Performance and Durability Evaluation of Bamboo Reinforced Cement Concrete Beams

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Abstract— A big part of population in India is still homeless due to raising unaffordability of housing structures. People sleeping on roadsides and living in slums is a common sight in Indian cities. To overcome this problem India today needs millions of houses for their growing population, making concrete as the most widely to be used material in the country. Concrete has found to have excellent compressive strength but poor in tensile strength, to take care of the tensile stresses steel is commonly used as reinforcing material in concrete. Production of steel is a very costly business and its use in concrete as reinforcing material increases the cost of construction by many folds. Also production of steel emits a large amount of green house gases causing considerable deterioration of the environment. The above mentioned socio-economic and environmental factors creates a necessity for finding an appropriate environment friendly and cheap material that can successfully substitute steel as reinforcement in concrete elements of a low cost dwelling for the poor and homeless people of the country. It is here that engineered bamboo can be of great value to Civil Engineers owning to its several net worthy features. Production of every tone of bamboo consumes about a tone of atmospheric CO_2 in addition to releasing fresh O2. From structural point of view bamboo has been used as a structural material from the earlier times as it possesses excellent flexure and tensile strength as well as high strength to weight ratio. All this necessitates examining bamboo-reinforced cement concrete in detail for its appropriateness as a structural material for construction of a low cost dwelling unit. The study focuses on evaluating the mechanical and durability properties of cement-concrete beams both singly and doubly reinforced with bamboo splints.

Keyword- Bamboo splints, Durability Test, Bamboo reinforced cement concrete beams, Modified Bamboo reinforced cement concrete beams, Flexure test.

I. INTRODUCTION

Bamboo is a strong, cheap, biodegradable and environment-friendly material. It belongs to the grass family, Gramineae and is one of the fastest growing woody plants on earth. Some species of bamboo can grow up to 1 meter in a day, finally reaching a culm length of 25 meter or more. Bamboo can be harvested in 3 to 5 years cycle. It grows on various topographies ranging from degraded lands to elevated grounds. Bamboo also acts as an effective soil stabilizer and helps to counter the green house effect. Because of its excellent engineering properties bamboo seems to be a prominent engineering material for the future. Researchers believes that in the near future, the world will witness more and more use of bamboo in construction for creation of simple, cheap and environmental friendly structures.

India is the second richest country in bamboo production, preceding China. About 136 species of bamboo occur in India [1]. 58 species of bamboo are found in the North-eastern states of the India alone.

The density of bamboo is very low lying in the range of 0.57-0.87, the initial moisture content decreases as we go along the height of bamboo Culm from bottom to top, the water absorption capacity and percentage increase in thickness of bamboo after 30 days of soaking in water is found to be as high as 60% of the saturated mass and 40% respectively, water absorption capacity of bamboo splints increase with the increase in number of nodes.

Bamboo Culm in compression fails in two modes cracking of fibres and crushing and the ultimate tensile strength of bamboo splints is high as 282 MPa which is comparable to the yield strength of steel. Under tensile loading bamboo splints shows brittle failure at node, making node as the most critical section for failure under tensile stresses [2]. The bamboo node shows ductile behaviour. The compressive strength of the bamboo is similar to the tensile strength and the behaviour is same as that of steel. The water absorption in bamboo is high so waterproofing of bamboo is required [3]. Four point bending test on the bamboo reinforced beam shows that bamboo splints reinforced beam shows better results than that of solid bamboo reinforced beam [4]. Bamboo reinforced concrete design is similar to steel reinforced concrete design if its mechanical properties are properly utilized hence providing an alternative method for low-cost construction in areas where steel reinforcement is costly [5]. The seismic force in bamboo housing system is very less as compared to the modern housing system [6]. [7] provides the methods of test for bamboo splints. [8] provides the detailed methods for conducting various tests on bamboo culm for determining its physical and mechanical properties.

II. Material and Methods

The following tests were performed to study the mechanical and durability properties of bamboo reinforced cement concrete beams (a) Durability test on bamboo splints (b) Third point loading flexure test on cement concrete beams doubly reinforced with bamboo splints with shear links, as per [9] and (c) Third point loading flexure test on cement concrete beams singly reinforced with bamboo splints without shear links, as per [9]. The details of the testing procedures have described in the next few paragraphs

A. Durability Tests on Bamboo Splints

The test specimens for evaluating the durability of bamboo splints were taken from different positions of the bamboo Culm (base, middle, top). The samples were 71mm to 76mm in length and 1.6mm to 2.2mm in width with full wall thickness, as tabulated in Table 1.

Table 1: Specimens details of Durability Test

Specimen	Length, l(cm)	Width, b(cm)	Thickness, t(cm)	Cross-section area, A = b x t (cm^2)
Specimens kept in H_2O Solution: pH=7				
W-1	71.0	1.60	0.60	0.96
W-2	74.4	2.00	0.90	1.80
W-3	74.6	2.00	1.20	2.40
Specimens kept in NaCl Solution: pH=7.5, Concentration-33.33gm/l				
S-1	74.5	2.20	0.40	0.88
S-2	74.0	1.90	0.80	1.52
S-3	76.0	2.20	1.00	2.20
Specimens kept in $Ca(OH)_2$ Solution : pH=14, Concentration-33.33gm/l				
C-1	71.5	1.60	0.50	0.80
C-3	74.0	2.20	0.80	1.76
C-4	73.7	2.10	1.00	2.10

To check the durability, the samples were subjected to alternate wetting (submerging the specimens in three separate containers one containing plain water other containing NaCl solution and the third containing Ca(OH)2 solution) and air drying for 12 hours per day continuously for a period of around 60 days at room temperature. After 60 days of undergoing alternate wetting and drying cycles, the samples were taken out from their respective containers and air dried for 24 hours. This is shown in Figure 1.

To find if there was any loss in their tensile strength or not, a tensile load was applied on the cross section of all specimens individually on a universal testing machine. The strain rate for all of the specimens was kept constant i.e. 0.06mm/min. The load at which the specimen failed was divided with the cross-sectional area to obtain the ultimate tensile strength of the specimen. The results obtained were compared with an average value of actual tensile strength of the splints and percentage loss of tensile strength in individual specimen due to alternate wetting and drying in different environments was calculated.

B. Third point loading flexure test on cement concrete beams doubly reinforced with bamboo splints and shear links [9]

The study was carried out to find out by what amount the modulus of rupture and ductility of cement concrete beam gets improved on doubly reinforcing it with a cage of bamboo splints. To take care of shear cracks equally spaced shear links of bamboo were provided at regular intervals.

To reduce the water absorption capacity of the bamboo and to improve the bamboo concrete bond strength one part of the samples tested were reinforced with modified bamboo splints i.e. bamboo splints coated with a layer of bitumen and sand mixture (1 part bitumen in 2 parts of sand).

Concrete mix design for beams was done as per [10] and the concrete used for preparation of beams was of M20 grade (f_{ck} = 20MPa). This is shown in Table 2.

Three different types of total nine cement concrete beams (50cm x 10cm x 10cm) samples were prepared. This included (a) three samples of Plain cement concrete beam (PCC - Type I), (b) Three samples of Bamboo reinforced cement concrete beam (BRCC-Type II) and (c) Three samples of Modified bamboo (bamboo splints coated with bitumen & sand mixture) reinforced cement concrete beam (MBRCC – Type III). The details of the beams have been tabulated and shown in Table 2. Sample preparations for Type II and Type III tests have been shown in Figure 2 and 3 respectively.

All the specimens were subjected to Third point loading flexure test as per [9] procedure after 7 days, 14 days & 28 days of curing, individually on a universal testing machine at a constant strain rate. The load-displacement readings were taken at regular intervals for each specimen, using a digital indicator and the load-displacement curves were plotted.

Using the below mathematical expression the modulus of rupture of beams was calculated.

$$f_b = \frac{3 \times p \times a}{b \times d^2} \quad (1)$$

Where: f_b = Modulus of rupture, MPa; p = Maximum load, N; b = Width of beam, mm; d = Depth of beam, mm; a = Distance between line of fracture and nearest support, mm.

Table 2: Concrete mix design for plain, singly and doubly reinforced beams

Concrete mix design-[10] Grade of Concrete-M20 f_{ck} = 20 MPa (All quantities for 1m^3 volume of concrete)				
Materials	Water	Cement	Fine Aggregate	Coarse Aggregate
Quantities	191.6 liter	383.0 kg	546.0 kg	1188 kg
Design Mix	W/C ratio 0.5	1: 1.4: 3.1		

Table 3: Plain and doubly reinforced cement concrete beams details.

Specimen	Reinforcement dimensions, cm l x b x h	Percentage reinforcement		Clear cover, cm	Thickness of stirrups, cm	No. of stirrups spaced at 13.33 cm
		Tension	Compression			
PCC-1	-	-	-	-	-	-
PCC-2	-	-	-	-	-	-
PCC-3	-	-	-	-	-	-
BRCC-1	46 x 1.5x 0.8	2.40%	2.40%	2.0	0.50	4
BRCC-2	46 x 1.5 x 0.8	2.40%	2.40%	2.0	0.50	4
BRCC-3	46 x 1.5 x 0.8	1.65%	1.65%	2.0	0.50	4
MBRCC-1	46 x 1.5 x 0.8	2.55%	2.55%	2.0	0.50	4
MBRCC-2	46 x 1.5 x 0.8	2.40%	2.40%	2.0	0.50	4
MBRCC-3	46 x 1.5 x 0.8	2.49%	2.49%	2.0	0.50	4

C. Third point loading flexure test on cement concrete beams doubly reinforced with bamboo splints and without shear links [9]

The study was carried out to determine the improvement in modulus of rupture and ductility of cement concrete beam on singly reinforcing it with bamboo splints and without the application of shear links.

To improve the bamboo concrete bond strength, 0.3cm-0.5cm deep grooves inclined at 45^0 were made on the inner part of bamboo stirrups at a spacing of 2 cm. This has been shown in Figure 4.

Concrete mix design for beams was done as per [10] and the concrete used for preparation of beams was of M20 grade (f_{ck} = 20MPa) and has already been shown in Table 2.

Similar to the above testing conditions (sub section B) three different types of total nine cement concrete beams (50cm x 10cm x 10cm) samples were prepared including (a) three samples of Plain cement concrete beam (PCC - Type I), (b) Three samples of Bamboo singly reinforced cement concrete beam (BSRCC-Type II) and (c) Three samples of Modified bamboo (bamboo splints coated with bitumen & sand mixture) singly reinforced cement concrete beam (MBSRCC – Type III). The details have been tabulated in Table 4 and sample preparations for Type II and Type III tests have been shown in Figures 5 and 6 respectively.

All the specimens were subjected to Third point loading flexure test as per IS 516:1959 procedure, after 28 days of curing, individually on a universal testing machine at a constant strain rate. The load-displacement observations were taken at regular intervals for each specimen, using a digital indicator and the load-displacement curves were plotted. The modulus of rupture of the beam was calculated using equation (1).

Table 4: Plain and doubly reinforced cement concrete beams details.

Specimen	Reinforcement dimensions, cm l x b x h	Percentage reinforcement		Clear cover, cm	Thickness of stirrups, cm	No. of stirrups spaced at 13.33 cm
		Tension	Compression			
PCC-1	-	-	-	-	-	-
PCC-2	-	-	-	-	-	-
PCC-3	-	-	-	-	-	-
BSRCC-1	46 x 1.5x1.0	1.50%	-	2.0	-	-
BSRCC-2	46 x 1.5 x 0.8	1.20%	-	2.0	-	-
BSRCC-3	46 x 1.5 x 0.9	1.35%	-	2.0	-	-
MBSRCC-1	46 x 1.5 x 0.8	1.20%	-	2.0	-	-
MBSRCC-2	46 x 1.5 x 1.0	1.50%	-	2.0	-	-
MBSRCC-3	46 x 1.5 x 0.9	1.35%	-	2.0	-	-

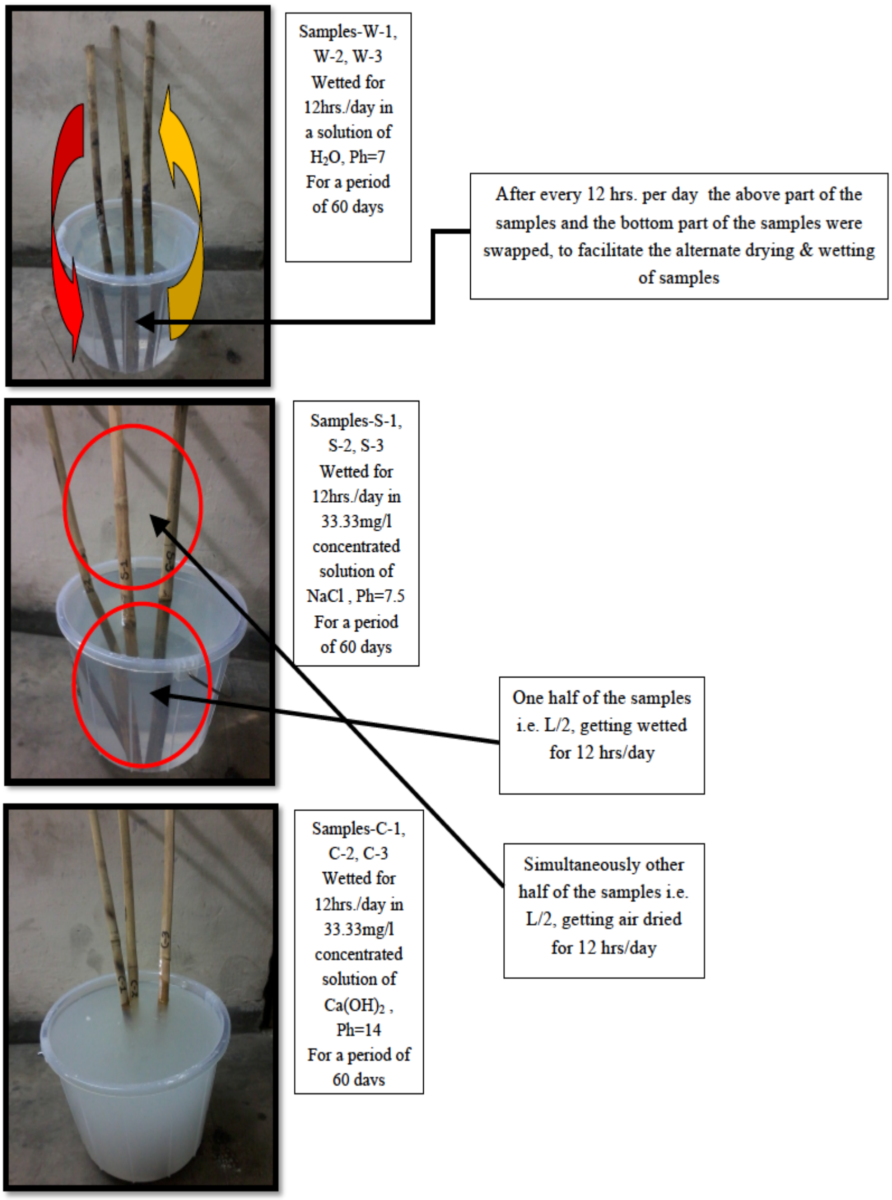


Figure 1: Specimen details and test procedure of durability test.

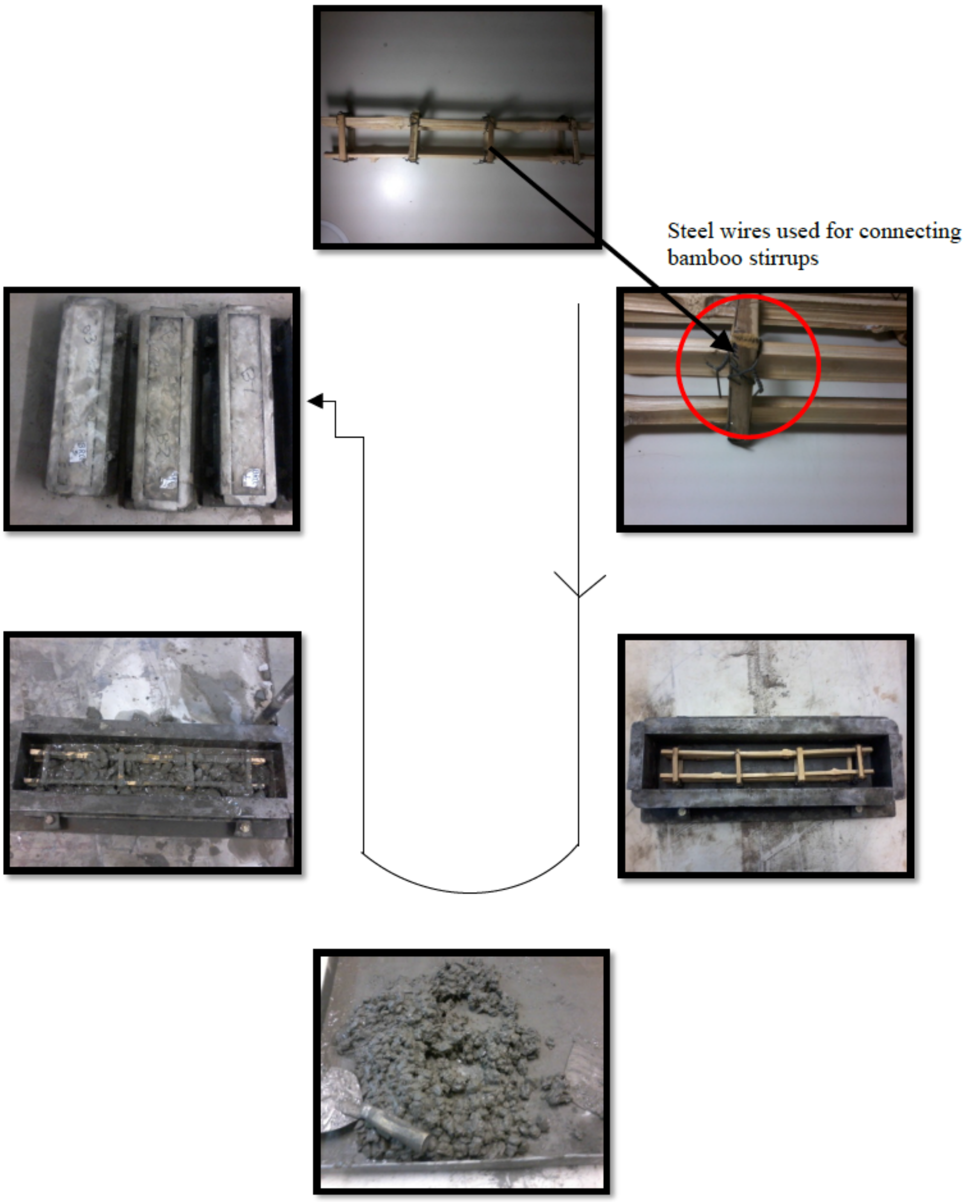


Figure 2: Preparation of BRCC beam elements (Type – II).

Figure 3: Preparation of MBRCC beam elements (Type – III).

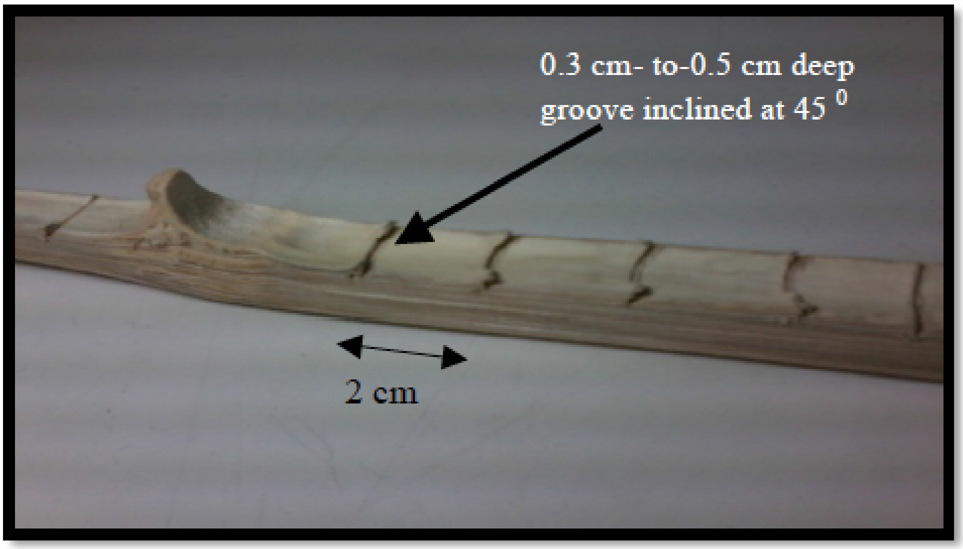


Figure 4: Grooves made for improving bond strength

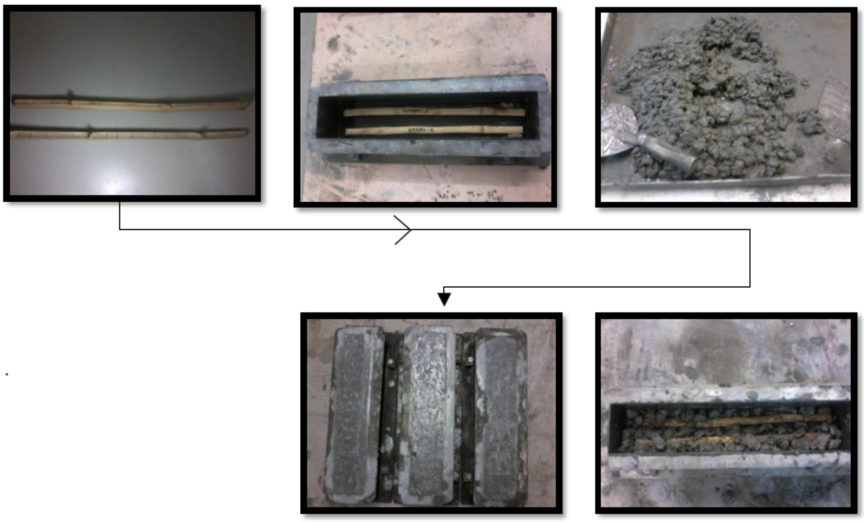


Figure 5: Preparation of MBSRCC beams

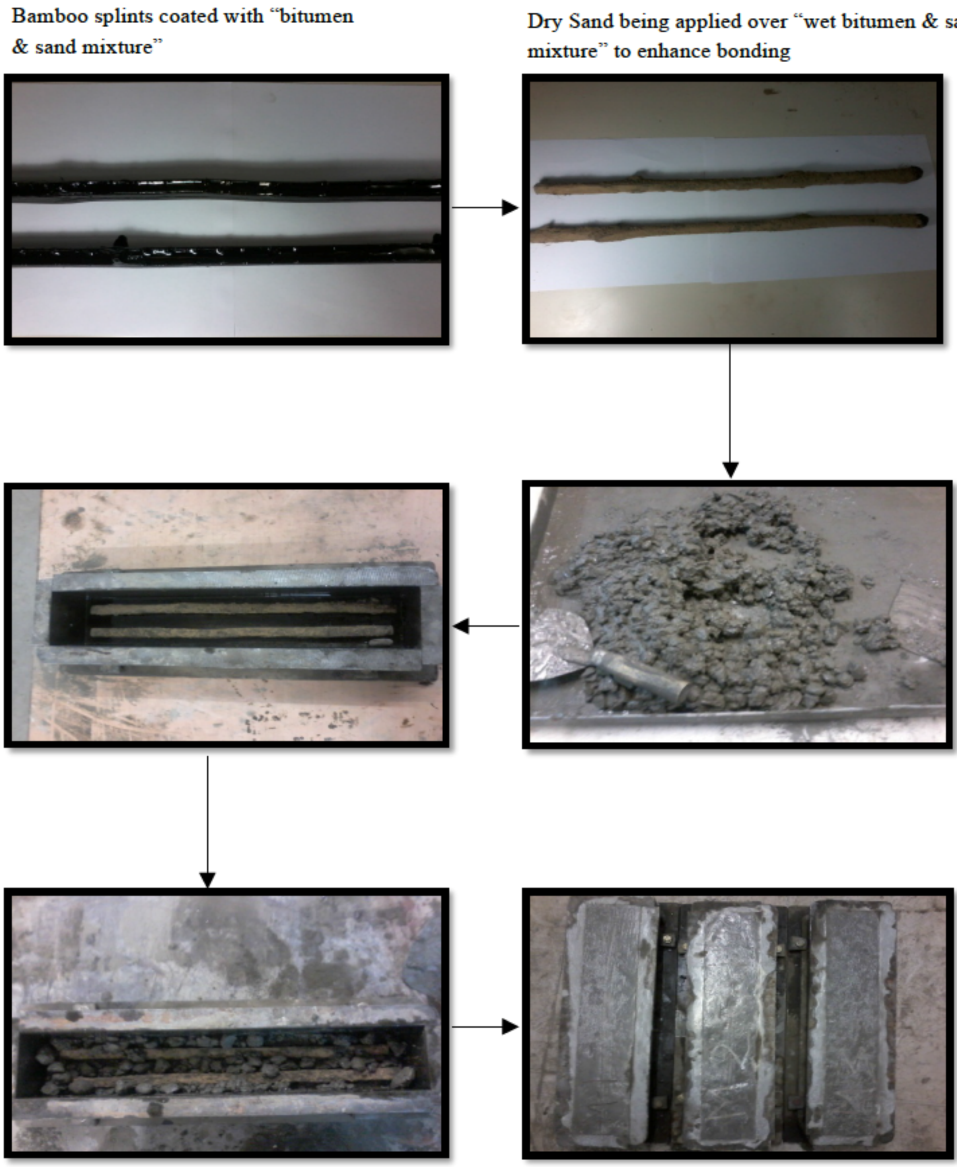


Figure 6: Preparation of BSRCC beams

III. Results and Discussions

A. Durability Tests on Bamboo Splints

The test results Table 5 shows that there is a significant loss of ultimate tensile strength of bamboo splints when they undergoes alternate swelling & shrinkage in the presence of alkalis, chlorides and moisture, the actual environmental conditions they possibly would be exposed to, when used as reinforcement in concrete elements, hence putting a question over the use of bamboo splints as reinforcement in concrete.

Table 5: Durability Test: calculation of percentage loss of ultimate tensile strength.

Sample	Actual tensile strength, f_t, (MPa)	Initial Average tensile strength, f_i, (MPa)	Loss of tensile strength f_i-f_t, (MPa)	%loss of tensile strength $((f_i-f_t)/f_i) \times 100$
Specimens kept in H_2O Solution : pH-7				
W-1	227.083	282	054.917	19.47%
W-2	203.333		078.667	27.89%

W-3	165.000		117.000	41.48%
			Average percentage loss of tensile strength=	29.61%
Specimens kept in NaCl Solution : pH-7.5, Concentration-33.33gm/l				
S-1	237.500		044.500	15.78%
S-2	178.947		103.053	36.54%
S-3	216.818	282	065.182	23.11%
			Average percentage loss of tensile strength=	25.11%
Specimens kept in $Ca(OH)_2$ Solution : pH-14, Concentration-33.33gm/l				
C-1	248.888		033.112	11.74%
C-3	179.545		102.455	36.33%
C-4	170.952	282	111.048	39.36%
			Average percentage loss of tensile strength=	29.14%

Charts comparing ultimate tensile strength and percentage loss of ultimate tensile strength after subjecting the bamboo splints specimens to alternate wetting and drying in differ environments were plotted and shown in Figure 7.

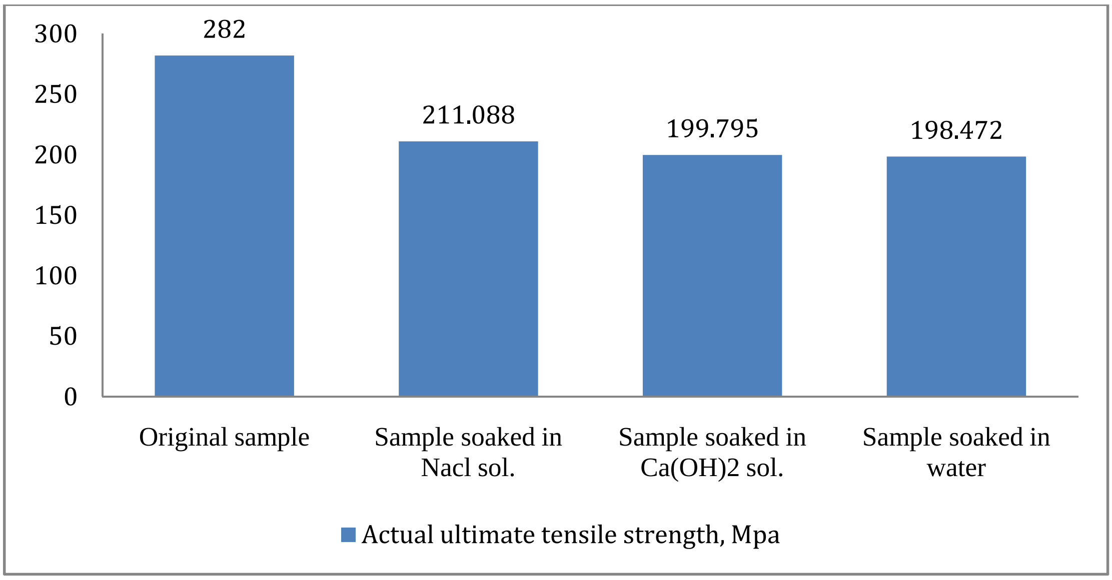


Figure 7: Chart comparing actual ultimate tensile strength after subjecting the specimens to alternate wetting & drying.

Highest loss of ultimate tensile strength of about 29.61% was observed in bamboo splints samples that were soaked in plain water followed by 29.14% in that soaked in $Ca(OH)_2$ solution and minimum of 25.14% in that soaked in NaCl solution. This is shown in Figure 8.

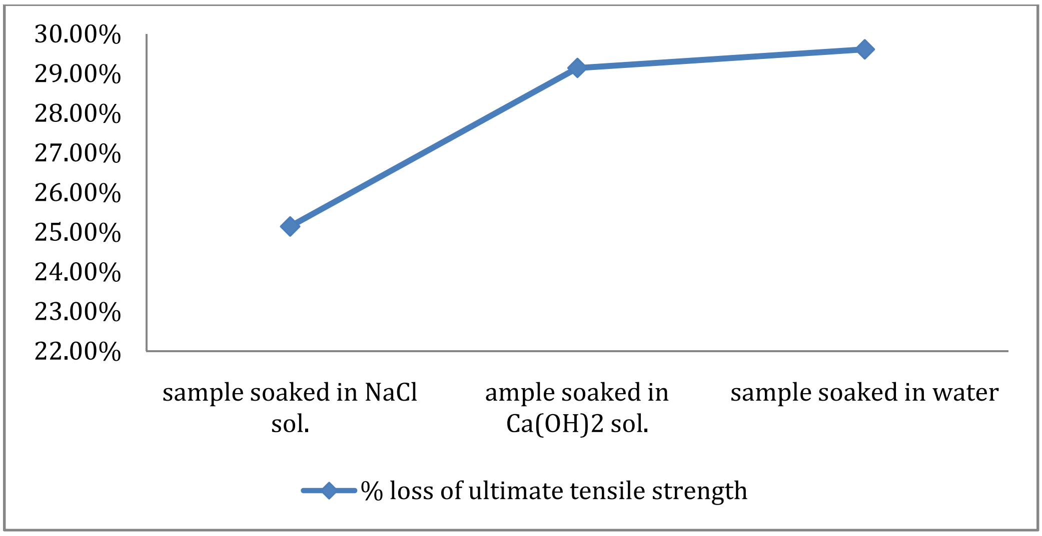


Figure 8: Chart comparing percentage loss of ultimate tensile strength after subjecting the specimens to alternate wetting & drying.

Heavy fungal attack was observed on the surface of one of the bamboo splint (W-1), soaked in plain water, causing rotting of bamboo & disintegration of fibers. This has been illustrated in figure 9.

Figure 9: showing heavy fungal attack on the surface of one of the bamboo splint (W-1), soaked in water, causing rotting of bamboo & disintegration of fibers

Minor fungal attack was observed on the bamboo splints which were wetted in $Ca(OH)_2$ solution at nodes; though the attack did not caused any disintegration of fibre or rotting of bamboo. In addition to fungal attack deposition of calcium took place on the bamboo surface. This is shown in Figure 10. No fungal attack was observed on any of the bamboo splint which was wetted in NaCl Solution, neither at nodes nor at the inner surface. This is shown in Figure 11.

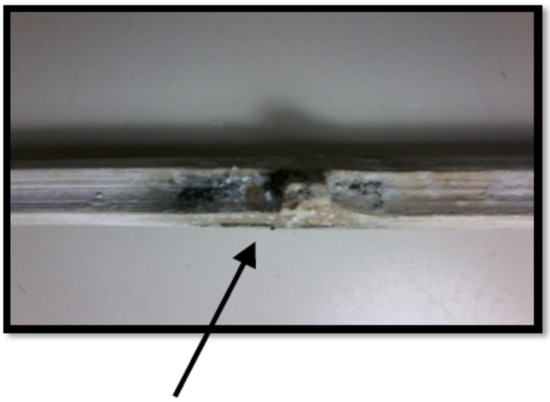


Figure 10: showing minor fungal attack on the bamboo splint which was wetted in $Ca(OH)_2$ sol. at node. In addition to fungal attack deposition of calcium took place on the bamboo surface

Figure 11: shows that no fungal attack was observed on the bamboo splints which were wetted in NaCl Solution, neither at nodes nor at the inner surface.

The swelling and shrinkage of bamboo is attributed to its high water absorption and high water releasing properties due to its hygroscopic nature, hence this swelling and shrinkage of bamboo can be controlled up to some extent by using a water proof material (like bitumen) coating over the surface of bamboo splints before using them as a reinforcing material. The water proofing material will not only prevent the swelling & shrinkage of bamboo nut will also prevent the bamboo from coming in contact with alkalis and chlorides.

The samples wetted in plain water and $Ca(OH)_2$ solutions shows a heavy fungal attack at nodes and at inner surface of the splints, leading to rotting of bamboo surface and disintegration of fibres. This necessitates the application of an anti-fungal compound such as Boric Acid, over the bamboo splints before using them as a reinforcement material in concrete.

No fungal attack and minimum loss of ultimate tensile strength was observed in the bamboo splints which were wetted in NaCl Solution, making bamboo a prominent material to be used as reinforcement in concrete subjected to costal environments.

B. Third point loading flexure test on cement concrete beams doubly reinforced with bamboo splints and shear links (IS 516-1959)

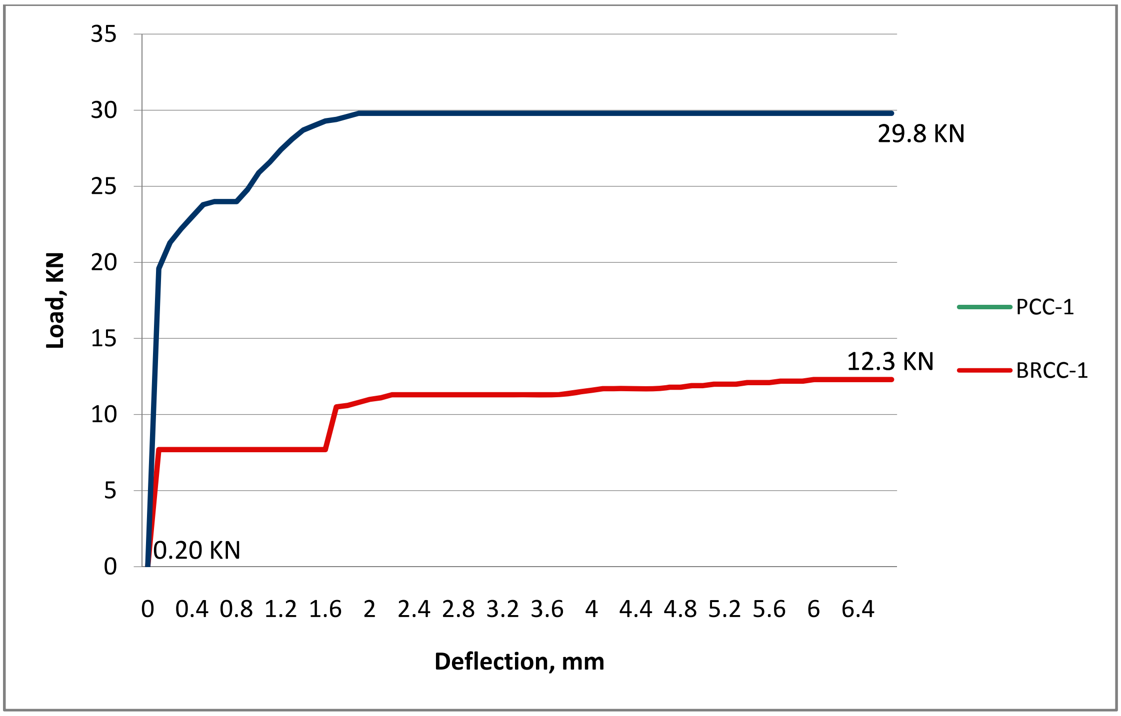
Table 6 shows load at failure, deflection of mid section, modulus of rupture values of the specimens tested.

Table 6: load at failure, deflection of mid section, modulus of rupture values of the plain and doubly reinforced beam specimens tested.

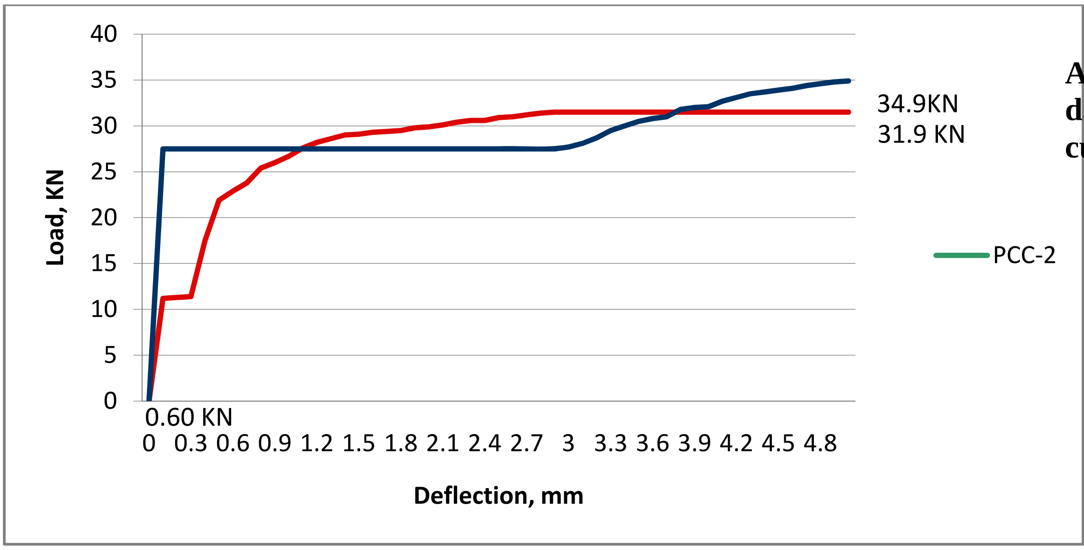
Sample	Curing period	Load at Failure, KN	Displacement of mid-section at failure, mm	Modulus of rupture of beams, MPa
PCC-1	7 days	00.2	0.0	00.90
PCC-2	14 days	00.6	0.0	00.18
PCC-3	28 days	13.7	0.1	04.93
BRCC-1	7 days	12.3	6.7	03.32
BRCC-2	14 days	31.9	7.5	09.57
BRCC-3	28 days	32.0	9.9	11.52
MBRCC-1	7 days	29.8	1.9	08.94
MBRCC-2	14 days	34.9	5.4	09.42
MBRCC-3	28 days	40.7	6.6	13.52

Figure 12 displays the Load-vs.-deflection curve of each of the specimen tested (for 7, 14 and 28 days respectively) which show that curves follow a straight line variation until the appearance of first crack in concrete. Immediately following the first crack there was flattening of the deflection curve (may be due to local bond slippage), followed by another fairly straight line variation but with a decrease slope, until ultimate failure of member occurs.

The load carrying capacity of cement-concrete beams increased by 2.3 times when doubly reinforced with Non-treated Bamboo splints, and by 2.9 times when doubly reinforced with Treated Bamboo splints, after 28 days of curing respectively. This is shown in Figure 13. The Modulus of rupture of cement-concrete beams increased by 2.3 times when doubly reinforced with Non-treated Bamboo splints, and by 2.7 times when doubly reinforced with Treated Bamboo splints, after 28 days of curing respectively. This is shown in Figure 14.

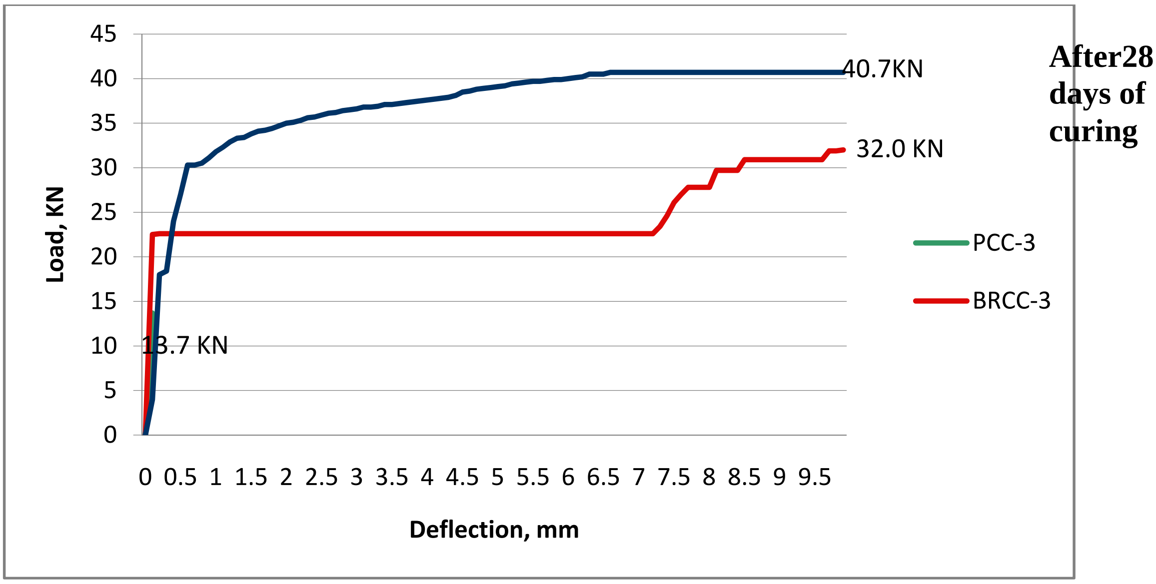


(a)



After14 days of curing

(b)



(c)

Figure 12: Load-vs.-deflection curves of plain and doubly reinforced cement concrete beam specimens after (a) 7, (b) 14 and (c) 28 days of curing respectively.

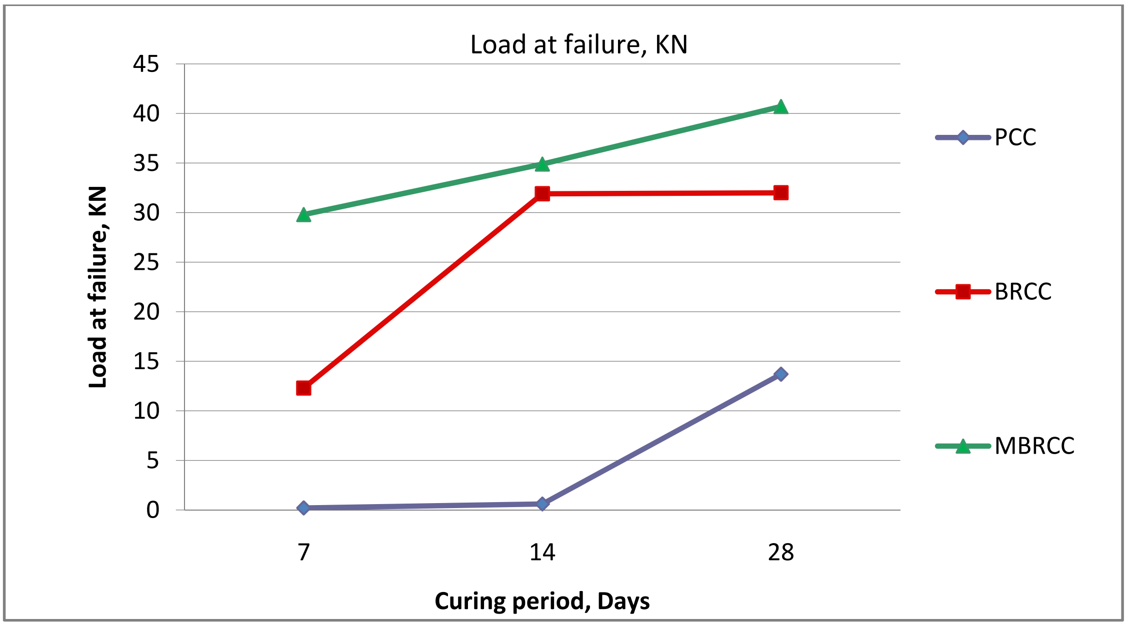


Figure 13: Graphical Representation of load at failure of plain and doubly reinforced beams.

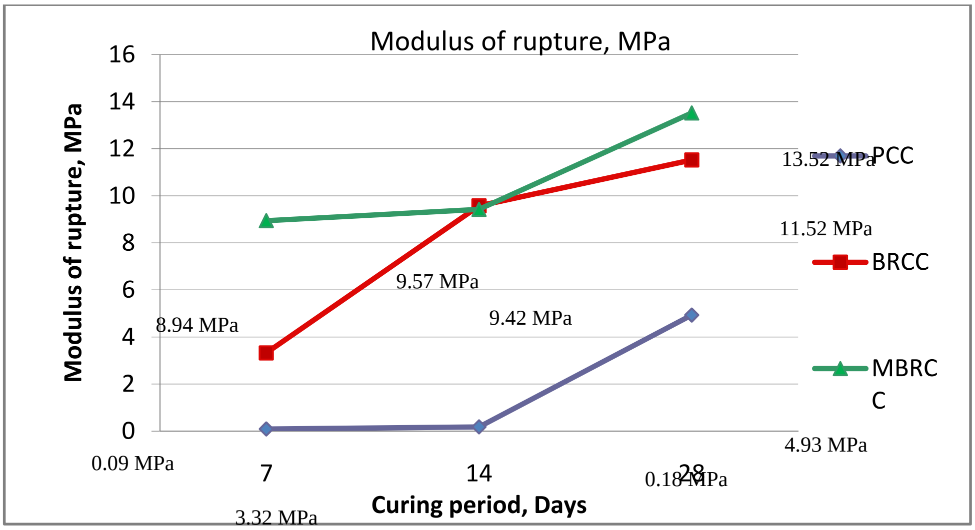


Figure 14: Graphical representation of comparing modulus of rupture of plain and doubly reinforced beams.

Deflection of mid-section up to 9.9mm was observed in the beams reinforced with Non-Treated bamboo splints, and up to 6.6mm was observed in the beams reinforced with Treated bamboo splints before ultimate failure, hence reinforcing concrete beams with bamboo splints imparted sufficient ductility to the beams preventing sudden brittle failure at ultimate loads. This is observed from Figure 15.

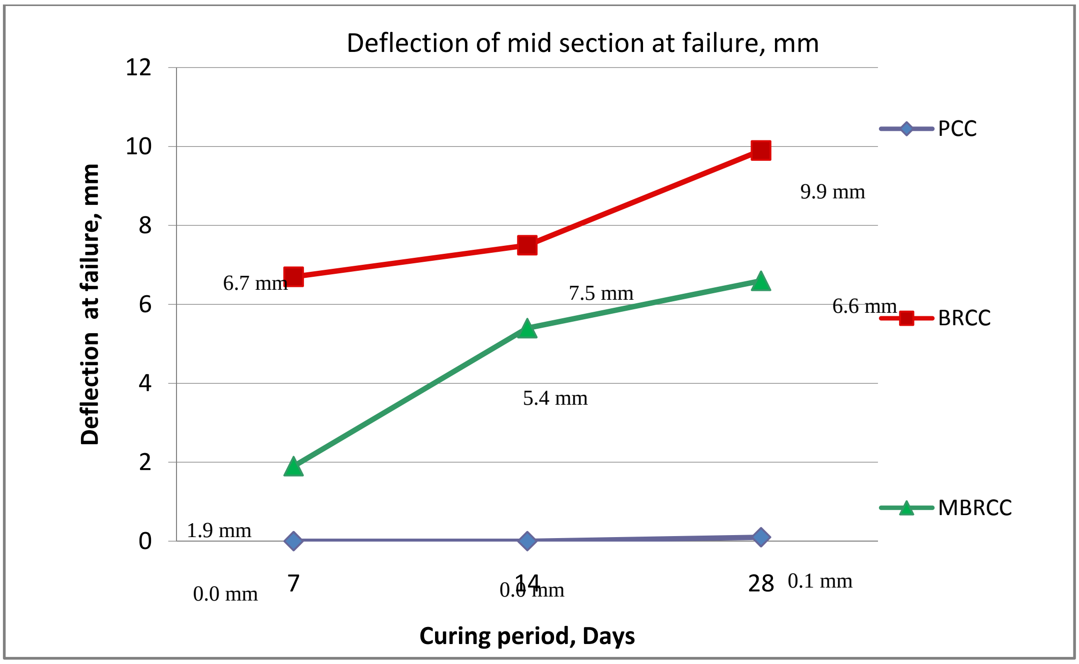


Figure 15: Chart comparing deflection of mid section at failure of plain and doubly reinforced beams.

It was observed that all the doubly reinforced beams failed by the combination of one of the following modes of failure as summarised in Table 7. Primarily the failures occurred due to Longitudinal splitting of bamboo in tension, Flexure tension, Flexure shear, Web shear and Crushing of concrete. However, it was observed that beam MBRCC-2 failed due to flexure shear.

Table.7: Modes of failure, Number and types of crack observed on testing of plain and doubly reinforced beam specimens.

Beam	**Failure mode**		**Number & types of cracks**
	Predicted	**Actual**	
PCC-1	Pure Flexure.	Pure Flexure.	1 Flexure crack
PCC-2	Pure Flexure.	Pure Flexure.	1 Flexure crack
PCC-3	Pure Flexure.	Pure Flexure.	1 Flexure crack
BRCC-1	Splitting of bamboo.	Diagonal tension failure; Crushing of concrete.	1 Flexure crack; 1Web-shear crack.
BRCC-2	Splitting of bamboo.	Bamboo splitting at node, at mid-section of the beam; Breaking of shear link.	1 Flexure crack; 2Web-shear crack; 1Flexure-shear crack.
BRCC-3	Splitting of bamboo.	Pure flexure; Crushing of concrete; Bond failure.	1 Flexure crack
MBRCC-1	Splitting of bamboo.	Diagonal tension failure; Crushing of concrete.	2 Flexure cracks; 1 Web-shear crack
MBRCC-2	Splitting of bamboo.	Flexures shear; Breaking of shear link.	2 Flexure-shear cracks.
MBRCC-3	Splitting of bamboo.	Bamboo splitting at node, at mid-section of the beam; Breaking of shear link.	1 Flexure crack; 1 Web-shear crack; 1Flexure-shear crack.

Of the total six doubly reinforced beams tested only two of the beams failed by splitting of bamboo in tension, rest four of the beams failed either by shear failure, flexure shear failure or pure flexure failure because improper bonding between reinforcement and concrete which didn’t allow proper transfer of tensile stresses from concrete to bamboo splints.

Figure 16 shows the behaviour of BRCC beam under loading and Figure 17 shows the behaviour of MBRCC beam under loading.

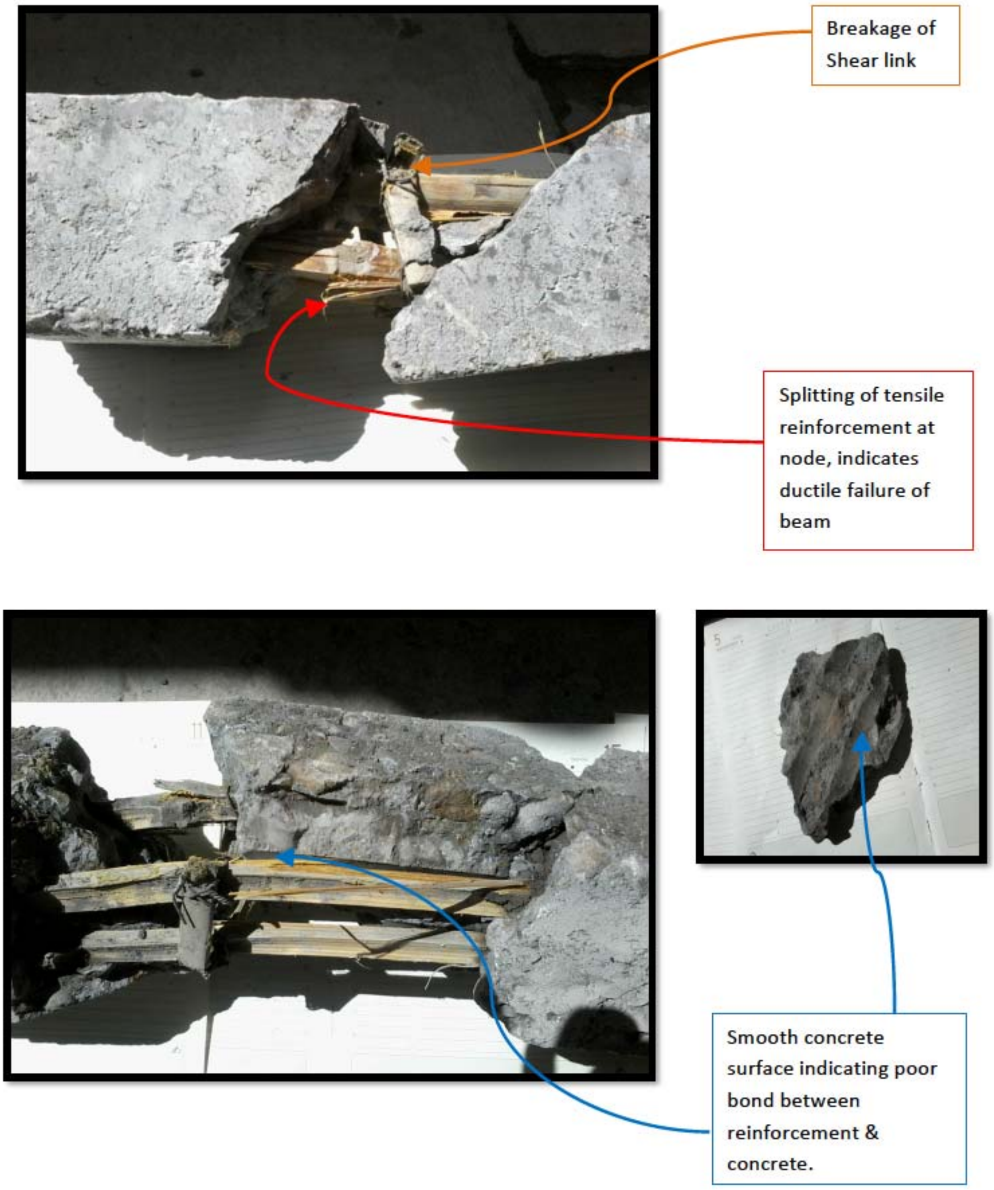


Figure 16: Behaviour of BRCC beams

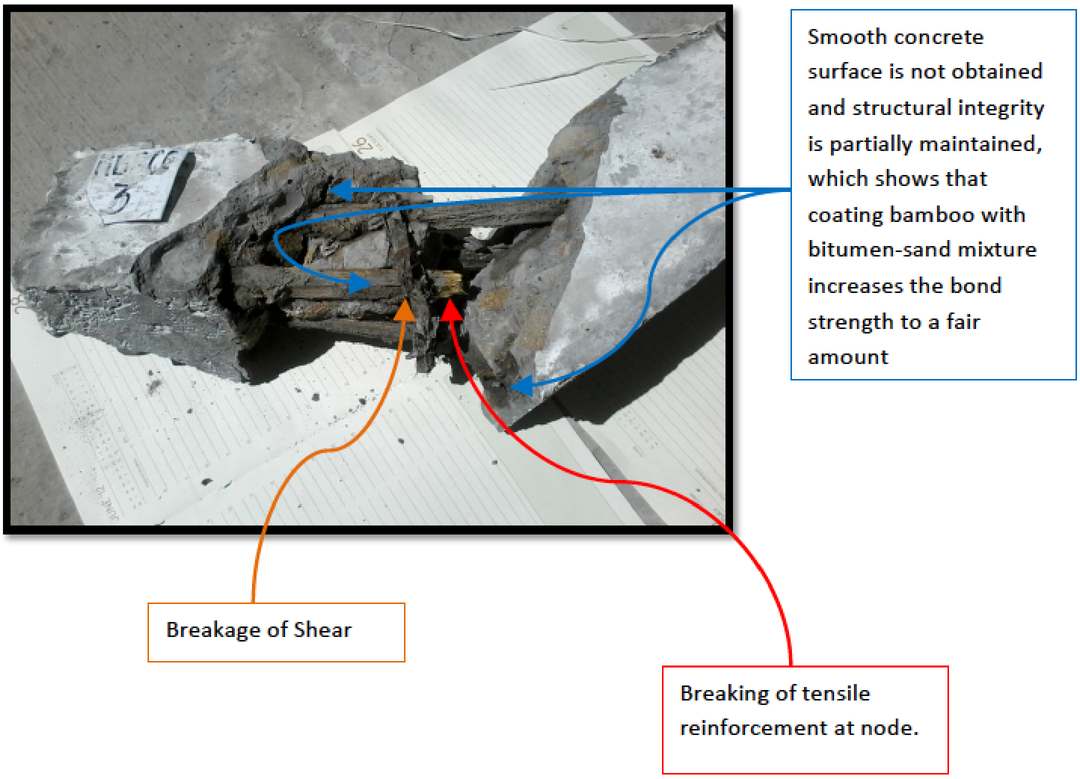


Figure 17: Behaviour of MBRCC beams

C. Third point loading flexure test on cement concrete beams doubly reinforced with bamboo splints without shear links (IS 516-1959)

Table 3.3.A. shows load at failure, deflection of mid section, and modulus of rupture values of the specimens tested.

Table 8: load at failure, deflection of mid section, modulus of rupture values of the plain and singly reinforced beam specimens tested.

Specimen	Curing period	Load at Failure, KN	Displacement of mid-section at failure, mm	Modulus of rupture of beams, MPa
PCC	28 days	13.70	00.010	04.930
BSRCC	28 days	43.30	15.70	19.485
MBSRCC	28 days	52.20	07.90	22.707

Figure 18 displays the Load-deflection curve of each of the specimen tested which shows that Load-deflection curves followed straight line variation until the appearance of first crack in concrete. Immediately following the first crack there was flattering of the deflection curve (may be due to local bond slippage), followed by another fairly straight line variation but with a decrease slope, till ultimate failure of member occurred.

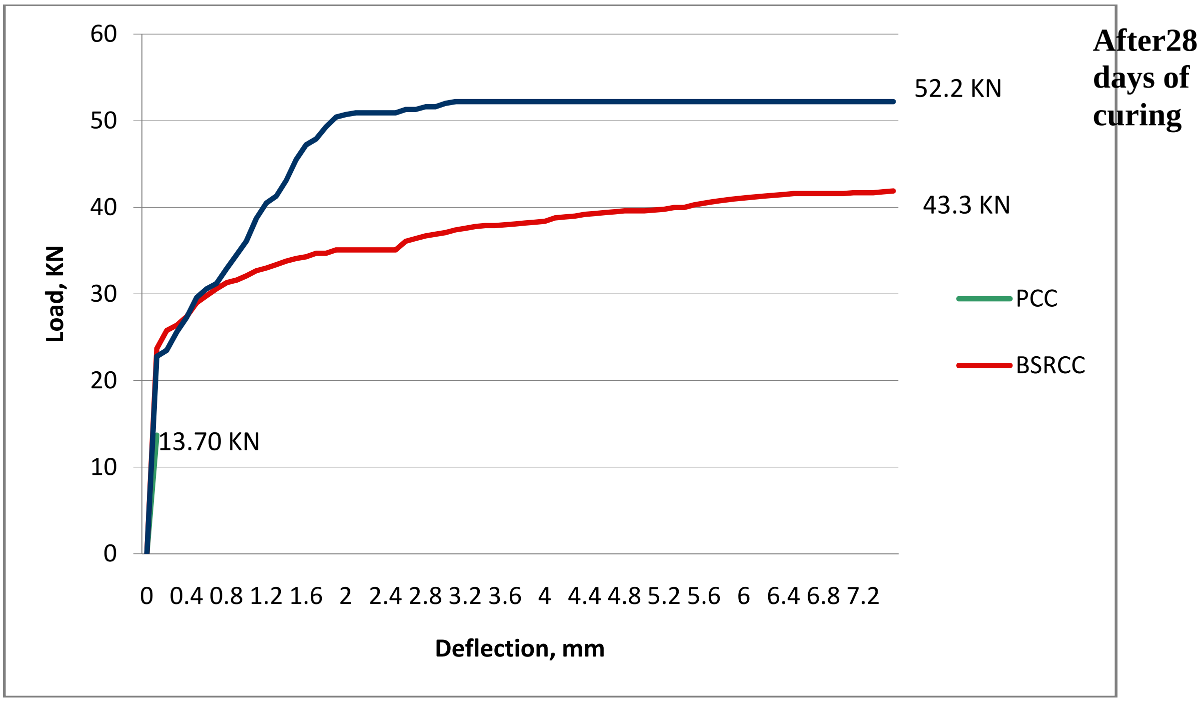


Figure 18: Load-vs.-deflection curves of plain and singly reinforced cement concrete beam specimens after 28 days of curing.

The load carrying capacity of cement-concrete beams increased by 3.16 times when singly reinforced with Non-treated Bamboo splints, and by 3.81 times when singly reinforced with Treated Bamboo splints, after 28 days of curing respectively. This is shown in Figure 19

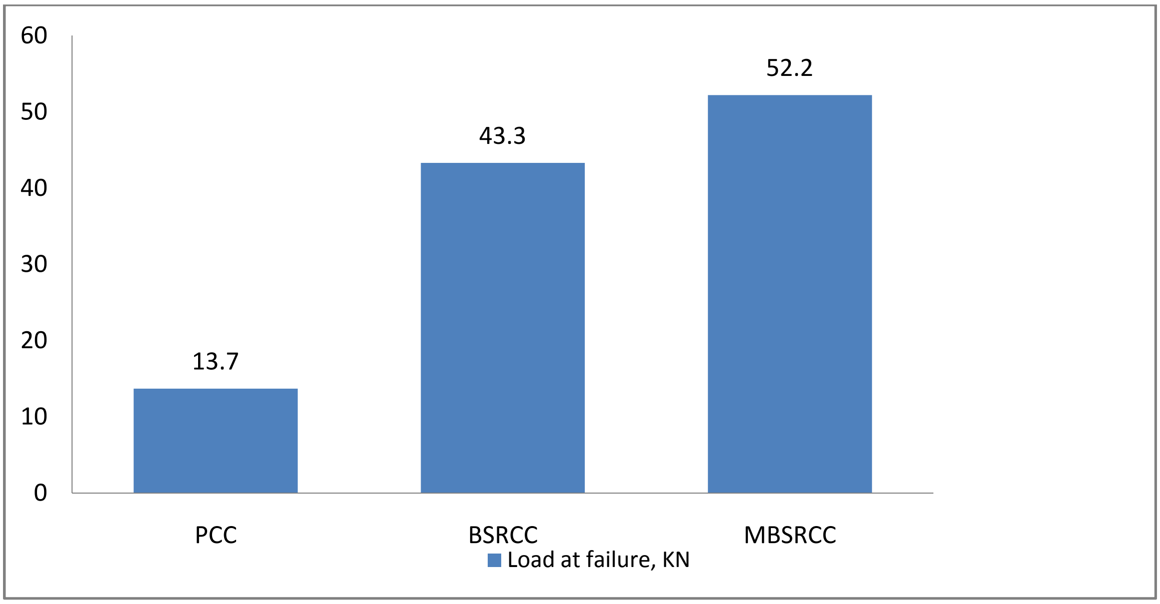


Figure 19: Bar Chart comparing load at failure of plain and singly reinforced beams.

The Modulus of rupture of cement-concrete beams increased by 3.95 times when singly reinforced with Non-treated Bamboo splints, and by 4.60 times when singly reinforced with Treated Bamboo splints, after 28 days of curing respectively as shown in Figure 20.

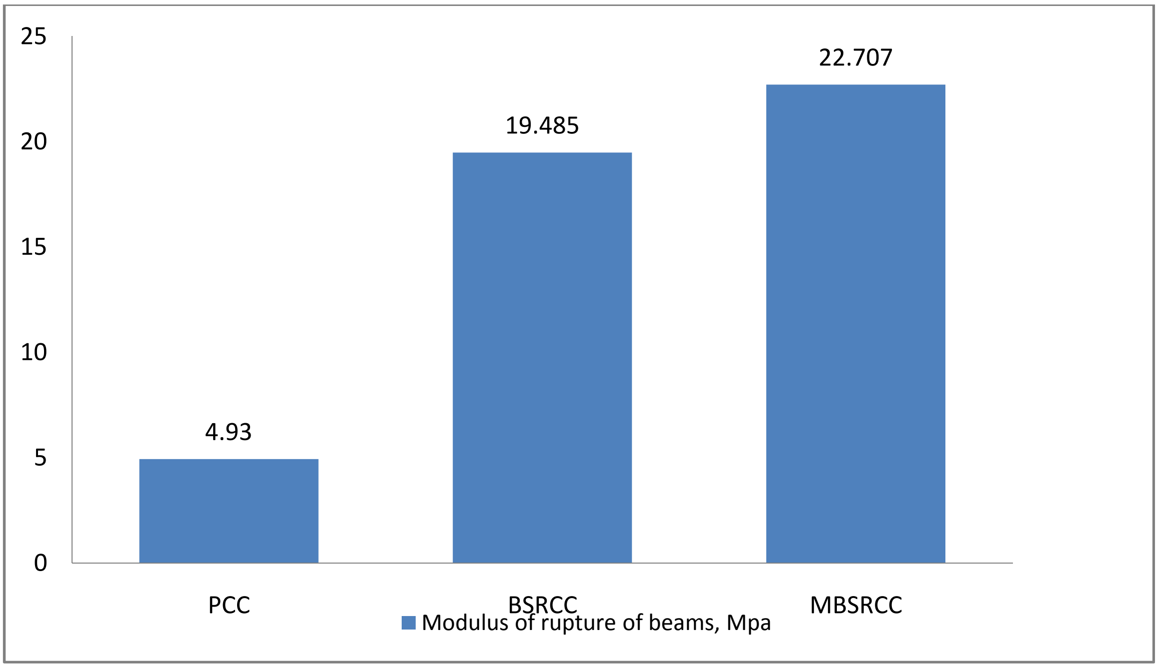


Figure 20: Bar Chart comparing modulus of rupture of plain and singly reinforced beams.

Deflection of mid-section up to 15.70 mm was observed in the beams singly reinforced with Non-Treated bamboo splints, and up to 7.90 mm was observed in the beams singly reinforced with Treated bamboo splints before ultimate failure, hence reinforcing concrete beams with bamboo splints imparted sufficient ductility to the beams preventing sudden brittle failure at ultimate loads. This is observed from Figure 21.

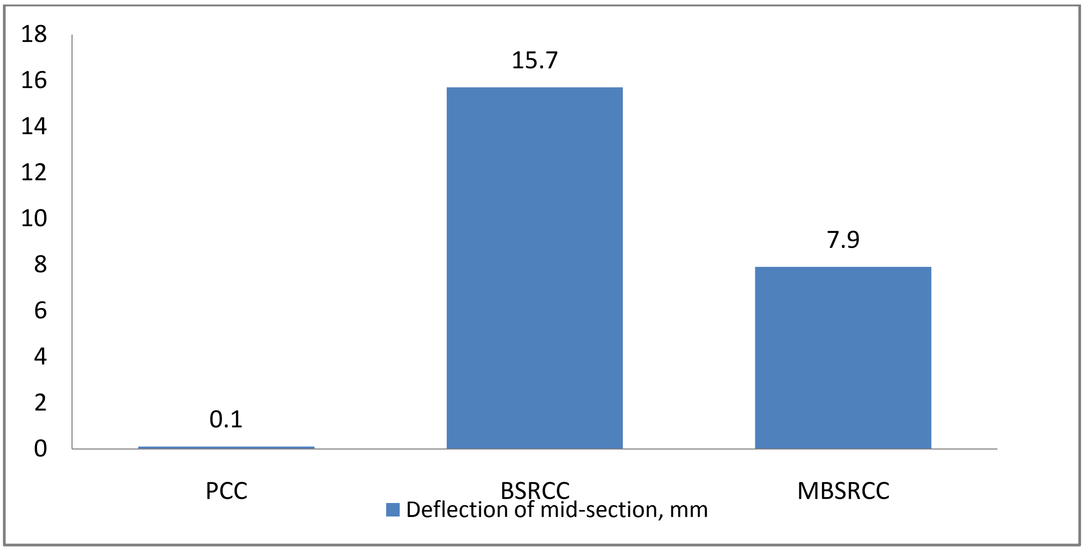


Figure 21: Chart comparing deflection of mid section at failure of plain and singly reinforced beams.

All the singly reinforced beams failed by the combination of one of the following modes of failure including Longitudinal splitting of bamboo in tension, Flexure tension, Flexure shear, Web shear and Crushing of concrete. These have been highlighted in Table 9.

Table 9: Modes of failure, Number and types of cracks observed on testing of plain and singly reinforced beam specimens.

Beam	Failure mode		Number & types of cracks
	Predicted	Actual	
PCC-1	Pure Flexure.	Pure Flexure.	1 Flexure crack
PCC-2	Pure Flexure.	Pure Flexure.	1 Flexure crack
PCC-3	Pure Flexure.	Pure Flexure.	1 Flexure crack
BSRCC-1	Splitting of bamboo.	Diagonal tension failure; Crushing of concrete.	1 Flexure crack, 1 Web-shear crack, 1 Flexure-shear crack.
BSRCC-2	Splitting of bamboo.	Pure flexure; Crushing of concrete.	1 Flexure crack; 1 Web-shear crack.
BSRCC-3	Splitting of bamboo.	Pure flexure; Crushing of concrete; Splitting of bamboo.	1 Flexure crack.
MBSRCC-1	Splitting of bamboo.	Diagonal tension failure.	1 Flexure-shear crack, 1 Web-shear crack
MBSRCC-2	Splitting of bamboo.	Pure flexure; Crushing of concrete.	1 Flexure crack.
MBSRCC-3	Splitting of bamboo.	Diagonal tension failure.	2 Flexure cracks; 1 Web shear crack.

Out of the total six singly reinforced beams tested only one of the beams failed by splitting of bamboo in tension, rest of the five beams failed either by shear failure, flexure shear failure or pure flexure failure because improper bonding between reinforcement and concrete did not allowed proper transfer of tensile stresses from concrete to bamboo splints.

In case of MBSRCC beams the grooves got filled up by Bitumen + Sand mixture making them ineffective in enhancing the concrete bamboo bond resulting in poor transfer of stresses between the two, because of this, splitting of bamboo did not occurred in any of the MBSRCC beams.

Most of the reinforced beams failed in diagonal tension (Web-Shear Cracks) near the supports, which suggest that bamboo reinforced beams without proper design of shear reinforcement, will not be safe for usage.

Figure 22 shows the behaviour of BSRCC beam under loading and Figure 23 shows the behaviour of MBSRCC beam under loading.

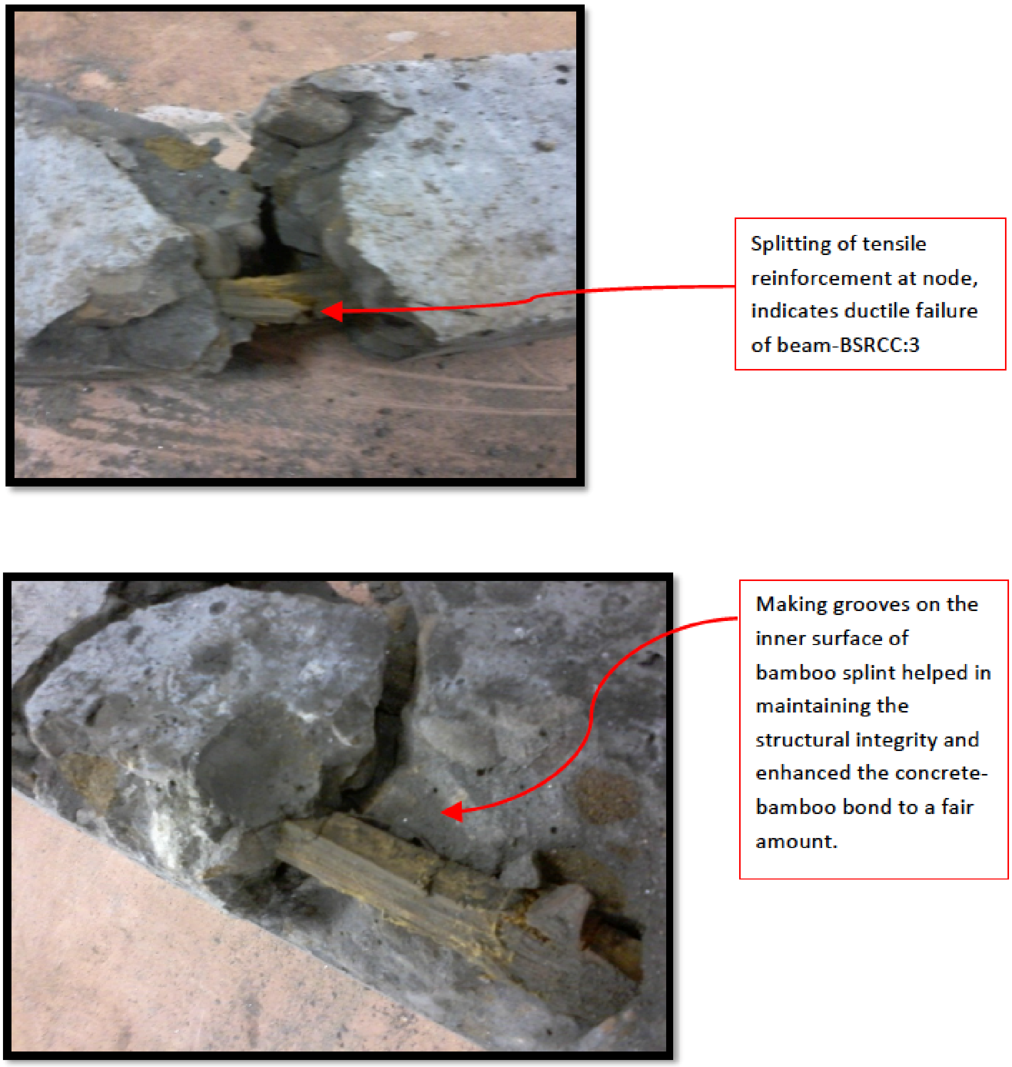


Figure 22: Behaviour of BSRCC beams

Figure 23: Behaviour of MBSRCC beams

IV. CONCLUSIONS

25.14% of loss in ultimate tensile strength was observed in the samples wetted in NaCl solution. 29.14% of loss in ultimate tensile strength was observed in the samples wetted in Ca(OH)2 solution & 29.61% of loss in ultimate tensile strength was observed in the samples wetted in plain water which was highest among the three, generally because of the rotting and disintegration of fibres.

The samples wetted in plain water and Ca(OH)2 shows a heavy fungal attack at nodes and at inner surface of the splints, leading to rotting of bamboo surface and disintegration of fibres. This necessitates the application of an anti fungal compound such as Boric Acid, over the bamboo splints before using them as a reinforcement material in concrete.

The loss in ultimate tensile strength of bamboo splints due to swelling and shrinking of bamboo is attributed to its high water absorption and high water releasing properties due to its hygroscopic nature, hence this swelling and shrinking of bamboo can be controlled up to some extent by using a waterproof material like bitumen, coating over the surface of the bamboo splints before using them as a reinforcement material. The waterproofing material will not only prevent the swelling and shrinkage of bamboo but will also prevent the bamboo from coming in contact with alkalis and chlorides.

No fungal attack and minimum loss of ultimate tensile strength was observed in the bamboo splints which were wetted in NaCl Solution, making bamboo a prominent material to be used as reinforcement in concrete subjected to costal environments.

The load carrying capacity of cement-concrete beams increased by 2.3 times when doubly reinforced with Non treated Bamboo splints and increased by 2.9 times when doubly reinforced with Treated (Bitumen + sand mixture coated) bamboo splints, after 28 days of curing respectively, as compared to that of plain cement concrete beams after 28 days of curing.

The load carrying capacity of cement-concrete beams increased by 3.16 times when singly reinforced with Non treated Bamboo splints and increased by 3.81 times when singly reinforced with Treated (Bitumen + sand mixture coated) bamboo splints, after 28 days of curing respectively, as compared to that of plain cement concrete beams after 28 days of curing.

Significant amount of deflections were observed in the beams reinforced with bamboo splints, before ultimate failure, hence reinforcing concrete beams with bamboo splints imparted sufficient ductility to the beams preventing sudden brittle failure at ultimate loads.

Most of the reinforced beams failed in diagonal tension (Web-Shear Cracks, breakage of shear link in case of doubly reinforced beams) near the supports that suggest that bamboo reinforced beams without proper design of shear reinforcement will not be safe for usage.

ACKNOWLEDGMENT

This study was conceptualized and all experiments were carried out in the Department of Civil Engineering, Jaypee University of Information Technology, Waknaghat, Solan, Himachal Pradesh 173234, India.

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