding, bamboo fails in a brittle manner. Due to cracking and higher deflection, steel-reinforced concrete is able to give enough notice before failing as a result [11].

Using a hot-press technique, epoxy was infused into the material. Under strain, the majority of the composite bamboo splints broke. The bond is therefore undervalued. Yet, untreated composite bamboo specimens surprisingly had a stronger bond than raw bamboo, whether it had coatings or not. This could be caused by the composite bamboo's improved surface condition, increased resistance to moisture change and shrinkage, and the material's higher mechanical capabilities in the transverse direction [12]. In addition, bamboo's smooth surface minimises friction and permits the reinforcements to move without forming a solid bond, while splints shrink and lose touch with concrete when moisture is lost from them. Bond breakdown brought on by the alkalinity of concrete is another potential reason for bamboo's poor bond [13]. Splints that have been painted with oil or treated with Black Japan have, in comparison to untreated splints, 34% and 10% reduced bond strengths, respectively. Oils that dry quickly, like linseed oil, may be able to stop moisture absorption without lubricating the concrete or weakening the bond [14].

Despite this, bamboo splints used as reinforcement in concrete have a substantially larger area to perimeter ratio, which makes it more challenging for cement to fully hydrate inside the bamboo fibres. According to the test results, the node's Young's modulus is half that of the culm [15]. This difference is caused by the node's more complicated microstructure. From the surface of the culm to its interior, the fibres are shorter and vary in length. As a result, when bamboo is loaded, the fibres do not immediately experience stress; instead, they initially have a tendency to straighten, which results in greater stresses and a decrease in the measured Young's modulus [16]. However, the tensile strength was harmed more by the node's existence. The results of this investigation show that the bamboo's tensile stress vs. strain curve is linear until failure, and that the bamboo's tensile strength and Young's modulus were unaffected by sixty cycles of soaking and drying in a calcium hydroxide and tap water solution [17].

Although the durability behaviour of bamboo reinforcing concrete is outside the purview of this study, it was appropriate to describe long-term consequences like creep and durability to highlight the need for further research on the topic and to deter any hasty use of bamboo as reinforcement [18]. Without proper durability treatment and concern for creep effects, the structure's long-term safety cannot be ensured, deflection and cracking may exceed the values expected for short-term behaviour [19]. The minimum moisture content required to shield bamboo against fungus is unknown. Also, it is unclear how bamboo durability against fungal would change if it is embedded into concrete [20]. It's interesting to note that, according to the moment-curvature analysis, the stiffness of the slabs in the pre-cracked stage was lower than that of the theoretical model. The load-deflection behaviour of slabs reinforced with bamboo is clearly affected by the bond-slip mechanism from the moment the load is applied. The big initial deflection issue will be resolved and the bond slip strength will be increased by improving the way bamboo bars and concrete interlock [21].

Bamboo might be used as a concrete reinforcement. The stress-strain curves of bamboo make it evident that material has a lower stiffness modulus than steel. As a result, at maximum tension, it cannot prevent concrete from shattering. But the flexural test of the bamboo-reinforced beam revealed that the load-bearing capacity of a beam of the same size may be increased by combining bamboo with concrete reinforcement [22]. When compared to a plain concrete beam of the same size, the load-bearing capacity of a bamboo-reinforced concrete beam rose by almost three times. The maximum deflection of a beam made of unreinforced concrete is around 1.5 times that of a beam made of bamboo. If masonry offers a more affordable and environmentally friendly alternative to steel, even if its tensile strength is only approximately one-third that of steel, it is still enough for masonry structures. However, there is still a tonne of room for further study in this area [23].

2. MATERIALS AND METHODS

2.1. Bamboo

Because it was suggested that bamboo replace traditional steel bar reinforcing, mature bamboo with excellent tensile strength was employed. The three-year-old bamboo variety Bambusa arundinacea was employed in the investigation.

Bamboos for slab reinforcement that were one metre long and around three years old were acquired from a nearby market. The average node spacing was 300 mm, while the outside diameter at the base ranged from 30 to 40 mm. The well-seasoned, faultless, and randomly selected bamboo was only employed in its basal and middle parts. According to the tension test performed on the specimens without nodes, the maximum tensile strength was up to 293.05 N/mm^2, whereas it was only up to 133.01 N/mm^2 for the specimen with node. The values of the specimen with node's ultimate tensile strength were employed for the current inquiry. Figure 1 shows the image of bamboo used in this research.

2.2. Cement

The cement of grade OPE 33 is used in this research. The cement sample exhibited a specific gravity of 3.12, indicating a dense material. Consistency was measured at 31.2%, suggesting a balanced mix for workability and strength. Initial setting time was prolonged, at 110 minutes, while final setting time reached 225 minutes, indicating slower hydration kinetics. Soundness was within acceptable limits at 2 mm, indicating minimal expansion upon hydration. Notably, the concrete displayed commendable compressive strength, with axial strengths of 32.45 N/mm^2 at 7 days and 53.60 N/mm^2 at 28 days. This robust strength development signifies excellent curing and hydration processes, promising durability and structural integrity. These results underscore the effectiveness of the concrete mix design in achieving desired performance characteristics, essential for construction applications.

2.3. Fine aggregate

The analysis of the river sand sample revealed a fineness modulus of 2.86, indicating a moderately fine aggregate suitable for concrete production. With water absorption measured at 1%, the sand exhibited low porosity, which is favorable for maintaining concrete workability and durability. Bulk density was determined to be 1865 kg/m^3, indicating a compact material suitable for construction applications. The specific gravity of 2.65 suggests a typical density for sand. Bulking of sand was observed to be 2%, implying a slight increase in volume upon moisture addition, a common characteristic of fine aggregates. Organic impurities were minimal at 0.2%, meeting standard requirements for concrete production. These findings affirm the suitability of the sand for use in concrete mixes, ensuring adequate workability, strength, and durability.

Figure 1: Bamboo.

2.4. Coarse aggregate

The analysis of the aggregates revealed variations in properties between the 12 mm and 10 mm fractions. The fineness modulus by dry sieving for the 12 mm fraction was 6.654, while for the 10 mm fraction, it was 6.3. This indicates a slightly coarser gradation for the 12 mm fraction. Water absorption was observed to be lower for the 12 mm fraction at 0.40% compared to 0.50% for the 10 mm fraction, suggesting better resistance to moisture ingress for the larger aggregate size. Bulk density was higher for the 10 mm fraction at 1710 kg/m^3 compared to 1630 kg/m^3 for the 12 mm fraction, indicating denser packing of the smaller aggregates. Specific gravity followed a similar trend, with the 10 mm fraction exhibiting a higher value of 2.82 compared to 2.74 for the 12 mm fraction. These differences highlight the importance of carefully selecting aggregate sizes to achieve desired concrete properties, considering factors such as workability, strength, and durability.

2.5. Mild steel

The mechanical characterization of the mild steel specimen yielded insightful results. The unit weight was determined to be 0.617 kg, indicating the mass per unit volume of the material. Young's modulus, a measure of its stiffness, was found to be 2×10^2 N/mm^2, reflecting its ability to resist deformation under load. The ultimate tensile stress, representing the maximum load a material can withstand before failure, was recorded at 415 N/mm^2, showcasing the steel's strength. Furthermore, the percentage of elongation, which measures the material's ability to deform before breaking, was observed to be 21%, suggesting good ductility. These findings underscore the favorable mechanical properties of the mild steel, making it suitable for various structural and engineering applications where strength, stiffness, and ductility are vital factors.

3. RESULTS AND DISCUSSION

3.1. Pull out test

The pull-out test results provide valuable insights into the performance of different specimens regarding embedment and failure modes. The steel-reinforced concrete specimen exhibited the highest pull-out load at 59.1 kN, primarily experiencing tensile failure. Natural bamboo, while not as robust as steel-reinforced concrete, still demonstrated respectable performance with a pull-out load of 33.8 kN, primarily failing due to bond failure. Epoxy coated bamboo and epoxy with sand-coated bamboo showed improved performance compared to natural bamboo, with pull-out loads of 34.1 kN and 37.9 kN, respectively. Both epoxy-treated bamboo specimens primarily failed due to bond failure. Figure 2 and 3 shows the image of pull out test and graphical representation of results.

Figure 2: Pullout test.

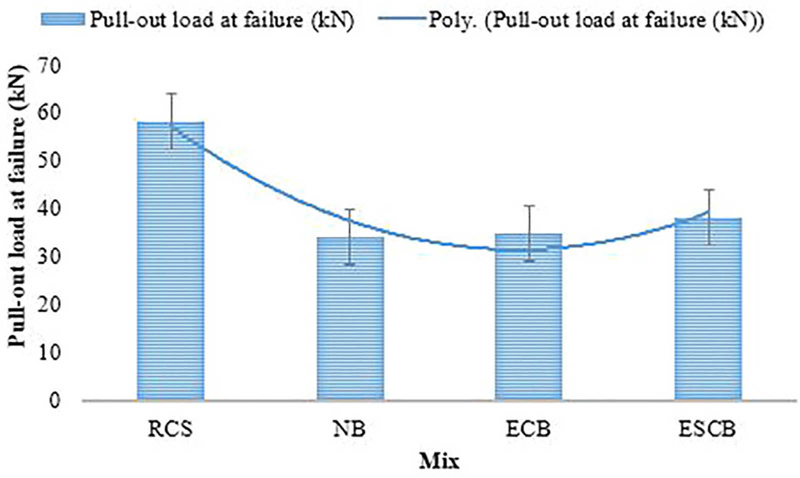

Figure 3: Graphical representation of pullout test.

Figure 4: Bond strength.

3.2. Bond strength

The bond strength results provide valuable insights into the performance of different specimens under embedment conditions. The steel-reinforced concrete exhibited the highest bond strength at 7.27 MPa, primarily experiencing tensile failure. Natural bamboo, while not as strong as steel-reinforced concrete, still demonstrated reasonable performance with a bond strength of 4.19 MPa, primarily failing due to bond failure. Epoxy coated bamboo and epoxy with sand-coated bamboo showed improved bond strength compared to natural bamboo, with values of 4.40 MPa and 4 MPa, respectively. The failure mode for epoxy-treated bamboo specimens varied, with bond failure being predominant. Figure 4 and 5 shows the image of bond test and graphical representation of results.

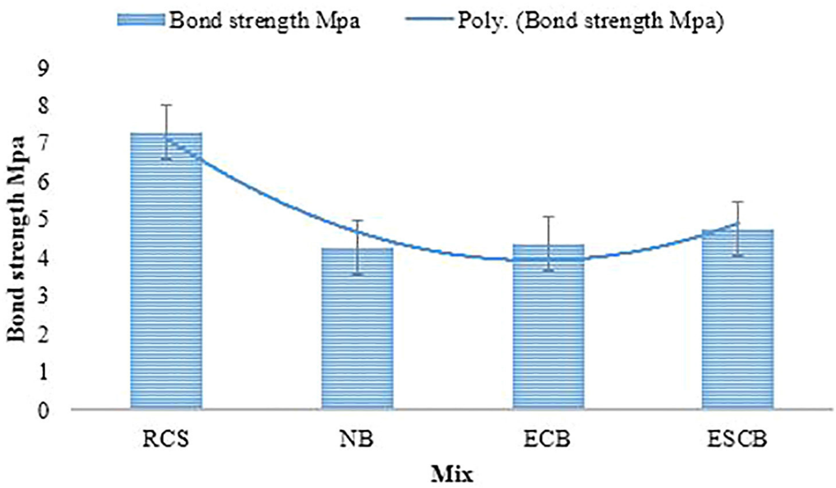

Figure 5: Graphical representation of bond strength.

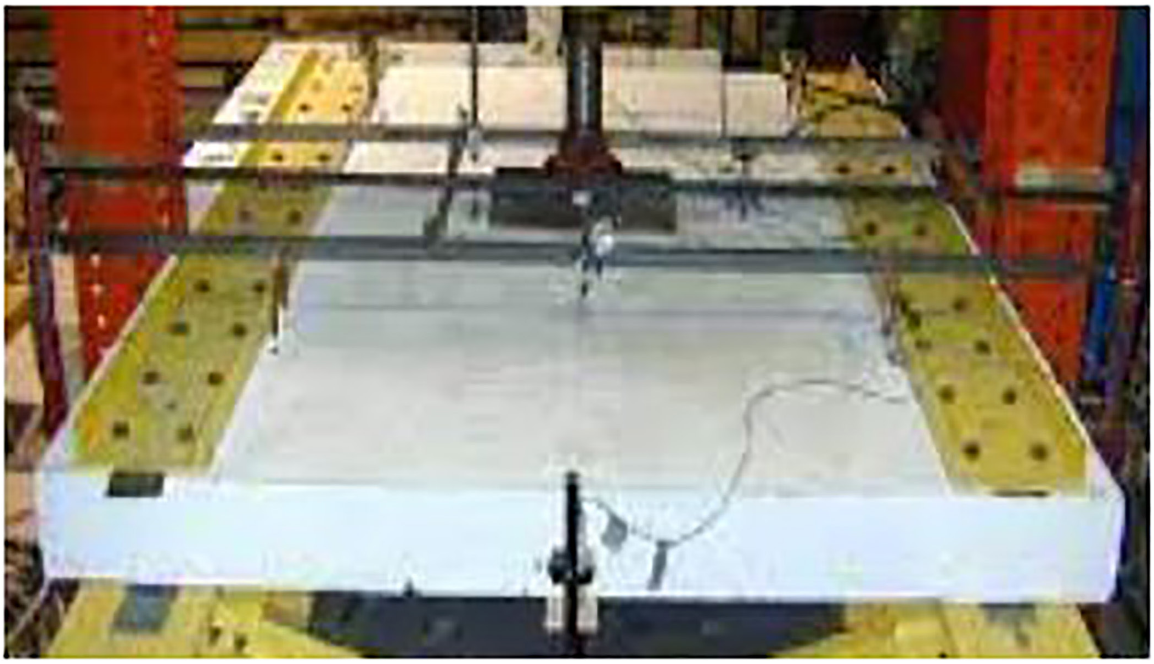

Figure 6: Flexural behavior.

3.3. Flexural behavior

The flexural behavior of the different mixes was evaluated based on the load applied and the corresponding deflection. The results indicate varying performance across the specimens. The SRC (Steel Reinforced Concrete) mix exhibited a load of 43.06 kN with a deflection of 2.16 mm. Natural Bamboo (NB) demonstrated higher load-bearing capacity with 33.10 kN load and a deflection of 1.91 mm. Epoxy Coated Bamboo (ECB) mix showed a load of 36.06 kN with a relatively higher deflection of 2.89 mm, while Epoxy with Sand-Coated Bamboo (ESCB) recorded a load of 42.29 kN with a similar deflection of 2.84 mm. These results indicate that the Epoxy with Sand-Coated Bamboo (ESCB) displayed the highest load-bearing capacity among the tested mixes, suggesting its potential as a viable alternative for reinforcement in structural applications requiring flexural strength. Figure 6 and 7 image of flexural behavior and graphical representation of flexural behavior.

3.4. Ultrasonic pulse velocity test

The Ultrasonic Pulse Velocity (UPV) measurements provide insights into the velocity of sound waves through the different mixes. The SRC (Steel Reinforced Concrete) mix displayed the highest UPV at 4.52 km/s, indicating

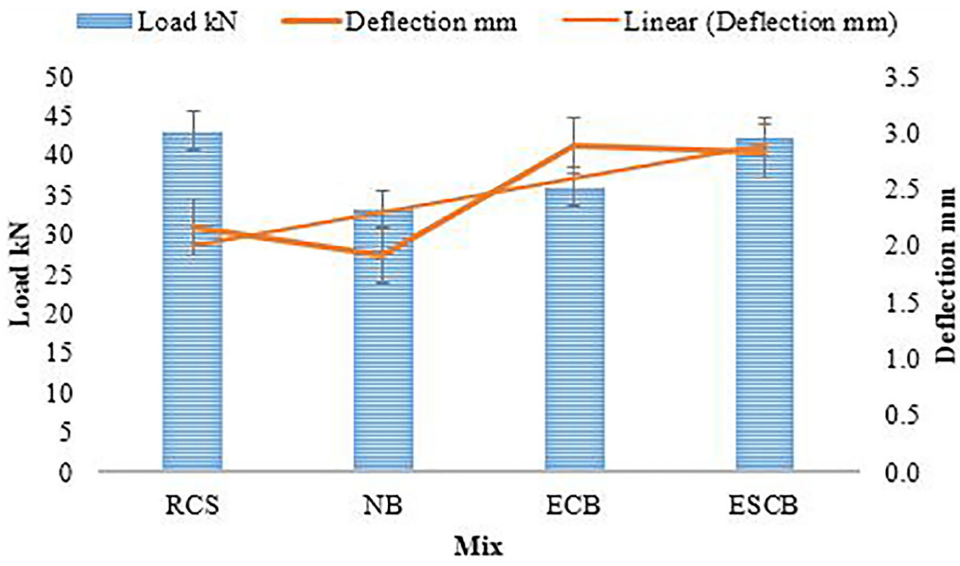

Figure 7: Graphical representation of flexural behavior.

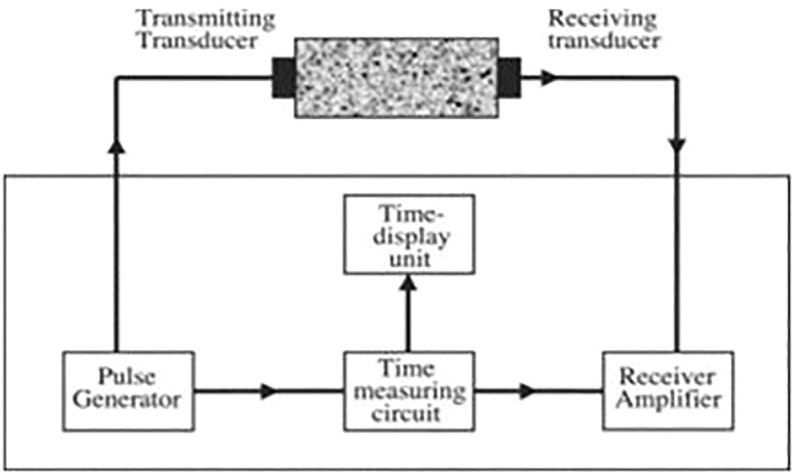

Figure 8: Ultrasonic pulse velocity test.

efficient transmission of sound waves through the material. Natural Bamboo (NB) exhibited a slightly lower UPV of 3.54 km/s, followed by Epoxy Coated Bamboo (ECB) with 3.25 km/s, and Epoxy with Sand-Coated Bamboo (ESCB) with 3.45 km/s. These results suggest that the SRC mix, being conventional concrete with steel reinforcement, has the highest integrity in terms of sound wave transmission, possibly due to the homogeneity and denser nature of the material. However, the UPV values for bamboo mixes indicate decent structural integrity, with NB demonstrating the highest velocity among the bamboo mixes. These findings imply the potential suitability of bamboo-reinforced mixes for structural applications, albeit with slightly lower performance compared to conventional concrete. Figure 8 and 9 image of ultrasonic pulse velocity and graphical representation of ultrasonic pulse velocity test results.

3.5. Static load test

3.5.1. Steel reinforced concrete (SRC)

The test results outlines the response of a structural reinforced concrete (SRC) specimen under static loading conditions. Here's the analysis of the data: Initially, with no applied load, both displacement (δ) and stress (σ) were zero, as expected. As the load increased incrementally from 5 kN to 70 kN, the displacement (δ) of the specimen increased gradually from 0.48 mm to 7.71 mm. Correspondingly, the stress (σ) experienced by the specimen increased steadily from 50 N/mm^2 to 700 N/mm^2. The strain (ε) also increased linearly with the load, ranging from 0.813×10^{-3} to 13.058×10^{-3}. This data provides insights into the structural behavior of the SRC specimen under

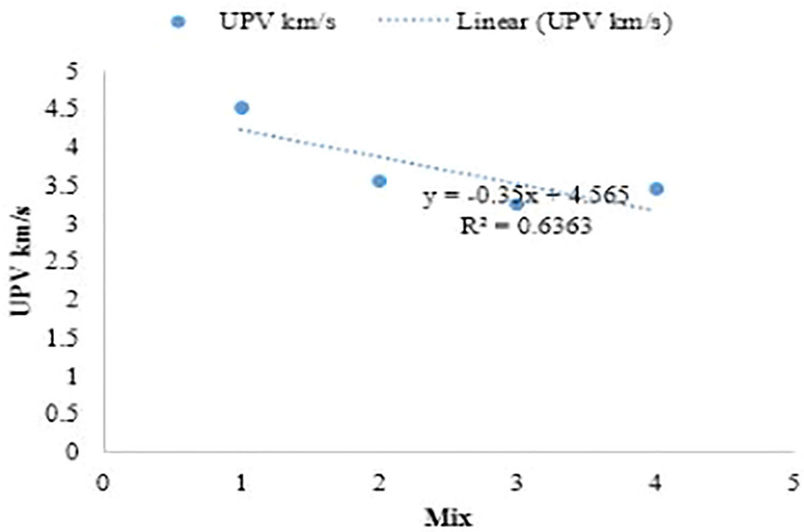

Figure 9: Graphical representation of ultrasonic pulse velocity test.

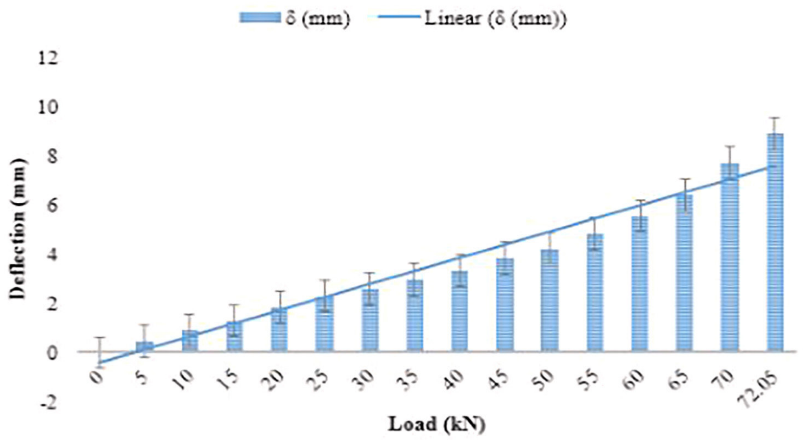

Figure 10: Graphical representation of load deflection curve of SRC slab under static loading.

increasing static loads, illustrating the relationship between applied force, resulting deformation, stress, and strain. Such information is essential for evaluating the structural performance and safety of the SRC specimen under different loading conditions, aiding in the design and analysis of reinforced concrete structures. Figure 10 shows the graphical representation of load deflection curve of SRC slab under static loading.

3.5.2. Natural bamboo reinforced concrete (NBRC)

The test results presents the response of a natural bamboo reinforced concrete specimen under static loading conditions. Here's the analysis based on the given parameters: Initially, with no applied load, both displacement (δ) and stress (σ) were zero, which is expected. As the load increased incrementally from 5 kN to 50 kN, the displacement (δ) of the specimen increased gradually from 0.19 mm to 4.45 mm. Correspondingly, the stress (σ) experienced by the specimen increased steadily from 50 N/mm^2 to 500 N/mm^2. The strain (ε) also increased linearly with the load, ranging from 0.32×10^{-3} to 7.42×10^{-3}. This data provides insights into the structural behavior of the natural bamboo reinforced concrete specimen under increasing static loads, illustrating the relationship between applied force, resulting deformation, stress, and strain. Such information is crucial for evaluating the structural performance and safety of bamboo-reinforced concrete structures under different loading conditions, aiding in their design and analysis. Figure 11 shows the graphical representation of load deflection curve of NBRC slab under static loading.

3.5.3. Epoxy coated bamboo reinforced concrete (ECBRC)

The provided data illustrates the response of an epoxy coated bamboo reinforced concrete (ECBRC) specimen under static loading conditions. Here's the analysis based on the given parameters: Initially, with no applied

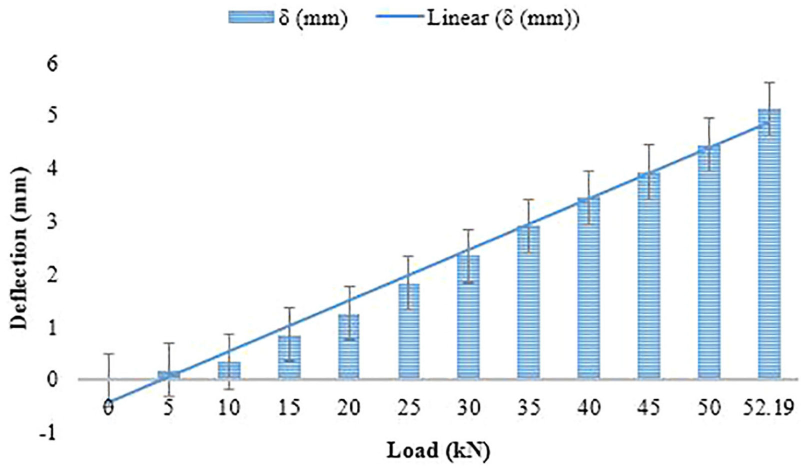

Figure 11: Graphical representation of load deflection curve of NBRC slab under static loading.

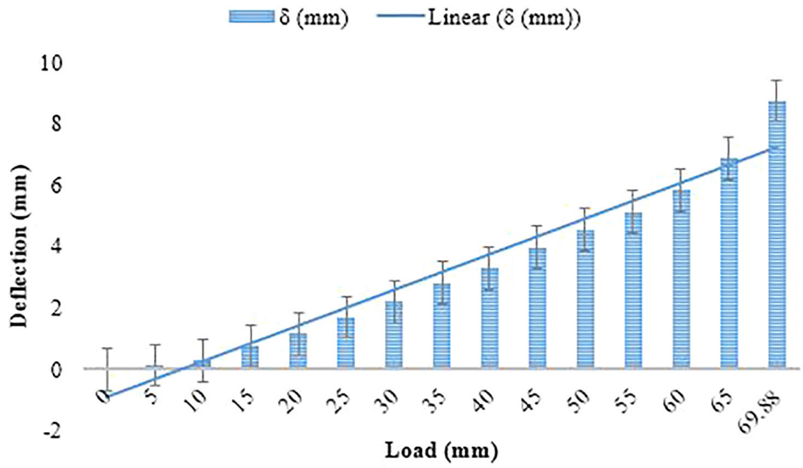

Figure 12: Graphical representation of load deflection curve of ECBRC slab under static loading.

load, both displacement (δ) and stress (σ) were zero, which is expected. As the load increased incrementally from 5 kN to 69.88 kN, the displacement (δ) of the specimen increased gradually from 0.13 mm to 8.74 mm. Correspondingly, the stress (σ) experienced by the specimen increased steadily from 50 N/mm^2 to 698.8 N/mm^2. The strain (ε) also increased linearly with the load, ranging from 0.22×10^{-3} to 14.57×10^{-3}. This data provides insights into the structural behavior of the epoxy coated bamboo reinforced concrete specimen under increasing static loads, illustrating the relationship between applied force, resulting deformation, stress, and strain. Such information is essential for evaluating the structural performance and safety of ECBRC structures under different loading conditions, aiding in their design and analysis. Figure 12 shows the graphical representation of load deflection curve of ECBRC slab under static loading.

3.5.4. Sand-Coated Bamboo Reinforced Concrete (ESCBRC)

The data provided represents the response of an epoxy with sand-coated bamboo reinforced concrete (ESCBRC) specimen under static loading conditions. Here's the analysis based on the given parameters: At the beginning, with no applied load, both displacement (δ) and stress (σ) were zero, which is expected. As the load increased incrementally from 5 kN to 70.02 kN, the displacement (δ) of the specimen increased gradually from 0.12 mm to 7.82 mm. Correspondingly, the stress (σ) experienced by the specimen increased steadily from 50 N/mm^2 to 700.2 N/mm^2. The strain (ε) also increased linearly with the load, ranging from 0.2×10^{-3} to 13.03×10^{-3}. This data provides insights into the structural behavior of the epoxy with sand-coated bamboo reinforced concrete specimen under increasing static loads, illustrating the relationship between applied force, resulting deformation, stress, and strain. Such information is crucial for evaluating the structural performance and safety of ESCBRC structures under different loading conditions, aiding in their design and analysis. Figure 13 shows the graphical representation of load deflection curve of ESCBRC slab under static loading.

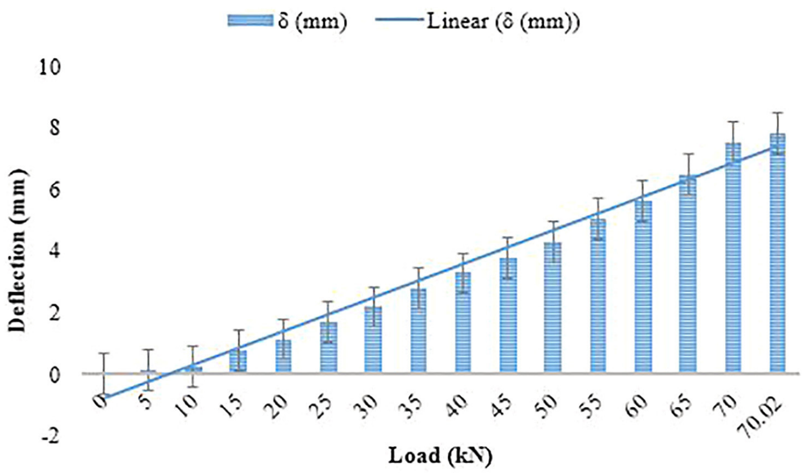

Figure 13: Graphical representation of load deflection curve of ESCBRC slab under static loading.

4. CONCLUSION

Bambusa arundinacea (BA) variety of bamboo can be used as reinforcement in various structural members such as beam, slab, column etc. in bamboo reinforced concrete. The conducted experiments, evaluating the performance of different reinforced concrete specimens under static loading conditions, offer valuable insights into the structural behavior and mechanical properties of the materials. The tests encompassed various reinforcement types, including steel, natural bamboo, epoxy coated bamboo, and epoxy with sand-coated bamboo, shedding light on their suitability and efficacy in construction applications. Overall, the results demonstrate that while conventional steel-reinforced concrete exhibits superior mechanical properties, including higher load-bearing capacity and stiffness, alternative reinforcement materials such as bamboo, when appropriately treated with epoxy coatings, can offer competitive performance. Natural bamboo and epoxy-coated bamboo both showcased respectable load-bearing capacities and deformation characteristics, making them promising alternatives for sustainable construction practices.

The epoxy with sand-coated bamboo reinforced concrete (ESCBRC) specimen displayed commendable mechanical properties, with significant load-bearing capacity and deformation resistance. This suggests the potential of incorporating natural materials like bamboo, reinforced with epoxy and sand coatings, into structural applications, balancing performance with sustainability. The findings underscore the importance of exploring alternative reinforcement materials in the construction industry, driven by the imperative of sustainable development and reducing environmental impacts. Bamboo, with its renewability and strength, emerges as a promising candidate for reinforcing concrete structures, particularly when combined with epoxy coatings to enhance durability and performance.

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