BAMBOO (BETUNG SPECIES) FIBER COMPOSITE PLATE FOR EXTERNAL STRENGTHENING OF RC BEAMS

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ABSTRAK

Gentian semula jadi telah digunakan untuk menggantikan gentian sintetik dalam pembuatan komposit kerana gentian semula jadi lebih mesra alam berbanding dengan gentian sintetik. Satu penyelidikan telah dijalankan untuk mengenal pasti sifat mekanikal buluh spesies Betung dan potensinya untuk difabrikasikan sebagai komposit berasaskan gentian buluh (BFCP) sehubungan dengan penggunaannya dalam menambahkan kekuatan luaran rasuk konkrit bertelulang. Dalam kajian ini, buluh yang digunakan diperoleh dari Raub, Pahang. Ciri-ciri mekanikal buluh mentah dan kering telah dikaji melalui ujian mampatan dan ujian tegangan. BFCPs dalam nisbah isipadu gentian 0.4 telah difabrikasikan dan diuji dengan ujian lenturan (ASTM D790-03) dan ujian tegangan (ASTM D3039) untuk menentukan sifat-sifat mekanikalnya. Ujian pemuatan empat titik telah dijalankan untuk mengkaji kekuatan rasuk konkrit bertetulang yang dipasang dengan BFCP. Hasil kajian menunjukkan bahawa buluh spesies Betung mempunyai kepadatan sebanyak 0.807 g/cm^3. Dalam ujian mampatan, sampel buluh yang diuji gagal dalam dua mod, iaitu penghancuran gentian dan retakan gentian. Sampel buluh yang kering telah mencapai kekuatan mampatan sebanyak 19.5 % berbanding dengan sampel buluh yang mentah. Sebaliknya, keputusan menunjukkan bahawa kekuatan tegangan sampel mentah telah bertambah sebanyak 45 % berbanding dengan sampel yang kering. Selain itu, dalam ciri-ciri mekanikal, BFCP telah menunjukkan ketinggian sebanyak 666 % dan 178 % dalam kedua-dua kekuatan lenturan dan kekuatan tegangan berbanding dengan sampel epoksi. Pengekatan antaran serat buluh dengan resin epoksi dalam BFCP telah menambahbaikkan ikatan struktur dan ciri-ciri mekanikalnya. Melalui ujian pemuatan empat titik, data menunjukkan bahawa rasuk konkrit bertetulang yang ditampalkan dengan BFCP sebanding dengan rasuk konkrit kawalan dengan nisbah kekuatan sebanyak 96 % dan 97 %. Kajian juga menunjukkan kekuatan rasuk konkrit yang diperkuatkan dengan BFCP telah meningkat sebanyak 10-12 % berbanding dengan rasuk konkrit yang tanpa sebarang pengukuhan. Dalam pemerhatian corak-corak retakan, hanya sedikit retakan yang muncul di bahagian yang ditampal dengan BFCP. Pemasangan BFCP mampu mengalihkan retakan tegak ke pinggir plat dengan membentuk retakan pepenjuru. Ini membuktikan bahawa aplikasi BFCP sangat berkesan untuk menambahbaikkan kekuatan lenturan dan ia berpotensi untuk digunakan sebagai bahan pengukuhan luaran untuk memulihan kekuatan rasuk konkrit bertetulang.

ABSTRACT

Natural fibers are being introduced to replace the synthetic fiber in the manufacturing of fiber composites due to its environmental friendly behavior. A research had been conducted to investigate the mechanical properties of bamboo (Betung species) and its potential to be used as bamboo fiber composite plate (BFCP) for the external strengthening of reinforced concrete (RC) beams. Raw bamboo culms were obtained from Raub, Pahang. Mechanical behaviour of raw and dried bamboo specimens was tested under compression test and tension test. All the BFCPs with 0.4 fiber-to-volume ratio have been fabricated and tested for flexural test (ASTM D790-03) and tensile test (ASTM D3039) to determine the mechanical properties. Four-point loading test was conducted to study the behaviour of reinforced concrete (RC) beam under external strengthening effect with BFCP. The result showed that bamboo of Betung species has a density of 0.807 g/cm^3. In compression test, bamboo culms fail in two modes: fiber cracking and fiber crushing. Dried bamboo specimens recorded 19.5 % higher in compression strength than raw bamboo specimens. There was an improvement of 45 % of average tensile strength in raw bamboo samples compared to dried specimens. In terms of mechanical behaviour, BFCP has higher flexural and tensile strength than pure epoxy samples where the flexural and tensile strength of BFCP increased by 666 % and 178 % respectively. The interfacial adhesion between the bamboo fiber and epoxy resin in BFCP greatly improved the structural bonding and mechanical properties. From the four-point loading test, BFCP strengthened beams had achieved the total load bearing capacity of 96 % and 97 % compared to solid control beam. Compared with un-strengthened beam, the load bearing capacity of BFCP strengthened beam increased by 10 % and 12 %. Installation of BFCP manage to divert the vertical cracks at the tension zone to the edge of the plate forming diagonal cracks. This proved that BFCP has potential to be used as external strengthening material in RC beams.

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LIST OF SYMBOLS

%	Percentage
mm	Millimeter
m	meter
N/mm2	Newton per millimeter square
g/cm3	Gram per centimeter cube
mL	Milliliter
N	Newton
kN	Kilo Newton
°C	Degree Celsius
g	Gram
mm/min	Millimeter per minute
mm2	Millimeter square
MPa	Mega Pascal
D	Distance from the support (mm)
V	Volume

LIST OF ABBREVIATIONS

BFCP	Bamboo Fiber Composite Plate
BFCPs	Bamboo Fiber Composite Plates
CAN	Chemical Assisted Natural
CB	Control Beam
CFRC	Carbon Fiber Reinforced Composite
CO_2	Carbon Dioxide
GFRC	Glass Fiber Reinforced Composite
INBAR	International Network for Bamboo and Rattan
LBC	Laminated Bamboo Composite
NFRCs	Natural Fiber Reinforced Composites
NaOH	Sodium Hydroxide
NFCP	Natural Fiber Composite Plate
RC	Reinforced Concrete
RM	Ringgit Malaysia
SFCP	Synthetic Fiber Composite Plate
SFCPs	Synthetic Fiber Composite Plates
ST-B	Strengthened Beam
US$	United States Dollar
UST-B	Un-strengthened Beam
UTM	Universal Testing Machine

CHAPTER 1

INTRODUCTION

1.1 Research Background

Due to the concerns over environment, there has been a lot of research in recent years towards the potential of natural fiber as an alternative to synthetic fiber especially in construction industries. Synthetic fibers that commonly used are polyethylene, aramid, polyesters, carbon and others hybrid fibers. Synthetic fibers are used due to their high performance in terms of strength, susceptible to fungus attack and water resistance. However, the mode of disposal of these artificial fibers becomes an issue which may threaten the environment because they are non-biodegradable. Hence, there are extensive of studies on the application of natural plant fibers like jute, kenaf, sisal, silk and bamboo fiber as an alternative to the synthetic fibers (Tong, 2017). Compare with artificial fibers, nature fibers tend to be more environmental friendly as they are biodegradable, renewable, and readily available in natural form and possess adequate strength. They offer more economical and environmental advantages and start to become emerging materials in engineering field (Lau *et al.*, 2018).

A study by Mohamed and Appanah (1998) showed that only 0.6 million tons of bamboo stocks in Malaysia that are being used commercially instead of the total amount of 7.0 million tons. Based on the statistic, this quantity has reached an estimated value of RM 3 million. Due to the rapid growth rate of bamboo and its great productivity, bamboos production has reached a huge amount of 30,000,000 tons (Faruk *et al.*, 2012). Bamboos are the largest green grass family *Poaceae* in the subfamily *Bambusoideae.* There are more than thousand species of bamboo found in diverse climate (Eichhorn *et al.*, 2001). Out of these, 18 bamboo species have been used as fiber for composites. Therefore, suitable and convenient methods should be implemented to fabricate bamboo composites and optimize its benefit as natural resources (Okubo, Fujii and Yamamoto, 2004).

Bamboo fibers are also called `natural glass fiber` due to its longitudinal alignment of fibers which produces high strength with respect to its weight. High performance composite parts are produced from these fiber configurations at low implementation cost with the help of advance technology (Perremans *et al.,* 2018). Compare to other natural fibers, bamboo fiber also has lower cellulose content and a smaller microfibrillar angle which contribute to both volume resistivity and mechanical strength. Those cellulose fibers inside the bamboo composite material are embedded in lignin matrix, aligned along the length of the bamboo which then produces maximum flexural strength, rigidity and tensile (Ray, Das and Mondal, 2004). Due to the superior tensile strength and modulus of elasticity, bamboo fibers become common materials used in polymeric composites (Deshpande et al. 2000). Another research showed that the tensile strength of bamboo fiber reached a high value about 330 MPa which is higher than other natural fiber reinforced green composites (Cao, Shibata and Fukumoto, 2006).

Bio-composites made of bamboo fibers are considered as green and environmentally responsible eco-products. Epoxy resins are used as the matrix in the fabrication of composite plates. With the combination of two materials, it can enhance the stiffness, flexural, tensile strength, and resistance to corrosion of the composites plate. They are preferable to be installed externally as structural material to strengthen the reinforced structures due to its light weight, ease in installation, high strength and abundant resources (Chin *et al.*, 2012). Therefore, it is possible to increase the number of application for bamboo fiber reinforced composite plate to replace the costly and non-biodegradable synthetic fibers. In the latest development, the interest of utilizing natural fiber was shifted to the aerospace industry (interior), automotive, marine and even civil construction materials (Bansal, Ramachandran and Raichurkar, 2017).

The strengthening of existing civil structures must be considered when environment factors such as moisture and weathering affect the lifespan of the whole buildings (Alam and Al Riyami, 2018). To extend the design life of the structure, several strengthening methods like applying the bolts, widening the span and externally bonded fiber reinforced plates on RC structures have been implemented (Jumaat and Alam, 2008). These applications tend to repair and upgrade the existing structures in term of design life time and load bearing capacity.

1.2 Problem Statement

The fabrication of composite plate is commenced by using synthetic fibers due to their high strength, stiffness and longer life span. Moreover, synthetic fiber composite plates (SFCPs) tend to be more resistant to corrosion, water, adverse environment and thermal stability (Begum K and Islam MA, 2013). These unique characteristics enable them to be adapted and equipped easily on most structures. Despite these advantages, SFCPs have plenty of drawbacks and the biggest restriction is the high production cost. They are also non-biodegradable as this would lead to environment hazards as the fabrication process produces a significant amount of carbon dioxide gaseous (CO_2). Based on these reasonable analyses, renewable natural plant fibers composites are increasingly gaining attention as viable alternative to SFCPs over years.

Although natural plant fibers especially bamboo fibers are taking advantage of strong material properties and environmental friendly, it has a low comprehensive utilization rate and automation. The problem is that the bamboo industry produces no high value products and it fails to maximize the ecological and economic strengths (Wang et al., 2013). Although a great work has been made on potential of natural fiber composite materials as alternative solution in construction industries, research on the suitability of bamboo fiber composite plates (BFCP) for externally strengthening the reinforced concrete structures is rare.

All these issues have led to explore of possible BFCP to replace some of the traditional engineering materials that are not environmentally friendly which used and resolve these issues. Natural plant fibers have unequivocally contributed economic prosperity and sustainability in our daily lives. To this end, in the present research work, an attempt has been made to reveal the physical and mechanical properties of bamboo fiber as well as the potential of BFCP to be used as external strengthening materials on RC structures.

1.3 Research Objectives

The aims of this research are to study the mechanical properties of bamboo specimens (Betung species) as well as the fabricated bamboo fiber composite plate (BFCP) followed by the applicability of its composite plates for external strengthening on RC beams. The objectives of the research work are specified as follow:

i. To determine the mechanical properties of bamboo specimens in term of compressive and tensile strength.

ii. To determine the mechanical properties of BFCP as external strengthening material through flexural and tensile test.

iii. To evaluate the structural behaviour of RC beams strengthened in flexural zone using BFCP in terms of load deflection, crack patterns and failure mode.

1.4 Scope of Study

In this study, bamboo species with scientific name of *Dendrocalamus asper* (Betung species) had been chosen to determine its mechanical properties in term of compressive and tensile strength. Bamboo culms were selected from different portions of raw bamboos as the specimens for compression test. Followed by tensile test, few bamboo splints were prepared and cut into desired length.

Later in the fabrication of bamboo fiber composite plate (BFCP), the raw bamboo must be treated both chemically and mechanically to extract the natural fibers. Firstly, they were treated by 10 % sodium hydroxide (NaOH) solution for 48 hours (Tong, 2017). The processed bamboo specimens were then passing through a mill rolling process to extract the bamboo fibers. In the fabrication of BFCP, bamboo fibers were mixed with epoxy in a fiber volume fraction of 40 % through hand lay-up method. Both the tensile and flexural specimens were designed in a rectangular cross-section with specific dimension. The ultimate flexural and tensile strength of BFCPs were determined by using Universal Testing Machine (UTM) according to ASTM standards.

Four-point loading test was conducted on reinforced concrete (RC) beams to study the behaviour of RC beams that strengthened externally with BFCP at flexural zone. Three categories of RC beams were casted: control beam (CB), unstrengthen beam (UST-B) and BFCP strengthened beam (ST-B). The cracks patterns of the beams were observed and marked. Deflection behaviour and failure mode were also determined and analysed.

1.5 Research Significance

Development of renewable raw materials on production of natural fiber composites tends to be the alternatives for synthetic fibers due to the increased pressure from global community to preserve the nature resources. Application of natural fibers on construction materials and structures especially in external strengthening of RC beams has been approached due to environmental concerns. Synthetic fibers are non-biodegradable, pose harmful effect on both human being and environment yet natural fibers can reduce these negative impacts.

This study was focus on the mechanical properties of bamboo specimens as well as the composite plates. The tensile and flexural strength of the composite plates that fabricated were determined and compared with the neat epoxy samples. Also, the performance of bamboo fiber reinforced composite plates (BFCPs) in improving the flexural strength of reinforced concrete (RC) beams was investigated. Old existing structures have higher risk of failure due to increasing loading and shorter design life. Therefore, BFCPs seem to be a green solution to transfer the load and restrict the stress distributed on beams. This research aimed to reveal the effectiveness and potential of BFCPs on external strengthening of RC beams and it was measured in the terms of crack patterns, failure mode and load deflection.

The applications of BFCPs in construction industry have considerable attention because of low weight, good mechanical properties, biodegradable, being abundant and they also pose the minimal environment and health hazard. Chemical treatment of the bamboo fiber with thermoplastic such as epoxy tends to improve both the physic-mechanical and thermochemical properties of the BFCPs. Therefore, it has high possibility to replace the synthetic and use in large scale in global production.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

The potential, physical and mechanical properties of plant fiber, bamboo in previous research are discussed in this chapter. There are many factors and consideration that contributed to the selection of bamboo fiber as the alternatives in different industries. The compressive strength and tensile strength of bamboo specimens were determined and compared with several synthetic fiber composites. Treatment of raw bamboo fiber and the ways to enhance its strength by mixing with thermoplastic were also discussed. This chapter also focus on methods used to fabricate the bamboo fiber composite plate (BFCP) as well as to determine the tensile and flexural strength of BFCP. Application and configuration of several natural fiber composite plates on RC beams are being observed and analysed.

2.2 Plant Fiber

Plant fibers are made up of cellulose which produces long; often highly lustrous fibers compare to animal fibers. Plants can be classified as primary and secondary plants based on their usage. Primary plants are purposely grown to optimize their use of fiber content for example jute, sisal, kenaf and bamboo. Fibers in secondary plants are used as by-product and some general secondary plants are coir, oil palm and pineapple (Faruk *et al.*, 2012). Selection of natural fibers is highly dependent on where they are grown and what part of the plant they are harvested (O'Donnell, Dweib and Wool, 2004). The plant fibers can be further grouped into six main categories according to their origin and derivation of plant (Ramesh, Palanikumar and Reddy, 2017) as shown in the Figure 2.1.

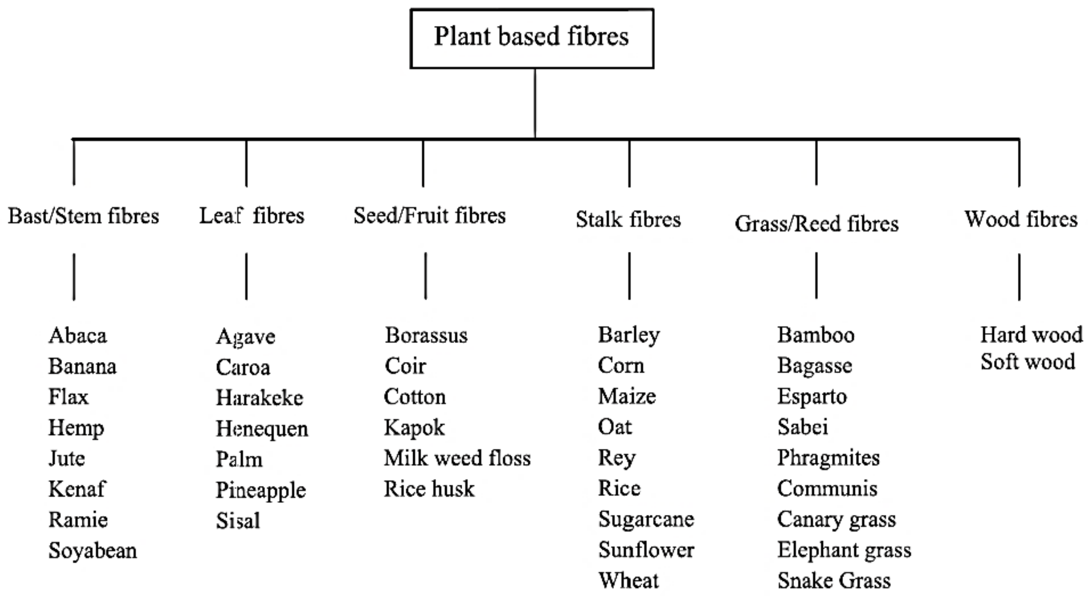


Figure 2.1: Plant based fiber classification.

Source: Ramesh et al. (2017)

Taj (2014) also summarized the fibers and their origin of countries as listed in Table 2.1. Properties of lignocellulose fibers depend mainly on chemical composition as well as the structures of the plant. Most plant fibers are made up of cellulose, hemicellulose, lignin and other water-soluble compounds which contribute to the overall properties of the fiber. Cellulose is the stiffest component and it greatly enhanced the efficiency of the by-products (composites) produced. Hemicellulose is taking part in thermal degradation, biodegradation, and micro-absorption. Lignin is more thermally stable but it is weak to UV degradation (Jawaid and Abdul Khalil, 2011). Other critical factors including the microfibrillar angle, cross section and polymerization degree also affect the design and application of fiber composites (Al-bahadly, 2013). Lignocellulose fibers in plants have the advantage of being renewable, lower cost, light in weight and they are becoming more marketing appeal. Combinations of natural fibers and biodegradable polymers as matrices are the ways to preserve and conserve the environment, which they can be decomposed when reaching the life span.

Table 2.1: Fiber and origin of countries.

Flax	:	Borneo
Hemp	:	Yugoslavia, China
Sun Hemp	:	Nigeria, Guyana, Siera Leone, India
Ramie	:	Hondurus, Mauritius
Jute	:	India, Egypt, Guyana, Jamaica, Ghana, Malawi, Sudan, Tanzania
Kenaf	:	Iraq, Tanzania, Jamaica, South Africa, Cuba, Togo
Roselle	:	Borneo, Guyana, Malaysia, Sri Lanka, Togo, Indonesia, Tanzania
Sisal	:	East Africa, Bahamas, Antiqua, Kenya, Tanzania, India
Abaca	:	Malaysia, Uganda, Philippines, Bolivia
Coir	:	India, Sri Lanka, Philippines, Malaysia

Source: Taj (2014)

Based on the statistic, glass fiber has recorded the price of 1200-1800 US$/tonne but it is only 200-1000 US$/tonne for plant fibers (Satyanarayana, Guimarães and Wypych, 2007). Plant fibers are also much less dense than synthetic fibers which are around the range of 1200-1500 kg/m^3 compared to a value of 2500 kg/m^3 for glass fibers. In developing country like West African, Bangladesh, and Tanzania, lignocellulose fiber becomes a part of the economic incomes. Annually, there is a huge amount approximately 30 million tonnes of lignocellulose fibers are produced and processed. Many of them are applied in automobiles industries, clothing, building materials and sport equipment (Jawaid and Abdul Khalil, 2011). However, natural fibers have some weakness such as low moisture resistance, poor wetability and they are also incompatibility with certain polymeric matrices. Undefined plant fibers are not suitable to be used in the fabrication of load bearing composites with its unsatisfactory mechanical properties. The properties can be improved by treating with chemicals like sodium hydroxide permanganate and peroxide as well as physical treatment prior composite fabrication (Ho *et al.*, 2012).

2.3 Bamboo Fiber

Bamboo is a giant woody grass with more than 1000 species which is grown naturally in varied climates, mostly can be found abundantly in tropics (Gratani *et al.*, 2008; Abdul Khalil *et al.*, 2012). Bamboo is grouped into true grass family *Poac*eae, which is a subfamily belongs to *Bambusoideae* (Liu *et al.*, 2012). It is recognized as a rapid growing plant due to its distinct characteristic that it has rhizome-dependent system. With fast growing cycle and great productivity, it is considered as the most suitable plant to be grown and harvested. An estimated value of 31.5 million hectares across the 21 countries has been occupied by bamboos (Buckingham, Wu and Lou, 2014). China and India have practice the use of bamboo in large scale among the countries. Meanwhile for the bamboo production areas in Peninsular Malaysia, there are only 421.722 hectares, about 7 % of total forest land (Mohamed *et al.*, 2007). Although there are thousands species of bamboo found, only 58 species turned to wood-based products in industries and 18 species used in fabrication of composites (Buckingham *et al.*, 2011).

With the increasing potential of bamboo in different industries, the International Network for Bamboo and Rattan (INBAR) was formed to promote the bamboo-based products (Buckingham *et al.*, 2011). As the result, high bamboo communities have been emerged and this creates a good environment for soil erosion control, water conservation, and land rehabilitation (Zhou *et al.*, 2005). Therefore, there is encouragement in the use of mechanical processed bamboo culms in industrial processing for composite products (Marsh and Smith, 2007). The capacity of bamboo`s sustainable harvesting makes it as an alternative for wood products. China, as the countries with highest usage of bamboo, it has been using most of its bamboo to produce furniture, composite boards, flooring and even house making (ZhaoHua and Kobayashi, 2004).

2.3.1 Mechanical Properties

Mechanical properties such as compressive and tensile strength of bamboo fibers are influenced by their physical, chemical and morphological properties. The superior mechanical properties of bamboo came from its main constituent and the unidirectional arrangement of the fiber inside tissue (Wai, Nanko and Murakami, 1985). Modulus of elasticity increases with the cellulose content and inversely proportional to the microfibrillar angle (Liu *et al.*, 2012). Bamboo cellulose fibrils in axial orientation maximize the longitudinal elastic modulus while the transverse rigidity increases with percentage of lignification (Wang *et al.*, 2012). Bamboo has a smaller microfibrillar angle of 2°-10° and it composed of 32 % lignin content and these lead to high tensile strength, flexural strength and the rigidity of the structure (Tong, 2017). This moderate lignin content makes bamboo fiber more brittle compared to other natural fiber (Shi *et al.*, 2012). However, with the removal of lignin content from bamboo fiber by alkaline treatment, the tensile modulus and overall strength of bamboo fiber can be highly improved (Amada *et al.*, 1997). Previous research has figured out that plant fibers are better than glass fibers and they can replace the synthetic fiber materials (Joshi *et al.*, 2004).

In term of strength and stiffness efficiency, bamboo is comparable to steel and the production energy that required for bamboo is only 0.1 % of the total amount required for steel (Verma *et al.*, 2017). Laminated Bamboo Composites (LBCs) are produced using epoxy resin and the mechanical properties have been examined under different loading conditions. In term of average strength, LBCs have advantage over the softwoods and like hard woods. This proved that the LCBs can achieve up to the strength of certain wood-based composites and used for structural applications.

Abdul Khalil et al. (2012) investigated that the mechanical and physical properties of bamboo fiber reinforced epoxy composites were comparable to glass fiber reinforced epoxy composites as shown in Table 2.2. Bamboo fiber composites can reach the tensile strength up to 165 MPa, almost targeting the lowest tensile strength of glass fiber composites which was 180 MPa. Bamboo fibers can actually replace up to 25 weight percentage of glass fibers without reducing the mechanical properties of glass fiber composites (Mandal *et al.*, 2010). With the adding of bamboo fibers, the modulus strength of fabricated bio-composites had gradually increased.

Biswas et al. (2015) investigated the physical and mechanical strength of jute and bamboo fiber reinforced epoxy resin unidirectional void free composites. The tensile and longitudinal flexural strength of bamboo fibers composites were greater than jute fiber composites. Both the natural fiber-based composites were fabricated by using vacuum technique. Bamboo fiber composites had a tensile strength of 392 MPa and longitudinal flexural strength of 226 MPa. These positives results led to the high potential of bamboo fiber in replacing the artificial fibers.

Table 2.2: Comparative properties of bamboo fiber based reinforced composites.

	Comparative properties					
		Tensile strength (MPa)	Tensile modulus (GPa)	E (%)	Flexural strength (MPa)	Flexural modulus (GPa)
Fibre	BF	500–575	27–40	1.9–3.2	100–150	10–13
	GF	124–150	7–10	2.5–4.8	110–150	5–9
Composites	BF–EP V_f 65%	87–165	3–15	1.7–2.2	107–140	10–12
	GF–EP $V_f = 65\%$	180–220	5–10	2.7–3.5	195–250	7–12

Source: Abdul Khalil et al. (2012)

2.3.1.1 Compressive Strength

Bamboo has been used as composite material as it generates high flexural and compressive strength as well as high strength to weight ratio from structural point of view. From the compression test, it was found that the compressive strength of bamboo reached a high value of 90.72 MPa which was comparable to steel and concrete (Gupta, Ganguly and Mehra, 2015). Another research found out that bamboo with larger thickness exhibited higher force capacity or high compressive strength and the strength decreased significantly with the increase in its outer diameter (Lo, Cui and Leung, 2004). Compared with other wood species used as raw material for composite products, bamboo showed higher compression strength parallel to grain than woods. Bamboo might be suitable as the raw material for products that bear unidirectional load (Chaowana and Barbu, 2017). Table 2.3 summarizes the mechanical properties of some bamboo species in term of compression strength and other measurable properties.

Table 2.3: Compression strength for different types of bamboo species.

Bamboo species	Modulus of rupture (MPa)	Modulus of elasticity (MPa)	Shear strength parallel to grain (MPa)	Compression strength parallel to grain (MPa)
Balanocarpus heimii	122.0	1800	13.7	69.0
B. blumeana	99.8	4100	4.5	24.0
B. vulgaris	62.3	6100	4.0	25.3
D. asper	85.7	6300	5.4	31.5
G. scortechinii	52.4	4800	4.3	27.0
G. levis	78.5	5100	4.8	40.0
Koompassia malaccensis	100.0	1700	10.0	54.7

Source: Chaowana et al. (2017)

2.3.1.2 Tensile Strength

When compared with bamboo, the energy required for processing the common construction materials such as steel and concrete is approximately 50 times more energy than for bamboo. This in another way had turned bamboo to an attractive alternative to steel in tensile loading applications with the tensile strength of 370 MPa (Budi and Rahmadi, 2017). According to Ghavami (1995), the ratio of tensile strength to specific weight of bamboo was six times greater than that of steel. Another research by Gupta et al. (2015) revealed that the ultimate tensile strength of bamboo splints can reach up to 282 MPa which was comparable to the structure steel of 250 MPa. This proved that bamboo can sustain the tensile loads in a concrete flexure element. Also, the stress versus strain curve of bamboo splint was plotted and the result had shown that bamboo was a viscous and elastic material and it exhibited time dependent strain elasticity.

2.4 Extraction of Bamboo Fiber

There are specific techniques used for the extraction of bamboo fibers from the raw bamboos culms. Conventional method which included the mechanical and chemical extraction is the common way to deal with bamboo fiber (Zakikhani *et al.*, 2014). Appropriate technique and extraction procedure are the critical factors that may affect the properties of extracted fiber, wastage, cost and their impacts on environment.

2.4.1 Mechanical Extraction

Mechanical extraction is more environmental friendly and cut down use of chemical reactants. Crushing is one of the ways the raw bamboo splints are cut down mechanically into smaller pieces by a roller crusher. They are being processed into coarse fibers and boiled at 90°C for 10 hours, and dried in rotary dryer before putting them in dehydrator (Phong *et al.*, 2011). However, the outcomes might be unsatisfied where the fibers might break down and become too short or powdered form due to over-processing (Ashimori *et al.*, 2004). Rolling mill is another convenience machine used to extract the bamboo fibers. The bamboo culm is cut from nodes into smaller pieces, it then become strips with desired thickness (free of nodes). They were soaked in water for 1 hour to separate the fibers before passing through the rolling mill at low speed and pressure. Then the weak-bonded rolled strips were soaked in water for 30 min and then separated into fibers with a razor blade (Yao and Zhang, 2011).

2.4.2 Chemical Extraction

Chemical extraction of bamboo fiber involves with the use of alkali as well as chemical retting to decrease the percentage of lignin content. In alkaline treatment, bamboo strips are immersed in 1.5 N NaOH solution and heated at 70°C for 5 hours. The alkali treated bamboo strips are then pressed and separated by a steel nail. The extracted fibers are dried in oven after washing with water. There was another approach that soaked bamboo strips in 1 N sodium hydroxide for 72 hours (Deshpande, Bhaskar Rao and Lakshmana Rao, 2000). Alkali treatment was able to enhance the interfacial bonding and improved the surface adhesion of composites (Takagi and Ichihara, 2004). The quality of the bamboo fibers can be preserved and less damaged products can be obtained from this extraction method. Alkali treatment able to enhance the interfacial bonding and improves the surface adhesion of composites (Takagi and Ichihara, 2004). In chemical retting, Chemical Assisted Natural retting (CAN) procedure was used to reduce the lignin and water content in fibers. Bamboo culm was cut in longitudinal direction to form thin slab. They were then immersed in zinc nitrate, $Zn(NO_3)_2$ solutions followed by a neutral pH solution for 116 hours in a BOD incubator and lastly boiled in water for 1 hour. This method was able to remove high percentage of lignin content compared with alkaline and acid retting but the moisture content was high (Kaur, Chattopadhyay and Kaur, 2013).

2.4.3 Combined Mechanical and Chemical Extraction

In combine extraction method, bamboo fibers are treated with alkaline and chemical then followed by compression moulding technique (CMT) and roller mill technique (RMT). Both techniques produce flat bamboo strips, which enable easy separation of processed strips into individual or single fiber. There is another way which only involves a roller to extract the fibers. The nodes of the bamboo culm were removed, and the internodes left were sliced longitudinally into strips. The bamboo strips were treated with sodium hydroxide solution (NaOH) with concentration of 1-3 % at 70°C for 10 hours. Roller is used to extract the fiber from alkali-treated strips. The bamboo fibers were washed with water and then dried in oven at 105°C for 24 hours (Phong *et al.*, 2011). However, different extraction procedures for bamboo fiber lead to different mechanical properties as shown in Table 2.4.

Table 2.4: Mechanical properties of bamboo fibers based on the extraction procedures.

Fibre	Extraction procedure	Tensile strength (MPa)	Young's modulus (Gpa)
Bamboo	Mechanical		
	Steam explosion	516	17
	Steam explosion	441 ± 220	36 ± 13
	Steam explosion	383	28
	Steam explosion	441	35.9
	Steam explosion	615–862	35.45
	Steam explosion	308 ± 185	25.7 ± 14.0
	Rolling mill	270	–
	Grinding	450–800	18–30
	Retting	503	35.91
	Crushing	420 ± 170	38.2 ± 16
	Chemical		
	Chemical	341	19.67
	Chemical	450	18
	Chemical	329	22
	Alkaline	419	30
	Alkaline	395 ± 155	26.1 ± 14.5
	Combined mechanical and chemical:		
	Chemical + Compression	645 Max: 1000	–
	Chemical + Roller mill	370 Max: 480	–

Source: (Okubo, Fujii and Yamamoto, 2004; Osorio *et al.*, 2011; Phong *et al.*, 2011; Ratna Prasad and Mohana Rao, 2011; Biswas *et al.*, 2015)

2.5 Surface Treatment Method

Bamboo fiber has low compatibility with the polymer matrix used during fabrication process. There is only low adhesion exists between the surface area of the fibers and polymer, which make it unsuitable to be used readily with the polymer matrix to produce composite products. Although bamboo fiber has comparable strength to synthetic fibers such as glass fibers, its weak mechanical performance of bamboo composites leads to a shorter lifespan. This possesses negative impacts on environment due to the wastage or misapply of natural fibers. Previously some researches have been done to investigate the efficient ways to modify the superficial structure of fibers such as adding chemical groups into the fiber contents. It also can be done by removing or reducing some constituents to change the properties of natural fibers (Belgacem and Gandini, 2008).

2.5.1 Pre-treatment

Pre-treatment can be applied on fiber surface to remove the unnecessary substances such as starch, pectineus and sugar that interfere the mechanical anchoring of polymeric matrix on bamboo fibers. It means to clean the surface and increase the roughness (Monteiro *et al.*, 2011).

2.5.2 Chemical/Alkaline Treatment

Chemical treatment is also known as mercerization which it intends to activate the hydroxyl group (OH^-) in bamboo fibers. Without any treatment, hydroxyl group will react with water molecules through hydrogen bonding and this leads to the ease of moisture absorption. The poor adhesion between the hydrophobic non-polar matrices and hydrophilic cellulosic fibres led to a weak fiber matrix formation and poor composite products (Mohanty and Nayak, 2010). These ionic groups presented in cellulose and lignin and they contributed to the hydrogen bonding within the fibers (Costa *et al.*, 2017). More cellulose is formed when weakening of hydrogen bonds occurred, which presents itself as a net in molecular structure. Reaction with water allows the cellulosic structure to turn to polymorphic instead of monoclinic form. This process also improves the solubilization of hemicellulose and lignin which then directly increase the roughness of fiber and form a stronger structure.

The alkaline treatment improves the impregnation of bamboo fibers with polymeric resin instead of reducing the mechanical performance of the fibers. Treated bamboo fiber composite has higher mechanical properties compared to those without any treatment due to improvement in mechanical adhesion between fiber and the matrix as listed in Table 2.5. Bamboo composites with the fibres treated with sodium hydroxide tend to have bending, tensile and compressive strength and stiffness of 7, 10, 81, and 25 % higher, respectively than the untreated composites (Manalo *et al.*, 2015).

Table 2.5: Uniaxial tensile test results of bamboo fibers with alkaline treatment and without alkaline treatments.

Fibers	Young's modulus *(GPa)*	StD *(GPa)*	Tensile strength *(MPa)*	StD *(MPa)*	Failure strain (%)	StD *(%)*
Bamboo_WT	8.70	2.85	179.4	72.8	2.02	0.68
Bamboo_TB	10.77	4.46	209.4	105.9	1.64	0.48
Bamboo_TC	12.22	6.92	234.7	149.1	1.93	0.86

Source: Costa et al. (2017)

2.6 Polymer Resin

Polymer resins are mixed with fibers in the fabrication of composite and they are very useful in transferring stress between the fibers. They create a barrier for composite against the outside environment and protect the fibers from any mechanical abrasion. They can be divided into two categories: thermosetting and thermoplastic. Thermoset is a hard and rigid material that does not change in shape or stretch the way as thermoplastics. They were supposed to be more suitable as rigid domains than thermoplastic polymers due to the highly cross-linked which possess superior mechanical properties (Zhang *et al.*, 2014). Some common thermoset polymers are epoxy resin, vinyl ester and unsaturated polyester. Thermoset plastics are cured by chemical reaction where the strong cross-linking molecules bonds are formed. Thermoset cannot be melted once cured and the composite products are more heat resistance, high toughness and solvent resistance. Unsaturated polyesters were versatile in properties and applications due to the room temperature cure capability, good mechanical properties and transparency (Aziz *et al.*, 2005). A comparative study of several thermosets was shown in Table 2.6 and this displayed that epoxy resin had higher mechanical strength than polyester resin and vinyl ester resin (Al-bahadly, 2013).

Table 2.6: Comparative study of polyester, epoxy and inyl ester resins.

Properties	Polyester Resin	Epoxy Resin	Vinylester Resin
Density (g/cm^3)	1.2-1.5	1.1-1.4	1.2-1.4
Young's modulus (GPa)	2-4.5	3-6	3.1-3.8
Tensile strength (MPa)	40-90	35-100	69-83
Compressive strength (MPa)	90-250	100-200	----
Tensile elongation to break (%)	2	1-6	4-7
Cure shrinkage (%)	4-8	1-2	----
Water absorption 24 h at 20 °C	0.1-0.3	0.1-0.4	----
Fracture energy (KPa)	----	----	2.5

Source: Al-bahadly (2013)

Thermoplastics are existed in solid state and they required heat to be applicable. No chemical reaction occurs during the reaction, but only changes of the state of the polymer. After cooling, thermoplastic can retain its shape and functions normally. However, it is not susceptible to high temperature and high pressure as it will soften and affect the mechanical performance. Only some thermoplastics useable for the fabrication of fiber reinforced composites like polyethene, polypropylene, polystyrene and polyvinyl chloride (PVC). The processing temperature should not exceed 230°C which will cause fiber degradation. Most commonly used thermoplastics are non-biodegradable therefore it is essential to develop biodegradable materials with expected properties to reduce the negative impact on environment.

2.6.1 Epoxy

In year 2010, the global epoxy resins production had reached up to 2 million tonnes and it was estimated to hit a target of 3 million tonnes by 2017. According to Scarponi et al. (2016), addition of epoxy matrixes to rigid fibers is able to increase the stiffness as well the strength of construction materials and products. Biodegradable fibers need to be reinforced with thermoset resin to improve their properties and epoxy was commonly used as polymer with jute and bamboo fibers (Soykeabkaew, Supaphol and Rujiravanit, 2004; Mandal *et al.*, 2010). Flexural properties of two types epoxy resins which are bio-epoxy and traditional epoxy as shown in Table 2.7. Research done by

Biswas et al. (2015) had proved that the flexural strength with longitudinal and transverse fiber distribution of bamboo and jute increased as reinforced with epoxy polymer. Natural fibers-epoxy based composites can replace the carbon- epoxy composite without much affecting the tensile strength, flexural strength, and flexural modulus (Ramana and Ramprasad, 2017). Epoxy resin had dominant over other resins in the manufacturing of high performance materials due to its high mechanical stiffness, toughness, chemical resistance, and excellent adhesive properties (Gojny *et al.*, 2005).

Table 2.7: Flexural properties for bio-epoxy and traditional epoxy.

Specimen	Flexural strength (MPa)	Flexural modulus (GPa)
Bio-epoxy		
0 J	107.32 ± 0.28	5.33 ± 0.09
5 J	90.22 ± 7.03	4.77 ± 0.07
10 J	68.49 ± 5.37	4.48 ± 0.11
15 J	60.53 ± 1.86	3.75 ± 0.33
20 J	45.40 ± 4.55	2.55 ± 0.45
Traditional epoxy		
0 J	108.50 ± 1.19	5.26 ± 0.08
5 J	78.30 ± 10.67	4.70 ± 0.17
10 J	63.19 ± 0.81	4.11 ± 0.29
15 J	52.33 ± 0.80	3.58 ± 0.06
18 J	47.44 ± 3.39	3.38 ± 0.06

Source: Scarponi et al. (2016)

2.7 Bamboo Fiber Reinforced Composite (BFRC)

Natural fiber reinforced composites (NFRCs) are emerging as a feasible alternative to synthetic fiber reinforced composites especially in civil engineering applications. Abdul Khalil et al. (2012) had shown the versatility of bamboo fibers application and the study also mentioned that bamboo has significant potential in composite making due to its high strength and environmentally friendly nature. Osorio et al. (2011) also concluded that bamboo fiber reinforced epoxy composites can be used to replace the carbon fiber and glass fiber based composites. Table 2.8 shows the advantages of bamboo fiber over glass fiber in terms of cost, mode of disposal and renewability.

Table 2.8: Comparison between bamboo fiber and glass fiber in several terms.

	Bamboo	Glass
Density	Low	Higher than bamboo fibre
Cost	Low	Higher than bamboo fibre
Disposal	Biodegradable	Non-biodegradable
CO_2 absorption	Yes	No
Recyclability	Yes	No
Renewability	Yes	No
Energy for extraction	Low	High

Source: Kushwaha et al. (2010); Phong et al. (2011); Trujillo et al. (2013)

According to Biswas et al. (2015), the bamboo fiber reinforced epoxy composite had higher tensile and flexural strength than jute reinforced epoxy composite. Table 2.9 and Table 2.10 display the comparison between jute and bamboo in terms of tensile and flexural strength. As the result, bamboo fiber has been selected as one of the most widely used natural fibers in fabricating composites.

Table 2.9: Tensile properties of jute and bamboo composites.

Name of the fiber	Tensile strength (MPa) ± STD	Young's modulus (GPa) ± STD	Stain to failure (%) ± STD
Jute (52 wt%)	216 ± 1.02	31 ± 1.34	0.78 ± 0.05
Bamboo (57 wt%)	392 ± 8.51	29 ± 1.25	1.38 ± 0.02

Source: Biswas et al. (2015)

Table 2.10: Flexural properties of jute and bamboo composites.

Fiber	Flexural strength (MPa) ± STD	Flexural modulus (GPa) ± STD
Jute (52 wt%)	158 ± 18.90	18 ± 1.92
Bamboo (57 wt%)	226 ± 25.13	19 ± 1.32

Source: Biswas et al. (2015)

Due to environment concerns, several natural fiber reinforced composites (NFRCs) have been selected and brought into the competitive market. Compared with synthetic fiber composites, NFRCs provide much more advantages compare to synthetic fibers including high strength to weight ratio, high temperature strength and high creep resistance and high toughness. NFRCs also show their advantages in light weight, high durability and design flexibility.

2.7.1 Hand lay-up method

Large group of polymeric composites are manufactured or fabricated by hand lay-up although the manufacturing processes have been undergoing technical changes and evolved with times. This was mainly due to its flexibility which allowed the manufacturing of a large variety of shapes and this method did not require extensive investments (Avila and Morais, 2005). The mechanical properties of the composite products are affected by the stacking influence, fiber volume ratio and cure process. Hand lay-up method can be separated into 4 stages: preparation of mould, gel coating, lay-up and curing. A layer of resin is firstly poured into a prepared mould, followed by the reinforcement (fiber). The laminating resin is then applied to the reinforcement by brushing or rolling to remove all the entrapped air. The steps are continued until desired thickness is achieved. The layered structure was left for the curing process where the heat is produced. An appropriate drying process of reinforcement in an oven was critical prior to resin wet out to prevent the problems of poor wetting and expel moisture entrapment in the composite. The additional resin might be needed to improve the impregnation and facilitate a better and smooth finish.

2.7.2 Fiber Volume Ratio

Fiber volume ratio is defined as the ratio of fiber used or fiber loading over the entire volume of a fiber-reinforced composite material. These composite materials are made up of natural fibers and polymer resins with different volume fractions. As the volume of fiber being used increases, there is a reduction in the amount of resin applied. Increasing in fiber loading leads to the increasing of mechanical strength of due to the high cellulose content. One benefit of natural fiber composite materials is that they are light in weight and able to possess adequate strength. By identifying the appropriate combination of resin matrix and fibers, a stiff and load bearing composite can be made that meets the basis requirements of certain application.

Several attempts have been carried out recently by researchers to study the impact of varying fiber volume fraction on the mechanical properties of the natural fiber composite products. According to Keck et al. (2016), the crack path in flax fiber reinforced composite materials was not only affected by stress state, but also the fiber direction and fiber volume fraction as well. The tensile strength increased with increasing fibre volume fraction as shown in Figure 2.2.

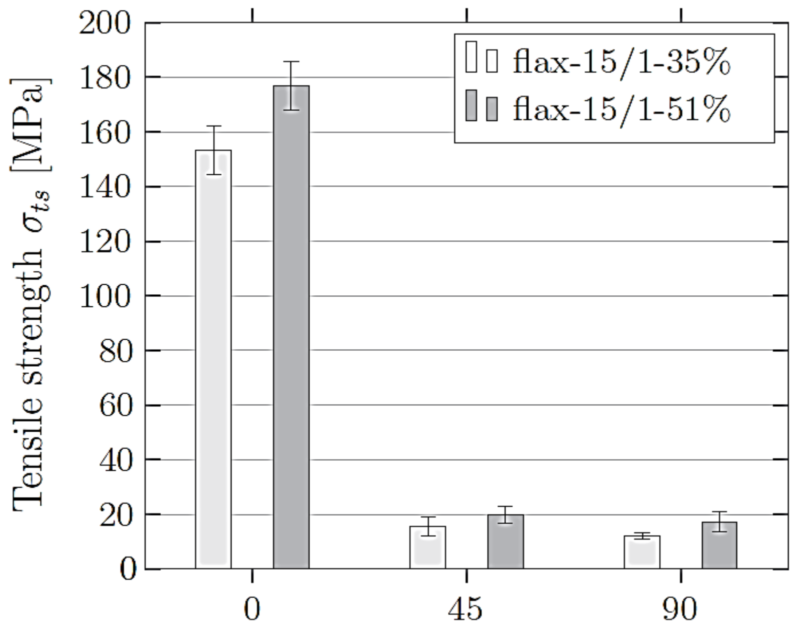


Figure 2.2: The relationship between tensile strength and fiber volume ratio.

Source: Keck et al. (2016)

Swapnil et al. (2017) investigated that fiber volume ratio of 50 % achieved better mechanical properties. Further increased in fiber content increased the mechanical strength but the composite started to delaminate. The best ratio for the fiber and resins was 50:50 which was better to achieve the optimum strength. Hemp fiber composite with fiber volume content of 40 % tended to increase the flexural strength by 193.24 % compare to pure matrix as displayed in Table 2.11 (Haghighatnia, Abbasian and Morshedian, 2017). Also, Senthil Kumar et al. (2014) figured out the best flexural strength of short banana fiber-polyester composite is obtained at fiber volume content of 40 %.

Table 2.11: Flexural properties of hemp fiber composites at different fiber contents.

Fiber content (%)	Flexural Strength (MPa)	Flexural Modulus (MPa)
0	7.55((± 0.05)[a]	156.78(± 13.30)
20	10.73(± 0.85)	217.93(± 28.04)
30	20.40(± 2.03)	554.85(± 138.90)
40	22.14(± 0.48)	586.83(± 7.03)

Source: Haghighatnia et al. (2017)

2.8 Mechanical Test on Fiber Composite

Mechanical analysis was carried out to determine a material`s mechanical properties and the respond of it towards the actions, load and force. All the samples were fabricated according to ASTM standard: ASTM D 790-03 and ASTM 3039 for flexural test and tensile test respectively.

2.8.1 Flexural Test

The flexural strength of fiber composites such as jute and pineapple leaf reinforced polyester and epoxy composites were determined from previous study. The variation of flexural strength of fiber composites varying fiber content is presented in Figure 2.3. The flexural strength increased with the increasing in fiber content in both polyester and epoxy matrix. The flexural strength of fiber reinforced epoxy composite was better than fiber polyester composite. With 0.42 volume fraction of fiber, the ultimate flexural strength of the polyester and epoxy composites recorded a high value of 232.85 MPa and 239.37 MPa respectively (Indra Reddy *et al.*, 2018).

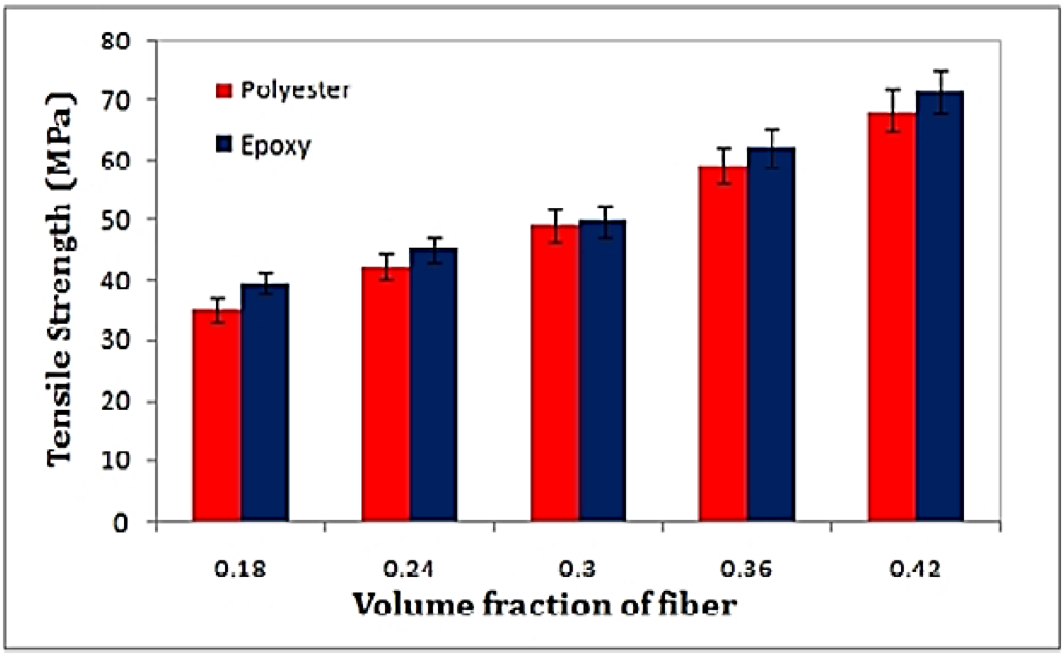


Figure 2.3: Flexural strength of polyester and epoxy composite varying fiber content.

Source: Indra Reddy et al. (2018)

Another research was carried out by preparing 5 samples with dimension of 100 mm long by 25 mm wide by 3 mm thick. By referring to ASTM D 790 M-86 test method I, procedure A, three-point bend tests were performed to measure flexural properties. The ultimate flexural strength and modulus of jowar fibre reinforced composites, along with sisal and bamboo composites at approximately 0.40 volume fraction of fibre, are presented in Table 2.12 for comparison (Ratna Prasad and Mohana Rao, 2011).

Table 2.12: Ultimate flexural strength of plain polyester and various fiber composite.

Name of the composite	Volume fraction of fibre	Ultimate flexural strength (MPa)	Flexural modulus (GPa)
Plain polyester	0.00	55.08	1.535
Jowar	0.407	134	7.87
Sisal	0.40	99.5	2.49
Bamboo	0.40	128.5	3.70

Source: Ratna Prasad et al. (2011)

2.8.2 Tensile Test

Tensile specimens with dimension 230 mm x 25 mm with thickness of 3 mm and 5 mm of test were prepared to perform tensile test in accordance with the ASTM D-3039 standard. Krishna Adhikari et al. (2017) found out that the tensile strength was increasing with the increase in volume fraction of fiber up to 15 %. The maximum value of tensile strength for 3 mm and 5 mm thick specimens at 15 % fiber loading were 25.21 MPa and 32.38 MPa respectively as plotted in Figure 2.4. The poor interfacial adhesion between fibers and matrix which exceeded 15 % fiber loading had caused the decreased in tensile strength. However, compared to 3 mm thick specimen, 5 mm specimen which had greater thickness showed higher strength due to better bonding of fibers and matrix.

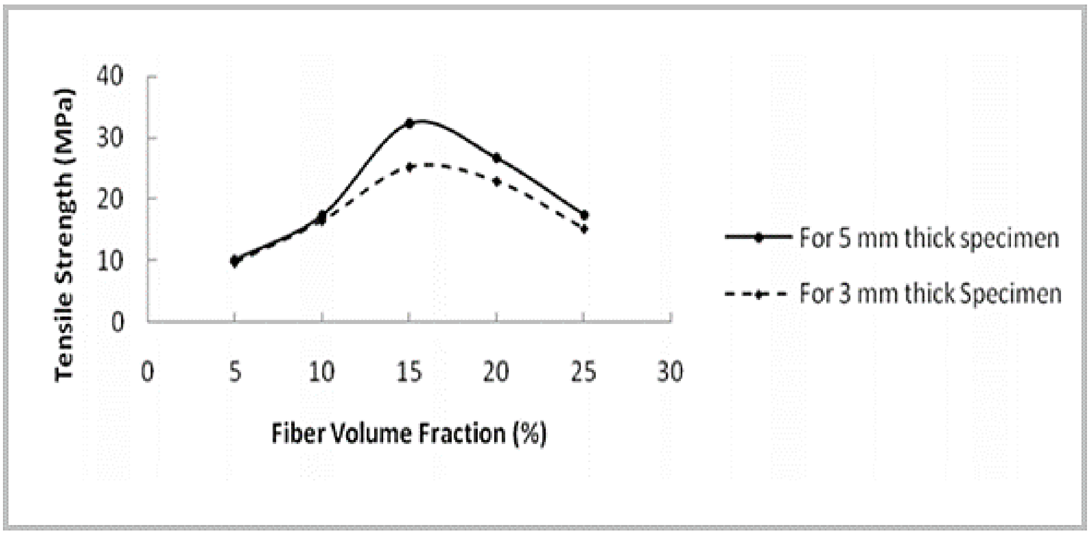


Figure 2.4: Tensile strength for various volume fraction of fiber.

Source: Krishna Adhikari et al. (2017)

Padmaraj et al. (2018) conducted the tensile tests as per ASTM D-3039 and maintained the specimens in dimension of 200mm x 25mm x 4mm. The tensile strengths versus stain data of coir, areca and hybrid composites are shown in Figure 2.5. All the fiber composites had similar tensile strength of 21.2 MPa, 19.83 MPa and 22.32 MPa for areca husk, coir and hybrid composite respectively. Tensile properties of the fiber composites mostly depended on the aspect ratio of fiber, distribution of fibers and bonding between the matrix and fibers.

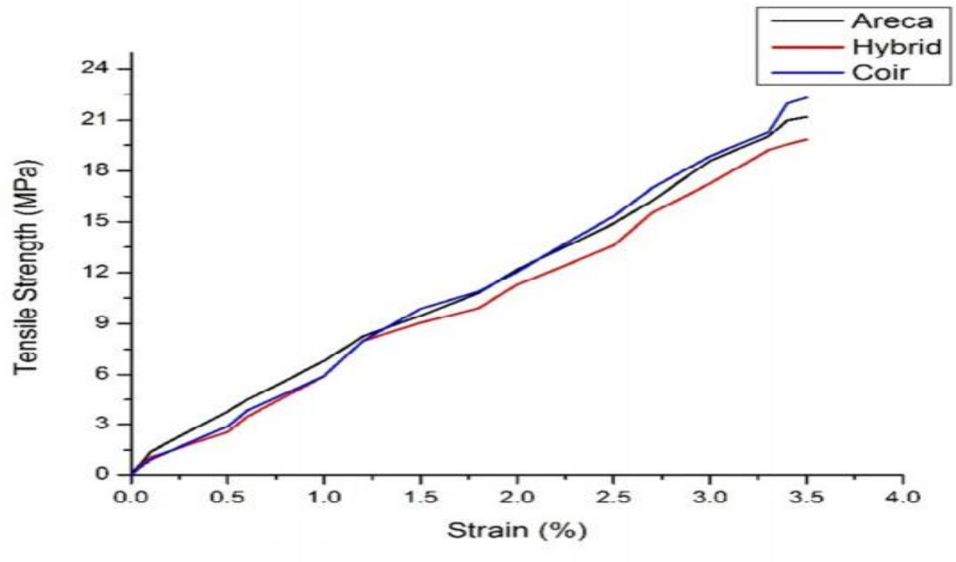


Figure 2.5: Stress vs Strain Graph of different composite materials.

Padmaraj et al. (2018)

2.9 RC Beams Strengthened Externally by NFRC

Natural fiber reinforced composites (NFRC) have many applications in external strengthening of reinforced concrete structures (Chin *et al.*, 2012). There are several types of fiber including the kenaf, jute, sisal, and bamboo which have been used in the fabrication of composites.

2.9.1 Sisal Fiber Reinforced Composite

Sen et al. (2014) had revealed that the potential of sisal fiber reinforced composite (SFRC) to replace with carbon fiber reinforced composite (CFRC) and glass fiber reinforced composite (GFRC). Sisal fiber was reacted with epoxy resin and hand lay-up method was used in the fabrication of composite plate. These fiber composites were applied on reinforced concrete beams to identify the optimum flexural strength. Ultimate bearing capacity, failure mode and behaviour of RC beams were identified as the SFRC, CFRP, GFRP were bonded externally to the beams at several configurations as shown in Figure 2.6. For fully wrapped SFRC, the strengthening effect of the reinforced concrete beams was significant, and it increased by 112.5 %. The ductile failure occurred with no concrete crushing and de-bonding at high loads. The ultimate load bearing capacity of beam when bounded with SFRP was the highest with value of 65.2 % compared to CFRP and GFRP, 50 % and 37.5 % respectively. SFRC has dominant over the carbon and glass fiber reinforced composite in term of flexural strength and load deflection behaviour. As sisal fiber is environment friendly, economic and high strength material, it can be used extensively as strengthening material for flexural properties of reinforced concrete structures.

Wrapping configuration	Strengthening material	Beam designation	Type of strengthening
Nil 	Nil	Control Specimen Con1, Con2	No Strengthening
Full wrapping 90°, single layer	Sisal FRP	SF1, SF2	Flexural Strengthening using sisal FRP
	Carbon FRP	CF1, CF2	Flexural Strengthening using carbon FRP
	Glass FRP	GF1, GF2	Flexural Strengthening using glass FRP
Strip wrapping 90°, single layer	Sisal FRP	SF3, SF4	Flexural Strengthening using sisal FRP
62 mm strips at 124 mm C/C (at a clear gap of 62 mm) so as to achieve 50% of total area strengthening, with end clear gap of 49 mm	Carbon FRP	CF3, CF4	Flexural Strengthening using carbon FRP
	Glass FRP	GF3, GF4	Flexural Strengthening using glass FRP

Figure 2.6: Summary for beam test strengthened by SFRC, CFRP and GFRP.

Source: Sen et al. (2014)

2.9.2 Kenaf Fiber Reinforced Composite

Alam et al. (2016) successfully developed a shear strengthening method for reinforced concrete beams by using kenaf fiber reinforced polymer laminate (KFRP). KFRP were fabricated using cold press hand lay-up method with epoxy resin and Sikadur 30 adhesive. Various fiber contents were used and 25 % of fiber content was the optimal mix ratio. Control beam, KFRP strengthened beam and carbon fiber reinforced polymer (CFRP) laminate strengthened beams were prepared for the shear test. The result showed that KFRP laminate strengthened beam failed by rupture of KFRP laminate then followed by shear which indicated that the full strength of the laminate contributed in shear strength of beam. However, CFRP failed in flexural shear then debonding of laminate. Premature shear failure was occurred in control beam. KFRP laminate strengthened beam had 33 %

and 2 % higher failure load that control beam and CFRP laminate strengthened beam respectively as shown in Figure 2.7. The high percentage of load bearing showed that KFRP laminate was able to enhance the shear capacity of beams through external strengthening by reducing the number and width of cracks in shear span.

Beam ID	Failure load (kN)	Increased load of strengthened beam over control (%)	Shear crack (kN)	Micro debonding started at (kN)	Strains of reinforcements at failure (micro)	
					Flexural reinforcement	Shear reinforcement
CB	137	–	45	–	2,771	5,390
KFRP	182	33	90	138	3,644	2,194
CFRP	184	35	90	145	4,042	1,696

Figure 2.7: Experiment results for control beam, KFRP laminate strengthened beam and CFRP laminate strengthened beam.

Source: (Alam, Hassan and Muda, 2016)

2.9.3 Bamboo Fiber Reinforced Composite Plate

Lim (2017) had investigated the used of bamboo fiber vinyl ester-reinforced composite plate (BFRCP) in external strengthening of reinforced concrete beams. BFRCPs were fabricated using hand lay-up method and different volume ratio in the range of 10 % to 40 %. Four-point loading system was carried out to analyse the ultimate load, deflection, crack patterns and failure type in different beam conditions. For the RC beams without openings, application of BFRCPs had increased the ultimate load for about 2 % compared to the one without any strengthening. This indicates that BFRCP was able to improve the strength of the beam to carry higher load. In term of ultimate load for cracking to occur, the first crack happened at load about 50 kN for unstrengthen beam while cracks were formed at load 52 kN in the beams strengthening with BFRCP.

2.10 Summary

There were a lot of assessments on the mechanical properties such as tensile and flexural strength of natural fiber reinforced composite based on past researchers. However, there is lack of information and experiment procedures using bamboo fiber reinforced composites for external strengthening of RC beams. Hence, there is a need to study the potential of bamboo fibers as alternative in external strengthening material on RC beams.

Although, a significant number of research works have been conducted to develop composite plates using natural fibres for automotive industry, however, fabrication of high strength bamboo fibre-based composite plates for flexural strengthening of reinforced concrete structure is lacking. Moreover, research to develop natural fibre non-biodegradable composites for strengthening application is still at infancy stage. The objectives of this research are to determine the mechanical strength of bamboo specimens through compression and tensile test. Fabrication of high strength bamboo fiber composite plates (BFCP) was conducted and tested under flexural and tensile tests. BFCP was then applied on flexural zone of reinforced concrete (RC) beams to study the structural behaviour of RC beams under load deflection, crack pattern and failure mode.

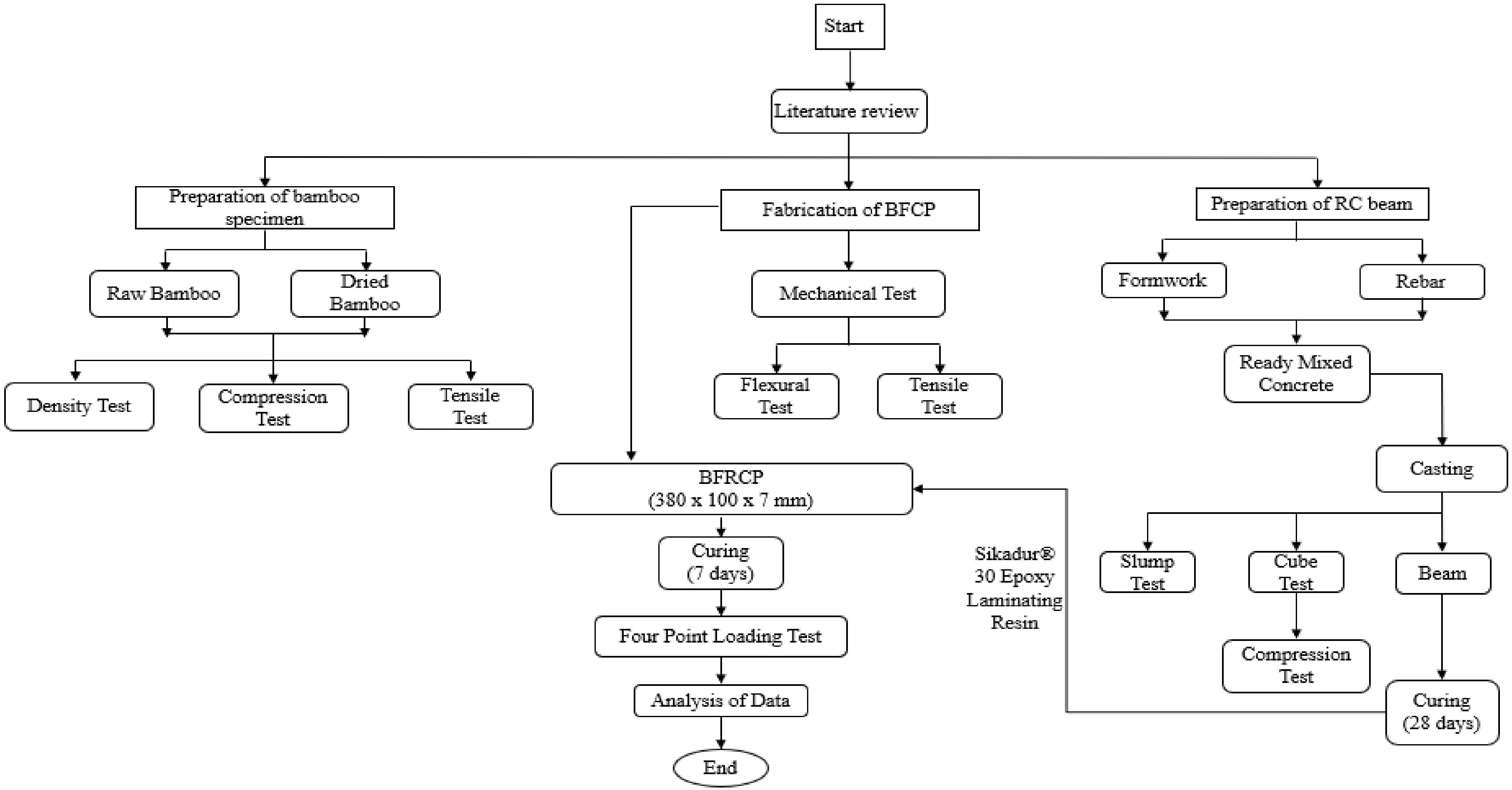
CHAPTER 3

METHODOLOGY

3.1 Introduction

This chapter outlines the procedures for preparing bamboo specimens to conduct compression and tensile test. Preparation of bamboo fiber composite plate (BFCP) which including the bamboo fiber extraction, treatment, surface modification method and reinforced with epoxy resin was another set of experimental work. The composite plates were produced by hand lay-up method then they were tested for tensile and flexural strength. The application of BFCP as external strengthening material on RC beams and the behaviour of RC beams in term load deflection, crack pattern and failure mode were determined.

3.2 Research Methodology



3.3 Preparation of Materials

All the materials used are listed in this section. The procedures of material preparation and functions of each material are described in detail.

3.3.1 Bamboo specimen

The type of bamboo that was chosen in this study was bamboo species Betung with the scientific name *Dendrocalamus asper*. Raw bamboo culms with the age of between 2-3 years old were harvested by labours from the tropical forest in Raub, Pahang. Six hollow bamboo culms each with the length of 300 mm were prepared. All the specimens were prepared with 1 node only and there was no cracking on the specimen prior compression test. The ends of the both side of the bamboo culm were filed to ensure a smooth surface for compression. Another six bamboo splints were taken from different portions of bamboo culm after splitting by using a bamboo splitter. All the specimens were cut into 600 mm and only one node was present in each sample. The bamboo specimens were then further divided into two groups whereby three of them are oven-dried for 24 hours and the remaining were kept as raw sample. Measurements were made on the outer and inner diameter of raw bamboo specimens including the thickness and weight of each sample. The procedures were repeated for dried bamboo sample.

Figure 3.1: Raw bamboos (Betung species) were harvested from Raub, Pahang.

3.3.2 Bamboo Fiber

The fiber extraction process involved with both the chemical and mechanical method. Heavy-duty bamboo splitter with 10 ways was used to cleave the raw bamboo into longitudinal strips. The nodal parts were then cut and removed. The bamboo fibers were dried and treated with 10 % of sodium hydroxide (NaOH) for about 48 hours to break down the lignin content. The soften bamboo strips were washed with distilled water to remove the alkali content. Later, they were dried under the sun to remove excess moisture contents before passing through the mill roller machine to obtain monofilaments fibers. The processed bamboo fibers were rinsed with distilled water to eliminate the alkaline content and any impurities. Individual bamboo fibers were obtained and washed thoroughly until a pH value in the range of 5-6 was obtained. The neutral bamboo fibers were then dried in an oven with controlled temperature of 60 °C for 24 hours. Manual separation method was used to obtain finer individual fibers to avoid any voids during fabrication process. The dried bamboo fibers were then placed into a vacuum desiccator for 24 hours.

Figure 3.2: The nodal part was removed to ease the extraction of fiber.

Figure 3.3: Mill rolling was used for extraction of bamboo fiber.

3.3.3 Thermosetting Matrix

The thermosetting polymer used in the fabrication of composite plate consisted of two parts: Part A, epoxy (D.E.R. 331) and Part B (Jointmine 905-3S). Epoxy is a water-white or yellow polymer resin used to improve the chemical resistance and thermal stability of materials or composites. It has a density of 1.16 g/cm^3 at 25 °C. Part B, Jointmine 905-3S functions as a harder to enhance the abrasion, moisture and chemical resistance after curing. It is a transparent liquid with a density of 1.03 ± 0.03 g/cm^3. Both epoxy resin (D.E.R. 331) and hardener (Jointmine 905-3S) were mixed thoroughly by a ratio of 2:1 (based on fiber volume ratio) for 5 minutes.

3.4 Testing of Bamboo Specimen

Several tests had been carried out to determine the mechanical properties of bamboo (Betung species) and its composite samples through fabrication of bamboo fiber composite plate (BFCP). BFCP`s potential to be used as strengthening material in RC structures was determined through four-point loading test.

3.4.1 Density Test

Test specimens were prepared by choosing the different positions of the bamboo culm including base, middle and top. Then, they were cut into dimension of 25 x 25 mm in length and width with full wall thickness. Water displacement method was used to measure the green volume (V) of the bamboo specimen individually. All the test specimens were oven-dried for 24 hours at 100 °C to obtain the oven dry mass (m). The densitiy (mass per volume) of the all the bamboo specimens was calculated and the average reading was obtained.

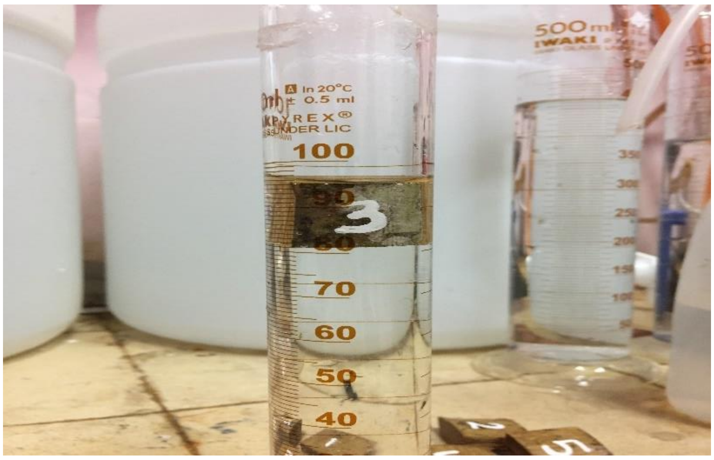


Figure 3.4: Water displacement method was used in density test.

3.4.2 Compression Test

The compression test was carried on hollow bamboo culms with one node to determine the compressive strength of the single bamboo specimen. Both the oven-dried and raw bamboo samples that prepared in length of 300 mm were tested individually by using Universal Testing Machine (UTM). Compressive load with a constant loading rate of 0.05kN/sec is applied on the cross section of all specimens. The failure mode of the bamboo specimen was observed.

Figure 3.5: Compression test was conducted on hollow bamboo specimen.

3.4.3 Tensile Test

The tensile test was conducted on bamboo splints with one node to determine the ultimate strength. All the oven-dried and raw samples with the length of 600 mm and width of approximately 20 mm were prepared. Tensile load was applied on the cross section of all the specimens individually with a strain rate of 0.06 mm/min.

Figure 3.6: The bamboo splint was fixed to UTM equipment for tensile test.

3.5 Fabrication of Bamboo Fiber Composite Plate (BFCP)

In the fabrication of composite plate, treated bamboo fiber with adequate amount of epoxy resin were prepared. Hand lay-up method was used, and it was carried out at room temperature. The dimension of BFCP was specified by the size of stainless steel mould used. For tensile test, size of 25 x 250 mm, and a thickness of 5 mm mould was being used. On the other hand, the dimension of flexural specimen was 127 mm in length, 12.7 mm in width and 6 mm in thickness. To apply the BFCP on RC beam, larger composite plates with dimension of 100 x 380 mm and thickness of 7 mm were casted.

The exact amount of epoxy resin and fiber loading that being used were calculated by using a fiber volume ratio of 40 %. Before the fabrication of BFCP, a layer of mould releasing agent (honey wax) was placed around the mould. Also, a Teflon paper was put underneath the base of the mould. These steps aimed to minimize the adhesion between the composite plate and the mould and allowed easy disassembly. Thin films of polymer resins and bamboo fibers were arranged layer by layer uniformly according to sequences. The process started with pouring a thin layer of epoxy resin into the steel mould then followed by fine bamboo fibers in unidirectional. Then, second layer of resin was placed, and it formed interfacial bonding with previous bamboo fiber layer. Again, another layer of bamboo fibers were placed on the previous layer and arranged neatly. The steps were repeated until it reached the thickness of BFCP required for each test as mentioned above. To obtain a smooth surface and remove any unnecessary air bubbles formed inside the voids of plate, the top part of the mould was compressed during curing process. It was then cured at room temperature for 24 hours to promote the resin and fiber`s cross linking. For post curing, fabricated BFCP plate will be placed in oven with temperature of 110°C for 4 hours followed by placing in desiccator for 24 hours before testing. All the procedures were repeated for the fabrication of pure epoxy samples without fiber loading.

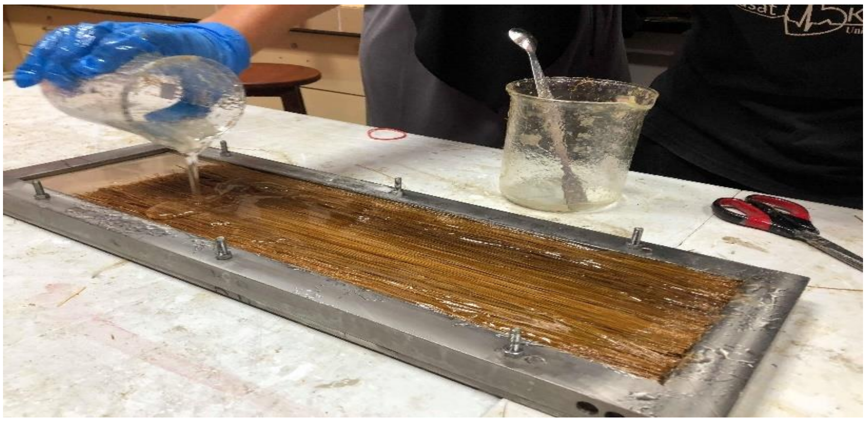


Figure 3.7: Hand lay-up method was used for the fabrication of BFCP.

Figure 3.8: BFCP samples.

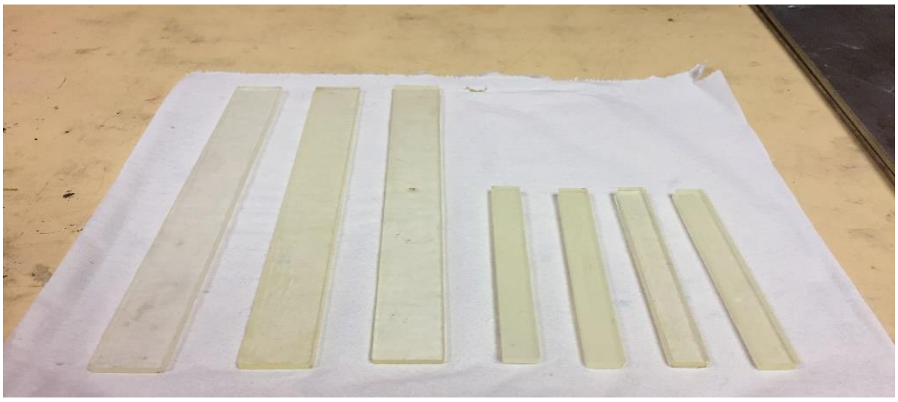


Figure 3.9: Pure epoxy samples.

Figure 3.10: BFCPs with larger dimenison were prepared to be applied on RC beams.

3.6 Testing of BFCP

In this section, mechanical tests such as flexural and tensile test were conducted to determine the mechanical properties of bamboo fiber reinforced composite plate (BFCP).

3.6.1 Tensile Test

Tensile test was performed according to ASTM D-3039 standard by Universal Testing Machine Equipment (UTM). Neat epoxy and BFCP specimens with dimension of 250 mm, 25 mm, and 5 mm in length, width and thickness respectively were prepared. The tensile specimen was positioned vertically in the grips of tensile machine. Uniaxial loads were applied through both ends of the specimen with test speed of 5 mm/min. The test stopped until the samples fractured, and the ultimate tensile strength was recorded. The steps were repeated for three samples and the stress-strain graph is plotted.

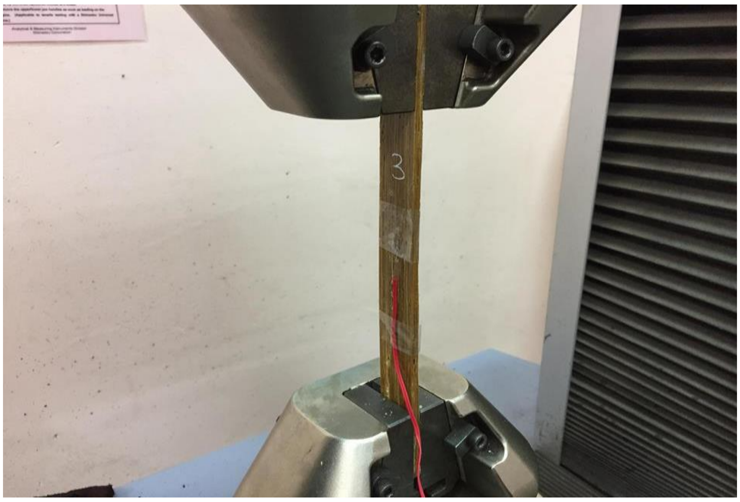


Figure 3.11: Tensile test for BFCP.

3.6.2 Flexural Test

The neat epoxy and bamboo fiber reinforced composite (BFRC) plates were prepared in the dimension of 127 mm in length, 12.7 mm in width and 6 mm in thickness. The specimens were tested under the ASTM D790-03 test method I, procedure A. The specimen was supported at a distance of 10 mm away from the edge of its ends. UTM was used to carry out the three-point bending test with the strain rate of 5 mm/min.

Figure 3.12: Flexural test for neat epoxy specimen.

3.7 Reinforced Concrete Beam Casting

A total of seven reinforced concrete (RC) beams were prepared and the beams are grouped into three categories: controlled solid beam (CB), un-strengthened beam (UST-B) and bamboo fiber composite plate (BFCP) strengthened beam (ST-B). The preparation work and beam casting were carried out at Concrete Laboratory, Faculty of Civil Engineering (FKASA).

3.7.1 Erection of Formwork

In the preparation of formwork for beam, 25.4 x 50.8 mm timber and plywood were used. Silicone was applied on the formwork to prevent leakage during concrete casting. All the beams were casted simultaneously with the dimension of 100 x 130 mm and length of 1600 mm. Lubricant oil was applied on the inner surface of the formwork to ease the demoulding of formwork after curing.

Figure 3.13: Silicone gun was used to seal up gaps inside the formwork.

3.7.2 Reinforcement Bar

All the RC beams had the same design of steel reinforcement at compression and tension area. Main longitudinal bar used was 10 mm in diameter with cross section area of 78.5 mm^2 while the shear link had a diameter of 6 mm and cross section of 28.3 mm^2. The shear links were placed with the spacing of 300 mm from center to center along the beam length. For the un-strengthened beam, the shear link at the midspan was removed to study the performance of BFCP in external strengthening of RC beams. The longitudinal steel bars were tied up with shear link at intersection points to form a reinforcement cage. Concrete spaces were casted and tied around the rebar to ensure the casted beam had a concrete cover of 25 mm and prevent the steel reinforcement from corrosion.

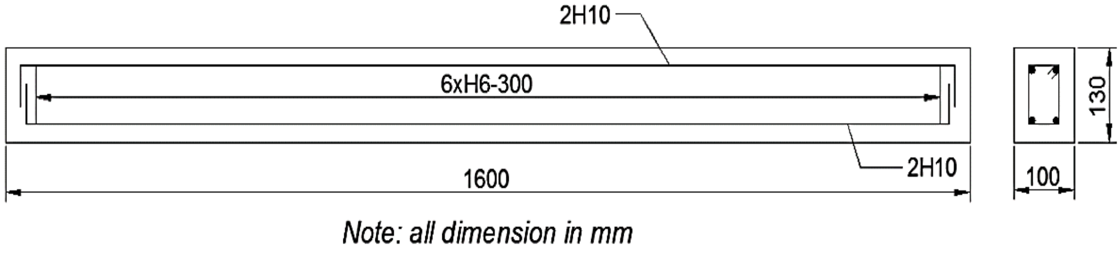


Figure 3.14: Illustration of rebar in solid control beam (CB).

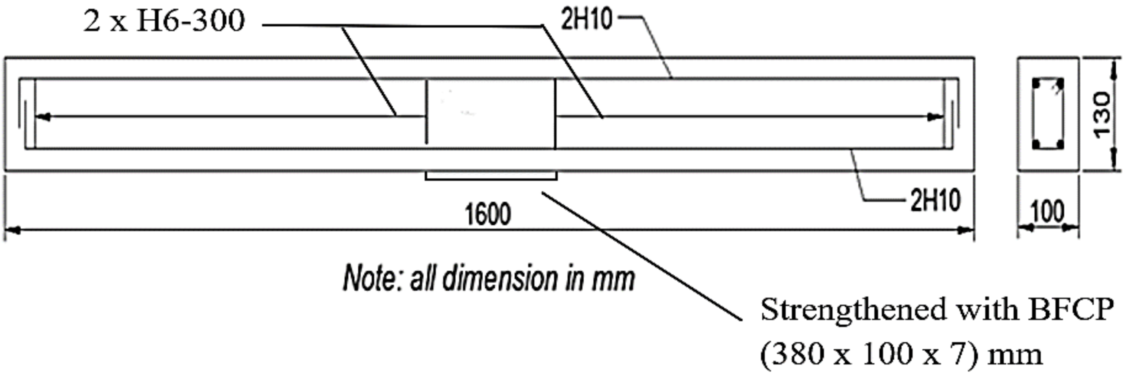


Figure 3.15: Illustration of rebar in BFCP strengthened beam (ST-B).

Figure 3.16: Spacer blocks were tied with the rebar.

3.7.3 Concrete

Ready-mixed concrete was considered in this study to ensure concrete homogeneity. A designed strength of 30 N/mm^2 was used and supplied by PAMIX Sdn. Bhd. It was designed with water cement ratio of 0.5, and the allowable slump test measurement was 75 ± 25 mm.

Figure 3.17: Ready-mixed concrete was supplied by PAMIX Sdn. Bhd.

3.7.4 Beam Casting and Curing

All necessary checking must be conducted especially during formwork preparation. The formwork should be cleaned, rigid and there was no gap or holes around the formwork. Slump test was performed to measure the workability of the concrete. Nine cubes with dimension of 150 x 150 x 150 mm were prepared for cube test. All the beams were casted simultaneously and vibrated properly with the aid of vibrator poker to prevent honeycomb. Over vibrating should be avoided by placing in the vibrator for about 5-30 seconds. Formworks for beam were dismantled after 24 hours. To promote the curing, wet gunny bags were placed on the beam surface and wetted periodically. The process was continued for 28 days to achieve the ultimate strength. The nine cubes were demoulded and placed in water tank for curing. The beam surface was painted and marked with consistent gridline. On the other hand, the compression test for the cubes was carried out after 3, 7, 14 and 28 days, with 3 cubes in each stage.

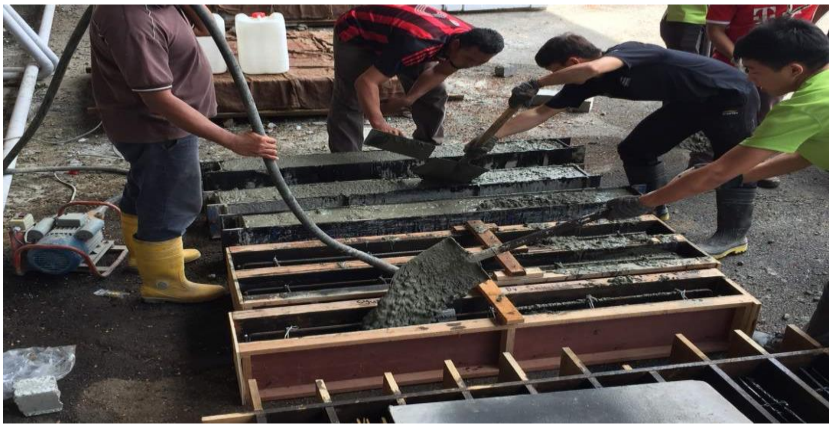


Figure 3.18: All the beams were casted simultaneously.

Figure 3.19: Concrete cubes were prepared.

3.8 BFCP Strengthening System

3.8.1 Sikadur® 30 Adhesive

Sikadur®-30 was used to bind the bamboo fiber composite plate (BFCP) to RC beams. It was made up of two components: Part A white resin and Part B black hardener. It was selected due to its ability to provide strong adhesion between two materials, and high mechanical properties. It can be easily mixed and handled by trowel. The ratio of resin to hardener in Sikadur®-30 was 3:1. They must be mixed properly until a uniform light grey colour mixture was formed within 70 minutes pot life. The pot life would be longer at low temperature and shorter at high temperature. The curing process went for seven days to achieve the strongest binding. It must be protected from rain for at least 24 hours after application.

Figure 3.20: Sikadur®-30 epoxy laminating resin consisted of two parts: Part A white resin and Part B black hardener.

3.8.2 Strengthening Configuration

The surface at the bottom soffit of the RC beams were roughed and cleaned with air blower to remove the dirt and impurities. This aimed to improve the interaction and bonding between the concrete surface and BFCP with dimension of 380 x 100 mm in length and width and thickness of 7 mm. The well mixed Sikadur® 30 was applied to the roughed surface and one side of BFCP. To strengthen the flexural zone, the BFCP was placed at distance of 610 mm away from the beam end. BFCP was pressed out uniformly from the middle to sides to ensure that all the resins are evenly distributed on the surface between the concrete and composite plate. All the apparatus was cleaned with thinner immediately to prevent hardening of resin. After curing the beam specimens for 7 days, they were ready for four-point loading test.

Figure 3.21: The surface of beam was roughed before installation of BFCP.

Figure 3.22: BFCPs were attached to the RC beams.

3.9 Laboratory Testing

3.9.1 Slump Test

Slump test was conducted according to BS EN 12350: Part 2 (2009). The workability and consistency of concrete were determined from this simple test. Common tools involved were slump cone, base pate and tamping rod.

3.9.2 Compression Test

Compression test was carried out following the BS 1881: Part 116 (1983) standard. The 9 cubes were removed from curing water tank after 3, 7,14 and 28 days, each time with 3 cubes. The specimens were subjected to compression until failure. The ultimate load which they can sustain was recorded.

Figure 3.23: Compression test for one of the cubes after curing for 7 days.

3.9.3 Four Point Loading Test

Four-point loading test was conducted on the solid control beam as well as both the unstrengthen and strengthened with BFCP. RC beams were supported by two support points and two-point loads were applied vertically downward until the beams failure. The beam was simply supported at both ends, 100 mm from the edge of the beams and it has effective length of 1400 mm. Two concentrated loads were acting vertically downwards on the beam and they were 400 mm away from the supports. The distance between the two-point loads were 200 mm. Linear variable displacement transducers (LVDTs) were installed at the bottom of the beam (mid-span) to measure the deflection of the beam. The crack patterns were observed, and the failure mode was determined. All the results of unstrengthen and strengthened beams with BFCP were compared with the solid control beam.

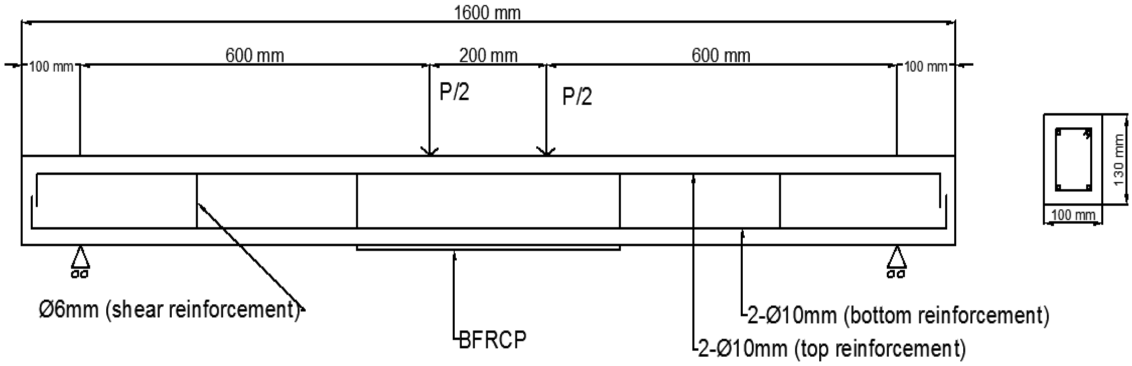


Figure 3.24: Schematic diagram for four-point loading test.

Figure 3.25: The setting of four-point bending test for control beam.

3.10 Summary

Table 3.1: Summary of tests involved with bamboo specimen, bamboo fiber composite plate (BFCP) and beam specimens.

Sample	Condition	Experimental Test	Standard
Bamboo Specimen	Raw, dried	Compression Tensile	- -
Bamboo Fibre Composite Plate	Pure epoxy, 40% fibre-volume-ratio	Tensile Flexural	ASTM D-3039 ASTM D 790
Beam Specimen	CB UST-B ST-B	4-Point Loading	-

Table 3.2: Summary for beams specimens.

Beam Specimen	Beam Dimension (B x H x L) mm	Flexural zone
CB 1	100 x 130 x 1600	Solid controlled beam
CB 2	100 x 130 x 1600	
CB 3	100 x 130 x 1600	
UST-B1	100 x 130 x 1600	Unstrengthen
UST-B2	100 x 130 x 1600	Unstrengthen
ST-B1	100 x 130 x 1600	BFCP-strengthened
ST-B2	100 x 130 x 1600	BFCP-strengthened

CHAPTER 4

RESULTS AND DISCUSSION

4.1 Introduction

In this part, all the results obtained from the experimental works and laboratory testing were analysed and interpreted. The scope of work included the mechanical test of raw and dried bamboo specimens, behaviour of bamboo fiber composite plate (BFCP) under mechanical tests and the strengthening effect of BFCP on the RC beams in flexure under four-points loading test.

4.2 Density Test

Density test was carried out to determine the density of bamboo (Betung species) since different bamboo species have different density. Density for five bamboo samples was calculated individually. Due to the inconsistency of the bamboo culm thickness, the bamboo specimens had small variation in their weight and volume. The density of bamboo was in the range of 0.7 to 0.86 g/cm^3 and an average value of 0.807 g/cm^3 was obtained.

Table 4.1: The density for five specimens of bamboo culms.

Specimen	Initial Weight (g)	Oven-dried Weight (g)	Volume, V (cm^3)	Density (g/cm^3)
1	5.78	4.92	7	0.703
2	6.00	5.14	6	0.857
3	5.89	4.98	6	0.830
4	5.74	4.90	6	0.817
5	5.83	4.97	6	0.828
			Average	0.807

4.3 Mechanical Test

Slump test and compressive strength for ready-mixed concrete were determined. Also, raw and dried bamboo specimens were prepared for compression test and tensile test. Mechanical behaviour of bamboo fiber composite plates (BFCPs) were determined in terms of flexural and tensile strength. Four-points loading test was conducted to examine the application of BFCP on the RC structures as external strengthening material.

4.3.1 Fresh and Hardened Properties of Concrete

To determine the workability of fresh ready-mixed concrete and the design strength after completing curing, slump test and compression test were performed.

4.3.1.1 Slump Test

From the observation of the slump test result in Figure 4.1, it was a shear slump with the value of 130 mm. This indicates that the water-cement ratio was too high where the ready-mixed concrete was too wet and had high workability.

Figure 4.1: Shear slump was observed during slump test.

4.3.1.2 Compression Test

The compressive strength of concrete was determined for curing period of 3, 7, 14 and 28 days. This main purpose was to ensure that the concrete design mix achieved the minimum targeted strength of 30 MPa. The mean compressive strengths of the concrete cubes were 10.84 MPa, 25.54 MPa, 30.21 MPa and 31.88 MPa for 3, 7, 14 and 28 days respectively as listed in Table 4.2. The result shows that the compressive strength of 31.88 MPa recorded at 28 days was satisfactory.

Table 4.2: Compressive strength of concrete cube.

Day	No. of sample	Compressive Strength (MPa)	Average Compressive Strength (MPa)
3	1 2 3	11.35 10.74 10.44	10.84
7	1 2 3	25.00 25.18 26.43	25.54
14	1 2 3	30.21 29.44 30.98	30.21
28	1 2 3	32.26 30.53 32.84	31.88

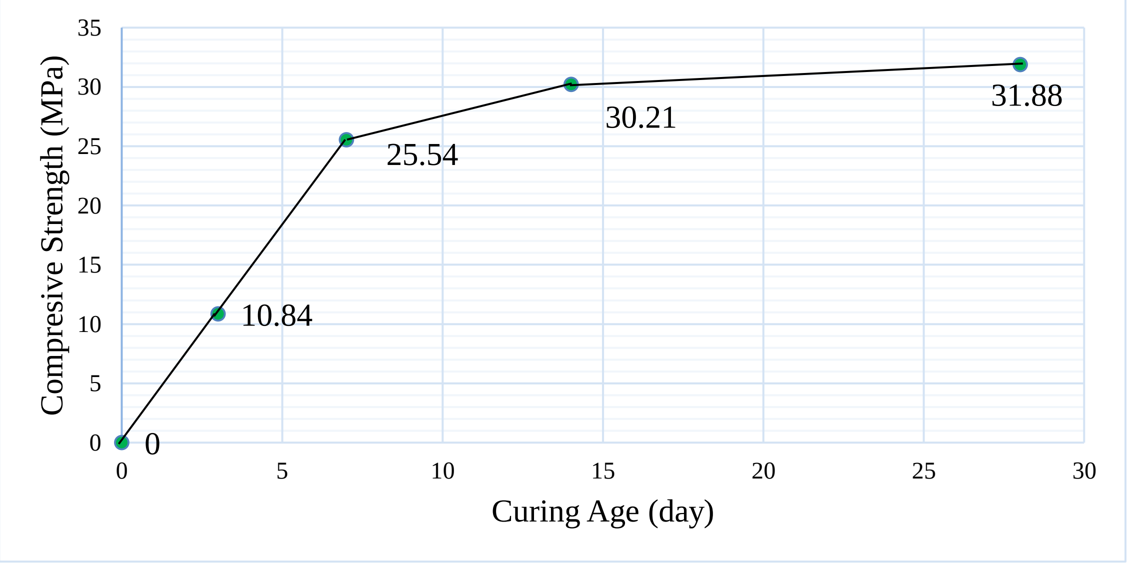


Figure 4.2: Graph of compressive strength of concrete against sample age.

From the beginning of the curing process until day 7, the compressive strength of the cubes increased rapidly which is displayed by the steep slope of the graph. High early strength of the cubes had been achieved within one week with the compressive strength of 25.54 MPa. The average compressive strength gradually increased until it met the required strength which was 30 MPa. The graph had reached a peak of 31.88 MPa after 28 days therefore all the casted concrete beams were in satisfactory condition with desired characteristics.

4.3.2 Bamboo Specimen

Mechanical properties of bamboo specimens were determined under compression test and tensile test. The compressive strength and tensile strength of bamboo specimens were identified by using Universal Testing Machine (UTM). All the results of the mechanical testing on raw and dried bamboo specimens were analysed.

4.3.2.1 Compressive Strength for bamboo culms

Compression test was conducted to determine the compressive strength of hollow bamboo culms with one node. Table 4.3 shows the dimension of raw and dried bamboo specimens that prepared for compression test. There was a small difference in the thickness, diameter as well as the cross-sectional area of each bamboo samples. This was mainly due to the inconsistency in diameter and thickness of the selected bamboo that between the age of 2-3 years old. According to Gupta et al. (2015), the compressive strength of bamboo specimen with internode had been found to be higher than that samples without internode. Present of internode contributed to the dense mass at node and additional cross-sectional which turned the bamboo wall thicker at both sides. Therefore, all the tested bamboo specimens had one node present on them. Under constant loading rate of 0.05 kN/sec, bamboo under compression was seen to fail in two patterns: cracking and crushing of fibers, as shown in Figure 4.3 and Figure 4.4 respectively.

Table 4.3: Dimension for raw and dried bamboo specimen.

Condition	Sample	Gauge length (mm)	Thickness (mm)	Outer diameter (mm)	Cross Sectional Area (mm^2)
Raw	1	301	13.73	99.74	3710.442
	2	300	13.21	101.98	3684.472
	3	300	14.15	102.31	3919.532
Dried	1	300	15.24	101.11	4111.806
	2	303	11.47	85.01	2650.289
	3	299	14.15	98.87	3766.592

Figure 4.3: Cracking of bamboo fibers.

Figure 4.4: Crushing of bamboo fibers.

From the compression test, the raw bamboo specimens can sustain slightly lower loading than dried bamboo specimens as shown in Table 4.4. The strength of untreated or raw bamboo specimens contributed to peak load of 187.22 kN followed by 179.03 kN and 165.18 kN. An improvement in the resistance towards compression was observed in dried bamboo specimens. The ultimate load of this category reached the values of 244.94 kN followed by 185.04 kN and 158.38 kN as shown in Figure 4.5. While measuring in term of stress, the ultimate compressive strength of raw bamboo groups reached the peak values of 44.52 MPa, 45.68 MPa and 50.81 MPa. The compressive strength increased and achieved 49.13 MPa, 59.57 MPa and 59.76 MPa in dried bamboo groups.

Table 4.4: Summary for load and compressive strength.

Condition	Sample	Load (kN)	Ultimate Compressive Strength (MPa)	Average Compressive Strength (MPa)
Raw	1	165.18	44.52	47.00
	2	187.22	50.81	
	3	179.03	45.68	
Dried	1	244.94	59.57	56.15
	2	158.38	59.76	
	3	185.04	49.13	

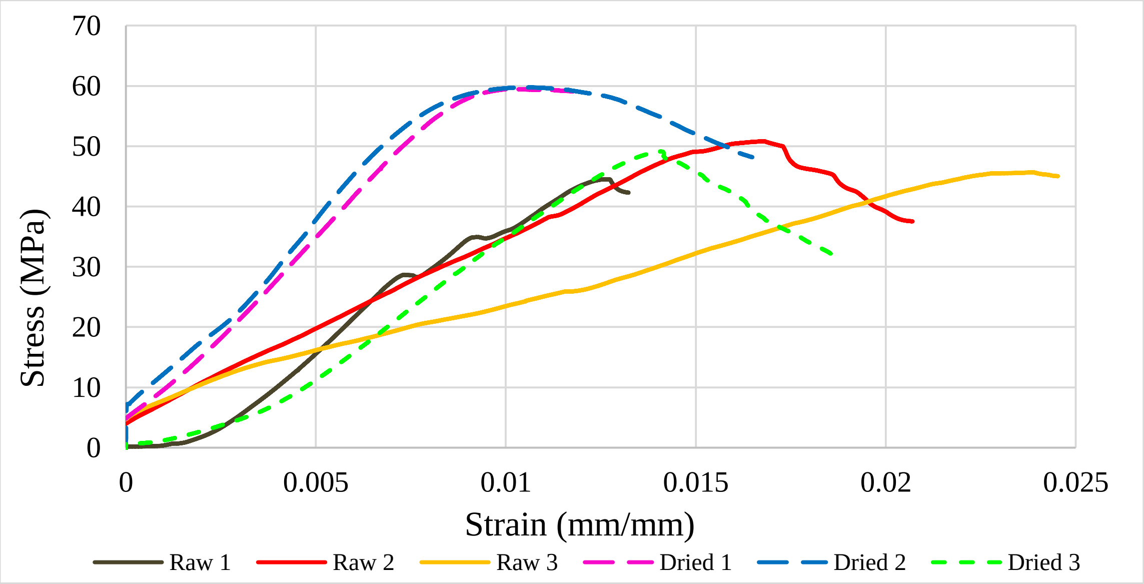


Figure 4.5: Graph of stress versus strain for the raw and dried bamboo specimen.

From Table 4.4, dried bamboo specimen showed higher average compressive strength of 56.15 MPa compared to raw bamboo specimens which is 47 MPa. The difference between the ultimate compressive strength of two bamboo groups is 9.15 MPa, which is 19.5 % of the ultimate strength in raw bamboo group. The possible reason is the oven dried bamboo specimens tended to be harder and stiffer while the raw bamboo specimens are brittle with the present of moisture content. The void that existing in the raw bamboo specimen reduced the cohesion and bonds between the fiber matrix, thus the load bearing capacity also decreases.

4.3.2.2 Tensile Strength for bamboo splints

Tensile test was carried out on bamboo splints to identify the ultimate tensile strength of bamboo. The dimension for the raw and dried bamboo samples including the cross-sectional area are listed in Table 4.5. Figure 4.6 shows that all the bamboo specimens had shown failure at the middle node, where it was the most critical section under tensile stresses. This was due to the high stress concentration at the node area when there was a change of boundary. In addition, there was only fine granules of wood present at the node instead of fibers where the node serves as the starting and terminating point of fibers.

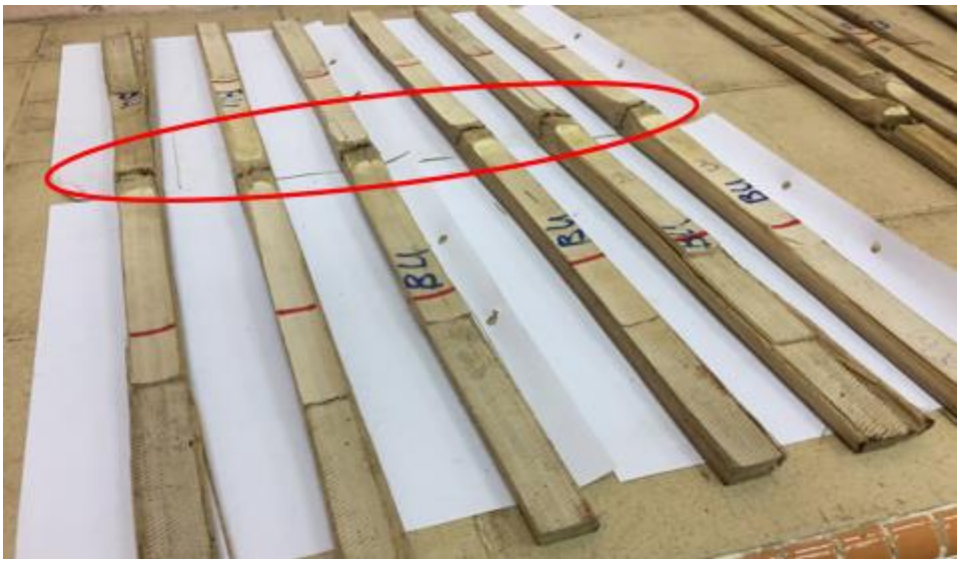


Figure 4.6: Failure of bamboo splints at middle node under tensile load.

Table 4.5: Dimension of raw and dried bamboo splints for tensile test.

Condition	Sample	Gauge length (mm)	Thickness (mm)	Width (mm)	Cross Sectional Area (mm^2)
Raw	1	300	14.35	22.12	317.422
	2	300	14.97	22.29	333.681
	3	300	14.29	21.05	300.805
Dried	1	300	14.07	19.58	275.491
	2	300	14.29	21.05	300.805
	3	300	14.03	22.39	314.132

The graph of stress versus strain curve under tensile test was plotted for all the specimens is shown in Figure 4.7. The tensile stresses of the raw bamboo splints achieved the peak value of 145.90 MPa, 143.44 MPa and 129.84 MPa for each sample. On the other hand, the dried bamboo splints showed lower tensile strength where the ultimate allowable tensile stress is only 109.96 MPa followed by 97.38 MPa and 81.53 MPa. Table 4.6 summarizes the average ultimate tensile strength of raw and dried bamboo splints. From the analysis, the raw bamboo specimen had higher average ultimate tensile strength which was 139.73 MPa compared to 96.29 MPa in dried bamboo specimens. In dried specimens, there was a reduction of 43.44 MPa or about 45 % of the total average tensile strength in raw bamboo specimen. Bamboo specimens that subjected to heat or elevated temperature can be resulted in degradation of lignin and hemicelluloses of bamboo specimens. Hence, the reduction of strength is mainly caused by the alteration of the matrix layer inside the dried bamboo specimens.

Table 4.6: Comparison of tensile strength between raw and dried bamboo specimens.

Condition	Sample	Ultimate Tensile Strength (MPa)	Average Ultimate Tensile Strength (MPa)
Raw	1	129.84	139.73
	2	145.90	
	3	143.44	
Dried	1	97.38	96.29
	2	109.96	
	3	81.53	

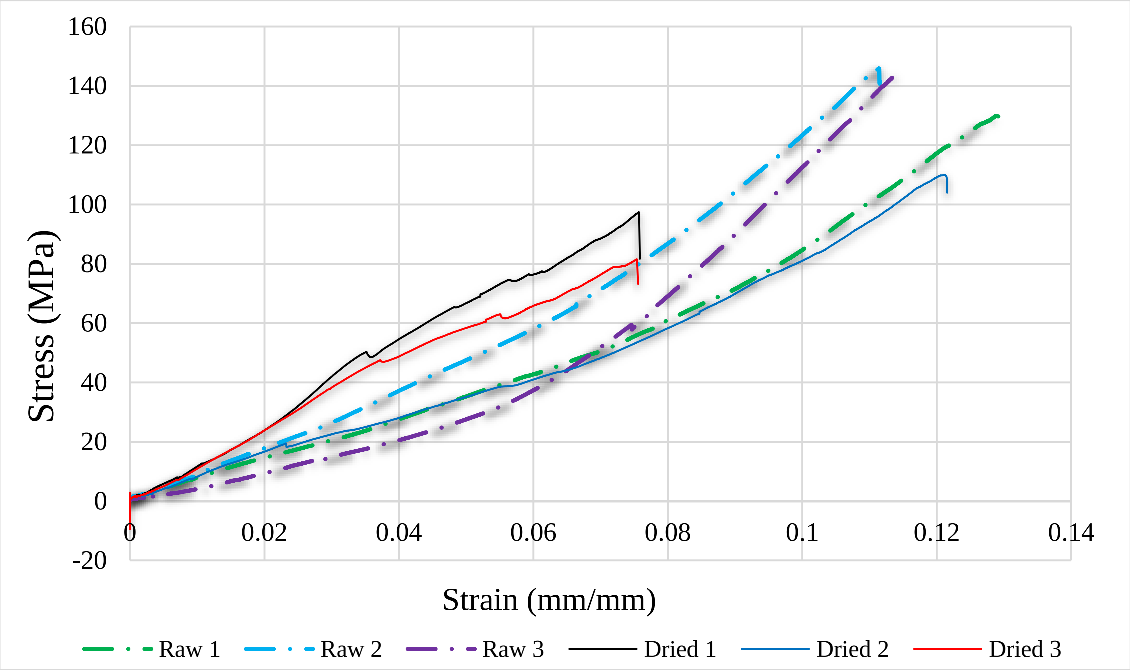


Figure 4.7: Graph of stress versus strain under tensile test.

4.3.3 Bamboo Fiber Composite Plate (BFCP)

Mechanical test was conducted to determine the flexural and tensile strength of bamboo fiber composite plate (BFCP) with specific dimension. The following section discussed all the result and outcome of related test.

4.3.3.1 Flexural Strength

For flexural strength test, pure epoxy plate and bamboo fiber composite plate (BFCP) with 0.4 volume-to-fiber ratio have been fabricated. The ultimate load of both types of specimens are listed in Table 4.7. The maximum peak loads that can be sustained by the pure epoxy specimens were inconsistent with the values of 80.38 N, 38.88 N and 56.53 N. On the other hand, BFCP samples showed higher peak load of 463.64 N, 420.22 N and 463.45 N. When considering the flexural strength, pure epoxy specimens possess lower flexural strength with the peak value of 28.22 MPa followed by 19.84 MPa and 13.65 MPa as shown in Figure 4.8. The inconsistent result may be caused by the existence of bubbles in the sample during fabrication process. Present of bubbles creates the void inside the sample and this turns the plate brittle and weak in flexural test. Bamboo fiber composite plate contributed to higher flexural strength of 162.76 MPa, 147.52 MPa and 162.69 MPa.

While comparing in terms of average peak loading, neat epoxy specimen showed that it can only sustain an average load of 58.6 N as shown in Figure 4.8. About 666.4 % improvement of load bearing capacity in BFCP compared to neat epoxy specimens where BFCPs can withstand the load up to 449.1 N before the failure occurred. In term of average ultimate flexural strength, BFCP again showed that it was stronger than pure epoxy where the flexural strength increased by 666.5 %, from 20.57 MPa (pure epoxy) up to 157.66 MPa (BFCPs). The interfacial adhesion between the bamboo fiber and epoxy resin has formed stronger bond and a rigid matrix arrangement within the structure which then turned it into a strong composite product.

Table 4.7: Summary of flexural test for pure epoxy and BFCP specimens.

Sample		Peak Load (N)	Average Peak Load (N)	Average Ultimate Flexural Strength (MPa)
Pure Epoxy	1	80.38	58.60	20.57
	2	38.88		
	3	56.53		
BFCP	1	463.64	449.10	157.66
	2	420.22		
	3	463.45		

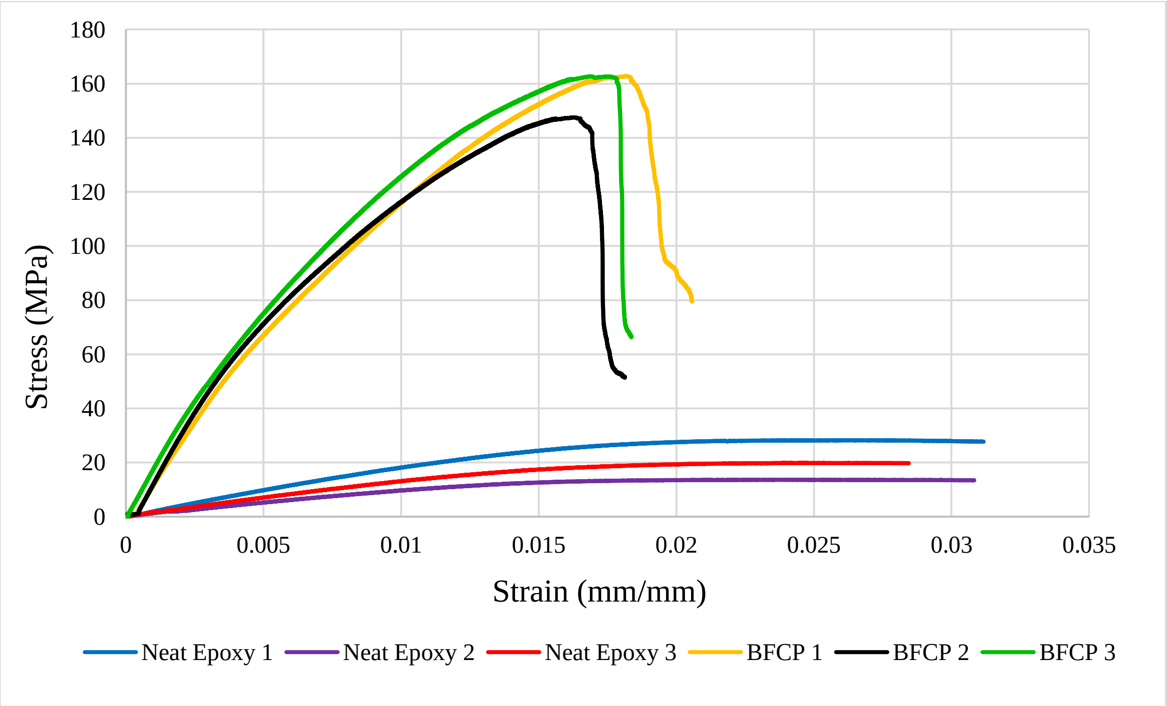


Figure 4.8: Graph of stress versus strain under flexural test.

4.3.3.2 Tensile Strength

Table 4.8 summarizes the result of tensile test for pure epoxy and bamboo fiber composite plates (BFCP). For the plain epoxy specimens, the maximum peak load that obtained was 3010.54 N while for BFCP, the value was 8469.03 N. The ultimate tensile strength of epoxy samples only reached up to 21.73 MPa, 23.34 MPa and 24.08 MPa which is weaker than BFCP. Composite plate with bamboo fiber loading showed improvement in tensile strength whereby each of the specimens achieved ultimate strength of 63.08 MPa, 62.61 MPa and 67.75 MPa respectively. The graph of stress versus strain in Figure 4.9 shows the steep slope of one of the epoxy specimen at the beginning of the test, but then the tensile strength increased until the failure occurs. This may be due to improper fitting of the specimen at the Universal Testing Machine (UTM). The specimen slide away when the tensile loading was being applied.

When comparing the average peak loading, it was clearly shown that BFCP exhibited higher load bearing capacity, which was about 180 % higher than pure epoxy specimens as it sustained the ultimate loading of 8059.92 N compared to 2877.31 N in epoxy samples. There was improvement of about 178 % of ultimate tensile strength in BFCP as it achieved 64.48 MPa compared to the lower one which was 23.05 MPa. In BFCP configuration, the strong adhesion between the bamboo fiber and epoxy resin contributed to the high tensile strength hence it greatly improved the mechanical properties of the composite product.

Table 4.8: Summary of tensile test.

Type	Sample	Peak Load (N)	Average Peak Load (N)	Tensile Strength (MPa)	Average Ultimate Tensile Strength (MPa)
Neat Epoxy	1	2904.88	2877.31	23.34	23.05
	2	2716.52		21.73	
	3	3010.54		24.08	
BFCP	1	7885.00	8059.92	63.08	64.48
	2	8469.03		67.75	
	3	7825.72		62.61	

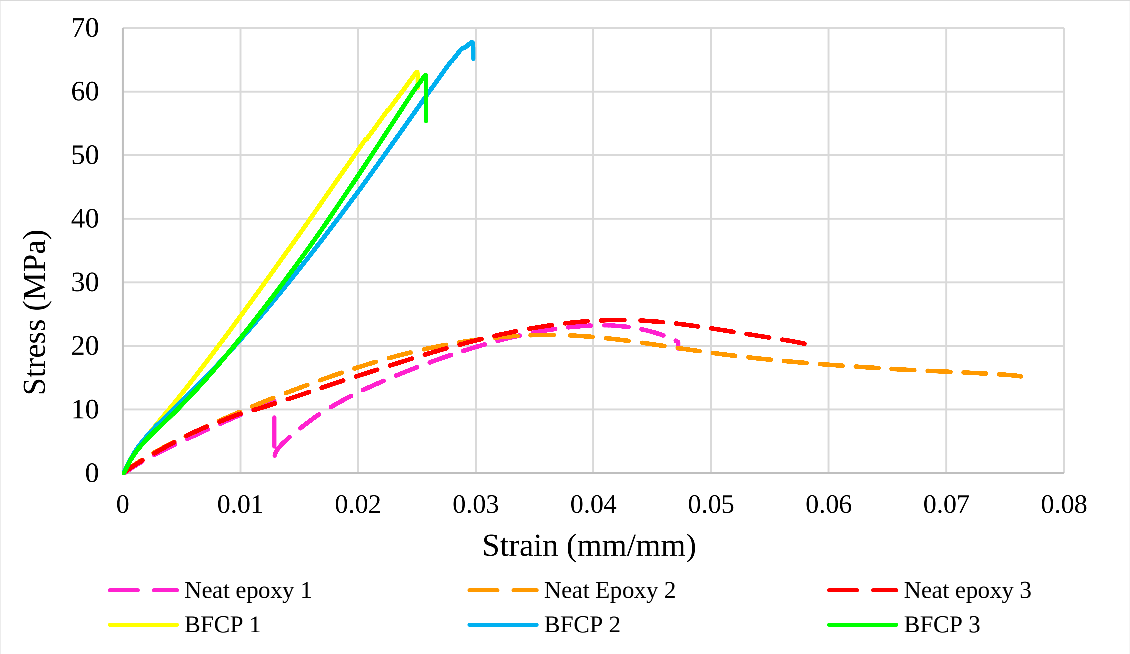


Figure 4.9: Graph of stress versus strain under tensile test.

4.3.4 RC Beam under Four-Point Loading Test

In four-point loading test, control beam (CB), un-strengthened beam (UST-B) and BFCP strengthened beam (ST-B) were tested. Bamboo fiber composite plate (BFCP) with 0.4 fiber-volume ratio has been fabricated in dimension of 380 x 100 x 7 mm in length, width and thickness respectively. Sikadur-30 adhesive has been used to bond the BFCP on the bottom soffit of RC beam. Analysis and comparison were made based on the ultimate load and deflection, crack pattern and failure mode on each type of beams.

4.3.4.1 Load and Deflection Analysis

Solid Control Beam (CB)

When the loading was being applied, a steady upward trend was observed in Figure 4.10 where the deflection was directly proportional to the load. At deflection of about 11 mm and 12 mm, CB 1 and CB 3 were in strain hardening stage until they reached the ultimate load of 25.22 kN and 26 kN respectively. Upon reaching the ultimate load, a sharp drop can be observed. In CB 2, the yield stress point was reached at load of about 24 kN with a deflection of 11mm. The behaviour of the beam then changed into plastic behaviour with a constant increase in load with increase in deflection. The ultimate load that recorded in CB 2 was 24.7 kN with the maximum deflection of 19.82 mm.

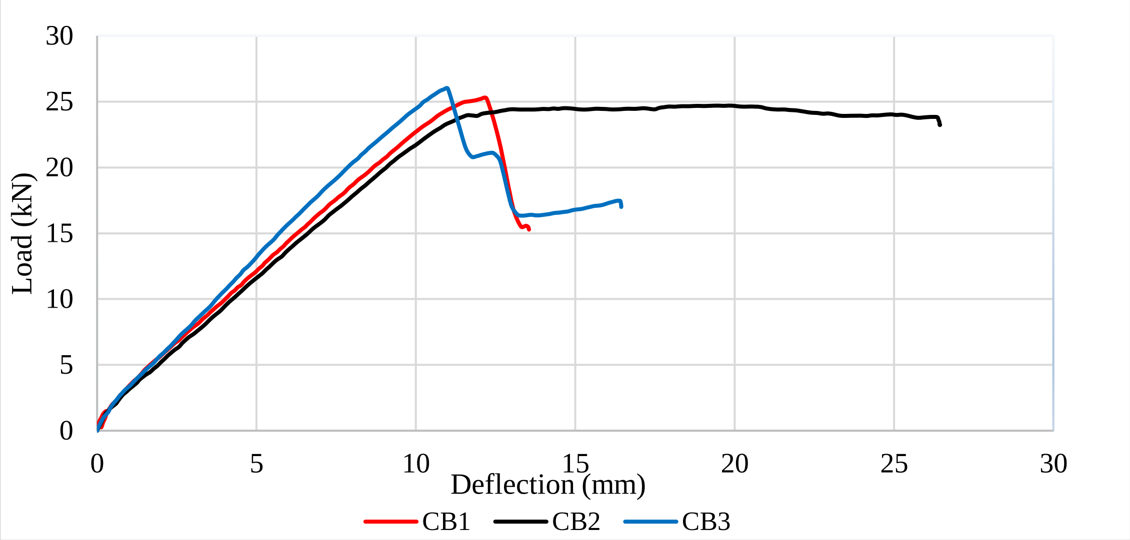


Figure 4.10: Graph of load versus deflection for solid control beams (CB).

Un-strengthened Beam (UST-B)

Referring to Figure 4.11, the value of the load and deflection remained proportional with a steep slope upward curve. In UST-1, the beam failed at peak load of 21.43 kN and 8.41 mm of deflection. On the other hand, the yield stress point in UST-2 occurred at load of about 17 kN and deflection of 8 mm. After the yielding point, the graph shows a progressive increase in load and deflection until it reaches the ultimate load point of 17.42 kN and maximum deflection of 16.97 mm. Beyond the ultimate load, the deflection of the beam was increasing appreciably with the load declined dramatically.

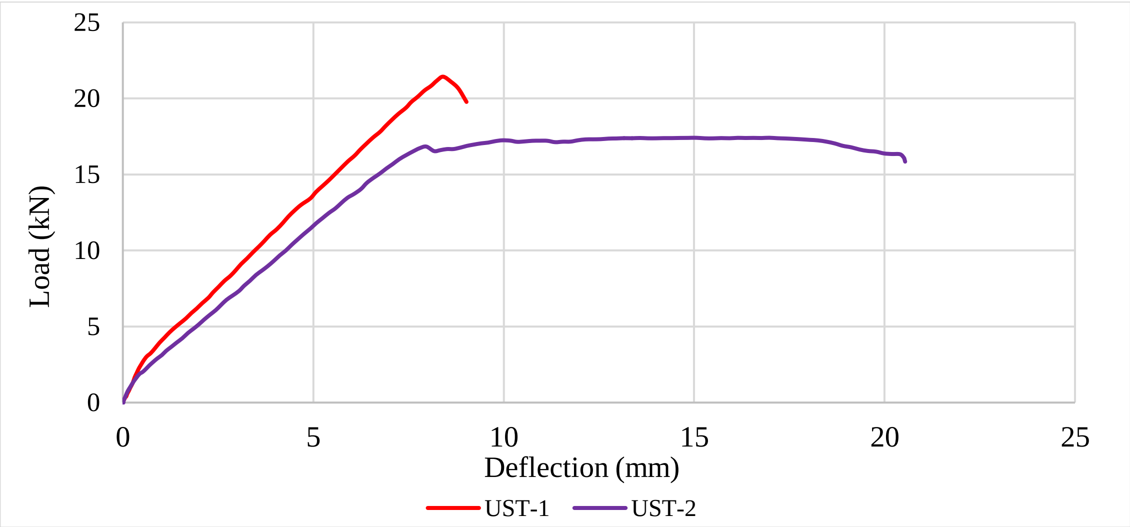


Figure 4.11: Graph of load versus deflection for un-strengthened beams (UST-B).

BFCP Strengthened Beam (ST-B)

Figure 4.12 shows the relationship between load and deflection for BFCP strengthened beams. The deflection of the strengthened beam was proportional to the load at the strain hardening stage. Prior the breaking point, both the beams achieved the ultimate load of 23.65 kN and 23.98 kN with the maximum deflection of 12.08 mm and 15.47 mm respectively. The load dropped gradually with the increase in deflection and the load was carried by the BFCP that attached to the bottom soffit of the beam.

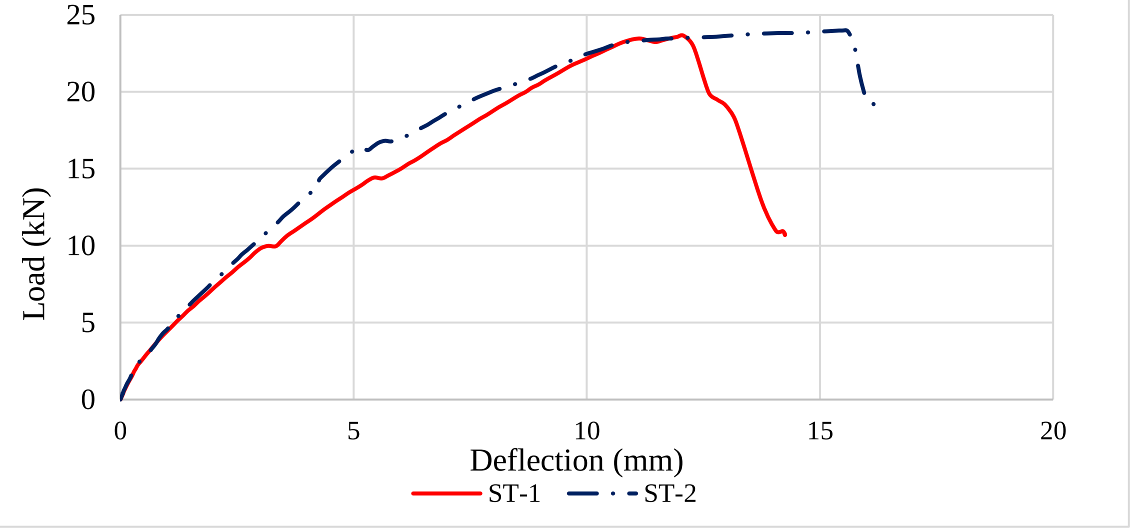


Figure 4.12: Graph of load versus deflection for BFCP strengthened beams.

Comparison between Solid Control Beam (CB), Un-Strengthened Beam (UST-B) and BFCP Strengthened Beam (ST-B)

Referring to Figure 4.13, the solid control beam (CB 2) failed gradually after reaching the yield point at deflection of about 11 mm. It started to deform when reaching the peak load of 24.70 kN at maximum deflection of 19.5 mm. With the full shear link configuration, it exhibited ductile failure in solid beam compared to other beam specimens. Un-strengthened beam (UST-B1) only achieved the ultimate load of 21.43 kN and maximum deflection of 8.41 mm. There was a reduction in ultimate load of about 13 % compared to CB due to the elimination of shear link at the tension zone which reduced the ultimate load carrying capacity of the RC solid beam significantly.

It was found that the both the BFCP strengthened beams had achieved the higher load bearing capacity than un-strengthened beam (UST-B1) which were about 10 % and 12 % with the ultimate load of 23.65 kN and 23.98 kN respectively. The maximum deflection in BFCP strengthened beams also increased to 12.08 mm and 15.47 mm which were 44 % and 84 % compared to un-strengthened beam. The result indicates that BFCP had potential to externally enhance the strength of the beam at tension zone compared to un-strengthened beam. In comparison, ST-B1 and ST-B2 were comparable to solid control beam with the load bearing capacity of 96 % and 97 %. In BFCP strengthened beams, there was only 3-4 % increment in load to restore the load bearing capacity in solid beam.

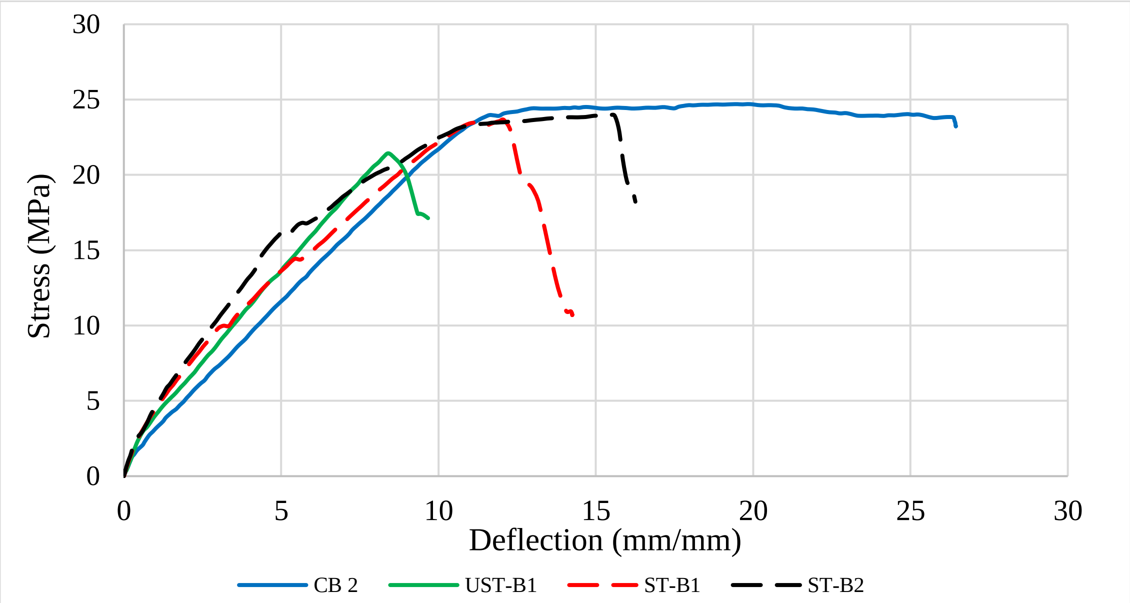


Figure 4.13: Load deflection curve for different beam specimens.

4.3.4.2 Crack Pattern and Failure Mode

Figure 4.14 to Figure 4.16 show the crack patterns and failure mode of solid control beams. When the load was being applied, the vertical cracks firstly appeared at the tension zone or midspan of beam. In control beam, CB 1, the first crack appeared at load of 6 kN while for both CB2 and CB3, the cracks appeared at load of 4 kN. The cracks continued to form along the beam and elongated towards the neutral axis of the beam until failure. The vertical cracks eventually turned diagonal cracks at the support upon beam failure. Shear failure was observed in CB1 and CB3 while ductile failure was observed in CB2.

Figure 4.14: Crack pattern in CB 1.

Figure 4.15: Crack pattern in CB 2.

Figure 4.16: Crack pattern in CB 3.

Figure 4.17 and Figure 4.18 show the crack patterns of un-strengthened beam. Vertical cracks were formed along the tension zone and penetrated into the neutral axis of beam similar as the solid control beam whereby the cracks were seen concentrated at the beam midspan. The first crack formed on both beams at the load of 4 kN. Removal of shear link at the flexure zone did not affect much the crack patterns formed. However, it was significant that the diagonal crack was observed in UST-B1 and the failure mode of the beam was in shear.

Figure 4.17: Crack pattern in UST-B1.

Figure 4.18: Crack pattern in UST-B2.

Figure 4.19 and Figure 4.20 illustrate the cracks pattern for bamboo fiber composite plate (BFCP) strengthened beam. Based on observation, there were very few vertical cracks observed at the midspan of the beam or the flexural zone due to the presence of BFCP. At load of 5 kN and 4 kN for ST-B1 an ST-B2 respectively, first cracks started to appear at the edges of the plate or strengthened zone. More vertical cracks are formed and elongated towards the neutral axis until the beam failure. This proved that the application of BFCP had improved the strength of the beam at the tension zone by diverting the flexural cracks to appear at the edge of the plate. Diagonal cracks were observed at the right part of the both beams.

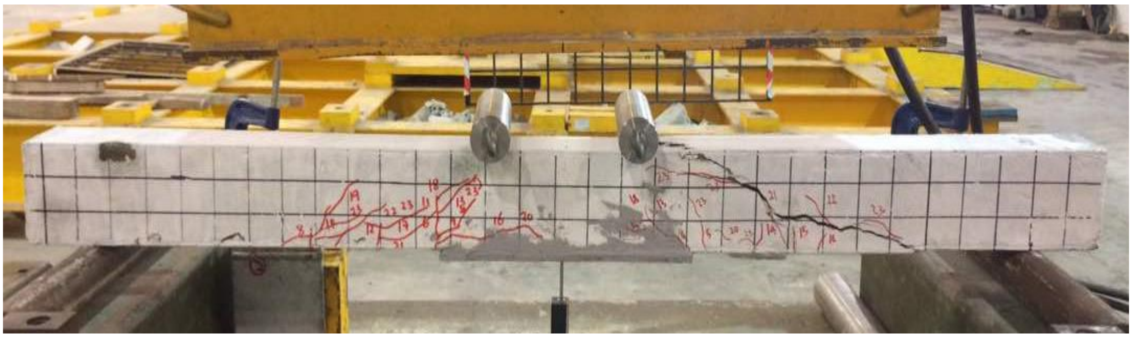


Figure 4.19: Crack pattern in ST-B1.

Figure 4.20: Crack pattern in ST-B2.

Table 4.9: Summary of four-point loading test.

Beam type	Sample	Ultimate Load (kN)	Average Ultimate Load (kN)	Deflection (mm)
Solid Control Beam	CB 1	25.22	25.31	12.22
	CB 2	24.70		19.82
	CB 3	26.00		11.00
Un-strengthened Beam	UST-B1	21.43	19.43	8.41
	UST-B2	17.42		16.97
BFCP Strengthened Beam	ST-B1	23.65	23.82	12.08
	ST-B2	23.98		15.47

Table 4.10: Summary of crack pattern and failure mode.

Beam Type	Description
Solid control beam (CB)	- Vertical cracks along the beam - Concentrated crack at midspan - Diagonal crack in CB 1 and CB 3 - Shear failure in CB1 & CB3, ductile failure in CB2
Un-strengthened beam (UST-B)	- Vertical cracks along the beam - Concentrated crack at midspan - Diagonal crack in UST-B1 - Shear failure in UST-B1, ductile failure in UST-B2
BFCP strengthened beam (ST-B)	- Vertical cracks mainly occurred outside the strengthening zone - Less cracks formed at midspan - Diagonal crack in both beam specimens. - Shear failure in both ST-B1 & ST-B2

CHAPTER 5

CONCLUSION

5.1 Introduction

The main purpose of this study was to determine the physical and mechanical properties of bamboo species Dendrocalamus asper (Buluh Betung). The potential of this kind of bamboo to be processed as bamboo fiber composite plate (BFCP) in replacing synthetic fiber was determined. This chapter summarized all the results and data obtained from the mechanical test that have been conducted which include density test, compression and tension test for bamboo specimens as well as flexural and tension test for bamboo fiber composite plate (BFCP). Four-point loading test was conducted on RC beams strengthened with BFCP. Few recommendations and suggestion are presented.

5.2 Conclusion

All the objectives of this study are achieved throughout the experimental works. Based on the data and results, several conclusions are listed as follows:

i. Failure of bamboo culms under compression test can be grouped into two types: fiber cracking and fiber crushing. Compared to raw bamboo specimen, dried bamboo culm had higher compression strength which was about 19.5 % due to its stiffer and rigid structure. In term of tensile strength, there was improvement of about 45 % in tensile strength of raw bamboo specimens compared to dried bamboo specimens.

ii. All bamboo fiber composite plate (BFCP) samples achieved higher flexural and tensile strength than the pure epoxy plate which were 666 % and 178 % respectively. The interfacial adhesion between the bamboo fiber and epoxy resin had formed stronger bond within the structure.

iii. BFCP strengthened beams had achieved the total load bearing capacity of 96 % and 97 % compared to solid control beam. Compared with un-strengthened beam, the load bearing capacity of BFCP strengthened beam increased by 10 % and 12 %. Installation of BFCP manage to divert the vertical cracks at the tension zone to the edge of the plate forming diagonal cracks. This proved that BFCP has potential to be used as external strengthening material in RC beams.

5.3 Recommendation

Recommendations are listed to improve the results obtained from the test and the quality of the bamboo fiber composite plate (BFCP):

i. The spacing between the shear links inside the reinforced concrete beam must be evenly divided and within the maximum spacing to avoid earlier failure of beam

ii. The thickness of BFCP should be controlled within 4-6 mm to allow it efficiently performs as external strengthening material on beam.

iii. Shorter reinforced concrete beam can be casted as an alternative solution to the crisis of short bamboo fiber that obtained during extraction of fiber.

5.4 Limitation

In the present study, it was found that inner wall of the most bamboo culms cracked prior compression test. Bamboo of Betung species has thick wall and this has caused the earlier cracking at the internodes prior testing. Another difficult part was the insufficient length of the extracted bamboo fiber. Short distance between the nodes produced only short fiber that less than 380 mm. Short BFCP that fabricated gave poor performance as strengthening material. Therefore, BFCP strengthened beam in previous test cannot fully meet the design strength of control beam.

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APPENDIX A

GANTT CHART

Week	FYP1																		Sem Break					FYP2																		
	Sept				Oct				Nov					Dec				Jan					Feb				Mar				Apr				May					Jun		
Task	1	2	3	4	1	2	3	4	1	2	3	4	5	1	2	3	4	1	2	3	4	5	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	5	1	2	3
Research Topic	■	■	■	■																																						
Literature Review	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■								
Formwork Preparation												■	■																													
Rebar Preparation														■	■																											
Presentation FYP 1																■																										
Logbook and Proposal Submission																■	■																									
Preparation of Materials																■	■	■	■	■	■	■	■	■	■																	
RC Beam Casting																										■																
Beam Curing																										■	■	■	■													
Bamboo Specimen Testing																												■	■													
BFCP Fabrication																														■	■	■										
Flexural Test of BFCP																																■										
Tensile Test of BFCP																																■										
BFCP Fabrication (Beam)																																■	■	■								
Four Point Loading Test																																			■							
Result and Analysis																														■	■	■	■	■	■	■	■					
Thesis Writing				■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■	■			
Presentation FYP 2																																							■			
Thesis Submission																																							■	■	■	■

APPENDIX B

CALCULATION FOR THE AMOUNT OF MATERIAL USED FOR BAMBOO FIBER COMPOSITE PLATE (BFCP) FABRICATION

Flexural Specimen

Density of Bamboo Fiber	=	0.807 g/cm^3
Density of Epoxy Resin	=	1.2 g/cm^3
Dimension of Bamboo Fiber Composite Plate (BFCP)	=	127 x 12.7 x 6 mm
Volume of BFCP	=	9677.4 mm^3 / 9.677 cm^3

Material used

Sample	Fiber (%)	Weight (g)	Resin (%)	Weight (g)	No of Specimen	Total Fiber (g)	Total Resin (g)
Neat Epoxy	0	0	100	12.483	3	0	37.449
BFCP	40	3.124	60	6.967	3	9.372	20.901

Tensile Specimen

Density of Bamboo Fiber	=	0.807 g/cm^3
Density of Epoxy Resin	=	1.2 g/cm^3
Dimension of Bamboo Fiber Composite Plate (BFCP)	=	250 x 25 x 5 mm
Volume of BFCP	=	31250 mm^3 / 31.25 cm^3

Material used

Sample	Fiber (%)	Weight (g)	Resin (%)	Weight (g)	No of Specimen	Total Fiber (g)	Total Resin (g)
Neat Epoxy	0	0	100	37.50	3	0	112.50
BFCP	40	10.088	60	15.131	3	30.264	45.393

BFCP on RC Beam

Density of Bamboo Fiber	=	0.807 g/cm^3
Density of Epoxy Resin	=	1.2 g/cm^3
Dimension of Bamboo Fiber Composite Plate (BFCP)	=	380 x 100 x 7 mm
Volume of BFCP	=	266000 mm^3 / 266 cm^3

Material used

Sample	Fiber (%)	Weight (g)	Resin (%)	Weight (g)	No of Specimen	Total Fiber (g)	Total Resin (g)
Neat Epoxy	0	0	100	319.2	2	0	638.40
BFCP	40	85.865	60	128.797	2	171.73	257.594

APPENDIX C

CONCRETE MIX DESIGN COMPUTATION AND SUMMARY

PAMIX SDN BHD	**PAMIX SDN. BHD.** (Company No. 261694-H) A-9, 2ND & 3RD Floor, Pusat Komersial Kuantan Perdana, Jalan Tun Ismail, 25000 Kuantan, Pahang, Darul Makmur. Tel : 09-5172810 / 2813 / 2819 Fax : 09-5172821 / 2806 (A/C)	Document No. Revision No. Effective Date Page No.	: PSB-F-QA-01-02 : 0 : 01/04/2017 : 1 of 1

CONCRETE MIX DESIGN COMPUTATION & SUMMARY

Reference Standard : For Specifying Production And Compliance Creteria
(MS523: 1993 / BS 5328 / JKR 20800 - 0183 - 14 " Standard Specifications for Building Works 2014")

1	1.1	Characteristic Strength (OPC)	Specified **30 N/mm2 at 28 days** below which 5 % of test results may be expected to fall	
	1.2	Designed Standard Deviation	4 N/mm2	
	1.3	Designed Margin	1.64 * = 6.56 N/mm2	
	1.4	Target Mean Strength	**37.0 N/mm2**	
	1.5	Cement Type	OPC	
	1.6	Cement Source	PAHANG CEMENT	
	1.7	Aggregate Type : Coarse	Graded Granite	
		: Fine	Natural / Manufacturing Sand	
	1.8	Free Water / Cement Ratio Specified	0.48	
2	2.1	Specified Slump (NORMAL)	**75 +/- 25 mm**	
	2.2	Maximum Aggregate Size	20 mm	
	2.3	Type of Concrete	Ordinary	
	2.4	Free Water Content	160	Kg/m3
3	3.1	Cement Content (OPC)	330	Kg/m3
	3.2	Cement Content ( )	-	Kg/m3
	3.3	Maximum Cement Content	-	Kg/m3
	3.4	Minimum Cement Content	-	Kg/m3
4	4.1	Relative Density of Aggregate	2.6	
	4.2	Concrete Density	2322	Kg/m3 (Average)
	4.3	Total Aggregate Content	1832	Kg/m3
5	5.1	Grading of Fine Aggregate	BS 882 C or M Limit	
	5.2	Proportion of Fine Aggregate	43.3%	
	5.3	Fine Aggregate Content	793	Kg/m3
	5.4	Coarse Aggregate Content	1039	Kg/m3

6 6.1 **SUMMARY – NORMAL MIX PER CUBIC METRE**

Mix (Mpa)	Slump (mm)	Cement OPC (Kg/m3)	20mm granite (Kg/m3)	Sand (Kg/m3)	Water (Kg/m3)	A/C Ratio	W/C Ratio
30N	75 ± 25	330	1039	793	160	5.55	0.48

7 **ADMIXTURES**

Mighty 85RA (RETARDAR) at	500	ml / 100 kg of OPC @	**1.7**	lit / m3
Mighty 150M (PLASTICIZER) at	0	ml / 100 kg of OPC @	**0.0**	lit / m3

8 **REMARKS**

Mix Code : **T304**

Prepared by,
Name : *Abdul Aziz Bin Haji Mukhtar*
Position : Sr. QA/QC Executive

APPENDIX D

DATA SHEET OF SIKADUR® 30 EPOXY LAMINATING RESIN

Construction

Product Data Sheet
Edition 21/02/2012
Identification no:
02 04 01 04 001 0 000001
Sikadur®-30

Sikadur®-30

Adhesive for bonding reinforcement

Product Description	Sikadur®-30 is a thixotropic, structural two part adhesive, based on a combination of epoxy resins and special filler, designed for use at normal temperatures between +8°C and +35°C.
Uses	Adhesive for bonding structural reinforcement, particularly in structural strengthening works. Including: ■ Sika® CarboDur® Plates to concrete, brickwork and timber (for details see the Sika® CarboDur® Product Data Sheet, the "Method Statement for Sika® CarboDur® Externally Bonded Reinforcement" Ref: 850 41 05 and the "Method Statement for Sika® CarboDur® Near Surface Mounted Reinforcement" Ref: 850 41 07). ■ Steel plates to concrete (for details see the relevant Sika® Technical information).
Characteristics / Advantages	Sikadur®-30 has the following advantages: ■ Easy to mix and apply. ■ No primer needed. ■ High creep resistance under permanent load. ■ Very good adhesion to concrete, masonry, stonework, steel, cast iron, aluminium, timber and Sika® CarboDur® Plates. ■ Hardening is not affected by high humidity. ■ High strength adhesive. ■ Thixotropic: non-sag in vertical and overhead applications. ■ Hardens without shrinkage. ■ Different coloured components (for mixing control). ■ High initial and ultimate mechanical resistance. ■ High abrasion and shock resistance. ■ Impermeable to liquids and water vapour.

Tests

Approval / Standards	Deutsches Institut für Bautechnik Z-36.12-29, 2006: General construction authorisation for Sika® CarboDur®. IBMB, TU Braunschweig, test report No. 1871/0054, 1994: Approval for Sikadur®-30 Epoxy adhesive. IBMB, TU Braunschweig, test report No. 1734/6434, 1995: Testing for Sikadur®-41 Epoxy mortar in combination with Sikadur®-30 Epoxy adhesive for bonding of steel plates. Testing according to EN 1504-4

APPENDIX E

DATA SHEET OF EPOXY D.E.R 311

10. Stability and Reactivity

Stability/Instability
Stable under recommended storage conditions. See Storage, Section 7.
Conditions to Avoid: Avoid temperatures above 300°C (572°F) Potentially violent decomposition can occur above 350°C (662°F) Generation of gas during decomposition can cause pressure in closed systems. Pressure build-up can be rapid.

Incompatible Materials: Avoid contact with oxidizing materials. Avoid contact with: Acids. Bases. Avoid unintended contact with amines.

Hazardous Polymerization
Will not occur by itself. Masses of more than one pound (0.5 kg) of product plus an aliphatic amine will cause irreversible polymerization with considerable heat build-up.

Thermal Decomposition
Decomposition products depend upon temperature, air supply and the presence of other materials. Gases are released during decomposition. Uncontrolled exothermic reaction of epoxy resins release phenolics, carbon monoxide, and water.

11. Toxicological Information

Acute Toxicity
Ingestion
Very low toxicity if swallowed. Harmful effects not anticipated from swallowing small amounts.
LD50, Rat > 5,000 mg/kg
Eye Contact

Page 4 of 8

Product Name: D.E.R.* 331 Epoxy Resin **Issue Date:** 02.11.2006

Ingestion: Use good personal hygiene. Do not consume or store food in the work area. Wash hands before smoking or eating.

Engineering Controls
Ventilation: Good general ventilation should be sufficient for most conditions.

9. Physical and Chemical Properties

Physical State	Liquid
Color	White to yellow
Odor	Mild
Flash Point - Closed Cup	252 °C *PMCC, ASTM D93*
Flammable Limits In Air	**Lower**: Not applicable **Upper**: Not applicable
Autoignition Temperature	Not applicable
Vapor Pressure	Not applicable
Boiling Point (760 mmHg)	Not applicable.
Vapor Density (air = 1)	Not applicable
Specific Gravity (H2O = 1)	1.16 *Literature*
Liquid Density	1.156 - 1.166 g/cm3 @ 25 °C *ASTM D4052*
Freezing Point	Not Determined
Melting Point	Not Determined
Solubility in Water (by weight)	Insoluble
pH	Not Determined
Dynamic Viscosity	11,000 - 13,500 mPa.s @ 25 °C *ASTM D445*

APPENDIX F

DATA SHEET OF HARDENER JOINTMINE 905-3S

EPOCHEMIE

An associate company of Yun Teh Industrial Co., Ltd

Product Data Sheet

LIT/0508-905-3S

JOINTMINE 905-3S

INTRODUCTION

JOINTMINE 905-3S is a modified cycloaliphatic amine of low viscosity, low color and room temperature curing agent. It imparts good resistance to abrasion, moisture and chemical resistance. It has also low in toxicity than aliphatic amine and exhibit high gloss film and ideal for solventless free floor coating, self-leveling flooring and tank lining.

CHARACTERISTICS

- Low viscosity and transparent liquid
- Good working pot life
- Good chemical resistance
- High gloss and good color stability

APPLICATIONS

- Self-leveling floor coating
- High solid coating
- Chemical tank coating
- Water resistant tile grout

PACKING

Jointmine 905-3S available in 200kg net per drum

STORAGE CONDITIONS

At least 12 months from the date of manufacture in the original sealed container at ambient temperature. Store away from excessive heat and humidity in tightly closed containers.

SPECIFICATION

Amine value (mg KOH/g)	300 ± 20
Viscosity (BH type @25°C, cPs)	200 ~ 400
Color (Gardner)	<2
Equivalent Wt (H)	95

BASIC FORMULATION

Mix ratio (with EEW=190 epoxy resin) = 50 phr

TYPICAL PROPERTIES

Pot life (100g @25°C)	75 mins
Hardness (Shore D)	85
Thin film set time (@25°C)	5 hours

PHYSICAL PROPERTIES

Compressive Strength (JIS K6911)	1000kg/cm^2
Bending Strength (JIS K6911)	800kg/cm^2
Tensile Strength (JIS K6911)	700kg/cm^2

No guarantee, warranty, or representation is made, intended, or implied as to the correctness or sufficiency of any information, or as to the suitability of any chemical compounds for any particular use, or that any chemical compounds or use thereof are not subject to a claim by a third party for infringement of any patent or other intellectual property right. Each user should conduct a sufficient investigation to establish the suitability of any product for its intended use.

Epochemie International Pte Ltd., No.1, Woodlands Terrace, Singapore 738471
Tel : 65-67565680 Fax : 65-67560760, email : epochemie@pacific.net.sg

BAMBOO (BETUNG SPECIES) FIBER COMPOSITE PLATE FOR EXTERNAL STRENGTHENING OF RC BEAMS

Jacky Moh Neing Sheng, Chin Siew Choo*

Abstract

There is a large scale of industries that involved with the use of synthetic fibers due to their high performance in terms of strength and mechanical properties. However, the mode of disposal of these artificial fibers has caused the pollution problem to the environment since they are not bio-degradable. Due to concerns over environment, the use of natural fibers as the raw materials in the fabrication of composite product is highly recommended since they are readily available in natural forms and biodegradable. From this research, the mechanical properties of bamboo (Betung species) was determined from several tests and its fiber is being used as the raw material in the fabrication of bamboo fiber composite plate (BFCP) with a fiber-to-volume ratio of 0.4. Bamboo culms under compression test fail in two modes: fiber cracking and fiber crushing. Dried bamboo specimens recorded 19.5 % higher in compression strength than raw bamboo specimens. There was an improvement of 45 % of average tensile strength in raw bamboo samples compared to dried specimens. In terms of mechanical behaviour, BFCP has higher flexural and tensile strength than pure epoxy samples where the flexural and tensile strength of BFCP increased by 666 % and 178 % respectively. The interfacial adhesion between the bamboo fiber and epoxy resin in BFCP greatly improved the structural bonding and mechanical properties. From the four-point loading test, BFCP strengthened beams were comparable to the solid beam (control beam) with the load bearing capacity of 96% and 97%. There was an increment of 10% and 12% in load bearing capacity in BFCP strengthened beams compared to un-strengthened beams. In term of crack patterns, there was only little cracks formed at the BFCP strengthened part. Installation of BFCP was able to divert the cracks out of the strengthened zone. This proves that the application of BFCP on RC beams was able to improve the flexural strength and it has potential to be used as external strengthening material.

KEYWORDS | *Mechanical Properties, Bamboo Fiber, Bamboo Fiber Composite Plate (BFCP), Epoxy, External Strengthening*

*Corresponding author: scchin@ump.edu.my

INTRODUCTION

The latest development shows trend in utilizing natural fiber in many industries especially civil construction material [1]. This is due to the extensive use of these non-biodegradable products that possess harmful effect to environment through air pollution and high energy consumption. All these issues have led to the explore of possible natural fibers to replace some of the engineering materials. To overcome this issue, bamboo fibers has been selected as raw material due to its rapid growth rate and great productivity. They are biodegradable, renewable and offer more economical and environment advantages. Bamboo fibers are comparable to glass fiber due to its longitudinal alignment of fibers which produces high strength with respect to its weight [2]. Bamboo fiber epoxy-reinforced composites with approximately 0.4 fiber-volume-ratio achieved better mechanical properties where it showed high flexural strength [3]. Bio-composites made of bamboo fibers are considered as green products.

Combination of mechanical and chemical method has enable the convenience extraction of bamboo fiber. The bamboo culms are immersed with alkali solution prior subjecting to fixed rollers.

Epoxy resin are used as the matrix in the fabrication of composite plates. With the interfacial adhesion between epoxy and bamboo fiber, it can enhance the mechanical properties of the composite plates. Hand lay-up method is preferable as the fabrication method as it is the easiest, cheap and convenient way compared to other complicated process.

Bamboo fiber composite plate can restore the lost load bearing capacity of RC structures. [4]. They are preferable to be installed externally as strengthening material due to its light weight, ease in installation, high strength and abundant resources. The strengthening of existing civil structures must be considered to extend the lifespan and prevent the structural failure. This application tends to upgrade the existing structures on term of design life time and load bearing capacity.

METHODOLOGY

Preparation of Bamboo specimen and fiber

Bamboos culms with the age of 2-3 years old were harvested from Raub, Pahang. Raw and oven-dried bamboo samples were prepared for comrepssion and tensile test. In the extraction of bamboo fibers, the process involved with both chemical mechanical method. Another group of raw bamboo culms are being cut down by using 10 ways razor blade, then undergoes 10% of sodium hydroxide (NaOH) treatment for 48 hours. Later, they pass through mill roller machine to obtain monofilaments fibers. The processed fibers are then rinsed with distilled water to eliminate alkaline content and oven-dried for 24 hours before mixing with epoxy resin in the composite plate fabrication process.

Fabrication of Bamboo Fiber Composite Plate (BFCP)

Treated bamboo fiber with fiber volume ratio of 40% and adequate amount of epoxy resin were prepared for the fabrication of BFCP. Hand lay-up method was used where three layers of bamboo fiber were placed in unidirectional with a layer of epoxy between them. The bottom and top of the steel mould were covered by a layer of epoxy before placing the bamboo fibers. It was then cured in room temperature for 24 hours followed by oven dried for 4 hours prior testing.

Preparation of Reinforced Concrete Beam

Ready mixed concrete with compressive strength of 30 N/mm^2 was ordered to cast the reinforced concrete beams with dimension of 100 x 130 x 1600 mm in width, height and length respectively.

Table 1. BFCP samples for flexural and tensile test

Test	Dimension (mm)	ASTM Standard
Flexural	127 x 12.7 x 6	D 3039
Tensile	250 x 25 x 5	D790-03
Four-Point Bending Test	380 x 100 x 7	-

**BFCP- Bamboo fiber composite plate*

Figure 1. BFCP for flexural test.

BFCP Strengthening System on RC beams

The bottom soffit and surface of the RC beams were roughed and cleaned with air blower to remove the dirt and impurities. Sikadur®-30 was used to bind the bamboo fiber composite plate (BFCP) to RC beams. To strengthen the flexural zone, the BFCP was placed on the midspan of the beam at distance of 610 mm away from the beam end. BFCP was pressed out uniformly from the middle to sides. The curing process went for 7 days to achieve the strongest binding.

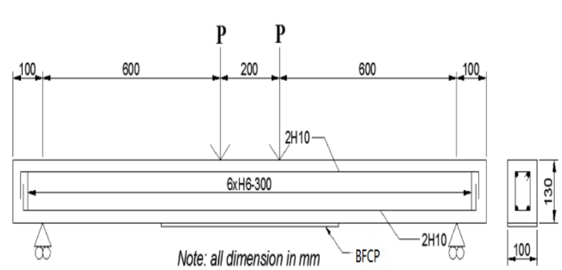

Figure 2. Schematic diagram of four-point loading test.

Conduct of Experiment

Density Test

Water displacement method was used to measure the green volume (V) of the single bamboo specimen. The sample is then oven-dried for 24 hours to obtain the dry mass. Total 5 specimens were prepared, and the average reading is obtained.

Compression Test and Tensile Test (Bamboo specimen)

In the compression test for bamboo culms, all specimens with one node only and no prior cracking were prepared. Based on previous research, the compressive strength of bamboo specimen with internode had been found to be higher than that samples without internode. [5] Universal Testing Machine (UTM) was used the compressive load is being applied at a constant rate of 0.05 kN/sec. It was similar in tensile test where the tensile load was applied on the cross section of all the specimens individually with a strain rate of 0.06 mm/min.

Figure 3. Compression test on bamboo culms.

Flexural and Tensile Test (BFCP)

In flexural test, the failure by inter-laminar of the flexural specimens were measure according to ASTM D790-03 test method I, procedure A. UTM was used to carry out the three-point bending test. Tensile test was performed according to ASTM 3039 standard. The test was stopped until the sample fracture and the ultimate tensile strength recorded.

Figure 4. Flexural test is conducted on epoxy sample.

Four-Point Loading Test

Three types of beams were prepared for 4-point loading test: solid beam, un-strengthened beam and BFCP strengthened beam. A magnus frame with load capacity started from 300N up to 500N was used. RC beams were supported by two support points and two-point loads were applied vertically downward until the beams failure. Linear variable displacement transducers (LVDTs) were installed at the bottom soffit to measure the deflection of the beam. They were connected to a data logger to record the deflection until beam failure. The crack patterns were observed marked on the painted beam surface. All the results of unstrengthen and BFCP strengthened beams were compared with solid beam.

Table 2. Summary of beam specimens under four-point loading test.

Beam Specimen	Beam Dimension (B x H x L) mm	Condition
1	100 x 130 x 1600	Solid beam as controlled beam
2	100 x 130 x 1600	
3	100 x 130 x 1600	
4	100 x 130 x 1600	Unstrengthen
5	100 x 130 x 1600	Unstrengthen
6	100 x 130 x 1600	BFCP Strengthened
7	100 x 130 x 1600	BFCP Strengthened

RESULTS AND DISCUSSIONS

Density Test

The density of bamboo was in the range of 0.7 to 0.86 g/cm^3. Based on the data in Table 4, an average value of 0.807 g/cm^3 was taken as the density of Buluh Betung.

Table 3. Density for Bamboo Betung species.

Sample	Oven-dried Weight (g)	Volume, V (cm^3)	Density (g/cm^3)
1	4.92	7	0.703
2	5.14	6	0.857
3	4.98	6	0.830
4	4.90	6	0.817
5	4.97	6	0.828
		Average	0.807

Compressive Strength for Bamboo Culms

Bamboo under compression was seen to fail in two patterns: cracking and crushing of fibers. Figure 9 and 10 show the graph of stress versus strain for raw and dried bamboo specimens. From the result, the ultimate compressive strength of raw bamboo groups reached the peak values of 44.52 MPa, 45.68 MPa and 50.81 MPa. The compressive strength increased to 49.13 MPa, 59.57 MPa and 59.76 MPa in dried bamboo groups where there the total improvement of the average ultimate compressive strength reached a high value of 19.5 %. The void that existed in the raw bamboo specimen reduced the contact surface area between the fiber matrix, thus the load bearing capacity also decreased.

Table 4: Summary for compression test.

Condition	Sample	Ultimate Compressive Strength (MPa)	Average Ultimate Compressive Strength (MPa)
Raw	1	44.52	47.00
	2	50.81	
	3	45.68	
Dried	1	59.57	56.15
	2	59.76	
	3	49.13	

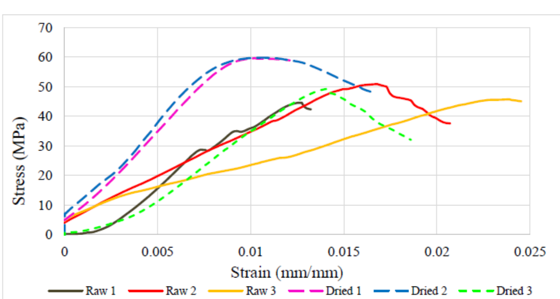

Figure 5. Graph of stress vs strain for raw and dried bamboo specimens.

Tensile Strength for Bamboo Splints

The raw bamboo specimen has higher average tensile strength which was 139.73 MPa or 45 % greater than dried bamboo specimens of 96.29 MPa. In dried specimens, there was a reduction of 43.44 MPa of the total average tensile strength. Bamboo specimens that subjected to heat or elevated temperature may damage the fiber matrix and bonding.

Table 5. Tensile result for bamboo splints

Condition	Sample	Ultimate Tensile Strength (MPa)	Average Tensile Strength (MPa)
Raw	1	129.84	139.73
	2	145.90	
	3	143.44	
Dried	1	97.38	96.29
	2	109.96	
	3	81.53	

Flexural Strength of BFCP

In Figure 11, while comparing in terms of average peak loading, neat epoxy specimen showed that it can only sustain average load of 58.6N as shown in Figure 11. About 87% improvement of strength shown in BFCP compared to neat epoxy specimens where BFCPs can withstand the load up to 449.1N before the failure occur. In term of average flexural strength, BFCP again showed that it was stronger than neat epoxy where the flexural strength increases by 666 %, from 46.28 MPa (neat epoxy) up to 157.66 MPa (BFCPs).

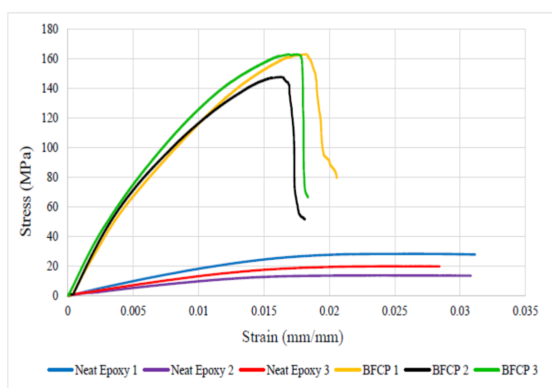

Figure 6. The comparison between neat epoxy and BFCP under flexural test.

Tensile Strength of BFCP

There was an improvement of 178 % of ultimate tensile strength in BFCP as it achieved 64.48 MPa compared to the lower one which was 23.05 MPa as shown in Figure 12. The strong adhesion between the fiber and epoxy resin contributed to the high tensile strength hence it greatly improved the mechanical properties of the composite product.

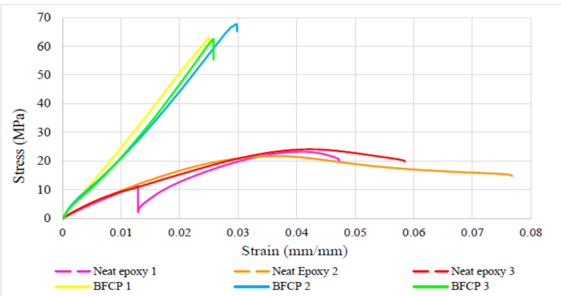

Figure 8. Comparison of ultimate tensile strength between neat epoxy plate and BFCP.

Four-Point Loading Test

Solid beam acheived the highest load bearing capacity compared to un-strengthened beam and BFCP strengthened beam which was 24.70 kN. ST-B1 and ST-B2 were comparable to solid control beam with the load bearing capacity of 96% and 97%. It was found that the both the BFCP strengthened beams had achieved the higher load bearing capacity than un-strengthened beam (UST-B1) which were about 10% and 12%. Installation of BFCP manage to divert the vertical cracks at the tension zone to the edge of the plate forming diagonal cracks. This proved that BFCP has potential to be used as external strengthening material in RC beams.

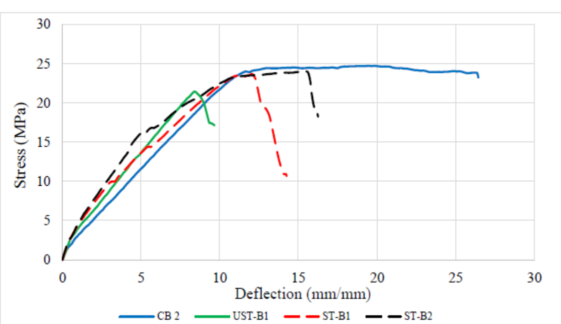

Figure 9. Load versus deflection for beam specimens

CONCLUSIONS

Compared to raw bamboo specimen, dried bamboo culms had higher compression strength which was about 19.5%. In term of tensile strength, there was an improvement of about 45 % in tensile strength of raw bamboo specimens compared to dried bamboo specimens. Bamboo fiber composite plate (BFCP) exhibited higher mechanical strength than pure epoxy plate with 666 % of flexural strength and 178 % of tensile strength respectively. BFCP strengthened beams had achieved the total load bearing capacity of 96% and 97% compared to solid control beam. Compared with un-strengthened beam, the load bearing capacity in BFCP strengthened beam had increased by 10% and 12%.

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