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PERFORMANCE OF AN EPOXY-FILLER-MODIFIED BAMBOO-REINFORCED CONCRETE SLAB

LASTNOSTI BETONSKIH BLOKOV MODIFICIRANIH Z EPOKSIDNIM POLNILOM IN OJAČITVIJO IZ BAMBUSA

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The necessity for a transition in the building industry towards sustainability has made bamboo-based construction more prevalent in recent decades. This paper demonstrates the development and performance evaluation of a newly developed cementitious composite slab panel containing nano-basalt powder (nBP) modified epoxy-coated bamboo as the reinforcement. The experimental research conducted on six slab panels ((600 × 450 × 50) mm), each having a different reinforcement type, demonstrated that the one with the nBP-modified epoxy-coated bamboo reinforcement showed significantly improved flexural performance by exhibiting better bonding characteristics. When compared to the uncoated bamboo-reinforced slab, the bond strength of the nBP-modified epoxy-coated bamboo-reinforced slab rose by about 32 %, to around 5.65 MPa. A flexural strength of about 73 MPa and a bond strength of about 6.26 MPa were attained due to the use of the nano-basalt powder modified epoxy-coated bamboo reinforcements with glass wrapping (nBGS). Comparing the nBGS slab to a slab of conventional cement concrete revealed an increase in the load-carrying capability of nearly 89 %.

Keywords: bamboo slab, epoxy coating, glass coating, basalt filler

Zaradi zahtev po prehodu na trajnostno naravnano družbo in gospodarstvo se je v zadnjem desetletju gradbeništvo usmerilo tudi v izdelavo konstrukcij in gradbenih elementov na osnovi bambusa. V člankuje predstavljen razvoj in ovrednotenje lastnosti na novo razvitih modificiranih cementnih kompozitnih blokov in plošč, ki vsebujejo nano-bazaltni prah (nBP) in ojačitev iz bambusa, prevlečenega z epoksidno smolo. Eksperimentalna raziskavaje bila narejena na šestih ploščatih blokih dimenzij (600 × 450 × 50) mm. Vsak betonski blok je vseboval drugačno vrsto ojačitve, pri čemer je imel betonski blok, modificiranz nBP in z epoksidno smolo prevlečeno ojačitev iz bambusa, boljšo upogibno trdnost zaradi boljših lastnosti medsebojne vezave. Primerjava betonskega bloka modificiranega z nBP in z epoksidno smolo prevlečeno ojačitev iz bambusa zbetonskim blokom, ki je bil ojačan le z neprevlečenim bambusom je pokazala, da ima prviza okoli 32 % boljšo vezavno trdnost, kar pomeni približno 5,65 MPa. Pri betonskem bloku, ki je vseboval nanobazaltni prah prevlečen s steklom (nGBS) in ojačitev iz bambusa, prevlečenega z epoksidno smolo pa so dosegli upogibno trdnost 73 MPa in vezivno trdnost okoli 6,26 MPa. Primerjava nBGS bloka s konvencionalnim cementnim blokom je pokazala, da ima prvi za približno 89 % boljšo nosilnost.

Ključne besede: betonski blok, ojačitev z bambusom, epoksidna prevleka, steklena prevleka, bazaltno polnilo

1 INTRODUCTION

Bamboo is renowned for its eco-friendly and sustainable qualities, as well as its superior strength-to-weight ratio.[1] Utilizing bamboo in building has resulted in substantial economic gains and reduced environmental impacts. Bamboo is a part of the grass family and is the fastest growing eco-friendly alternative to steel reinforcements for use in concrete. Due to their longevity and strength, bamboo structures resemble traditional RC structures constructed of steel and concrete.[2] Using bamboo as a reinforcement, it is possible to make very rigid slab panels that can be used for both structural and non-structural purposes.[3]

Reinforced concrete is one of the most extensively used materials in the construction; however, the cost and weight of the reinforcements make them expensive or non-renewable materials, restricting their use in the construction. To reduce this risk and improve the durability of reinforced concrete, in recent decades, the use of bio-based reinforcements has been attempted.[4] Bamboo has very good strength and stability, even in its natural form, and can be used as an efficient reinforcement material for structural use.[5,6] Bamboo is a material that can withstand both compressive and flexural loads, like structural steel, if the durability concerns are addressed.[7] Several researchers have investigated the use of bamboo as a reinforcement material for columns, beams, and slabs.[8–10] The excess water absorbed by bamboo fibers, i.e., the water in the concrete, leads to the weakening and splitting of the fibers, causing a considerable loss in durability over time.[11] Concrete is alkaline in nature and it affects the chemical nature of bamboo fibres.[12] Due to the smooth surface of the bamboo reinforcement, the anchorage interlocking and bonding between the reinforcement and the concrete material cause mechanical failure of the concrete matrix, which leads to mechanical fracture casting of slabs.[13]

Previously, coatings of epoxy, water-based solvents/paints and bitumen were employed to limit the

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penetration of concrete water into the bamboo reinforcement. The primary issue with such coatings is that they are effective for only a few years, after which they become brittle and lose their endurance.[14] The epoxy treated with nBP has stronger strength and durability than the epoxy used in the previous work.[15] Primarily, adhesion and surface roughness maintain the connection between the reinforcement and the concrete.[16] In the present study, a number of additives and coatings are presented as solutions for addressing the issue of using bamboo as the reinforcement for concrete structural elements. The research endeavored to use nano-basalt powder (nBP) as the filler in epoxy resin for coating bamboo reinforcements with glass-particle wrapping instead of sand wrapping. As a coating for reinforcement, epoxy has been utilised to resist water penetration into bamboo and sand has been utilized as a friction enhancer. The study attempts to use waste glass particle wrapping instead of sand wrapping for epoxy coating with an nBP-filler addition. Apart from the contribution of the coating to the durability of the reinforcement, the flexural performance and bond behavior of the composite material must be evaluated to ensure its structural integrity and viability for use in concrete structural elements which is the novelty of the research.

2 EXPERIMENTASL PART

2.1 Materials

2.1.1 Bamboo as the reinforcement

The present study tries to demonstrate the feasibility of using bamboo as the main reinforcement in a slab, focusing on the bond behaviour and flexural behaviour. The bamboo reinforcement selected was 5 y old and had a density of 1190 kg/m^3. The bamboo culms were immersed in boric acid and kept under treatment for about 72 h, after which they were dried for about 5 d at room temperature.

2.1.2 Epoxy resin as the coating agent

The epoxy resin used in the present study was obtained from ASTRRA Chemicals, Tamilnadu, India. The epoxy resin is generally a two-part polymer-based mixture containing epoxy resin (epichlorohydrin based resin) and a hardener (bisphenol A based). The curing of the epoxy resin used in the present study was done at room temperature. The mixing ratio of the hardener and epoxy resin was 1 : 1 by weight.

2.1.3 Basalt powder as the filler in epoxy

Basalt powder with a particle size of 40 μm was used in this study. The obtained basalt powder was ground in a ball mill to create a nanoparticle structure. The basalt particles were maintained on a tray and put inside a ball-milling machine with a number of metal bobs of various sizes. A rate of 300 min^{-1} and a milling time of 4 h were used.

2.1.4 Fabrication of the bamboo reinforcement

Bambus arundinacea (Indian bamboo) was selected for use as the reinforcement in this study because it possesses superior mechanical strength and physical properties. The National Building Code of India (2016) also recommended its use in building. The bamboo was collected with care, inspected for surface imperfections and given an initial chemical treatment before being covered with epoxy resin (1 : 1 ratio with the hardener). The coating was applied approximately 24 h prior to placing the bamboo inside a concrete-slab mold and before pouring the concrete. The present experiment consists of eight different slabs with different types of reinforcement, as shown in **Table 1**. To prevent the lumping and aggregation of the nanofiller (nBP), it was distributed in the epoxy matrix through thorough mixing. The percentage of nBP was fixed to be 10 % by weight of epoxy with the hardener to achieve better dispersion and greater durability. Two series of slabs were cast, one with sand blasting over the epoxy coating and the other with crushed angular glass particles coated over the epoxy. Two different grain sizes of glass aggregates of 1.5–0.8 mm and 0.85–0.3 mm were used to coat the epoxy and the ratio between them was kept as 1 : 3.

Table 1: Details of slab reinforcements employed in the study

Batch No.	Slab type	Reinforcement type	Designation
1	Plain cement concrete slab	None	PCS
2	Reinforced concrete slab	Steel	RCS
3	Bamboo reinforced concrete slab	Bamboo	BRS
4	Epoxy coated bamboo reinforced concrete slab	Epoxy coated bamboo	EBS
5	Epoxy/sand coated bamboo reinforced concrete slab	Epoxy + sand coated bamboo	SEBS
6	Epoxy/glass coated bamboo reinforced concrete slab	Epoxy + glass coated bamboo	GEBS
7	Epoxy/sand/nBP coated bamboo reinforced concrete slab	nBP modified epoxy/sand coated bamboo	nBSS
8	Epoxy/glass/nBP coated bamboo reinforced concrete slab	nBP modified epoxy/glass coated bamboo	nBGS

2.2 Casting and proportions

The M25 grade of concrete was used for the fabrication of concrete slabs. The mix design was carried out in accordance with IS-10262:2019, and concrete cubes and beams were tested in accordance with IS 456:2000 (reaffirmed 2021). The resulting mix design was 1 : 1.95 : 3.39 with a *w*/*c* ratio of 0.47. The slabs were cast as per Indian standards and the layout of the slab casting is schematically represented in the **Figure 1**. The dimensions of these lab panels were (600 × 450 × 50) mm, and the approximate dimensions of the rectangular strips of the

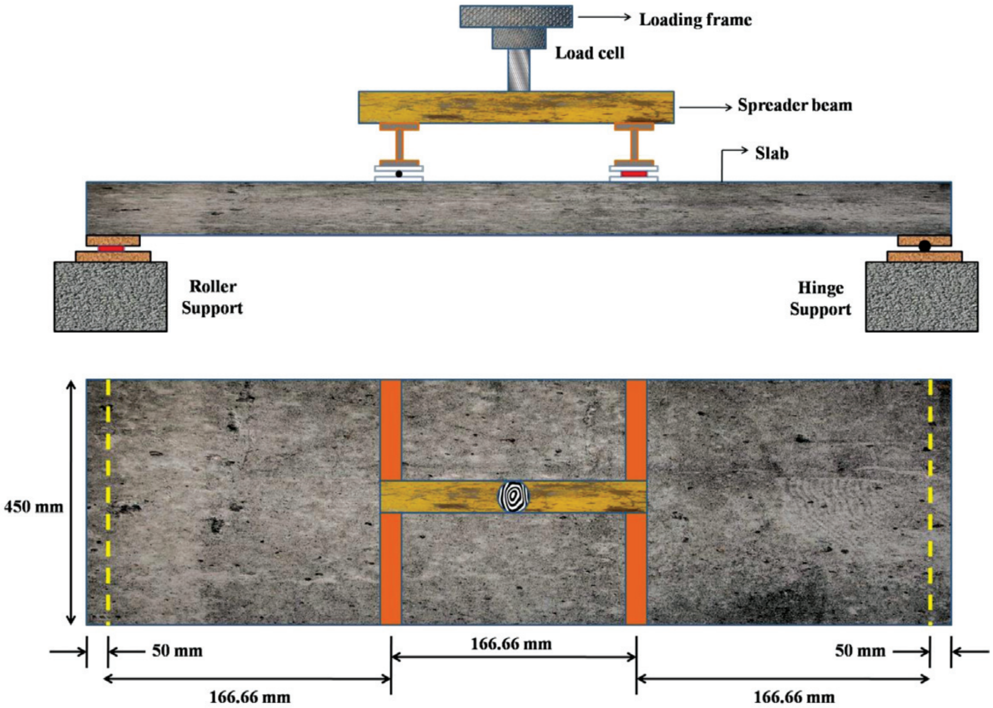

Figure 1: Experimental test set-up for cast slabs

bamboo reinforcements were (600 × 10) mm, with a thickness of 10 mm. The different types of reinforcements used for the slabs included conventional steel and modified bamboo. The slabs were cast in batches, and three slabs were cast for each type to ensure accuracy. The slabs were cast at room temperature and kept in the mold for 24 h before they were demoulded and kept under water for 28 d before testing.

2.3 Testing

The bonding behaviour of the bamboo reinforcement used for the slabs was determined by conducting a pull-out test on the concrete cylinders. As the behaviour and attributes of bamboo reinforcements differ from those of standard steel bars, their bond characteristics must be considered in order to visualise the subsequent impacts on cracking and deflection. **Figure 2** schematically illustrates the pressures influencing the bond strength between the concrete and the bamboo-composite reinforcement. The concrete cylinders for the pull-out strength test have been cast in accordance with ASTM-C192:2019 and for each reinforcement type; five samples were cast and tested in accordance with ASTM-D7913:2014. The length of the bamboo reinforcement is kept at five times the average diameter of the bar embedded in the concrete. The load is gradually applied at a rate of 20 kN/min until the specimen undergoes failure. A computerised acquisition system captures the pull-out load and slip values during the test. The bond stress calculation is done using Equation (1):

$$\tau = \frac{P}{(2a+2b)L_\mathrm{d}} \tag{1}$$

where τ is the average bond stress in MPa, P is the tensile force in N, d is the diameter of the bar in mm, and L_d is the bond length in mm. The slip of the bamboo reinforcement in concrete can also be obtained with Equation (2),

$$S = S_\mathrm{L} - S_\mathrm{F} \tag{2}$$

where S is the slip of the bars in mm, S_L is the slip at the load end in mm, and S_F is the slip at the free end in mm.

The specimens were subjected to flexural testing using a flexural testing machine conforming to the EN standard (EN 12390-4:2019) and the displacement near the point of load application was measured using a strain gauge placed in the centre of the slab. A hydraulic jack with a capacity of 250 kN was used to statically apply the load to the slabs, while the application of the load was controlled by a proving ring. The load was gradually increased by roughly 1.5 kN/s until the failure of the

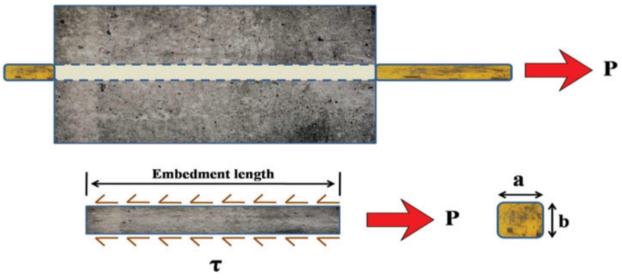

Figure 2: Bond strength between bamboo and concrete

slabs and the respective deflections were recorded until the specimens broke under the ultimate failure load.

3 RESULTS AND DISCUSSION

3.1 Bond behaviour

Figure 3 depicts typical load-deflection curves for tensile and bond failure of the bamboo reinforcement. The tensile failure indicates a load deflection curve that demonstrates an elastic and linear increase in the curve prior to the tensile failure of the specimen. The bond failure depicts the linear behavior of the material until the slippage caused by the bond failure forms a plateau-like region on the curve. Eventually, the bar separates from the specimen, resulting in bond failure and a decreasing load deflection curve.

Slipping failure of the specimens is another kind of failure that causes the specimen to break because the tensile-load fasteners cause a specimen to split. In the present study, the slabs failed due to tensile or bond failure. However, splitting failure was not observed. The concrete with the bamboo reinforcement exhibited bond failure owing to slippage, and the curves correlated with the bond-failure curve depicted in **Figure 4**. The RCC with steel reinforcement displayed a greater bond strength without any slippage or bond breakdown. The failure was entirely tensile and well linked with the tensile-bond failure curve.

Table 2 displays the bond strength results for the slabs and the mode of failure of the specimens. The bamboo bars had a cross-section of approximately (10 × 10) mm, and the length embedded in the concrete to determine the bond strength was around 200 mm. The bond strength of the epoxy-coated bamboo-reinforced slab was about 4.36 MPa, which corresponded very well with the bond strength value observed in a similar prior research. The increased bond strength of the nBP-modified epoxy-coated bamboo-reinforced slab (nBSS) was around 5.65 MPa, which is approximately 32 % stronger than the bond strength of the uncoated bamboo reinforced slab (BRS). According to the results, the addition of nBP to the epoxy resin enhanced the connection between the concrete and bamboo reinforcement. This enhancement in the binding strength is dependent mainly on the surface roughness of the epoxy layer, which is enhanced by the sand-coating process. The interlocking mechanism is much more essential for increasing the binding strength of the reinforcement, which is embedded in the concrete cylinder.[17]

The addition of nBP as the filler considerably improves the adhesiveness of the epoxy with the bamboo reinforcement, which further inhibits the bamboo bars from slipping. To cause tensile failure in the bamboo reinforcement, the frictional force displayed by the reinforcement bars must be larger than the pull-out force. If the pull-out load exceeds the tensile strength of the bamboo reinforcement, slippage occurs, resulting in bond failure. The epoxy-coated bamboo bar with glass coating exhibits a remarkable improvement in the bond strength, and its values are slightly closer to those of steel bars. Compared to the sand-spraying operation, glass blasting on the epoxy coating further boosts the binding strength to achieve values comparable to those of traditional steel reinforcements. The maximum bond strength of around 6.26 MPa is achieved by combining glass coating with the nBP filler-modified epoxy coating (nBGS). In contrast, the bamboo bars exhibited nearly identical behavior with and without epoxy coating, with just a 2.35 % change in the bond strength. Given that there is no statistically significant difference in the bond strength of the bamboo reinforcement with and without epoxy coating, the usage of plain epoxy coating has a very little or negligible influence on modifying the bond strength of the bamboo-reinforced concrete.

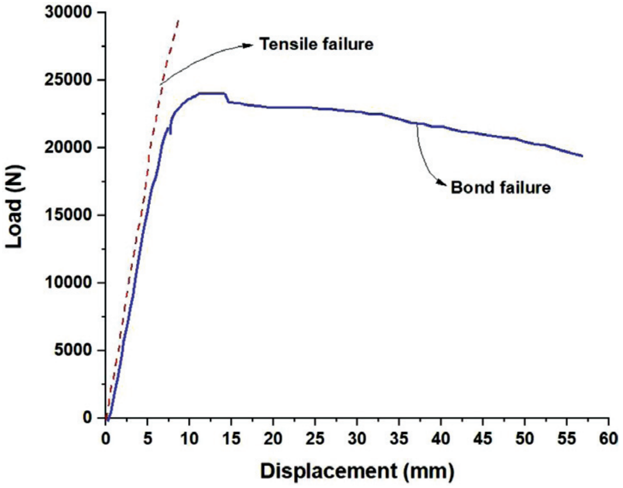

Figure 3: Typical load-deflection curve for different failure modes

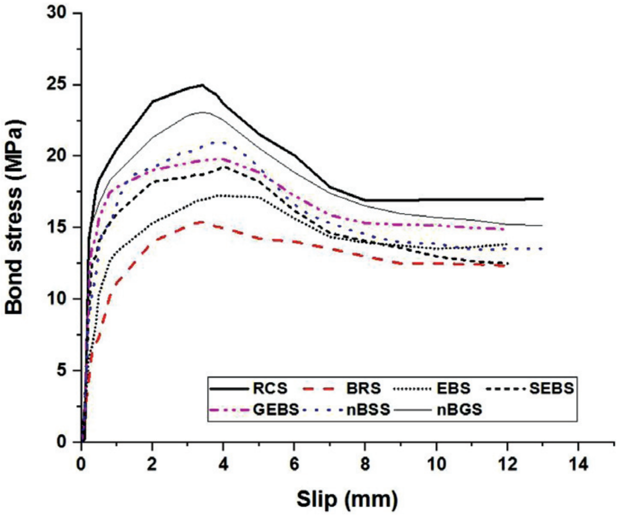

Figure 4: Bond stress/slip of developed slab composites

Table 2: Pull-out and bond strength of cast slabs

Slab	Embedment length (mm)	Pull-out load at failure (kN)	Bond strength (MPa)	Failure mode
RCS	200	58.3	7.29	Tensile
BRS	200	34.1	4.26	Bond
EBS	200	34.9	4.36	Bond
SEBS	200	38.1	4.76	Tensile
GEBS	200	40.2	5.03	Tensile
nBSS	200	45.2	5.65	Tensile
nBGS	200	50.1	6.26	Tensile

From the bond strength test, it can also be seen that the slip values of the plain bamboo reinforcements (BRs) were much higher; a value of 2.25 mm was obtained at the free end and the slip value at the load end was about 3.4 mm at the corresponding maximum bond stress, which can be evident from **Figure 4**. The nBP-modified epoxy-coated bamboo reinforcements showed relatively smaller values of the slip, indicating greater bonding of the reinforcement with the concrete. The slip values of the free end were much lower when compared to the load end of the nBP-modified epoxy-coated bamboo reinforcement. The slip values were reduced further when epoxy was used as the coating agent along with nBP micro-fillers and with sand coating. A better pull-out load at failure was obtained, reaching up to 50 kN with a higher bond strength of about 6.26 MPa, obtained for nBGS, but not higher than RCS. The bond strength of the bamboo reinforcements with nBP-modified epoxy coating and glass coating showed superior bond characteristics with minimum slippage and greater pull-out strength.

3.2 Flexural performance

The energy absorption capacity and results of the first crack formations for the slab panels after being subjected to flexural loading are shown in **Table 3**. The plain cement concrete slab (PCS) showed brittle failure due to a lack of reinforcements and the elastic behavior of the slab extended up to 38.5 kN, beyond which the failure was sudden. The average displacement exhibited by the PCS was 2.55 mm, indicating that the ductility of the PCS was much smaller when coupled with a low energy absorption capacity. The RCSs with 8-mm-diameter rods exhibited better flexural performance with a failure load attainment greater than 74.2 kN and an average displacement of 9.23 mm. Higher strain values indicate a higher energy absorption capacity of the RCC slab when compared to the other slabs. The bamboo-reinforced slabs, acting as structural slabs, showed relatively poor flexural performance. The load deflection behavior of all the slabs also clearly showed that the epoxy coating without nBP additives showed a relatively quick attainment of the first crack load and a relatively low ultimate load. The experimental ultimate load was reached at 72.1 kN when nBP was used as the reinforcing filler in the epoxy-resin coating. It can be clearly seen that the first crack load increased for the slab that contained epoxy coating reinforced with nBP. The slab that contained bamboo reinforcements with glass-wrapped nBP-modified epoxy coating exhibited the best flexural performance with a greater first crack load and ultimate load. The load-carrying capacity was increased by about 89 % for the nBGS slab when compared to the plain cement concrete slab (PCS).

The load deflection curves of the bamboo-reinforced slabs with different coatings are shown in **Figure 5**. The load deflection curve of the plain cement concrete clearly shows a steeper linear rise until the first crack load, after which a blunt non-linear fall is observed. The RCC slab exhibited ductile failure with a reasonable amount of flexural strength. The plain epoxy-coated bamboo-reinforced slab (EBRS) showed a linear increase in the load deflection, indicating elastic performance up to the first crack load, after which inelastic behaviour was observed. The load carrying ability of the nBP-modified epoxy-coated bamboo-reinforced slab showed about 30 % higher ultimate strength than the plain epoxy-coated BRS. The load deflection curve of the nBP-modified epoxy-coated slab with glass wrapping showed almost similar flexural performance as the steel bar reinforced slabs but with lower deflection values for the same load values. This shows a greater contribution of the nBP filler in epoxy, also showing better traits of bonding and resistance to deformation. Interestingly, the reduction in the deformation is an indicator of an increase in the flexural rigidity of the material accompa-

Table 3: Results obtained for loads and deflections

Mix Id	First crack		Ultimate crack		Ultimate to first crack load ratio	Ultimate to first crack deflection ratio	Energy absorption (J)
	Load (kN)	Deflection (mm)	Load (kN)	Deflection (mm)			
PCS	37.40	2.24	39.84	2.52	1.07	1.13	58.81
RCS	44.61	1.98	71.95	9.21	1.61	4.65	602.46
BRS	37.35	2.99	52.19	5.13	1.40	1.72	206.67
EBS	43.81	2.94	53.11	5.08	1.27	3.00	275.14
SEBS	51.77	2.44	70.02	7.82	1.35	3.20	499.09
GEBS	39.25	2.53	69.88	8.74	1.78	3.45	441.47
nBSS	44.81	2.72	71.71	8.31	1.60	3.06	460.91
nBGS	60.08	2.55	70.35	9.01	1.17	3.53	591.20

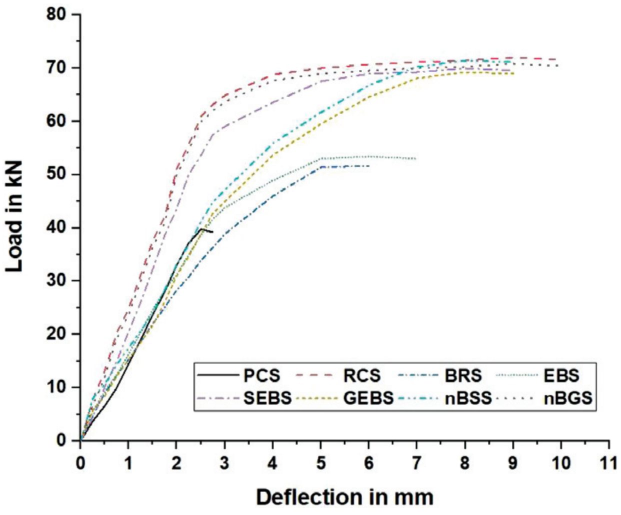

Figure 5: Load deflection responses of developed slab composites

nied by a modification in the modulus of elasticity of the epoxy resin due to the nBP and glass additions that minimized the deflection of the slab. However, no reduction in the ultimate flexural load was observed, confirming the bond strength results, and indicating that the nBP functioned as the strengthening agent in the epoxy matrix with a greater adhesiveness and reinforcing effect. Another possible explanation for this is that the improved ultimate flexural load accompanied by lower deformation may be caused by the glass coating on the nBP-modified epoxy resin, making the concrete relatively stiffer with its interlocking characteristics and making it resistant to bending.

4 CONCLUSIONS

This research presented a novel concept of utilizing nano-basalt powder modified epoxy resin as a surface coating agent for bamboo reinforcements in concrete slabs with glass-particle coating instead of the conventional sand coating. The bamboo reinforcements were subjected to the initial surface modification through a chemical treatment and then coated with epoxy resin with and without nBP fillers, and the performance was compared to the conventional plain cement concrete slabs and RCC slabs containing steel reinforcement. The investigated properties were the bond behavior of the bamboo reinforcement and the flexural performance of the slab in comparison to the steel reinforcement. The experimental results thus showed that the developed slab panels with nBP-modified epoxy-coated bamboo bars with added glass particles demonstrated in the present work are highly promising for use as the reinforcements in eco-friendly low-cost building components due to their distinct structural performance. In summary, the experimental study proposes an efficient and facile approach to developing high-strength bamboo-reinforced slabs using locally available materials and natural additives, as they can be considered promising building materials due to their unique structural performance.

The future part of the study will focus on the factors that affect the slip and stress distribution in a slab. The experiment shall also be extended to study the behaviour of the slab under cyclic and seismic loading. Precast slab panels for use in practical applications shall be developed.

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