REVISTAMATÉRIA V.29 N.3
ISSN 1517-7076 articles e20240067, 2024

An in-depth assessment of the structural integrity and advantages of bamboo-reinforced cement concrete elements (BRCC) with utilizing an alternative binding material: a comprehensive evaluation

Parthasaarathi Ramaani[1,3], Balasundaram Natarajan[1], Rathan Raj Rajendran[2]

[1]Karpagam Academy of Higher Education, Department of Civil Engineering. Coimbatore, Tamilndu, India.

[2]University of Technology and Applied Sciences, Civil and Architectural Section, Department of Engineering. Salalah, Oman.

[3]Hindusthan College of Engineering and Technology, Department of Civil Engineering. Coimbatore, Tamilnadu, India.

e-mail: sarathi0089@gmail.com, balasundaram49@gmail.com, rathan.raj@utas.edu.om

ABSTRACT

This study investigates the feasibility of using concrete reinforced with a blend of coir and bamboo as a sustainable building material. Bamboo, known for its robust yet lightweight nature, serves as a natural reinforcement with high tensile strength, enhancing structural properties. Various lengths and diameters of bamboo reinforcements are coated with gloss enamel and black coal tar for durability is employed in this study. Coir is sourced from coconut husks and recognized for its strength and resilience in composite construction. The research explores the combined action of coir rope fibers and bamboo to improve tensile strength, flexural strength, and durability in concrete slabs. Twelve slabs are examined with featuring of conventional reinforcements, dried bamboo, gloss enamel-painted bamboo and black coal tar-coated bamboo with different diameters. The mechanical properties of concrete specimens are subjected to compressive force test according to IS 456:2000. While steel-reinforced slabs exhibit superior strength, it is noteworthy that 1.75% of black coal tar-coated bamboo reinforcement with coir rope performs comparably to traditional steel reinforcement in conventional concrete.

Keywords: Renewable building materials; Bamboo reinforcement; Coir rope fibres; Tensile strength; Concrete reinforcement; Environmental sustainability.

1. INTRODUCTION

The construction industry is exploring sustainable alternatives like bamboo reinforcement and coir rope binding for concrete slabs to reduce environmental impact and resource consumption compared to steel. This investigation advocates using industrial and agricultural wastes as sustainable alternatives to natural aggregates in concrete production. Substituting coconut shell and oil palm shell for conventional coarse aggregate enhances concrete properties like workability, density, compressive strength under various curing conditions, splitting tensile strength, and Young's modulus, promoting eco-friendly construction practices PORDESARI *et al.* [1]. This study introduces the notched-slab fastener, a novel connector for timber-concrete composite floors, with the notch placed in the concrete slab instead of the timber beam, preventing cross-section loss. Experimental tests demonstrate its stable load behavior, high-energy dissipation, and damage concentration in the connector, offering significant benefits for structural integrity. YILMAZ *et al.* [2]. Study investigates bamboo-composite reinforcement in concrete, finding adequate bond strength uncoated, and epoxy-sand coating provides extra protection. JAVADIAN *et al.* [3]. Bamboo-reinforced concrete slabs with EPS infill 27% lighter, 6% less flexural strength, and better ductility than steel-reinforced slabs WIBOWO *et al.* [4].

Experimental investigation examines bamboo bars as reinforcement in concrete beams. Two methods are tested: partial and full replacement of steel with bamboo. Results show comparable load capacity to steel-reinforced beams, reduced deflection, and enhanced ductility. Bamboo offers promise for sustainable and cost-effective construction with optimized material usage GOVINDAN *et al.* [5]. Research highlights bamboo's potential as a sustainable construction material, emphasizing engineered forms like laminated bamboo and bamboo scrimber. Chemical and thermal treatments significantly impact their physical and mechanical properties. Bamboo scrimber exhibits superior mechanical properties compared to laminated bamboo. Fire performance is

Corresponding Author: Parthasaarathi Ramaani Received on 21/02/2024 Accepted on 09/06/2024

DOI: https://doi.org/10.1590/1517-7076-RMAT-2024-0067

enhanced with fire-retardant coatings, crucial for controlling heat release and toxic gas emissions. Bamboo reinforcement in concrete improves strength and toughness, with BRC panels coated in fire-protective compounds showing resilience to high temperatures, making them suitable for low-cost housing solutions BALA *et al.* [6]. Research shows coconut stem strips, treated with coal tar, can effectively reinforce concrete, serving as an eco-friendly alternative to steel for low-bearing structures like lintels and pavements. OFUYATAN *et al.* [7]. The study envisions applications in low-cost housing, rural infrastructure, and environmentally friendly construction projects, emphasizing the importance of correct material design and mixing for optimal structural performance ALBERTI *et al.* [8].

SHARMA *et al.* [9] focused on bamboo as a reinforcing material in concrete projects, highlighting its suitability for low-cost dwellings due to its strength and engineering properties. Review finds bamboo-reinforced concrete, despite bamboo's mechanical properties, faces significant durability and strength issues, making it an unsuitable, less environmentally friendly alternative to steel reinforcement. ARCHILA *et al.* [10]. Research on coconut husk, oil palm fruit, and sugarcane bagasse fibers shows they have suitable properties for reinforcing soil blocks, offering strength, reduced environmental impact, and cost benefits DANSO *et al.* [11]. Evaluates alternative reinforcement methods to steel in concrete, finding longer service life makes alternatives more cost-effective and sustainable, despite higher initial costs, with only 6% impact on investment KARLSSON *et al.* [12] Coconut shell concrete reduces plastic shrinkage cracking and increases deflection, providing better failure warnings than conventional concrete, and meets IS 456:2000 span-to-depth ratio requirements GUNASEKARAN *et al.* [13].

Bamboo has emerged as a greener alternative to traditional steel reinforcing bars, with several studies investigating its mechanical characteristics and potential applications in various structural components RANA *et al.* [14]. The study investigates bamboo's use in precast concrete structural wall panels, assessing three prototypes under two-way in-plane loading. Specimens with different aspect and thinness ratios were tested to failure. Aspect ratios of 1.667, 1.818, and 2 and thinness ratios of 12.5, 13.75, and 15 was considered. Varnished and sandblasted bamboo splints served as reinforcement. An empirical equation predicting ultimate strength under two-way action was derived from the study's findings GANESAN *et al.* [15]. The literature emphasizes sustainability in the building industry, with a focus on reducing carbon emissions and preserving finite resources. TURNER and COLLINS [16] highlighted the potential of eco-friendly building supplies to mitigate the carbon impact of the construction industry, emphasizing sustainable options such as bamboo and coir rope.

In the early stages of bamboo reinforced concrete (BRC) development, this study characterizes Bambusa balcoa's tensile properties statistically. Elastic modulus dominates stress-strain behavior, with high-fidelity finite element models validating findings. BRC beam models using these insights show good agreement with experiments, aiding rational design MONDAL *et al.* [17]. Chemically treated coconut fiber improves mechanical properties in concrete, despite reduced compressive strength, offering potential for low-cost, lightweight concrete structures with satisfactory crack performance HASAN *et al.* [18]. Fiber reinforced concrete (FRC) enhances concrete performance in various applications like tunnels, bridges, and pavements by improving mechanical properties and durability through the addition of steel, glass, synthetic, or natural fibers RAGAVENDRA *et al.* [19]. Compares bamboo-reinforced concrete beams with crushed sand, finding 50% bamboo substitution viable with minimal deformation, validating flexural strength experimentally AWOYERA *et al.* [20]. Replaces steel with bamboo in concrete slabs, demonstrating improved flexural behavior and comparable strength to conventional reinforced concrete slabs DATTA *et al.* [21]. Review highlights bamboo's potential as reinforcement in concrete, showcasing comparable mechanical properties to steel, potentially transforming the construction industry KUMAR P *et al.* [22]. White flour and zinc ash as admixtures in concrete can enhance setting time and compressive strength, offering an eco-friendly alternative to chemical admixtures while utilizing industrial waste (20% strength increase) ANANDARAJ *et al.* [23]. Bamboo can replace steel in concrete reinforcement for footplate foundations, achieving 82% strength and 93% ductility of steel-reinforced slabs, offering a cost-effective alternative for developing regions HARYANTO *et al.* [24]. Researchers investigate flexural behavior of preloaded self-compacted concrete beams strengthened with CFRP. CFRP laminates increase capacity by 47–153% and reduce deflection by 5–80% compared to CFRP sheets, showing varying ductility and load capacity HAMDY *et al.* [25].

MADANI *et al.* [26] Examines pullout behavior of 3D, 4D, and 5D steel fibers at different angles and lengths, finding peak energy in 5D fibers at 30° with 25 mm length. Cassava peel ash reduces initial compressive strength but improves over time in concrete. The study examines the influence of banana fiber length and volume fractions on concrete properties. Longer fibers outperform shorter ones at all volume fractions. Mix10, with 1.5% VF and 35 mm length, exhibits highest mechanical strength: compressive, splitting tensile, flexural, and bond stress increased by 7.37%, 20.96%, 24.13%, and 11.2%. ATTIA *et al.* [27]. Incorporating bamboo cellulose nanofibers (BCNF) modified with KH590, into autoclaved aerated concrete (AAC) enhances flexural and compressive strength significantly. The pseudoplastic nature of AAC slurry follows Bingham rheological model. Improved interfacial bonding between BCNF and AAC matrix is achieved through siloxane-hydroxyl reactions, utilizing renewable materials and granite powders for sustainable AAC production ZHANG *et al.* [28]. Utilizing rice husk ash (RHA), palm oil fuel ash (POFA), and sugarcane bagasse ash (SBA) as cementitious materials improves sustainability in concrete production. This review evaluates their properties and compares effects of thermal and non-thermal treatments on concrete strength and durability. SEM and XRD analyses confirm enhanced properties, suggesting future research avenues LIN *et al.* [29]. Strengthening TCC beams with mechanically fastened (MF) and externally bonded plus mechanically fastened (EB + MF) techniques improves ultimate load capacity by up to 85.4% and bending stiffness by 41.6% LING *et al.* [30]. Mechanically fastened and externally bonded (EB + MF) techniques significantly increase load capacity and bending stiffness in timber-concrete composite beams. Bamboo reinforcement with rubber-coated bamboo bars shows improved bond strength in concrete TERAI *et al.* [31]. Hybridizing coir fiber-reinforced polypropylene (PP) composites with glass fibers enhances tensile, flexural, and impact properties while reducing weight (6–20% lighter). Glass fiber substitution (0–30 wt%) improves mechanical strength and water resistance, making these composites promising for automotive and transportation applications seeking lightweight and eco-friendly alternatives WASTI *et al*. [32].

2. MATERIALS AND METHODS

2.1. Cement concrete ingredients

In this study, Ordinary Portland Cement (OPC) 53 is mixed with Portland cement, incorporating bamboo-reinforced strips as sustainable reinforcements. The concrete mix includes natural fine and coarse aggregates and potable water free from impurities. This research evaluates the structural performance, aligning conventional practices with better solutions.

2.2. Bamboo reinforced strips (physical properties of bamboo [IS 6874: 1997, IS 8242: 1997, ISO/TC 165N315, 2001, ISO 22157: 2004)

Approximately three years old, well-seasoned bamboo strips from Ernakulam, Kerala, India (coordinates: 9.9816° N, 76.2999° E) is collected for the research work and shown in Figure 1. Using coir fibres in concrete, it improves mechanical properties like, increased tensile strength, durability and crack resistance. Also offering a sustainable alternative to synthetic fibres in Figure 2. This bamboo is machine sawed and processed at a local sawmill. Bamboo strips of consistent diameters (16 mm to 25 mm) is obtained and shown in Figure 3 and Figure 4. To ensure the effective construction usage, bamboos moisture content is reduced to 12–15% for preventing warping and insect infestations.

The identified locations on the bamboo specimens are categorized into three sections: Top, Middle, and Bottom. The Top section exhibits an outer diameter of 18.12 mm, node spacing of 298 mm, a wall thickness of 5.81 mm and a cross-sectional area of 119.01 mm^2. Moving to the Middle section, the bamboo has an outer diameter of 24.24 mm, node spacing of 305 mm, a wall thickness of 6.23 mm and a cross-sectional area of 254.75 mm^2. Finally, the Bottom section showcases an outer diameter of 28.60 mm, node spacing of 318 mm, a wall thickness of 8.15 mm and a cross-sectional area of 328.45 mm^2. These geometric properties provide essential insights for understanding the structural characteristics of the bamboo specimens at different locations.

The study investigated four different samples formally as: Reinforced Steel Bar Concrete (RCC), Dried Bamboo Reinforced Concrete (DBRC), Gloss Enamel Bamboo Strip (GPBRC), and Black Coal Tar Bamboo Strip (TCBRC). Rigorous material selection and preparation was crucial, ensuring the feasibility of coir mixed bamboo-reinforced concrete slabs as a sustainable construction solution, maintaining quality throughout the study.

2.3. Preparation of concrete cubes & slab specimen

Cement concrete samples are measuring 150 mm × 150 mm × 150 mm. Sample specimen is meticulously prepared using an M_{20} concrete mix as depicted in Figure 5 and Figure 6. The concrete moulding process involved filling the mold in three layers and each one is compacted with 25 strokes using meddling rods. A total of 42 cubes are prepared and subjected to curing periods of 7, 14, 21, 28 and 56 days to assess the compressive strength. For the aim of this research work is 12 slabs are prepared for the strength analysis. The cement concrete slabs are comprising with dried bamboos, gloss enamel painted bamboos and black coal tar coated bamboos in the different diameters of 16 mm, 20 mm and 25 mm. The M_{20} grade of concrete mix is employed in a ratio

Figure 1: Bamboo reinforcement.

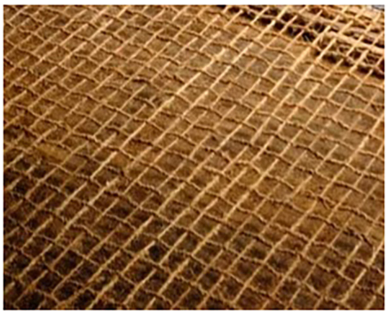

Figure 2: Coir rope.

Figure 3: 25 mm # bamboo.

Figure 4: Bamboo reinforcement.

of 1:1.5:3. Compressive strength test is conducted at intervals of 7, 14, 21, 28 and 56 days post-placement of cement concrete cube.

Utilizing a concrete mix with proportions of 1:1.5:3 for cement, fine aggregates and coarse aggregates and a water-cement ratio of 0.4. The samples are prepared with consistent crushed river rock for a pull-out experiment. Bamboo reinforced concrete slabs are prepared with a specified dimensions of 0.9 m width and 1.5 m length as shown in Figure 7. A Systematic reinforcement arrangement are mentioned in Figure 8. Cover value for the bamboo reinforced concrete slab is 20 mm.

The Compressive strength testing transpired on the 28th and 56th days. The degree of workability test systematically documented in Table 1 and Table 2, providing comprehensive insights into the concrete's performance and characteristics under varying conditions and curing durations.

Figure 5: Mixing of raw materials for M_{20} concrete.

Figure 6: Concrete cube specimens.

Figure 7: Slab concreting – bamboo reinforced concrete slab.

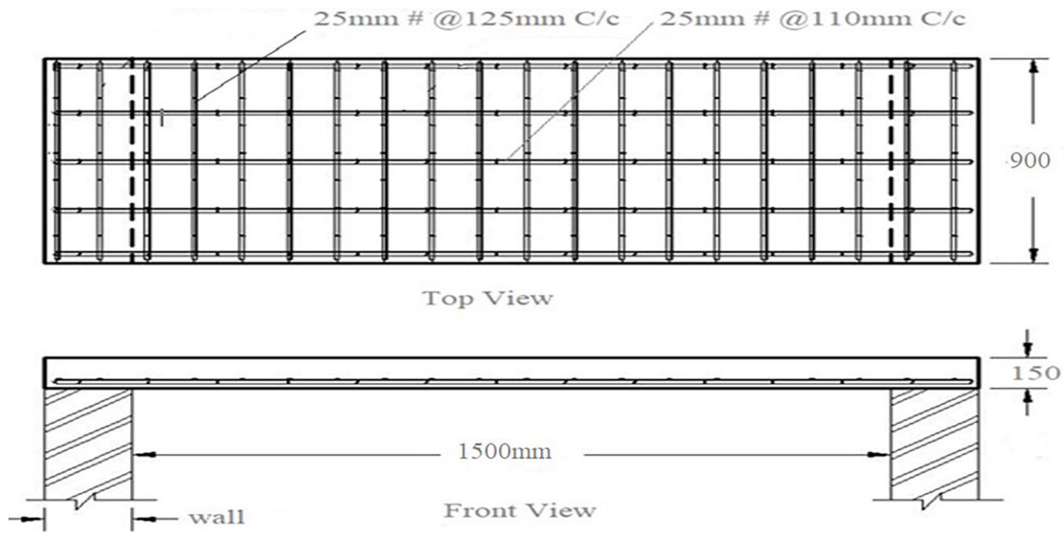

Figure 8: Reinforcement schematic drawing.

3. EXPERIMENTAL INVESTIGATION

3.1. Slump cone test on M_{20} grade fresh concrete

The concrete mix formulation consisted of 1000 grams of cement, 2300 grams of coarse aggregate and 1270 grams of fine aggregate. A measured quantity of 1000 ml of water is added to the concrete resulting in a water-to-cement (w/c) ratio of 0.4%. The slump value is indicating the consistency and workability of the concrete and measured at 95 mm in Figure 9. This value is classifying the mix as having a medium degree of workability in Table 1. This degree of workability suggests that the concrete demonstrated a balanced consistency, making it suitable for various construction applications. The meticulous control of these parameters ensures the desired properties and performance of the concrete mix during placement and subsequent curing processes.

3.2. Compaction factor test on M_{20} grade fresh concrete

The concrete mix components are meticulously measured, with 1000 grams of cement, 2300 grams of coarse aggregate and 1270 grams of fine aggregate. The volume of water added to concrete is 1000 ml. The weight of the empty mould is (W_1) 7260 grams, while the weight of the mould with partially compacted concrete (W_2) is 17280 grams and fully compacted concrete is (W_3) 18370 grams as shown in Figure 10. Calculations revealed the weight of partially compacted concrete ($W_2 – W_1$) as 1024 grams and fully compacted concrete ($W_3 – W_1$) as 11110 grams. The compaction factor was determined to be 0.92 in Table 2, indicating a medium degree of workability for the concrete mix, facilitating the assessment of its compatibility and behaviour during the construction process.

$$\text{Compaction factor Cf} = \frac{\text{Weight of partially compacted concrete}}{\text{Weight of fully Compacted concrete}} \tag{1}$$

$$= (W_2 - W_1) / (W_3 - W_1)$$

$$= 10.24 / 11.11$$

$$= 0.92$$

3.4. Compressive strength testing

Figure 11, the compressive strength test results for concrete specimens over different curing periods are presented in the Table 3. Specimens I, II and III was subjected to curing periods of 7, 14, 21, 28 and 56 days. At the 7-day compressive strength of cube is 9.25 N/mm^2, 8.95 N/mm^2 and 9.15 N/mm^2 for specimens I, II and III, respectively. In 7th day average compressive strength of concrete is 9.12 N/mm^2. The average compressive strength increased to 11.58 N/mm^2 at 14 days, 13.53 N/mm^2 at 21 days, 19.32 N/mm^2 at 28 days and 22.06 N/mm^2 at 56 days. These results are compared in Figure 12. The data provides a comprehensive understanding of the development of compressive strength in concrete over various curing durations.

Figure 9: Slump cone test.

Table 1: Slump values for M_{20} concrete.

S.NO.	DESCRIPTION	VALUES
1.	Weight of cement (Gms)	1000
2.	Weight of coarse aggregate (Gms)	2300
3.	Weight of fine aggregate (Gms)	1270
4.	Weight of water added	1000
5.	W/c ratio by weight (%)	0.4
6.	Slump value (mm)	95
7.	Degree of workability	Medium

Figure 10: Compaction factor test on concrete specimens.

3.5. Pull-out test on bamboo strips reinforcement

The objective of this test is to quantify the bond strength between bamboo reinforcement and concrete. Comparative assessments are made among bamboo specimens subjected to different treatments, untreated bamboos and steel bars to gauge their respective bond strengths as shown in Figure 13. The results of the water absorption test is utilized as criteria for the preparation and treatment of the specimens. The bamboo is carefully divided into splits, encompassing both the basal and intermediate parts. Specimens located in the internodal zone is selected for testing. Each specimen is standardized to a length of 1150 mm, adhering to the specifications of the Universal Testing Machine (UTM). Bamboos are variations in thickness, perimeter, cross-sectional area and coating with different solutions. These specimens are embedded to the full depth of a 150 × 150 × 150 mm concrete block and results are shown in Table 4.

Table 2: Compaction factor test for M_{20} concrete.

S.NO.	DESCRIPTION	VALUES
1.	Weight of cement (Gms)	1000
2.	Weight of coarse aggregate (Gms)	2300
3.	Weight of fine aggregate (Gms)	1270
4.	Volume of water added (ml)	1000
5.	Weight of empty mould (W_1) (Gms)	7260
6.	Weight of mould and partially compacted concrete (W_2) (Gms)	17280
7.	Weight of empty mould and fully compacted concrete (W_3) (Gms)	18370
8.	Weight of partially compacted concrete ($W_2 – W_1$) (Gms)	1024
9.	Weight of fully compacted concrete ($W_3 – W_1$) (Gms)	11110
10.	Compaction factor	0.92
11.	Degree of workability	Medium

Figure 11: Compressive force on concrete cube specimen – 56th Day.

Table 3: Compressive strength of cement concrete cube specimen – 7th to 56th day.

CURING PERIOD	SPECIMEN I (N/mm^2)	SPECIMEN II (N/mm^2)	SPECIMEN III (N/mm^2)	AVERAGE (N/mm^2)
7 days	9.25	8.95	9.15	9.12
14 days	11.75	11.05	11.95	11.58
21 days	13.5	13.25	13.85	13.53
28 days	18.95	19.15	19.86	19.32
56 days	21.18	22.26	22.75	22.06

$$\text{Ultimate bond stress } \tau = \frac{\text{Maximum force recorded}}{\text{Area of the specimen}} \tag{2}$$

The identification and characterization of concrete cubes ultimate bonding stress values are obtained in Figure 13. RCC 1 and RCC 2 represents the Reinforced Cement Concrete cubes reinforced with 8 mm and 10 mm # steel, respectively. Exhibiting the ultimate bonding stresses of 1.87 N/mm^2 and 1.92 N/mm^2. Dried

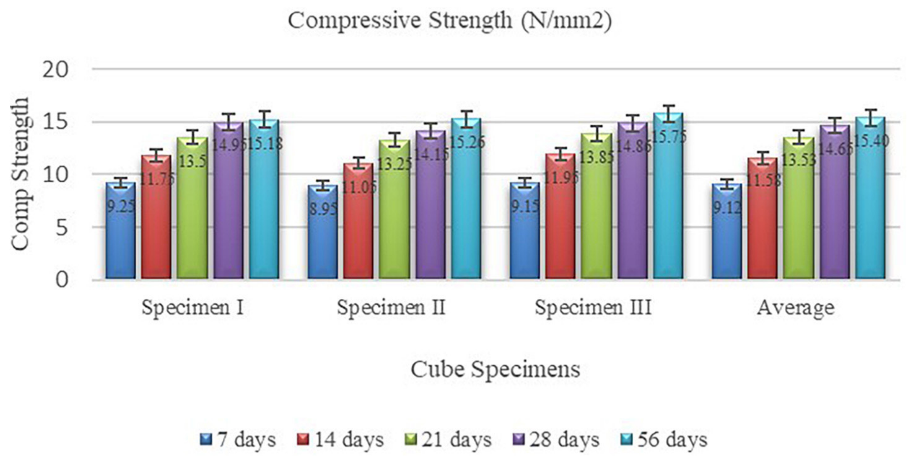

Figure 12: Compressive force on concrete cube – 7th to 56th Day.

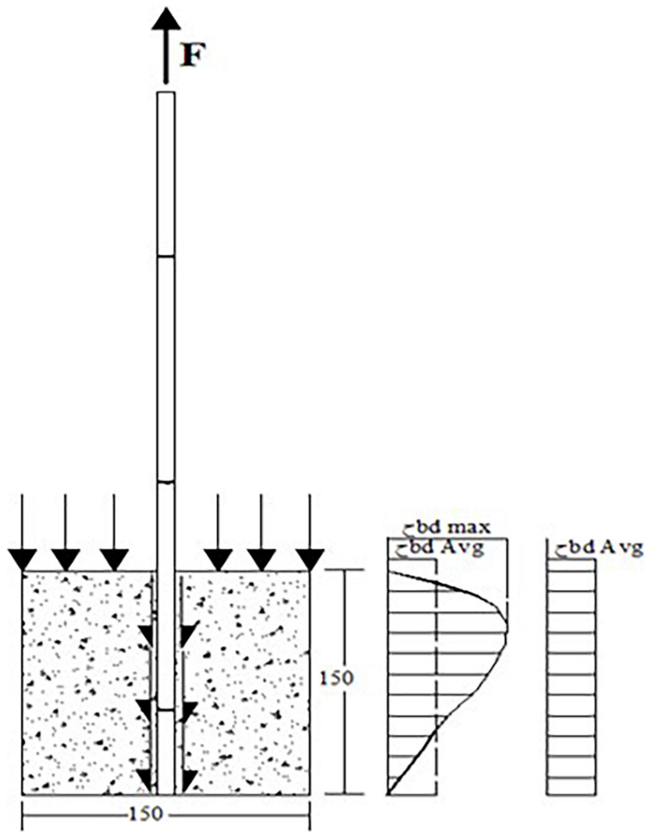

Figure 13: Pull-out test on bamboo strip embedded in concrete cube.

Bamboo Reinforced Concrete (DBRC) cubes, namely DBRC 1, DBRC 2, and DBRC 3, are reinforced with bamboo of diameters 16 mm, 20 mm, and 25 mm, respectively. Showcasing the ultimate bonding stress values of 0.93 N/mm^2, 1.02 N/mm^2, and 1.14 N/mm^2. Gloss Enamel Painted Bamboo Reinforced Concrete (GPBRC) and Tar Coated Bamboo Reinforced Concrete (TCBRC) cubes, with similar diameter variations, exhibit corresponding ultimate bonding stress values of 0.82 N/mm^2 to 1.13 N/mm^2 and 1.18 N/mm^2 to 1.43 N/mm^2, respectively. These comprehensive identifications provide insights into the diverse reinforcement configurations and bonding characteristics of the concrete cubes under consideration.

In comparing the ultimate bonding stress values of different reinforced concrete specimens, RCC 1, reinforced with 8 mm # steel, exhibits an ultimate bonding stress of 1.87 N/mm^2, while RCC 2, reinforced with 10 mm # steel, shows a slightly higher ultimate bonding stress of 1.92 N/mm^2. Contrastingly, Tar Coated Bamboo Reinforced Concrete (TCBRC) specimens demonstrate varying ultimate bonding stress values based

Table 4: Pull-out test results on cement concrete cube specimen.

IDENTIFICATION OF CONCRETE CUBE	DESCRIPTION OF REINFORCEMENT	DIAMETER OF REINFORCEMENT	ULTIMATE BONDING STRESS τ N/mm²
RCC 1	Reinforced cement concrete 1	8 mm # Steel	1.87
RCC 2	Reinforced cement concrete 1	10 mm # Steel	1.92
DBRC 1	Dried bamboo reinforced concrete 1	16 mm # Bamboo	0.93
DBRC 2	Dried bamboo reinforced concrete 2	20 mm # Bamboo	1.02
DBRC 3	Dried bamboo reinforced concrete 3	25 mm # Bamboo	1.14
GPBRC 1	Gloss enamel painted bamboo reinforced concrete 1	16 mm # Bamboo	0.82
GPBRC 2	Gloss enamel painted bamboo reinforced concrete 2	20 mm # Bamboo	0.94
GPBRC 3	Gloss enamel painted bamboo reinforced concrete 3	25 mm # Bamboo	1.13
TCBRC 1	Tar coated bamboo reinforced concrete 1	16 mm # Bamboo	1.18
TCBRC 2	Tar coated bamboo reinforced concrete 2	20 mm # Bamboo	1.21
TCBRC 3	Tar coated bamboo reinforced concrete 3	25 mm # Bamboo	1.43

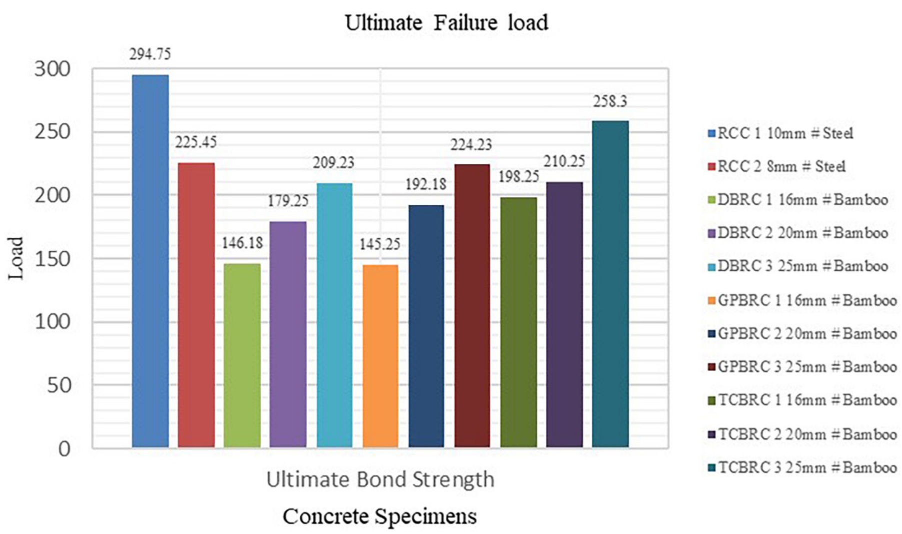

Figure 14: Ultimate bonding strength of bamboo concrete cube.

on bamboo diameters: TCBRC 1 (16 mm # Bamboo) has an ultimate bonding stress of 1.18 N/mm², TCBRC 2 (20 mm # Bamboo) has 1.21 N/mm² and TCBRC 3 (25 mm # Bamboo) shows the highest ultimate bonding stress at 1.43 N/mm² as shown in Figure 14. The ultimate bonding stress varies, with steel showing higher stress than bamboo, peaking at 2 N/mm² in Figure 15. This comparison highlights the influence of reinforcement material and diameter on the ultimate bonding stress, showcasing the performance variations within the tested concrete specimens in Table 4.

3.6. Crack and deformation analysis

Figure 16, depicts the schematic diagram of cyclic load is applied on the BRCC slab specimen. The cyclic load test on bamboo-reinforced concrete slab specimens evaluates the structural performance, including load-deflection behavior, ultimate load capacity under repeated loading conditions as shown in Figure 17. The concrete slabs

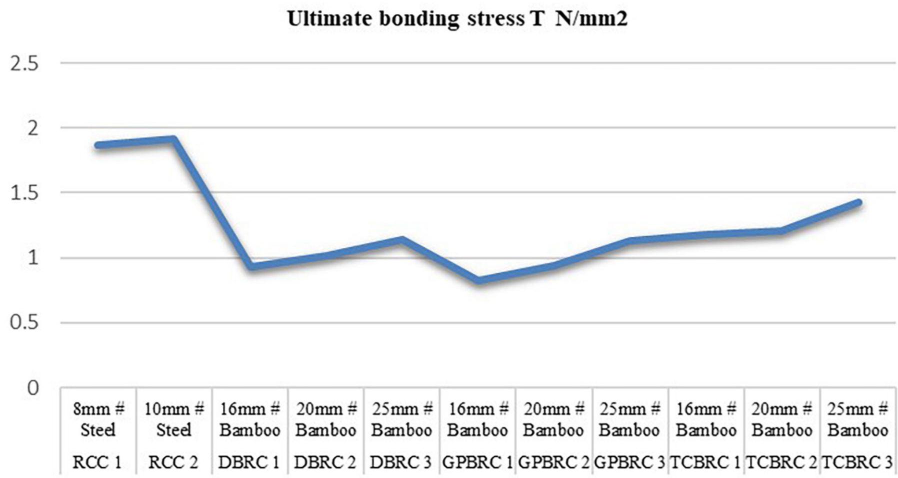

Figure 15: Graph for ultimate bonding strength of bamboo concrete cube.

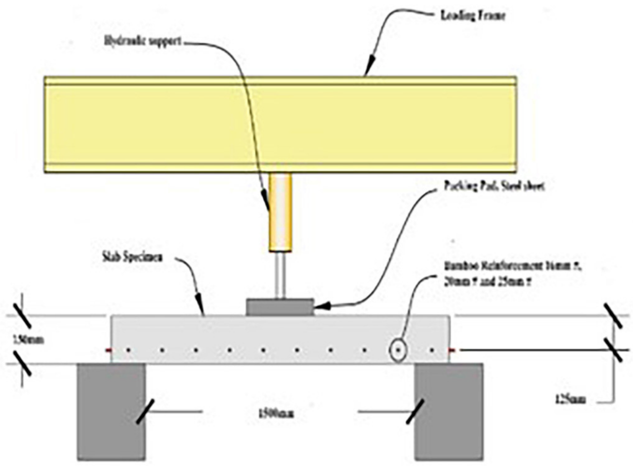

Figure 16: Schematic diagram of cyclic loading on slab specimen.

Figure 17: Cyclic load test on bamboo reinforced slab specimen.

under consideration, along with their respective reinforcement details and maximum failure loads, are systematically identified. RCC 1 and RCC 2 represent Reinforced Cement Concrete slabs reinforced with 10mm and 8 mm # steel, resulting in maximum failure loads of 294.75 KN and 225.45 KN, respectively. Dried Bamboo Reinforced Concrete (DBRC) slabs, namely DBRC 1, DBRC 2 and DBRC 3, are reinforced with bamboo of diameters 16 mm, 20 mm and 25 mm, revealing maximum failure loads of 146.18 KN, 179.25 KN, and 209.23 KN, respectively. Gloss Enamel Painted Bamboo Reinforced Concrete (GPBRC) and Tar Coated Bamboo

Table 5: Maximum failure load and deflection analysis.

IDENTIFICATION OF CONCRETE SLAB	REINFORCEMENT	MAXIMUM FAILURE LOAD (KN)	DEFLECTION (mm)
RCC 1	8 mm # Steel	225.45	6.42
RCC 2	10 mm # Steel	294.75	6.91
DBRC 1	16 mm # Bamboo	146.18	5.28
DBRC 2	20 mm # Bamboo	179.25	5.81
DBRC 3	25 mm # Bamboo	209.23	5.95
GPBRC 1	16 mm # Bamboo	145.25	5.26
GPBRC 2	20 mm # Bamboo	192.18	5.67
GPBRC 3	25 mm # Bamboo	224.23	5.83
TCBRC 1	16 mm # Bamboo	198.25	6.26
TCBRC 2	20 mm # Bamboo	210.25	6.47
TCBRC 3	25 mm # Bamboo	258.30	6.55

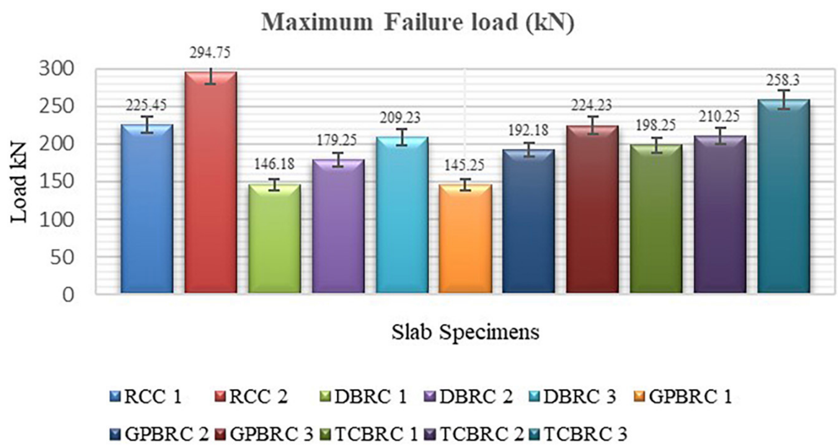

Figure 18: Maximum failure load on bamboo concrete slabs.

Reinforced Concrete (TCBRC) slabs, with analogous diameter variations, exhibit corresponding maximum failure loads ranging from 145.25 KN to 224.23 KN and 198.25 KN to 258.30 KN, respectively and mentioned in Table 5. This comprehensive identification provides insights into the diverse reinforcement configurations and structural performances of the concrete slabs as shown in Figure 18. Deflection comparison reveals varying structural behaviours. RCC slabs exhibit similar deflection, while bamboo-reinforced slabs generally show lower deflection, emphasizing potential advantages in structural performance in Figure 19.

3.7. Analysis of failure energy

The failure of bonds between bamboo and concrete can lead to strain in the concrete, particularly at long embedding distances. This issue typically arises when inadequate reinforcement is present, resulting in poor concrete connection. Strengthening the bamboo and improving the bond can induce more cracks, which distribute strain more evenly across the structure in Figure 20 and Figure 21.

A theoretical model has been developed to estimate the tensile strength of bamboo at bond failure across various bamboo densities and bond strengths. This model considers the stiffness of bamboo, recognizing that the bond strength may become too strong due to increased fractures. It establishes limits for the longitudinal bond, transitioning from a lower limit based on uncracked concrete bonding to a higher limit as bamboo reinforcement area and stiffness increase. Nonlinear regression techniques are employed to determine the maximum percentage of longitudinal bond utilization and the transition power. By fitting FE model outputs to the theoretical model, a high level of agreement (R2 score of 0.956) was achieved in Figure 22.

Theoretical model predictions, supported by FE findings, demonstrate the transition from the lowest to the maximum bond estimates relative to reinforcing area and bond strength. As bamboo stiffness increases, stress

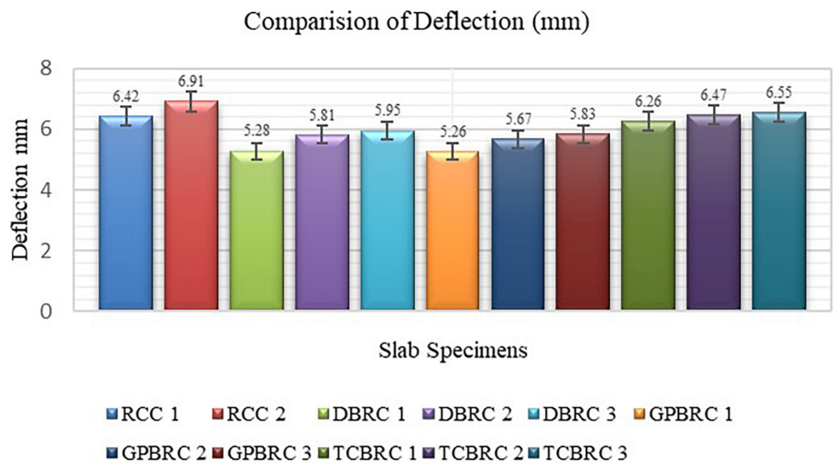

Figure 19: Comparison of deflections for bamboo concrete slabs.

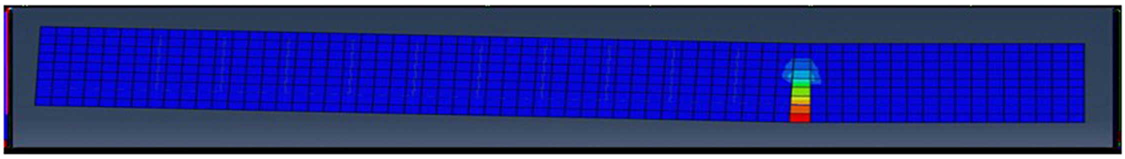

Figure 20: Cracking with low stiffness bamboo reinforcement at the maximum moment (ρ = 1.06%, E = 13.9 GPa).

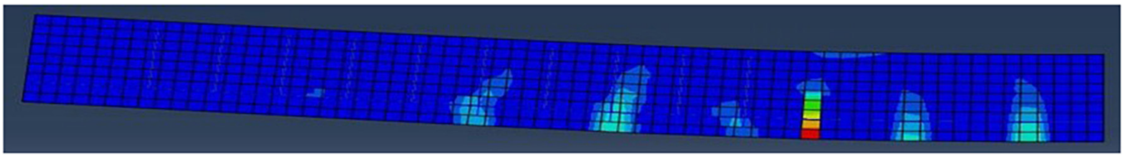

Figure 21: Snapshot of cracking with stiff reinforcement at the maximum moment (ρ = 8.47%, E = 13.9 GPa).

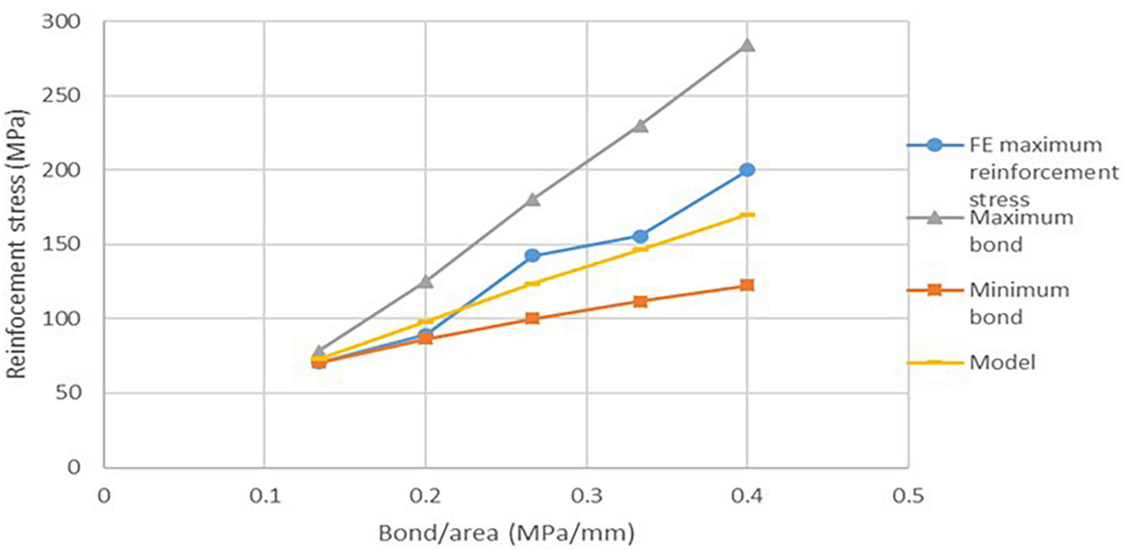

Figure 22: Maximum reinforcement stress result in the FE model at ρ = 2.32%.

distribution in critical bond portions shifts towards the maximum estimate. Utilizing the full tensile strength of bamboo is only feasible if it exceeds the strength achieved by maximum embedment into concrete. Failure to achieve this can result in diminished moment capacity and slab stiffness compared to stronger connections in Figure 23 and Figure 24.

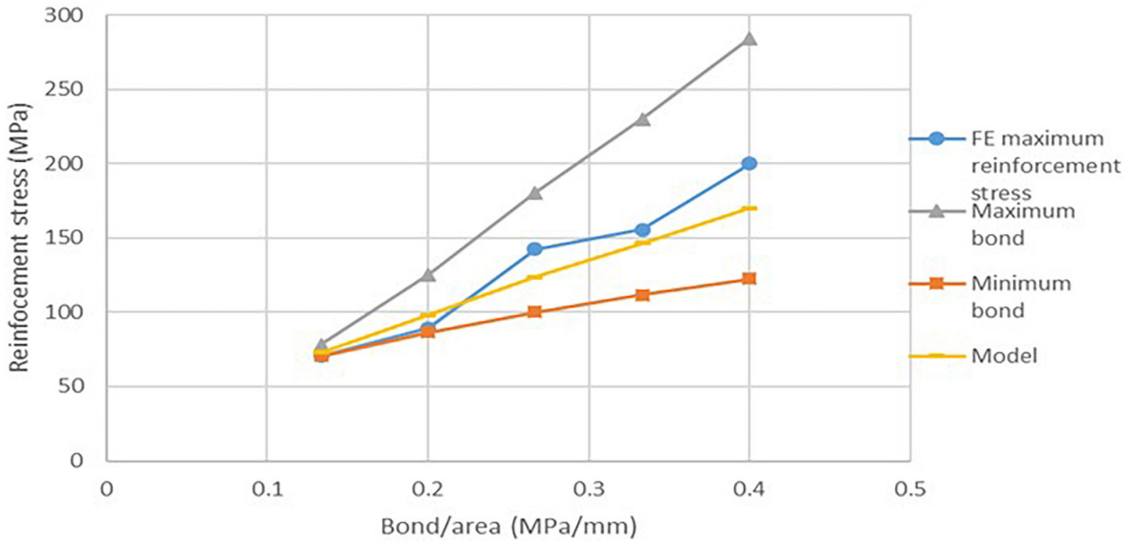

Figure 23: Maximum reinforcement stress result in the FE model at ρ = 3.17%.

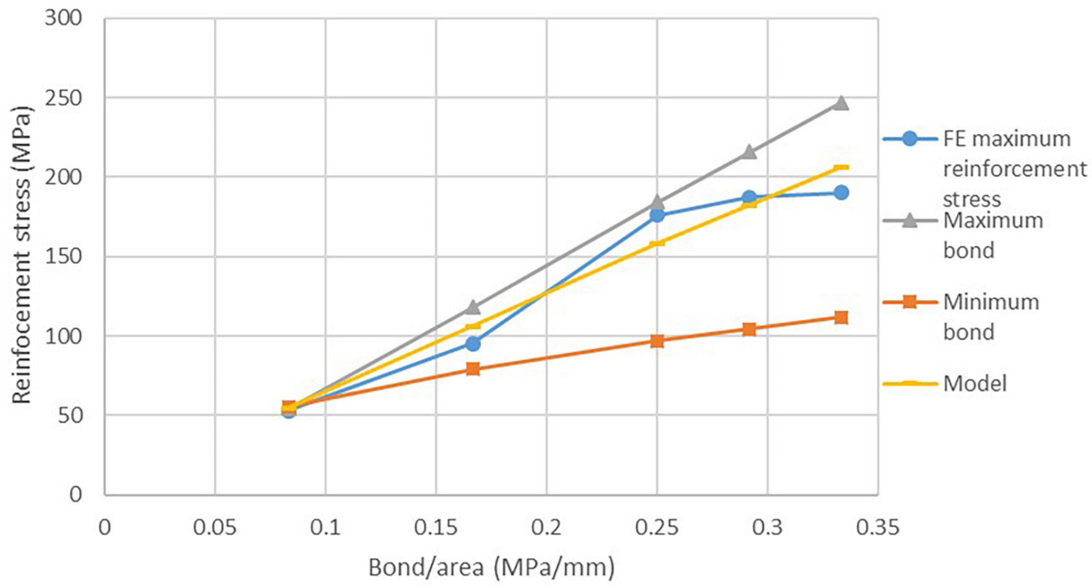

Figure 24: Maximum reinforcement stress result in the FE model at ρ = 6.357%.

3.8. A Scanning Electron Microscope (SEM)

Scanning Electron Microscopy (SEM) serves as a potent tool for examining the intricate microstructure and surface morphology of materials at atomic levels and its application in studying bamboo-reinforced concrete slabs with diverse coatings is paramount in this research. The comprehensive understanding of composition and interfacial features is a primary objective and SEM facilitates a detailed examination of the microstructure and surface morphology of the bamboo-reinforced concrete slabs. This includes scrutinizing the arrangement of bamboo strands, assessing coating thickness and studying the connection between bamboo and concrete.

SEM analysis proves crucial in determining the coatings' thickness and uniformity on bamboo strips, offering insights into their spread and adherence to the surface. The variations in coating thickness and homogeneity are pivotal factors influencing coating performance and protective properties. The examination of interfaces, such as coating-to-concrete and coating-to-bamboo interfaces, provides valuable information on adhesion and bonding. Strong adherence is imperative for the manifestation of the coating's endurance and protective capabilities.

In the analysis of bamboo-reinforced slabs with and without coir fibre rope as binding wire in composite sections, SEM examination plays a vital role in comparing structural properties. SEM micrographs of concrete incorporating different bamboo reinforcements, such as Gloss Enamel Painted Bamboo Reinforcement (GPBRC), Dried Bamboo Reinforcement (DBRC) and Tar Coated Bamboo Reinforcement (TCBRC), highlight

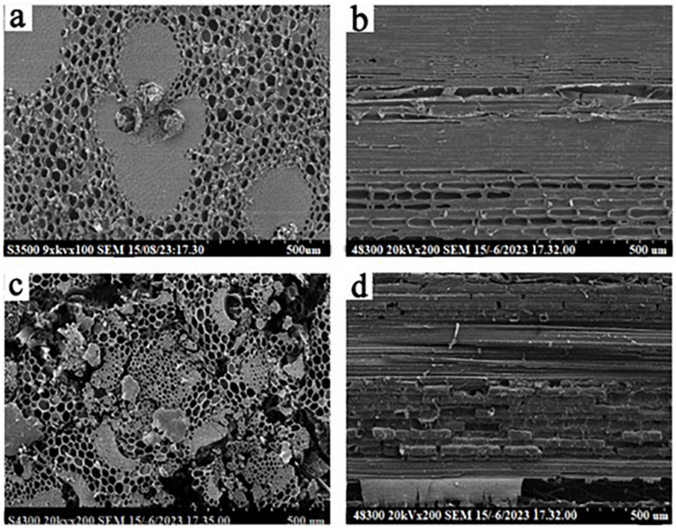

Figure 25: SEM analysis on bamboo reinforced concrete slab.

the presence of black coal tar-coated bamboo, suggesting improved durability and longevity due to inhibited pore capillary development under impact loads. Specific SEM images, such as the one depicting a 56-day-old concrete slab bound with 25 mm bamboo and coir rope, offer visual insights into the structural aspects of the composite material in Figure 25. The SEM analysis contributes significantly to the overall understanding of the microstructural and surface properties of bamboo-reinforced concrete, aiding in the evaluation of its performance and potential applications in construction.

4. RESULT AND DISCUSSION

The results presented in Table 5 provide a comprehensive overview of the trials conducted on concrete slabs reinforced with bamboo strips of various diameters, with a focus on the key features of Maximum failure load, deflections, compressive force and bonding strength. A detailed discussion is:

4.1. Compressive force results

The compressive strength test findings are providing crucial insights into the structural capabilities of the concrete specimens, shedding light on their performance under various age of concrete. The experiment is conducted in accordance with established as per Indian standards IS 10262 2016. Concrete mix design for the specimen is M_{20} with a mixing ratio of 1:1.5:3 for all the sample specimens. The compressive force percentile of the concrete mix exhibited a gradual increase over the curing period, adhering to standard benchmarks. After 7 days of curing, the compressive force percentile reached 10%, escalating to 25% at 14 days, 65% at 21 days, 90% at 28 days and reaching 99.0% at the 56^{th} day.

The compressive force readings demonstrated a consistent improvement in concrete strength with the progression of curing time. Early strength development was evident at 7 days, recording a value of 9.12 N/mm^2. Subsequent days witnessed a steady increase in strength, with values at 14 days, 21 days, 28 days and 56 days measuring 11.58 N/mm^2, 13.53 N/mm^2, 19.32 N/mm^2 and 22.06 N/mm^2, respectively. These results align with the grade of concrete mandated by IS 10262 2016, affirming the structural integrity of the samples.

Additionally, the load required to induce failure in the concrete cube samples exhibited a positive correlation with the curing duration. As the curing days increased, the load-bearing capability of the concrete showed a corresponding rise, indicating an enhancement in the structural integrity of the concrete over time. The correlation between curing time and load-bearing capability is detailed in Table 3 and showed in Figure 12. By providing substantial evidence supporting the assertion of increased structural robustness with prolonged curing periods. These findings contribute to the understanding of the concrete slabs performance and validate their compliance with industry standards, emphasizing their potential suitability for construction applications.

4.2. Pull-out test findings

The results on ultimate bonding stress reveal distinct characteristics among various reinforced concrete cubes. Steel-reinforced samples (RCC 1 and RCC 2) exhibit superior bonding stress compared to bamboo-reinforced counterparts (DBRC, GPBRC, and TCBRC). Notably, tar-coated bamboo reinforcement (TCBRC) showcases the highest bonding stress within the bamboo-reinforced specimens, emphasizing its efficacy in enhancing bond strength. Dried bamboo reinforcements (DBRC) demonstrate an incremental increase in bonding stress with growing diameter. Gloss enamel painted bamboo variants (GPBRC) display moderate bonding stress values. This comparative analysis underscores the substantial influence of reinforcement type and treatment on the bonding characteristics of the concrete cubes. Understanding these variations is crucial for assessing the structural performance and suitability of different reinforcement materials in diverse construction applications, contributing to informed decision-making in the field of civil engineering.

4.3. Cyclic load test findings

Figure 18 illustrates the outcomes of the cyclic test results, providing valuable insights into the impact resistance of concrete reinforced with different materials. These tests, assessing the ultimate load required to initiate failure in concrete structures, shed light on the structural resilience of the specimens. Various concrete compositions, including steel reinforcement, bamboo reinforcement, gloss enamel coating and black coal tar coatings are subjected to impact resistance calculations.

Steel-reinforced concrete demonstrated an impact strength resistance value of 294.75 kN, Gloss enamel-coated and dried bamboo strip-reinforced concrete, with a 16 mm diameter, exhibited impact strength resistance values of 146.18 kN and 145.25 kN, respectively.

Remarkably, black coal tar-coated bamboo-reinforced concrete (TCBRC) displayed the highest impact strength, withstanding 258.30 kN. These results emphasize the varying impact resistance of concrete specimens based on reinforcing conditions, with TCBRC exhibiting exceptional performance. The findings offer a comprehensive evaluation of the structural and impact strength properties of concrete slabs, underscoring the significance of bamboo reinforcement and coating techniques in enhancing performance and impact resistance.

5. CONCLUSION

The research findings reveal promising prospects for the use of black coal tar bamboo strips as a sustainable alternative to traditional steel reinforcements in concrete slabs. The ultimate strength carrying capacity of black coal tar bamboo strips is impressive, reaching 65% of the steel reinforcement slab, showcasing a substantial increase in strength ratio (1:1.5). Surprisingly, these bamboo-reinforced slabs exhibit behaviour like the control slab with steel reinforcement when fully cured. This suggests that bamboo strips, even at a modest percentage (1.8% bamboo), can effectively contribute to the structural integrity of concrete slabs, offering a sustainable material for bearing structures in construction.

a) The study emphasizes the economic value of bamboo trees, particularly when utilized as reinforcements in concrete. By addressing the drawbacks associated with steel reinforcements, bamboo strips present a viable and sustainable alternative. The research suggests that lightweight concrete structures could benefit significantly from the inclusion of bamboo stems.
b) Moving beyond the focus on black coal tar bamboo strips, the study explores the advantages of coir-blended bamboo-reinforced concrete (CBRC) slabs. A comprehensive approach encompassing mechanical testing and environmental impact assessment provides a holistic understanding of this new building material.
c) Durability analysis highlights the long-term resilience of CBRC slabs against environmental factors such as moisture, temperature fluctuations and decay. Proper preparation and treatment of bamboo and coir fibres contribute to the favourable mechanical properties of CBRC slabs, including notable tensile and flexural strength.
d) Environmental studies indicate that CBRC slabs have the potential to significantly reduce the carbon footprint of the building industry by offering an alternative to traditional concrete. The results showcase CBRC slabs as an effective and environmentally conscious option, particularly in regions with abundant bamboo resources.
e) While the study sheds light on various critical aspects, there are avenues for future research. Assessing the long-term performance and durability of CBRC slabs in diverse climates and conditions requires extended exposure testing and field research. Optimization of mix design through experimentation with different proportions and treatment procedures for various bamboo and coir fibres is another avenue for exploration. Additionally, exploring construction practices to enhance the feasibility and effectiveness of using CBRC slabs in real building projects is crucial.
f) Collaboration with industry stakeholders and policymakers to develop and revise building codes and standards related to CBRC is essential for widespread adoption. Researchers are also exploring the viability of hybrid composites, combining CBRC with other natural or recycled materials, to enhance sustainability.

Advanced testing methods, including non-destructive testing, can further enhance understanding of the structural behaviour and integrity of CBRC slabs.

g) Market acceptance and cost-benefit evaluations are imperative to promote the broad usage of CBRC in construction. These efforts will validate and expand upon the benefits of CBRC as a sustainable and structurally sound building option. As the construction industry evolves to address environmental concerns, CBRC emerges as a prospective contributor to sustainable and eco-conscious building practices.

6. BIBLIOGRAPHY

[1] PORDESARI, A.J., SHAFIGH, P., IBRAHIM, Z., *et al.*, "Engineering properties of coconut shell lightweight concrete: a comparative study", *Advances in Concrete Construction,* v. 12, n. 4, pp. 303–316, 2021. doi: https://doi.org/10.12989/acc.2021.12.4.303.

[2] YILMAZ, S., DEMIR, S., VURAL, N., *et al.,* "Experimental investigation of a prefabricated timber-concrete composite floor structure: notched-slab approach", *Advances in Concrete Construction,* v. 12, n. 1, pp. 13–23, 2021. doi: https://doi.org/10.12989/acc.2021.12.1.013.

[3] JAVADIAN, A., WIELOPOLSKI, M., SMITH, I.F.C., *et al.*, "Bond-behavior study of newly developed bamboo-composite reinforcement in concrete", *Construction & Building Materials*, v. 122, pp. 110–117, Sep. 2016. doi: http://doi.org/10.1016/j.conbuildmat.2016.06.084.

[4] WIBOWO, A., WIJATMIKO, I., NAINGGOLAN, C.R., *et al.*, "Structural behavior of lightweight bamboo reinforced concrete slab with EPS infill Panel", *AIP Conference Proceedings*, n. 1887, pp. 020024, 2017. doi: https://doi.org/10.1063/1.5003507.

[5] GOVINDAN, B., RAMASAMY, V., PANNEERSELVAM, B., *et al.*, "Performance assessment on bamboo reinforced concrete beams", *Innovative Infrastructure Solution*, v. 7, pp. 16, 2022. doi: https://doi.org/10.1007/s41062-021-00616-8.

[6] BALA, A., GUPTA, S., *et al.,* "Engineered bamboo and bamboo-reinforced concrete elements as sustainable building materials: a review", *Construction and Building Materials*, v. 394, pp. 132116, Aug. 2023. doi: http://doi.org/10.1016/j.conbuildmat.2023.132116.

[7] OFUYATAN, O., OLOWOFOYEKU, A., ADARAMAJA, G., *et al.*, "Potential use of coconut stem as reinforcement in concrete slab", *Case Studies in Construction Materials,* v. 13, pp. e00355, 2020. doi: https://doi.org/10.1016/j.cscm.2020.e00355.

[8] ALBERTI, M., ENFEDAQUE, A., GALVEZ, J., *et al.,* "Fibre reinforced concrete with a combination of polyolefin and steel-hooked fibres", *Composite Structures*, v. 171, pp. 317–325, Jul. 2017. doi: http://doi.org/10.1016/j.compstruct.2017.03.033.

[9] SHARMA, B., HARRIES, K.A., GHAVAMI, K., *et al.*, "Methods of determining transverse mechanical properties of full-culm bamboo", *Construction and Building Materials*, v. 38, pp. 627–637, Jan. 2013. doi: http://doi.org/10.1016/j.conbuildmat.2012.07.116.

[10] ARCHILA, H., KAMINSKI, S., TRUJILLO, D., *et al.*, "Bamboo reinforced concrete: a critical review", *Materials and Structures*, v. 51, n. 102, 2018. doi: https://doi.org/10.1617/s11527-018-1228-6.

[11] DANSO, H., *et al.,* "Properties of coconut, oil Palm and bagasse fibres: as potential building materials", In: *Proceedings of the 3rd International Conference on Natural Fibers: Advanced Materials for a Greener World*, pp. 21–23, Braga, Portugal, 2017.

[12] KARLSSON, J., *Alternative reinforcement approaches*, Göteborg, Sweden, Chalmers University of Technology, 2014.

[13] GUNASEKARAN, K., ANNADURAI, R., KUMAR, P.S., *et al.*, "Plastic shrinkage and deflection characteristics of coconut shell concrete slab", *Construction and Building Materials*, v. 43, n. 6, pp. 203–207, 2013. doi: http://doi.org/10.1016/j.conbuildmat.2013.02.019.

[14] RANA, M.N., DAS, A.K., ASHADUZZAMAN, M., *et al.,* "Physical and mechanical properties of coconut palm (Cocos nucifera) stem", *Bangladesh Journal of Scientific and Industrial Research*, v. 50, n. 1, pp. 3, Jun. 2015. doi: http://doi.org/10.3329/bjsir.v50i1.23808.

[15] GANESAN, N., INDIRA, P.V., HIMASREE, P.R., *et al.,* "Strength and behaviour of bamboo reinforced concrete wall panels under two way in-plane action", *Advances in Concrete Construction,* v. 6, n. 1, pp. 1–13, 2018. doi: https://doi.org/10.12989/acc.2018.6.1.001.

[16] TURNER, L.K., COLLINS, F.G., *et al.,* "Carbon dioxide equivalent (CO2-e) emissions: a comparison between geopolymer and OPC cement concrete", *Construction & Building Materials*, v. 43, pp. 125–130, Jun. 2013. doi: http://doi.org/10.1016/j.conbuildmat.2013.01.023.

[17] MONDAL, B., MAITY, D., PATRA, P.K., *et al.,* "Tensile characterisation of bamboo strips for potential use in reinforced concrete members: experimental and numerical study", *Materials and Structures*, v. 53, n. 5, pp. 128, Oct. 2020. doi: http://doi.org/10.1617/s11527-020-01563-z.

[18] HASAN, N.M.S., SOBUZ, H.R., SAYED, M.S., *et al.*, "The use of coconut fibre in the production of structural lightweight concrete", *The Journal of Applied Science*, v. 12, n. 9, pp. 831–839, 2012. doi: http://doi.org/10.3923/jas.2012.831.839.

[19] RAGAVENDRA, S., REDDY, I.P., DONGRE, A., *et al.,* "Fibre reinforced concrete- a case study", In: *Proceedings of the 33rd national Convention of Architectural Engineers and National Seminar on "Architectural Engineering Aspect for sustainable building envelopes" ArchEn-BuildEn-2017*, pp. 1–15, India, 2017.

[20] AWOYERA, P.O., KARTHIK, S., RAO, P.R.M., *et al.,* "Experimental and numerical analysis of large-scale bamboo-reinforced concrete beams containing crushed sand", *Innovative Infrastructure. Solution,* v. 4, pp. 41, 2019. doi: https://doi.org/10.1007/s41062-019-0228-x.

[21] MALI, P.R., DATTA, D., *et al.,* "Experimental evaluation of bamboo reinforced concrete slab panels", *Construction* and *Building Materials*, v. 188. pp. 1092–1100, 2018. doi: https://doi.org/10.1016/j.conbuildmat.2018.08.162.

[22] KUMAR, P., GAUTAM, P., KAUR, S., *et al.*, "Bamboo as reinforcement in structural concrete", *Materials Today: Proceedings*, v. 46, n. Pt 15, pp. 6793–6799, 2021. doi: https://doi.org/10.1016/j.matpr.2021.04.342.

[23] ANANDARAJ, S., ROOBY, J., AWOYERA, P.O., *et al.*, "Structural distress in glass fibre-reinforced concrete under loading and exposure to aggressive environments", *Construction* and *Building Materials*, v. 197, pp. 862–870, 2019. doi: https://doi.org/10.1016/j.conbuildmat.2018.06.090.

[24] HARYANTO, Y., WARIYATNO, N.G., HU, H.-T., *et al.*, "Investigation on structural behaviour of bamboo reinforced concrete slabs under concentrated load", *Sains Malaysiana*, v. 50, n. 1, pp. 227–238, 2021. doi: http://doi.org/10.17576/jsm-2021-5001-22.

[25] LATTIF, Y., HAMDY, O., *et al.,* "An experimental investigation of the flexural strengthening of preloaded self-compacted RC beams using CFRP sheets and laminates composites", *Advances in Concrete Construction,* v. 13, n. 4, pp. 307–313, 2022. doi: https://doi.org/10.12989/acc.2022.13.4.307.

[26] MADANI, S.A.H., MIRHOSSEINI, S.M., ZEIGHAMI, E., *et al.*, "Experimental investigation of the pull-out behavior of fiber concrete with inclination steel fibers", *Advances in Concrete Construction,* v.14, n. 5, pp. 299–307, 2022. doi: https://doi.org/10.12989/acc.2022.14.5.299.

[27] ATTIA, M.M., AL SAYED, A.A.K.A., TAYED, B.A., *et al.*, "Banana agriculture waste as eco-friendly material in fibre-reinforced concrete: an experimental study", *Advances in Concrete Construction,* v. 14, n. 5, pp. 355–368, 2022. doi: https://doi.org/10.12989/acc.2022.14.5.355.

[28] ZHANG, J., HUANG, F., WU, Y., *et al.*, "Mechanical properties and interface improvement of bamboo cellulose nanofibers reinforced autoclaved aerated concrete", *Cement and Concrete Composites*, v. 134, pp. 104760, 2022. doi: https://doi.org/10.1016/j.cemconcomp.2022.104760.

[29] LIN, Y., ALENGARAM, U.J., IBRAHIM, Z., *et al.*, "Effect of treated and untreated rice husk ash, palm oil fuel ash, and sugarcane bagasse ash on the mechanical, durability, and microstructure characteristics of blended concrete – A comprehensive review", *Journal of Building Engineering*, v. 78, pp. 107500, Nov. 2023. doi: http://doi.org/10.1016/j.jobe.2023.107500.

[30] LING, Z., LI, Z., LU, F., *et al.*, "Flexural strengthening of timber-concrete composite beams using mechanically fastened and externally bonded combining mechanically fastened strengthening techniques", *Journal of Building Engineering*, v. 78, pp. 107645, Nov. 2023. doi: http://doi.org/10.1016/j.jobe.2023.107645.

[31] TERAI, M., *et al.,* "Bond properties of bamboo reinforcement", *Journal of Building Engineering*, v. 86, pp. 108890, 2024. doi: https://doi.org/10.1016/j.jobe.2024.108890.

[32] WASTI, S., HUBBARD, A.M., CLARKSON, C.M., *et al.*, "Long coir and glass fiber reinforced polypropylene hybrid composites prepared via wet-laid technique", *Composites*, v. 14, pp. 100445, 2024. doi: https://doi.org/10.1016/j.jcomc.2024.100445.