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REVIEW ARTICLE

Review of physio-chemical and mechanical properties of bamboo as a reinforcement in concrete

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Abstract

Various researchers have investigated bamboo reinforcement as an alternative to steel; however, the findings of these studies are widely dispersed and have not been comprehensively synthesized. This review collates and consolidates existing research on the use of bamboo as a reinforcement material to support more focused and systematic future investigations. The article provides a concise overview of the physical, chemical, and mechanical properties of bamboo relevant to reinforcement applications. In addition, it highlights key research gaps and outlines future research directions to explore the potential of bamboo as a sustainable green building material for construction applications.

Keywords: Bamboo, reinforcement, concrete, water absorption, bond

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Introduction

Concrete's exceptional compressive strength and longevity have made it the most widely used construction material in the world. However, they are being reinforced by materials possessing good tensile strength to make them strong in tension. Steel bars are conventionally used for reinforcing concrete.

Considering the corrosive nature of steel, studies have been carried out on the use of various non-corrosive reinforcements like glass fibre reinforced polymer (GFRP) bars (Alnajmi and Abed, 2020; Benmokrane *et al.*, 1995; Kalpana and Subramanian, 2011; Lu *et al.*, 2021; Mohamed *et al.*, 2021), carbon fibre reinforced polymer (CFRP) bars (Benmokrane *et al.*, 2002; Singh and Chauhan, 2015; H. Do Yun *et al.*, 2023), basalt fibre reinforced polymer (BFRP) bars (Alnajmi and Abed, 2020; Mohamed *et al.*, 2021; Protchenko *et al.*, 2020), aramid fiber reinforced polymer (AFRP) bars (Anas and Alam, 2022; Knoff, 1987; Urbański, 2020; H. D. Yun *et al.*, 2008) and bamboo splints (Agarwal *et al.*, 2014; Ganesan *et al.*, 2018a; Ghavami, 1995; Javadian *et al.*, 2016; Kurian and Kalam, 1977; Kute and Wakchaure, 2014; Swamy, 1984; Vimala and Thippesh, 2021) as reinforcement in concrete.

Their physical properties were compared with mild steel bars (Gull *et al.*, 2020; IS 432 (Part 1), 1982), HYSD bars (IS 1786, 2008)_and high-strength bars (Hadi, 2008; IS 1786, 2008) and are given in Table 1.

Table 1: Properties of various reinforcements

Researcher	Type of Reinforcement	Mechanical Properties				
		Ultimate Tensile Strength MPa	Compres-sive Strength MPa	Shear Strength MPa	Modulus of Elasticity GPa	Bond Strength MPa
Gull *et al*., 2020; IS 432 (Part 1), 1982	Mild Steel	370 to 540	-	-	200	6.2
IS 1786, 2008	HYSD bars	500 to 600	-	-	200	35 to 60% greater than mild steel
Hadi, 2008; IS 1786, 2008	High Strength Bars	485 to 660	-	-	200	30 to 90% greater than mild steel
Alnajmi and Abed, 2020; Benmokrane *et al*., 1995; Lu *et al*., 2021; Mohamed *et al*., 2021	Glass Fibre Reinforced Polymer (GFRP) bars	500 to 1200	298.9 to 398	27.4 to 47.9	40 to 55	42% lower than that of mild steel bar
Benmokrane *et al*., 2002; Singh and Chauhan, 2015; H. Do Yun *et al*., 2023	Carbon Fibre Reinforced Polymer (CFRP) bars	1500 to 2200	360 to 399	283 to 371	128 to 145	3 times higher than that of mild steel
Alnajmi and Abed, 2020; Mohamed *et al*., 2021; Protchenko *et al*., 2020	Basalt Fibre Reinforced Polymer (BFRP) bars	1100 to 1565	362.7 to 471.9	170 to 210	44.5 to 71	29.5% greater than mild steel bar
Anas and Alam, 2022; Knoff, 1987; Urbański, 2020; H. D. Yun *et al*., 2008b	Aramid Fiber Reinforced Polymer (AFRP) bars	1724 to 2537	170 to 250	25 to 110	41 to 125	45% lower than that of mild steel bar
Agarwal *et al*., 2014; Ganesan *et al*., 2018a; Ghavami, 1995; Javadian *et al*., 2016; Kurian and Kalam, 1977; Kute and Wakchaure, 2014; Swamy, 1984; Vimala and Thippesh, 2021	Bamboo splints	48 to 321	25 to 106	40 to 62	6 to 75	50 to 98% lower than that of mild steel bar. (depend upon the type of treatment provided).

Studies were also carried out by researchers on the use of various non corrosive bars as reinforcements in concrete beams (Himasree *et al*., 2024; Jagadeesan *et al*., 2020; Kalpana and Subramanian, 2011; Karayannis *et al*., 2018; Rashid *et al*., 2005; Reyaz *et al*., 2014). The details of the beams are given in Table 2.

Table 2: Details of beams reinforced by various types of reinforcements

Investigator	Type of Reinforcement	Details of Test					Remarks of Type of Failure
		Length L (mm)	C/s of Beam B x H (mm×mm)	Loading Type	Ultimate Load kN	Stiffness kN/mm	
Reyaz *et al*., 2014	Mild Steel	1750	100×150	4 point	23.52	0.55	Flexural failure
Jagadeesan *et al*., 2020	HYSD bars	700	150×150	4 point	70.05	14.4	Flexural failure
Jagadeesan *et al*., 2020	High Strength Bars	700	150×150	4 point	68.4	14.4	Flexural failure
Kalpana and Subramanian, 2011	Glass fibre reinforced polymer (GFRP) bars	1800	250×250	4 point	81.52	5.8	Flexural failure
Karayannis *et al*., 2018	Carbon fibre reinforced polymer (CFRP) bars	2700	200×250	4 point	42.2	1.7	Diagonal tension failure
Jagadeesan *et al*., 2020	Basalt fibre reinforced polymer (BFRP) bars	700	150×150	4 point	69.35	14.4	Diagonal tension failure
Rashid *et al*., 2005	Aramid Fiber Reinforced Polymer (AFRP) bars	3000	150×300	4 point	136.9	1.86	Diagonal tension failure
Himasree *et al*., 2024	Bamboo	1200	100×150	4 point	28.25	1.71	Diagonal tension failure

Eventhough various reinforcements are available, bamboo is the only reinforcement which is eco friendly. Bamboo is an environmentally sustainable, cost-effective and renewable natural material, that falls under the family of Poaceae and have 1662 species in 121 genera (Jit Kaur, 2018). They flourish in the tropical and subtropical climatic conditions where most of the developing countries are located (Jit Kaur, 2018). Its good physical and mechanical properties make it an effective material in construction (Ghavami, 2005). While all the traditional building materials contribute greenhouse gases to the environment during their lifetime, bamboo absorbs CO_2 and releases O_2 into the atmosphere (Aarthi *et al*., 2021).

Even though bamboo possessess various disadvantages, such as they are susceptible to insect, termite, beetle and fungi attack, the use of properly treated bamboo culms can provide a minimum design life of 50 years (Kaminski *et al*., 2022). As some of the bamboo treatments used toxic materials for waterproofing, bonding, termite and insect resistance, bamboo reinforced concrete (BRC) construction was considered to be non environment friendly. Also BRC constructions were described as uneconomical as heavier sections are to be used to make it equally strong as that of reinforced cement concrete (RCC) structures (Archila *et al*., 2018). But the continuous researches being carried out on BRC have proposed various non toxic ways of treatments that make BRC construction a sustainable, safe, durable and environment friendly one.

Studies have been reported on the use of bamboo as whole culms or strips in the construction of single and two-storey bamboo houses (Das *et al*., 2012). Bamboo concrete composite structures, including columns and arches, have been developed by various researchers (Gupta *et al*., 2008; Korde *et al*., 2012; Chugh *et al*., 2012; Korde *et al*., 2015; Bhagat *et al*., 2021). Rather than the conventional whole bamboo structures, studies have been carried out on the structural application and performance of glubam (glue laminated bamboo) structures (Xiao *et al*., 2014).

The present study reviews the literature available on the physical, chemical and mechanical properties of bamboo and its use as reinforcement in various structural elements. Physical properties such as size, density, specific gravity, specific weight, water absorption, shrinkage and thermal expansion are dealt with in detail in this study.

The investigations carried out on the various mechanical properties of bamboo reinforcement such as tensile strength, compressive strength, modulus of elasticity, modular ratio, Poisson's ratio, shear strength, bending strength and bond strength are also discussed in detail. Furthermore, the preservation of bamboo and thetreatments suggested by investigators to address the problems caused by insects and fire arediscussed under its chemical properties. The study aims at providing confidence for those who wish to use bamboo in construction especially for reinforcing concrete by thoroughly understanding its properties.

Physical properties of bamboo

Size: Bamboo, when used as reinforcement in concrete, must ensure a uniform percentage of reinforcement throughout the cross-section of the structural element. But the length, diameter, wall thickness and internodal distance of bamboo vary with age and species. Even though many species are available, studies suggest the use of bamboo under the genera *Arundinaria, Bambusa, Cephalostachyum, Dendro-calamus, Gigantochloa, Melocanna, Phyllostachys, Schizostachyum, Guadua* and *Chusquea* for construction purposes as they possess better structural properties (Swamy, 1984).

The bamboo culms reach their maturity in 3 to 5 years and their physi-cal properties vary with their age and species. The structure of bamboo is not hollow throughout, in-stead, it is divided transversely by diaphragms known as nodes. Along the length of a bamboo culm, its diameter and wall thickness decreases whereas the internodal distance increases (Falayi *et al*., 2014). The length and diameter of bamboo vary typically from 3000 to 35000mm and 20 to 300mm, respectively, whereas their internodal lengths and wall thicknesses vary from 200 to 600mm and 2 to 20mm, respectively, depending upon the species (Didier *et al*., 2012; Ganesan *et al*., 2018b; Ghavami, 1995; Swamy, 1984). Typical sizes of bamboo splints/ culms used as reinforcement in concrete are given in Table 3.

Table 3: Size of bamboo splints/ culms used for reinforcing concrete

Researcher	Size of the splints/culms used		
	Width (mm)	**Thickness (mm)**	**Culm diameter (mm)**
Narayana and Rehman, 1962	-	-	32 to 57.2
Brink and Rush, 1966	19.1	-	-
Brink and Rush, 1966	-	-	19.1
Swamy, 1984	20 to 25	-	-
Kankam *et al*., 1988	5	5	-
Ganesan and Chandrakaran, 1991	10	10	-
Lima *et al*., 2007	16 to 22	4	-
Terai and Minami, 2011	-	-	15
Togati *et al*., 2012	20	-	-
Didier *et al*., 2012	20	-	-
Terai and Minami, 2012	-	-	19
Chugh *et al*., 2012	-	-	30
Chaaruchandra *et al*., 2012	-	-	30 to 40
Siddhpura *et al*., 2013	20	10	-
Sabnani *et al*., 2013	19.1	-	-
Sevalia *et al*., 2013	20	-	-
Pratima *et al*., 2013	20	-	-
Bhonde *et al*., 2013	15	-	-
Khan, 2014	10	10	-
Agarwal *et al*., 2014	20 to 28	3.2 to 5.4	-
Kute and Wakchaure, 2014	29.5 to 46.6	5.8 to 13.7	-
Bhonde *et al*., 2014	15	-	-
Pawar and Attar, 2015	10	10	-
Javadian *et al*., 2016	10	10	-
Siddika *et al*., 2017	-	-	12
Ganesan *et al*., 2018a	20	8 to 15	-
Mali and Datta, 2018	20	10	-
Ganesan *et al*., 2018	20	-	-
Muhtar *et al*., 2019	7, 10 and 15	10 and 15	-
Bhatiwal and Awari, 2019	20	8.5	-
Budi and Rahmadi, 2019	20	5	-
Etienne, 2019	19	-	-

Datta *et al*., 2019	19.1	-	-
Ganesan *et al*., 2019	20	-	-
Ramakrishnan *et al*., 2019	-	-	18
Datta *et al*., 2019	-	-	19.1
Puri *et al*., 2020	14 to 16	3 to 5	-
Rahim *et al*., 2020	20	10	-
Parasuram and Baskaran, 2020	15 to 20	-	-
Masud *et al*., 2021	10	10	-
Vijayabanu and Sivakumar, 2021	10	10	-
Yusra *et al*., 2021	21	10	-
Yathushan *et al*., 2021	15	-	-
Al-Fasih *et al*., 2021	-	-	-
Safiuddin and Hussain, 2021	-	-	12
NBC-Part 6, 2016	25	9	-
Harries and Rogers, 2022	29.6	3.9	-
Kantharuban and Krishnaiah, 2022	35	25	-
Pitake *et al*.,2022	35	10	-
Himasree *et al*., 2022	20	-	-
Kaminski *et al*., 2022	-	-	19
Harries and Rogers, 2022	-	-	34.6
IS 15912,2012	20 to 25	9	-

Rather than using bamboo as a whole culm, it can be used in the form of splints of typically 20mm in width and whole culms can be used as reinforcement in concrete if their diameter is less than 20mm (Brink and Rush, 1966).

Density

The density of any material is an important parameter to be considered to establish its contribution to the self-weight of the structure. The density of bamboo varies depending upon the culm diameter, wall thickness, alignment, structure and concentration of bamboo fibres at the nodes and the internodes. The porosity of solid bamboo decreases from bottom to top of the culm, indicating that the fibres are most closely packed towards the top of the bamboo culm. As a result, the density of bamboo increases from bottom to top of the culm (Ghavami, 2005). The density of bamboo was found to vary widely from 500 to 1960kg/m^3 (Ahmad *et al*., 2014; Didier *et al*., 2012; Govindan *et al*., 2022; Gutu, 2013; Javadian *et al*., 2016; Jit Kaur, 2018; Mali and Datta, 2018; Pitake *et al*., 2022) as shown in Table 4.

Table 4: Density of various species of bamboo

Investigator	**Species**	**Density (kg/m^3)**
Ahmad *et al*., 2014	-	1485
Jit Kaur, 2018	-	700 to 800
Didier *et al*., 2012	*Arundinaria alpina*	1140 to 1960
Mali & Datta, 2018	*Bambusa arundinacea*	1125
Govindan *et al*., 2022	*Bambusa tulda*	1125

Parasuram and Baskaran, 2020	*Bambusa vulgaris*	700
Pitake *et al*., 2022	*Bambusa vulgaris*	620
Gutu, 2013	*Dedroculumus lattiforus*	500 to 900
Javadian *et al*., 2016	*Dendrocalamus asper*	780
Budi and Rahmadi, 2019	*Dendrocalamus asper*	1230
Bhalla *et al*., 2008	*Dendrocalamus giganteus*	700
Mwero, 2020	*Dendrocalamus giganteus*	710
Pitake *et al*., 2022	*Dendrocalamus stocksii*	920
Wei *et al*., 2021	*Phyllostachus pubescens*	1100
Gutu, 2013	*Phyllostachys glauca*	560 to 960
Gutu, 2013	*Phyllostachys pubescen*	560 to 960

An example of how the density of bamboo at the nodes and internodes varies along its radial, longitudinal and tangential direction (Didier *et al*., 2012) is given in Table 5. The cross section of bamboo illustrating radial, tangential and longitudinal directions considered is depicted in Figure 1.

Table 5: Typical density values of bamboo in various directions

Density (kg/m^3)	At Internode		At Node	
	Min	**Max**	**Min**	**Max**
Radial	336	1283	331	1407
Longitudinal	323	1334	402	1244
Tangential	286	1303	237	1412

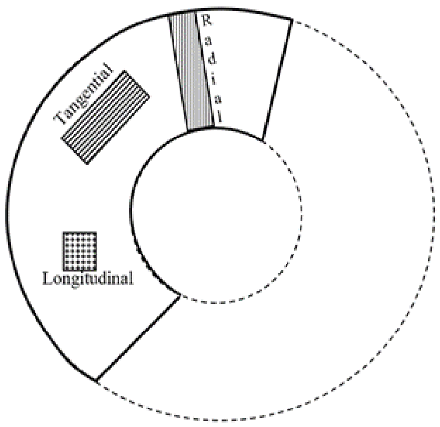

Fig 1: Cross section of bamboo illustrating radial, tangential and longitudinal directions

Specific gravity

Specific gravity is a value that relates the heaviness of a material to that of water. The specific gravity of bamboo was found to increase from the basal end to the distal end in the range of 0.3 to 0.8. It also differs with age, type and moisture content of bamboo. (Dange and Pataskar, 2017; Falayi *et al*., 2014; Ganesan and Chandrakaran, 1991; Gowtham and Rajesh, 2021; Kantharuban and Krishnaiah, 2022; Mwero, 2020; Swamy, 1984; Vijayabanu and Sivakumar, 2021).

Water absorption

As bamboo is a naturally absorbent material, this will adversely affect its strength and bond when used as reinforcement in concrete. Green or untreated bamboo can swell and shrink due to the absorption and release of water. Hence, it is necessary to check its water absorption before using it for construction purposes and to prevent water absorption during the pouring of fresh concrete. The natural moisture content of bamboo varies with its age (Falayi *et al*., 2014). For example, the culms of 3-year old bamboo possessed relatively low moisture content and hence it can be considered most suited for construction purposes.

Studies suggested that the preferred use of 3 to 4-year old bamboo is when it has a pronounced brown colour, provided it is not cut during spring or early summer as the moisture content in fibres tends to be higher during that time (Brink and Rush, 1966; IS 15912, 2012).

As with density, it was also observed that the moisture content of bamboo increases from the bottom to the top of the culm (Falayi *et al*., 2014). Specimens can be considered for assessing water absorption with typically a length and width of 25mm. After weighing the specimens, they are oven dried at 103±2 for 24 hours. The percentage reduction in weight of the sample after oven drying can be obtained as the moisture content of bamboo (IS 6874, 2008). The indicative moisture content of various species of bamboo is given in Table 6.

Table 6: Typical natural moisture content of various species of bamboo at the time of testing

Investigator	Species	Natural moisture (%)
Gowtham and Rajesh, 2021	-	13
Mali and Datta, 2018	*Bambusa arundinacea*	25
Himasree *et al*., 2015	*Bambusa bambos*	20
Masud *et al*., 2021	*Bambusa bambos voss*	24
Al-Fasih *et al*., 2021	*Bambusa heterostachya*	12
Govindan *et al*., 2022	*Bambusa tulda*	25
Mark and Russell, 2011	*Bambusa vulgaris*	14
Parasuram and Baskaran, 2020	*Bambusa vulgaris*	13
Pitake *et al*., 2022	*Bambusa vulgaris*	11
Al-Fasih *et al*., 2021	*Bambusa vulgaris vittata*	12
Javadian *et al*., 2016	*Dendrocalamus asper*	8

Budi and Rahmadi, 2019	*Dendrocalamus asper*	7
Muhtar, 2020	*Dendrocalamus asper*	12
Mwero, 2020	*Dendrocalamus giganteus*	41
Pitake *et al*., 2022	*Dendrocalamus stocksii*	11
Bhonde *et al*., 2014	*Dendrocalmus strictus*	32
Kantharuban and Krishnaiah, 2022	*Indocalamus wightianus*	15
Wei *et al*., 2021	*Phyllostachus pubescens*	7
Falayi *et al*., 2014	*Phyllostachys pubesces*	43

Studies have been conducted to determine the effect of immersion time on water absorption. For example, it was found that the water absorption of *Dendrocalamus strictus* was 30% after 1 day of immersion in water and it increased up to 45% at the end of 7 days (Ganesan, 1990; Kute and Wakchaure, 2014; Narayana and Rehman, 1962). Even though the absorption of water by bamboo was found to increase with immersion time, no significant increase was observed after 2 weeks of immersion in water (Figure 2).

Bamboo can absorb water up to 100% of its mass or more resulting in its anisotropic swelling ranging from 0.012 to 0.05% longitudinally and 2 to 5% diametrically (Geymayer and Cox, 1970; Swamy, 1984). The variation of water absorption along the length, width and thickness of bamboo was about 0.01, 0.08 and 0.12%. respectively. It may be noted that, due to water absorption, greater dimensional variation occurred across the thickness of the splints (Kute and Wakchaure, 2014). As bamboo is susceptible to water absorption, its swelling will develop cracks in concrete before loading (Kurian and Kalam, 1977) and its shrinkage on drying may promote debonding of the bamboo from the cement matrix. Hence proper measures must be considered to limit the water absorption of bamboo during concreting operations.

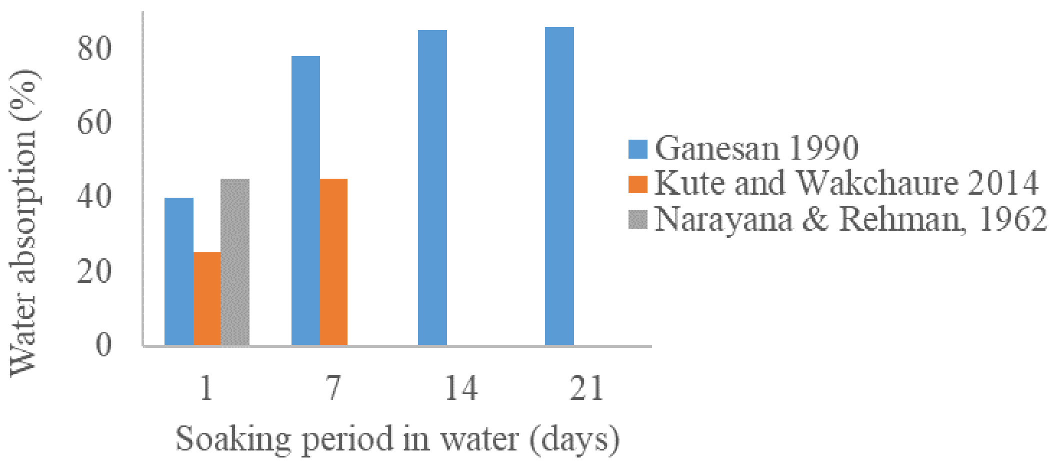

Fig 2. Variation of water absorption of bamboo with soaking period

Bamboo can be made more resistant against water absorption by various means. The water resistant coatings suggested by various investigators in the treatment of bamboo are given in Table 7. The different types of coatings provided to bamboo and their percentage of absorption after various soaking periods are given in Table 8.

Table 7: Water-resistant coatings for bamboo suggested by various researchers

Investigator	Water-resistant coating	
	Used	**Suggested**
Narayana and Rehman, 1962	Bitumen +kerosene (1:1), (1:1/2) and (1:1/4)	
Geymayer and Cox, 1970		Seasoned culms, varnish, asphalt emulsion paint, epoxy, polyester resin, saturating with non-evaporable liquids, treating with hydrophonic substances
Kurian and Kalam, 1977	40% resin in alcohol (3 coats) + white lead paint	
Swamy, 1984		Pre-soaking, saturating by non-evaporable liquids, varnish, asphalt emulsion paint, resin-alcohol mixture, paraffin-resin-linseed oil, bitumen kerosene mixture, epoxy, polyester resin, molten sulphur, high early age concrete, high grade cement
Ganesan, 1990	Varnish (2 coats)	
Ghavami, 1995	Negrolin	
Togati *et al*., 2012	Algicot RC-104	Native latex, coal tar, paint, dilute varnish
Sevalia *et al*., 2013; Siddhpura *et al*., 2013	Araldite, epoxy, coal tar	
Kute and Wakchaure, 2014	Painted, tar+kerosene, Black Japan	
Bhonde *et al*., 2014	Asphalt	
Agarwal *et al*., 2014	Untreated, araldite, tapecrete P151, anticorr RC, Sikadur 32 gel	
Javadian *et al*., 2016	Moisture seal, enamel coating, Exaphen coating. Truegrip BT, Truegrip EP	
Umniati *et al*., 2017	Paint (2 coats)	
Mali and Datta, 2018	Bond Tite	
Etienne, 2019	Bitumen	

Ramakrishnan *et al*., 2019	Araldite, bitumen
Muhtar *et al*., 2019	Sikadur 752
Bhatiwal and Awari, 2019	Bituminous paint, oil paint
Muhtar, 2020	Sikadur
Rahim *et al*., 2020	Tack coat
Parasuram and Baskaran, 2020	Varnish (2 coats)
Puri *et al*., 2020	Sikadur 32 LP
Yathushan *et al*., 2021	Varnish
Vijayabanu and Sivakumar, 2021	Bitumen
Fahim *et al*., 2022	Coal tar
Kantharuban and Krishnaiah, 2022	Epoxy (2 coats)

Table 8: Water absorption of bamboo after various treatments

Investigator	Soaking in water		Treatment
	Duration (days)	Water absorption (%)	
Narayana and Rehman, 1962	1	43	Untreated
	1	30	Bitumen +kerosene (1:1)
	1	15	Bitumen +kerosene (1:1/2)
	1	12	Bitumen +kerosene (1:1/4)
Ganesan, 1990	1	40	Untreated
	7	80	Untreated
	14	81	Untreated
Ghavami, 1995	4	4	Negrolin
Kute and Wakchaure, 2014	1	30	Untreated
	7	45	Untreated
	1	10	Painted
	7	19	Painted
	1	5	Tar+keosene
	7	11	Tar+kerosene
	1	4	Black Japan
	7	10	Black Japan

Puri *et al*., 2020	1	42	Untreated
	1	11	Sikadur 32 LP
Yathushan *et al*., 2021	1	8.5	Untreated

For contrasting examples of effectiveness, water absorption of untreated bamboo was 45% at the end of 7 days whereas it was less than 10% for those coated with Black Japan indicating better water resistance for these splints. It was found that the water absorption of Negrolin-coated bamboo after keeping them in water for 4 days was 4%, which indicates that Negrolin is a good waterproofing material (Ghavami, 1995).

Even though the epoxy coating is very costly, the moisture absorption of bamboo was reported to be as low as 0.4% and hence can be considered a very effective method (Swamy, 1984). Sikadur 32 LP is one of the most effective waterproofing materials, as may be observed from Table 8.

Shrinkage

Similar to the swelling of bamboo, it shrinks as it loses moisture that it had absorbed. This leads to the loss of the bond between bamboo and the surrounding concrete (Kurian and Kalam, 1977).

A shrinkage test carried out on freshly felled culms having a length of 100mm (IS 6874, 2008) showed that along the longitudinal direction, shrinkage was found to be negligible and hence can be neglected, while it is significant in the radial and transverse directions, ranging from 10 to 30% (Didier *et al*., 2012; Gutu, 2013; Puri *et al*., 2020; Swamy, 1984).

Thermal expansion

Thermal expansion of the concrete matrix and any reinforcement that constitutes a composite material is an important parameter to be considered to avoid the development of cracks. The thermal expansion of bamboo was found to be anisotropic as it is higher across the transverse direction compared to along its longitudinal direction. For example, the coefficient of thermal expansion of *Arundinaria tecta* along its longitudinal direction was approximately one third of that of concrete but was 10 times more than that of concrete in the transverse direction. The differential thermal expansion of bamboo and concrete can lead to the development of cracks and a subsequent loss of bond (Narayana and Rehman, 1962).

The coefficient of thermal expansion of bamboo was found to vary in the range of 26×10^{-6} to 58×10^{-6} /ºC compared to 10×10^{-6} /ºC for typical concrete (Ganesan and Chandrakaran, 1991). As the diurnal change in temperature can be 40ºC in some countries, there is a possibility of cracking and loss of bond in BRC. Hence proper cover should be provided to bamboo reinforcement to take care of the cracking of concrete due to temperature variations (Geymayer and Cox, 1970; Swamy, 1984). To prevent this a minimum cover of 15 to 20mm should be provided for bamboo reinforced structures (Brink and Rush, 1966).

Chemical properties of bamboo

Seasoning/Preservation

Seasoning of bamboo plays a major role in the removal of starchy sap and moisture thereby making it more durable for use as a building material. Bamboo can be seasoned for 4 to 6 weeks under a stream of water (Ganesan, 1990; Ganesan and Chandrakaran, 1991) or can be dried at the place of felling or can be air dried in a shelter for 30 days (Ghavami, 1995; Rahim *et al*., 2020; Togati *et al*., 2012).

Chemical preservation of bamboo to prevent borer attack can be carried out by treating it in a solution of arsenic pentoxide, copper sulphate or sodium dichromate (CCA) (Ganesan and Chandrakaran, 1991). Many chemical preservatives, like chromated copper arsenate, copper chrome boron, pentachlorophenol, boric acid–borax, zinc naphthenate, copper naphthenate, tebuconazole, 3–iodo 2–propanyl butyl carbamate, chlorothalonil, isothiozolones and synthetic pyrethroids, can also be used for improving the life of bamboo. However the toxicity associated with a few like CCA limits their use currently. Boron compounds are safe but are soluble in water and hence leachable (Jit Kaur, 2018). The method of treatment of bamboo includes surface application (brushing, dipping), vacuum/ pressure process, hot and cold process, fast fluctuating pressure process and the Boucherie process (IS 9096, 2006).

Against an alkaline atmosphere in water

Hydration of cement leaves the byproduct named calcium hydroxide ($Ca(OH)_2$) in the cement matrix. The advantage of $Ca(OH)_2$ is that it will maintain the pH of concrete at around 13 and thus play a vital role in preventing the corrosion of steel. Hence a study has been carried out to check the durability of bamboo splints in a solution of $Ca(OH)_2$ of pH 12.8 and those in BRC prisms stored in tap water of pH 7.5. Tension tests were carried out on the bamboo splints after 0, 7, 15, 30, 45 and 60 cycles of 24 hours of immersion and 24 hours of drying at 30ºC and 40% relative humidity. Even though the increase in the number of cycles removes the starchy sap as bamboo is treated, no significant reduction in its strength was observed as a result of immersion in tap water and in a solution of $Ca(OH)_2$. The scanning electron microscope images of bamboo splints taken before and after wetting and drying cycles also indicate no significant chemical or strength deterioration in them (Lima *et al*., 2007).

Against insect/termite attack

The strength of bamboo can be affected more by borers and termites than fungus. Hence treating them with a solution of arsenic pentoxide, copper sulphate and sodium dichromate can protect them from borers and termites for at least 35 years (Swamy, 1984). Boron-based preservatives are relatively cost-effective, less toxic and are resistant against termites, beetles and fungi. As they are soluble in water, they can be used effectively where the bamboo needs to be completely protected (Kaminski *et al*., 2022). Thus in general, either the use of copper sulphate solution immediately after the felling of bamboo or keeping them for 48 hours in a solution obtained by mixing borax and boric acid in the ratio of 2:3 in water have been proved to make them termite-proof. Bamboo splints or whole bamboo culms with holes drilled will effectively replace the starchy sap with the boric-borax mix solution, which will be later converted into crystals. Exposed bamboo will last for more than 10 years if proper termite-resistant treatments are provided (Kumari and Suneja, 2016). Studies have showed that bamboo immersed in 6% boric acid solution for 72 hrs can prevent it from insect and termite attacks (Govindan *et al*., 2022; Mali and Datta, 2018). A study has been carried out to check the effect of chemical preservation treatment and immersion time on the tensile strength of bamboo. This was done successfully by immersing bamboo splints without bark either in a solution containing 0.19kg of borax in 1kg of water or boric acid of 0.03kg in 1kg of water or a mixture of borax and 20, 40 and 60% of boric acid in every borax liquid (Prinindya and Ardiansyah, 2014).

Against fire attack

Bamboo can be made fire resistant by the application of a cost-effective composition comprising of ammonium phosphate, boric acid, copper sulphate, zinc chloride and sodium dichromate (Ganesan and Chandrakaran, 1991; Swamy, 1984). Limited studies have been carried out on the fire resistance of bamboo as it is protected by cover concrete in BRC structures.

Mechanical properties of bamboo

Tensile strength

Concrete, which is weak in tension, is reinforced by materials having high tensile strength to make the composite equally strong in tension. As bamboo is used as reinforcement in BRC structures, tension tests can be carried out on bamboo splints or culms to determine their tensile strength. Depending upon the species of bamboo, the tensile strength varies considerably. Grip failure (where the bamboo is crushed laterally by the jaws of the grip) can happen to bamboo splints under tension, where half -dog-bone-shaped ends can be provided to the splints (Bhonde *et al*., 2013; Ghavami, 1995; Javadian *et al*., 2016; Kurian and Kalam, 1977; Lima *et al*., 2007; Pratima *et al*., 2013; Wei *et al*., 2021) or the ends can be wound by GI wires (Fahim *et al*., 2022; Govindan *et al*., 2022; Rahim *et al*., 2020; Sabbir *et al*., 2011; Vimala and Thippesh, 2021) or Aluminium tabs of 3mm thickness can be firmly pasted with industrial adhesive on either side of the bamboo specimens to avoid the crushing in the jaws (IS 6874, 2008; Kute and Wakchaure, 2014). Typical values of tensile strength obtained for different species of bamboo are given in Table 9, although it should be noted that strengths vary widely within species, locations and clumps. It was observed from the table that, *Arundinaria tecta*, *Bambusa heterostachya*, *Dendrocalamus asper* and *Dendrocalamus strictus* species possessed an ultimate tensile strength of more than 300 MPa.

Nodal failure is a major type of defect observed in bamboo splints under tension due to the presence of discontinuous fibres at the nodes (Agarwal *et al*., 2014; Himasree *et al*., 2015; Rahim *et al*., 2020; Togati *et al*., 2012). The presence of nodes is a

Table 9: Typical average tensile strength of various species of bamboo

Researcher	Species	Average tensile strength (MPa)
Brink and Rush, 1966	-	124
Kurian and Kalam, 1977	-	211
Ganesan, 1990	-	87
Lima *et al*., 2007	-	98
Sabbir *et al*., 2011	-	122
Pratima *et al*., 2013	-	150
Siddhpura *et al*., 2013	-	174
Ahmad *et al*., 2014	-	104
Rahim *et al*., 2020	-	169
Gowtham and Rajesh, 2021	-	95
Fahim *et al*., 2022	-	116
Swamy, 1984	*Arundinaria gigantea*	152
Geymayer and Cox, 1970	*Arundinaria tecta*	371
Swamy, 1984	*Arundinaria tecta*	124
Mali and Datta, 2018	*Bambusa arundinacea*	200
Siddika *et al*., 2017	*Bambusa balcooa*	105
Puri *et al*., 2020	*Bambusa balcooa*	232
Jayagond *et al*., 2020	*Bambusa balcooa*	147
Vimala and Thippesh, 2021	*Bambusa balcooa*	105
Ganesan *et al*., 2018a	*Bambusa bambos*	125
Umniati *et al*., 2017	*Bambusa blumeana*	124
Ghavami, 1995	*Bambusa guadua superba*	112
Al-Fasih *et al*., 2021	*Bambusa heterostachya*	363

Vimala and Thippesh, 2021	*Bambusa jaintiana*	117
Ghavami, 1995	*Bambusa multiplex disticha*	74
Ghavami, 1995	*Bambusa multiplex raeusch*	95
Govindan *et al*., 2022	*Bambusa tulda*	152
Ghavami, 1995	*Bambusa tuldoidis*	104
Mark and Russell, 2011	*Bambusa vulgaris*	105
Parasuram and Baskaran, 2020	*Bambusa vulgaris*	90
Yathushan *et al*., 2021	*Bambusa vulgaris*	97
Vimala and Thippesh, 2021	*Bambusa vulgaris*	95
Pitake *et al*., 2022	*Bambusa vulgaris*	110
Ghavami, 1995	*Bambusa vulgaris imperial*	48
Ghavami, 1995	*Bambusa vulgaris schard*	128
Al-Fasih *et al*., 2021	*Bambusa vulgaris vittata*	250
Gutu, 2013	*Dedroculumus lattiforus*	197
Javadian *et al*., 2016	*Dendrocalamus asper*	320
Budi and Rahmadi, 2019	*Dendrocalamus asper*	197
Muhtar, 2020	*Dendrocalamus asper*	105
Muhtar, 2021	*Dendrocalamus asper*	126
Ghavami, 1995	*Dendrocalamus giganteus*	119
Bhalla *et al*., 2008	*Dendrocalamus giganteus*	120
Mwero, 2020	*Dendrocalamus giganteus*	120
Jayagond *et al*., 2020	*Dendrocalamus stocksii*	158
Pitake *et al*., 2022	*Dendrocalamus stocksii*	118
Narayana and Rehman, 1962	*Dendrocalamus strictus*	103
Swamy, 1984	*Dendrocalamus strictus*	95
Bhonde *et al*., 2013	*Dendrocalamus strictus*	96
Kute and Wakchaure, 2014	*Dendrocalamus strictus*	321
Bhonde *et al*., 2014	*Dendrocalamus strictus*	95
Haryanto *et al*., 2021	*Gigantochloa apus*	138
Agarwal *et al*., 2014	*Melocanna bambusoides*	186
Kankam *et al*., 1988	*Oxytenanthera abyssinica*	155
Wei *et al*., 2021	*Phyllostachus pubescens*	141
Gutu, 2013	*Phyllostachys glauca*	284
Gutu, 2013	*Phyllostachys pubescen*	197
Al-Fasih *et al*., 2021	*Schizostachyum brachycladum yellow*	113
Swamy, 1984	*Thyrpsostchya olivery gamble*	285

major factor that reduces the tensile strength of bamboo (Al-Fasih *et al*., 2021; Ghavami, 1995; Swamy, 1984). Splitting failure and grip failure also happened in various splints (Bhonde *et al*., 2013; Himasree *et al*., 2015; Sabbir *et al*., 2011). Even though the tensile strength of steel is 2.5 to 3 times that of bamboo, they possess approximately the same strength-to-weight ratio as that of bamboo (Gutu, 2013). Studies have also indicated that the presence of bark improves the tensile strength of bamboo (Al-Fasih *et al*., 2021).

The average tensile strengths of bamboo varies from about 75 to 370 MPa depending upon the species, age and moisture content. The location of the bamboo splint in the culm also plays a vital role in its strength as it decreases from the basal to the distal end. A moisture content of 40% can lead to a reduction of 60% in the tensile strength of bamboo indicating the necessity for its proper seasoning. Given that the presence of moisture reduces the strength of bamboo significantly, surface impregnation of bamboo by sulphur and resins like polyester and epoxies should be considered for improving its strength and modulus of elasticity (Swamy, 1984).

Compressive strength

Bamboo, if used as culms or splints as longitudinal bars in columns, will be subjected to compressive loads. Hence compressive strength tests need to be carried out on whole bamboo culm specimens, for example with a height to diameter ratio of 1.5 (Himasree *et al*., 2015; Kankam *et al*., 1988). Studies indicate that the compressive strength of a typical bamboo specimen without a node is approximately 1.3 times greater than that with a node, which indicates that the presence of nodes will reduce its compressive strength (Himasree *et al*., 2015; Rahim *et al*., 2020). Typical average values of compressive strength obtained for various species of bamboo are given in Table 10. *Bambusa dolichocalada hay, Bambusa strictus, Dendrocalamus stocksii, Phyllosta-chus pubescens* and *Phyllostachys makinoi hayata* has been found to possess a compressive strength of more than 80MPa.

Table 10: Typical average compressive strengths of various species of bamboo

Researcher	Species	Average compressive strength (MPa)
Brink and Rush, 1966	-	55
Kurian and Kalam, 1977	-	106
Rahim *et al*., 2020	-	39
Gowtham and Rajesh, 2021	-	80
Kantharuban *et al*., 2021	-	42
Swamy, 1984	*Arundinaria gigantea*	58
Swamy, 1984	*Arundinaria tecta*	25
Mali and Datta, 2018	*Bambusa arundinacea*	65
Ganesan *et al*., 2018a	*Bambusa bambos*	40
Swamy, 1984	*Bambusa dolichocalada hay*	85
Swamy, 1984	*Bambusa oldhamii munro*	69
Swamy, 1984	*Bambusa spinosa*	53
Swamy, 1984	*Bambusa stenostachya hackel*	72

Pitake *et al*., 2022	*Dendrocalamus strictus*	90
Gutu, 2013	*Dedroculumus lattiforus*	42
Bhalla *et al*., 2008	*Dendrocalamus giganteus*	55
Swamy, 1984	*Dendrocalamus latiflorus munro*	64
Pitake *et al*., 2022	*Dendrocalamus stocksii*	102
Swamy, 1984	*Dendrocalamus strictus*	37
Kankam *et al*., 1988	*Oxytenanthera abyssinica*	49
Wei *et al*., 2021	*Phyllostachus pubescens*	89
Gutu, 2013	*Phyllostachys glauca*	36
Swamy, 1984	*Phyllostachys makinoi hayata*	89
Gutu, 2013	*Phyllostachys pubescen*	65
Swamy, 1984	*Phyllostachys pubescens mazel*	77
Falayi *et al*., 2014	*Phyllostachys pubesces*	75
Swamy, 1984	*Thyrpsostchya olivery gamble*	55

It may be noted from Table 10 that the average compressive strength of bamboo can vary from about 25 to 105 MPa depending upon the species considered. Studies denote that the presence of nodes reduces the compressive strength of bamboo and the specimens will fail due to splitting and/or bearing (Himasree *et al*., 2015). The compressive strength of bamboo culm is higher when it is loaded longitudinally than diametrically. A comparison with Table 9 indicates that the compressive strength of bamboo is approximately one third of its tensile and bending strengths (Ghavami, 1995; Kurian and Kalam, 1977).

The stress-strain behaviour of bamboo under compression is slightly non-linear and its initial modulus of elasticity in compression varies from about 4.6 to 19.4 GPa. A study also found that green bamboo with about 40% moisture content possesses only 40% of the compressive strength as compared to seasoned bamboo, indicating a significant increase in the compressive strength of seasoned bamboo (Swamy, 1984). The age of bamboo also plays a major role in its compressive strength. As the age of bamboo increases from 1 to 5 years, its compressive strength increases by a factor of two (Falayi *et al*., 2014).

Modulus of Elasticity

Studies have been carried out to determine the Modulus of Elasticity (MoE) of bamboo in direct tension (Table 11). As may be observed, the low value of MoE of bamboo will lead to large deflections and wide cracks when used as reinforcement in flexural members (Geymayer and Cox, 1970; Kurian and Kalam, 1977; Yathushan *et al*., 2021). It may be observed that the value of MoE of bamboo varies from about 7 to 75 GPa depending on the species of bamboo. A significant increase in the MoE of treated bamboo was noted over untreated ones (Swamy, 1984). MoE tests carried out on the *Phyllostachys pubesces* samples collected from the bottom, middle and top regions of bamboo indicate that the value of MoE increases from the basal to the distal end (Falayi *et al*., 2014).

Modular ratio

The lower MoE leads to a lower modular ratio of bamboo of approximately 1 in BRC, which is approximately $1/10^{th}$ of that of steel in RCC. Hence large deflection and wider cracks will be a notable characteristic of BRC members in flexure (Kurian and Kalam, 1977).

Table 11: Modulus of Elasticity of various species of bamboo

Researcher	Species	Modulus of Elasticity (GPa)
Brink and Rush, 1966	-	17
Kurian and Kalam, 1977	-	18
Ganesan, 1990	-	11
Lima *et al*., 2007	-	13
Sabbir *et al*., 2011	-	51
Siddhpura *et al*., 2013	-	9
Kantharuban *et al*., 2021	-	73
Gowtham and Rajesh, 2021	-	17
Geymayer and Cox, 1970	*Arundinaria tecta*	20
Mali and Datta, 2018	*Bambusa arundinacea*	8
Siddika *et al*., 2017	*Bambusa balcooa*	7
Puri *et al*., 2020	*Bambusa balcooa*	16
Vimala and Thippesh, 2021	*Bambusa balcooa*	8
Ganesan *et al*., 2018a	*Bambusa bambos*	75
Ghavami, 1995	*Bambusa guadua superba*	11
Al-Fasih *et al*., 2021	*Bambusa heterostachya*	31
Vimala and Thippesh, 2021	*Bambusa jaintiana*	6
Ghavami, 1995	*Bambusa multiplex disticha*	14
Ghavami, 1995	*Bambusa multiplex raeusch*	11
Govindan *et al*., 2022	*Bambusa tulda*	7
Ghavami, 1995	*Bambusa tuldoidis*	12
Parasuram and Baskaran, 2020	*Bambusa vulgaris*	9
Vimala and Thippesh, 2021	*Bambusa vulgaris*	6
Ghavami, 1995	*Bambusa vulgaris imperial*	7
Ghavami, 1995	*Bambusa vulgaris schard*	10
Al-Fasih *et al*., 2021	*Bambusa vulgaris vittata*	24
Javadian *et al*., 2016	*Dendrocalamus asper*	21
Muhtar, 2020	*Dendrocalamus asper*	26
Muhtar, 2021	*Dendrocalamus asper*	18
Ghavami, 1995	*Dendrocalamus giganteus*	15
Bhalla *et al*., 2008	*Dendrocalamus giganteus*	14
Mwero, 2020	*Dendrocalamus giganteus*	14
Narayana and Rehman, 1962	*Dendrocalamus strictus*	13
Bhonde *et al*., 2013	*Dendrocalamus strictus*	20

Kute and Wakchaure, 2014	*Dendrocalamus strictus*	20
Agarwal *et al*., 2014	*Melocanna bambusoides*	24
Wei *et al*., 2021	*Phyllostachus pubescens*	17
Falayi *et al*., 2014	*Phyllostachys pubesces*	59

Poisson's ratio

No significant difference is observed in the value of Poisson's ratio between green and seasoned bamboo.

The value of Poisson's ratio varies from about 0.25 to 0.41 with an average value of 0.32 (Muhtar, 2021; Swamy, 1984), which is approximately the same as that of steel having Poisson's ratio ranging from 0.27 to 0.3 (Chmelko *et al*., 2024).

Shear strength

Shear strength tests can be carried out on internodal culm elements of length to outer diameter ratio of 1 (IS 6874, 2008). The shear strength of seven species of bamboo obtained by applying a shear load perpendicular to the fibres is given in Table 12.

The shear strength of different bamboo species usually varied from about 40 to 62 MPa (Ghavami, 1995) for various species of bamboo. Bamboo possessed approximately 10 times lower shear strength than that of mild steel (Swamy, 1984).

Bending strength (Flexural strength)

The Modulus of Rupture (MoR) or bending strength of bamboo can be considered as the maximum usable tensile strength. Bending tests on bamboo culms can be carried out on specimens having a length of 1000mm + 30 times the diameter at the middle point of the culm (IS 6874, 2008).

Bending strength tests have been carried out on 7 different species of bamboo specimens with widths and lengths of 4T and 16T, where T is the thickness of bamboo. It may be observed that the presence of nodes reduces the bending strength of bamboo culm. Studies indicate that the values of the MoR vary from about 71 to 207 MPa as given in Table 13 (Dange and Pataskar, 2017; Swamy, 1984).

The flexural MoR of bamboo varied from about 9.3 to 22.1 GPa for various species of bamboo (Ghavami, 1995; Swamy, 1984). *Bambusa oldhamii munro*, *Bmabusa dolichocalada hay*, *Dendrocalamus asper*, *Phyllostachys makinoi*

Table 12: Typical average tensile strength of various species of bamboo

Researcher	Species	Shear strength (MPa)
Ghavami, 1995	*Bambusa multiplex raeusch*	62
	Bambusa multiplex disticha	53
	Bambusa tuldoidis	55
	Bambusa guadua superba	48
	Bambusa vulgaris imperial	40
	Bambusa vulgaris schard	41
	Dendrocalamus giganteus	44

hayata and Phyllostachys pubescens mazel possessed bending strength more than 150 MPa.

A study has been carried out to find the influence of age and location on the bending strength of *Phyllostachys pubesces*. The bending strength of samples collected from the bottom, middle and top regions of bamboo and of various ages (1, 3 and 5 years) indicate that the MoR increases from the basal end to the distal end. It may be noted from the figure that the value of MoR increases from about 117 to 190MPa as the age of bamboo increases from 1 to 5 years (Falayi *et al*., 2014).

Bond strength

The composite action in BRC takes place when the load is transferred from concrete to bamboo through the bond between them. The bond between reinforcement and concrete depends on the chemical adhesion, friction and mechanical interaction between the surface of reinforcement and the surrounding concrete (Hamad, 1995). But the surface smoothness and the moisture susceptibility of bamboo can lead to loss of bond between bamboo and the surrounding concrete. This will adversely affect the load carrying capacity of BRC. Hence, proper measures are required to improve the bonding between bamboo and concrete. Numerous studies have been conducted by researchers to find effective methods for improving the bond between bamboo and the surrounding concrete, the details of which are summarised here. It was found that water and temperature can affect the bond between bamboo and concrete adversely.

Table 13: Typical bending strengths of various species of bamboo

Researcher	Species	Bending strength (MPa)
Swamy, 1984	*Arundinaria gigantea*	58
Mali and Datta, 2018	*Bambusa arundinacea*	90
Ghavami, 1995	*Bambusa guadua superba*	90
Ghavami, 1995	*Bambusa multiplex disticha*	60
Ghavami, 1995	*Bambusa multiplex raeusch*	71
Swamy, 1984	*Bambusa oldhamii munro*	160
Swamy, 1984	*Bambusa spinosa*	116
Swamy, 1984	*Bambusa stenostachya hackel*	138
Ghavami, 1995	*Bambusa tuldoidis*	87
Ghavami, 1995	*Bambusa vulgaris imperial*	42
Ghavami, 1995	*Bambusa vulgaris schard*	107
Swamy, 1984	*Bmabusa dolichocalada hay*	207
Javadian *et al*., 2016	*Dendrocalamus asper*	150
Muhtar, 2020	*Dendrocalamus asper*	153
Ghavami, 1995	*Dendrocalamus giganteus*	93
Swamy, 1984	*Dendrocalamus latiflorus munro*	134
Swamy, 1984	*Dendrocalamus strictus*	117
Swamy, 1984	*Phyllostachys makinoi hayata*	196
Swamy, 1984	*Phyllostachys pubescens mazel*	164

Bamboo absorb water during casting and curing, leading to its swelling in concrete. As a result, cracks may be developed before loading. But after curing, bamboo loses the moisture that it had absorbed and shrinks. The shrinking of bamboo will leave voids along its length. This indicates the necessity of using seasoned and treated bamboo splints in concrete (Ghavami, 2005). The main source of the bond between bamboo and concrete is the nodes that occur at frequent intervals, which protrude and anchor themselves in the concrete matrix on which it is being laid. The presence of nodes in bamboo makes it similar to that of deformed bars, but the bond developed in it is not continuous (Kurian and Kalam, 1977).

Even though the loss of bond due to shrinkage exists in BRC, the bond between bamboo and concrete is low anyway due to its smooth surface. Bond strength of bamboo is influenced by the treatment and condition of bamboo, size of protrusions and the spacing of nodes, age, curing conditions, strength and other properties of concrete. Seasoned bamboo possesses better bond strength than unseasoned (green) bamboo due to the low water absorption and the subsequent swelling and shrinkage of bamboo. A study suggests the use of bamboo splints rather than whole bamboo culms in concrete as it leads to an increased relative surface area and hence an increase in the pullout force (Swamy, 1984).

Investigations have been carried out by various researchers to study the effect of treatments on the bond strength of bamboo splints when used as reinforcement in concrete. Untreated bamboo splints possessed better bond strength compared to splints with waterproof coatings alone as the latter makes the surface smoother leading to the loss of bond between bamboo splints and the surrounding concrete. The presence of nodes and surface roughness improved the bond strength of bamboo in concrete by 15 to 22% (Kute and Wakchaure, 2014) and it was observed that flexural strength of the structure increases with the use of notched splints as reinforcement compared to those without notches. As the width of the notch increases, load carrying capacity also increases, indicating the significance of the width of notches (Budi and Rahmadi, 2019). The values of bond strength obtained for various treatments are given in Table 14. It may also be noted in Table 14 that the presence of nodes in bamboo led to a significant improvement in its bond strength as the nodes provide better grip (resistance) against pullout.

Although pre-soaking of bamboo is suggested by researchers to reduce the water absorption of bamboo from fresh concrete when used as reinforcement, no significant improvement in bond was observed in them. Hence the presoaked splints must be provided with proper treatment to ensure proper bonding between bamboo and concrete.

The bond strength of both treated and untreated bamboo splints/culms can be improved by increasing the cement content thereby decreasing the water to cement ratio in concrete. The bamboo in high early strength cement was found to possess better bond strength compared to that in Ordinary Portland cement (OPC) as high early strength cement requires less water for its hydration and thus the availability of water for the swelling of bamboo is low (Brink and Rush, 1966; Swamy, 1984).

As the coatings provided to bamboo splints can make the surface smooth, sprinkling zeolite powder on the surface of splints soon after the application of the coating can reduce the slip within the concrete and thus the bond strength can be improved. The bond strength of bamboo increased by a factor of two when fine zeolite powder was provided over a coat of oil or bituminous paint or Black Japan coating, irrespective of the presence of node within concrete. Even though coating splints with Black Japan reduces water absorption by 75%, it also reduces the bond strength by 10 % due to the surface smoothness of the coating (Kute and Wakchaure, 2014). Among the different methods, sprinkling sand over the various treatments like epoxy or polyester resin coating, bitumen, varnish or sulphur, resulted in an improved bond strength ranging from typically 0.81 to 1.38 MPa (Ganesan, 1990; Kute and Wakchaure, 2014; Swamy, 1984). It was also observed that the varnish coating provided over the splints for waterproofing reduced its bond with concrete. Hence measures must be taken to improve the bonding between bamboo splints and

Table 14: Typical bond strengths of treated and untreated bamboo

<table>
<tr><th rowspan="2">Investigator</th><th rowspan="2">Treatments</th><th colspan="2">Bond strength (MPa)</th></tr>
<tr><th>Without node</th><th>With node</th></tr>
<tr><td rowspan="6">Kurian and Kalam, 1977</td><td>Untreated</td><td colspan="2">0.59</td></tr>
<tr><td>Treated</td><td>0.78</td><td>0.9</td></tr>
<tr><td>Treated +sand</td><td>0.79</td><td>0.98</td></tr>
<tr><td>Treated +coir winding</td><td colspan="2">0.88</td></tr>
<tr><td>Treated +nailed</td><td>0.90</td><td>1.15</td></tr>
<tr><td>Treated +notches</td><td></td><td>0.81</td></tr>
<tr><td rowspan="8">Swamy, 1984</td><td>Untreated</td><td colspan="2">0.36</td></tr>
<tr><td>Untreated +steel wire winding</td><td colspan="2">0.52</td></tr>
<tr><td>Polyester+sand</td><td>0.56</td><td>0.81</td></tr>
<tr><td>Epoxy+sand</td><td>1.13</td><td>1.15</td></tr>
<tr><td>Varnish (2 coats)</td><td>1.11</td><td>1.27</td></tr>
<tr><td>Bitumen</td><td colspan="2">0.84</td></tr>
<tr><td>Epoxy</td><td colspan="2">1.13</td></tr>
<tr><td>Sulphur+sand</td><td colspan="2">1.38</td></tr>
<tr><td rowspan="4">Ghavami, 2005</td><td>Untreated</td><td>0.52</td><td>1.2</td></tr>
<tr><td>Negrolin +sand</td><td>0.73</td><td>1.55</td></tr>
<tr><td>Negrolin+sand+steelwire winding</td><td>0.97</td><td>1.8</td></tr>
<tr><td>Sikadur 32 gel</td><td colspan="2">2.75</td></tr>
<tr><td rowspan="6">Agarwal et al., 2014</td><td>Untreated</td><td colspan="2">0.13</td></tr>
<tr><td>Araldite</td><td colspan="2">0.23</td></tr>
<tr><td>Araldite + steel wire winding</td><td colspan="2">0.54</td></tr>
<tr><td>Tapecrete P 151</td><td colspan="2">0.32</td></tr>
<tr><td>Anticorr RC</td><td colspan="2">0.16</td></tr>
<tr><td>Sikadur 32 gel</td><td colspan="2">0.59</td></tr>
<tr><td rowspan="10">Kute and Wak-chaure, 2014</td><td>Untreated</td><td>0.73</td><td>0.9</td></tr>
<tr><td>Untreated +notched</td><td>0.85</td><td>0.92</td></tr>
<tr><td>Untreated +nailed</td><td>0.9</td><td>1.09</td></tr>
<tr><td>Untreated +steel wire winding</td><td>1.06</td><td>1.25</td></tr>
<tr><td>Oil painted</td><td>0.48</td><td>0.69</td></tr>
<tr><td>Oil painted + zeolite powder</td><td>0.71</td><td>0.93</td></tr>
<tr><td>Bitumen+kerosene</td><td>0.63</td><td>0.79</td></tr>
<tr><td>Bitumen +kerosene +zeolite powder</td><td>0.88</td><td>1.11</td></tr>
<tr><td>Black Japan</td><td>0.66</td><td>0.86</td></tr>
<tr><td>Black Japan +zeolite powder</td><td>1.06</td><td>1.19</td></tr>
</table>

Javadian *et al*., 2016	Untreated+normal concrete	3.61
	Untreated+ water-based epoxy in concrete (10% by weight of cement)	2.75
	Untreated+ water-based epoxy in concrete (25% by weight of cement)	3.52
	Moisture seal	3.47
	Moisture seal +fine sand	3.65
	Moisture seal +coarse sand	3.61
	Truegrip BT	2.42
	Truegrip BT+coarse sand	2.62
	Truegrip EP	3.3
	Truegrip EP+coarse sand	3.45
	ExaPhen coating	3.36
	ExaPhen coating+coarse sand	3.46
	Enamel coating	3.4
Muhtar *et al*., 2019	Untreated	1.0
	Untreated+hose clamp at 100mmc/c	1.1
	Sikadur 752+sand	2.5
	Sikadur 752+sand+hose clamp at 150mm c/c	3.4
	Sikadur 752+sand+hose clamp at 200mm c/c	3.1
Rahim *et al*., 2020	Untreated	1.87
	Tack coated	2.0
Al-Fasih *et al*., 2021	Untreated Bambusa vulgaris vittata	0.67
	Untreated Bambusa heterostachya	0.35

concrete after applying waterproof coatings (Masud *et al*., 2021). Even though the addition of sand particles can improve the bond strength due to the mechanical interlocking between the concrete matrix and the bamboo reinforcement, the size of sand particles did not play a significant role in the improvement of the bond (Javadian *et al*., 2016).

The bamboo splints coated with and without a tack coat possessed a bond strength of typically 1.33 and 1.23 times the bond strength of steel in concrete (Rahim *et al*., 2020). Sikadur 32 Gel coated splints had about 5.2 times more bond strength than that of the plain bamboo splints, followed by the Araldite coated splints wound by binding (Agarwal *et al*., 2014). It was found that the negrolin-sand-wire treatment improved the bonding between concrete and bamboo by about 1.86 times (Ghavami, 1995). Also, it should be noted that the bond strength of bamboo is independent of the embedded length as it remains constant beyond a certain length of embedding (approximately 300mm) depending on specimen cross sectional dimensions (Geymayer and Cox, 1970).

Use of shear connectors and anchorages, use of splints instead of whole bamboo culms, adoption of proper cover to reinforcement and the provision of proper spacing between the reinforcement could improve the bond and reduce the severity of cracking in BRC (Swamy, 1984). The bond strength can be further improved by mechanical treatments like winding metallic wires, coir ropes, use of nails as spikes, use of intermediate or end anchorages, shear connectors formed by cutting notches at intervals in whole bamboo and inserting metal plates perpendicularly into the whole bamboo culms at various locations (as depicted in Figure 3).

Studies have reported that treated and untreated bamboo splints with steel hose clamps at various spacings have enhanced bond strength and it was found that the bond strength increases with a decrease in the spacing of hose clamps (Muhtar *et al*., 2019). The methods suggested by various investigators for improving the surface roughness of bamboo that leads to better gripping between bamboo and the surrounding concrete are given in Table 15.

Research Gaps and Future Directions

With the aging infrastructure world over and stringent norms toward emission reduction, it is getting pertinent to review practices and deviations towards eco-friendly alternatives. One of such practices could have been the research on the use of bamboo as a reinforcement. It is quite evident from the studies above that it has limitations and various researchers have tried to address them to certain extent. The compilation highlights some of the most promising strategies for addressing critical challenges such as water absorption, differential thermal expansion, and bond strength.

Even though Himasree *et al*., (2024) has brought out that there are strength limitations in bamboo reinforced concrete applications; however, there

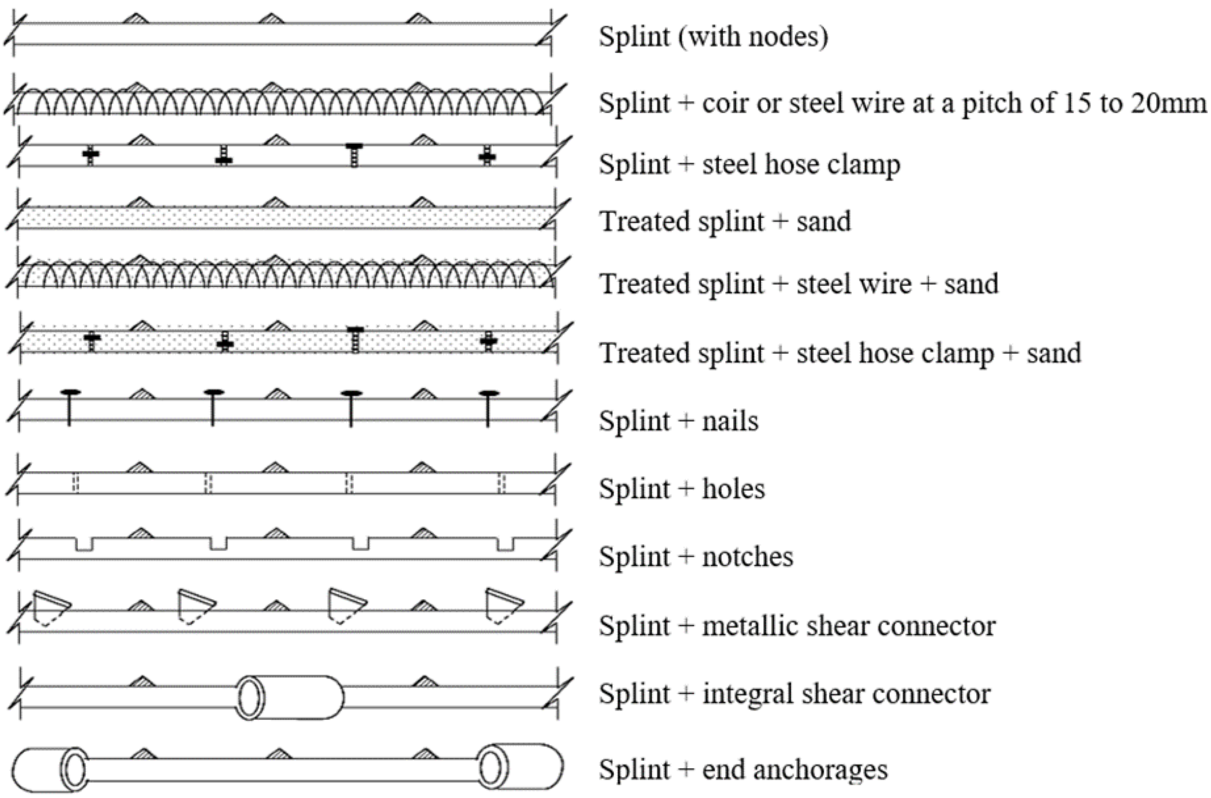

Fig 3. Methods suggested by various investigators for improving the bond between bamboo and concrete

Table 15: Methods suggested by various investigators for improving bond

Investigator	Methods used/suggested for improving bond
Narayana and Rehman, 1962	Bitumen kerosene (1:1/4) coating+Shear connectors
Geymayer and Cox, 1970	Splints with whole end sections, presence of nodes, epoxy+sand, Polyester resin +sand
Swamy, 1984	Winding metallic wires, coir ropes, shear connectors and anchorages (intermediate or end), nails as spikes, cutting notches at intervals in the whole bamboo, inserting metal plates perpendicularly into whole culm at various locations, splints instead of whole culms, proper cover to bamboo, proper spacing between culms, high strength cement, low water to cement ratio, polyester+sand, epoxy+sand, varnish (2 coats)+sand, bitumen+sand, sulphur+sand
Ganesan, 1990	Varnish (2 coats)+sand
Ghavami, 1995	Negrolin (2coats)+sand+wire winding
Sevalia *et al*., 2013; Siddhpura *et al*., 2013	Araldite +sand, epoxy resin+sand, coal tar+sand
Agarwal *et al*., 2014	Sikadur 32 gel
Ahmad *et al*., 2014	Coal tar+sand
Bhonde *et al*., 2014	Asphalt+sand
Himasree *et al*., 2015	Varnish+sand
Javadian *et al*., 2016	Moisture seal+sand, enamel coating+sand, ExaPhen coating+sand, Truegrip BT+sand, Truegrip EP+sand
Puri *et al*., 2017	Epoxy+sand
Umniati *et al*., 2017	Paint (2 coats)+sand
Mali and Datta, 2018	Bond Tite +sand +wire winding
Budi and Rahmadi, 2019	U notches made in splints
Etienne, 2019	Bitumen+sand
Ramakrishnan *et al*., 2019	Araldite +sand, bitumen+sand
Muhtar *et al*., 2019	Sikadur 752 +Hose-clamp ring+sand
Datta *et al*., 2019	Black-top emulsion, local latex, coal tar, paint, weaken varnish, water-glass (sodium silicate)
Muhtar, 2020	Sikadur+sand
Parasuram and Baskaran, 2020	Varnish (2 coats)+sand
Puri *et al*., 2020	Sikadur 32 LP +sand
Yathushan *et al*., 2021	Varnish+sand+wire winding
Vimala and Thippesh, 2021	Bitumen+sand
Fahim *et al*., 2022	Coal tar+sand
Kantharuban and Krishnaiah, 2022	Epoxy (2 coats)+sand

are plenty of ancillary applications where bamboo as a reinforcement can be recommended. Given that the world is poised toward massive infrastructure development, it becomes necessary to enlist the potential gaps for future research. These can be listed as under:

1) More rigorous research programs on the proven better solutions listed above, especially in the area of coatings, bond development, anchorage as well as thermal expansion, so that robust solutions can be derived. Eventhough Sikadur 32 Gel coated splints were found to perform better, more options may be evolved through comprehensive research.

2) Li and Shen, (2011) investigated the tensile strength of bamboo strip layers which varies from 350 MPa on the outer skin to as low as 40 MPa till the inner softer layers for a particular bamboo species. Such investigations will be required to give insight into various potential species which can be used as reinforcement.

3) Above aspect leads to another potential possibility of developing reinforcement through fusing high tensile strength layers only derived from different bamboo strips to achieve a required cross section in order to deliver significantly better and consistent strengths all along the layers in cross section, resulting in improved tensile strength of reinforcements and reliability.

4) New coatings and mechanical anchorage methods that can reduce the effects of thermal expansion in bamboo and enhance bond strength should be explored.

5) Since, thermal expansions results in loss of bond, it will be very interesting to investigate its performance for colder climate regions subjected to freeze and thaw.

6) Comparison of improvement in properties at species level with different treatment methods also needs to be investigated

7) One of the major limitations of bamboo reinforcement is its performance under dynamic loading, primarily due to inadequate bond development. However, detailed investigations into dynamic loading levels and stress concentration zones could enable the development of effective steel–bamboo–concrete composite solutions.

Optimism for the future application of bamboo as a reinforcement material arises from field investigations carried out at multiple locations in India, where bamboo has been employed as an alternative to steel. There are a variety of structures ranging from G+2 building, G+1 building, ground storey buildings, compound walls, piles, etc where the main reinforcement is completely replaced with bamboo in columns, beams and slabs and are nearly 15- 30 years old. Further, application of bamboo as a reinforcement for rigid pavements in Vietnam and Cambodia (Rolt and Cook, 2008) also confirms the utility of bamboo as a good reinforcement material.

As per Indian scenario, a kg of steel in remote locations will cost around Rs 100 where as a kg of bamboo would cost only Rs 2-3. Even after basic processing for better bond and treatments against termites/borers, the cost would be a maximum of Rs 5-6. Further, the cost of steel in RCC construction accounts for nearly 30% of the overall construction cost, whereas the use of bamboo can significantly reduce the overall construction costs.

Conclusions

This study explores the potential use of BRC construction at places where bamboo are grown in plenty and where the native people are unable to afford a home of their own due to the huge costs of construction materials. BRC can be used for the construction of structures for carrying light to moderate loads especially for the structures subjected to static loading rather than dynamic loading. Further research must be carried out to improve the load carrying capacity of BRC structures.

Application of BRC as precast wall panels for speedy construction can also be explored. It can even be considered for the construction of precast slabs resting on soils as rigid pavements especially on rural roads. Hence, more research is essential towards the performance of BRC precast components. The authors expect that through this paper one can get most of the information on bamboo as a reinforcement so that they can perform further research to find solutions that are acceptable as National and International Standards.

The physical and mechanical properties of bamboo increase from the bottom to the top of bamboo culm and it varies with its age. Hence, it is desirable to use bamboo of age 3-4 years for construction purposes. Bamboo possesses approximately the same strength to weight ratio as that of steel, indicating its potential to be used for cost-effective and sustainable construction. As bamboo is an anisotropic material, the effect of water absorption, shrinkage and thermal expansion will be different along the radial, longitudinal and tangential directions of bamboo. Therefore, proper seasoning must be done so as to remove the starchy sap and moisture content from bamboo. The use of seasoned bamboo can improve the bond strength of bamboo in concrete. Bamboo can be preserved by treating them with various chemicals. After providing different types of coating on bamboo to prevent water absorption, sprinkling sand over it will improve the bonding between bamboo and the surrounding concrete irrespective of the size of the sand grains. Coating bamboo splints with Sikadur 32 LP can reduce its water absorption to less than 1%. Black Japan and black top emulsion are also effective in resisting water absorption. If properly treated, bamboo will not deteriorate in concrete when subjected to water and it can last for more than 10 to 15 years. A boric borax mix solution is the most widely used solution for making bamboo resistant to insects and termites. The nodes need not be removed as the presence of nodes improve the bond strength of bamboo in concrete. It is advisable to use bamboo in the form of splints of 20mm width, rather than using whole bamboo culms for reinforcing concrete. The use of low water to cement ratios, high cement content, plasticizers and high early strength cement can reduce the water absorption of bamboo and thus improve the strength of the structure. When used as reinforcement in concrete, bamboo splints must be provided with a minimum cover of 15 to 20mm. There is a strong need for eco-friendly and cost-effective preservatives that will make BRC more efficient, attractive and acceptable for the construction industry.

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