MECHANICAL CHARACTERIZATION OF ARECANUT HUSK FIBRE COMPOSITE PANELS UNDER STATIC AND DYNAMIC LOADING CONDITIONS

Thesis

Submitted in partial fulfillment of the requirements for degree of

DOCTOR OF PHILOSOPHY

by

MURALIDHAR N.

DEPARTMENT OF APPLIED MECHANICS & HYDRAULICS
NATIONAL INSTITUTE OF TECHNOLOGY KARNATAKA,
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DECLARATION

I hereby *declare* that the Research Thesis entitled **MECHANICAL CHARACTERIZATION OF ARECANUT HUSK FIBRE COMPOSITE PANELS UNDER STATIC AND DYNAMIC LOADING CONDITIONS** Which is being submitted to the **National Institute of Technology Karnataka, Surathkal,** in partial fulfilment of the requirements for the award of the Degree of **Doctor of Philosophy** in the Department of **Applied Mechanics and Hydraulics,** is a *bonafide report of the research work carried out by me*. The material contained in this Research Thesis has not been submitted to any University or Institution for the award of any degree.

138040AM13P04, MURALIDHAR N.
Department of Applied Mechanics and Hydraulics

Place: NITK-Surathkal

Date: 26-12-2019

CERTIFICATE

This is to *certify* that the Research Thesis entitled **MECHANICAL CHARACTERIZATION OF ARECANUT HUSK FIBRE COMPOSITES PANELS UNDER STATIC AND DYNAMIC LOADING CONDITION** submitted by **MURALIDHAR N. (Register Number: 138040AM13P04),** as the record of the research work carried out by him, is *accepted as the Research Thesis submission* in partial fulfilment of the requirements for the award of degree of Doctor of Philosophy.

Research Guide

(Dr. VADIVUCHEZHIAN KALIVEERAN)

Chairman – DRPC

(Dr. AMBA SHETTY)

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ABSTRACT

Arecanut husk fibre is an agricultural waste, which does not contribute to the economy of arecanut plantation. The use of arecanut husk fibre as reinforcing material in the preparation of low cost and low density composite panels provides usability to arecanut husk. Low cost and low density composites have wide range of applications in construction industry, marine structures, automobile industry and aerospace industry. The present work focuses on extraction of arecanut husk fibre with alkali treatment process by using 6 % of sodium hydroxide solution, composite panel preparation and determination of mechanical properties of composite panels under static and dynamic loading condition. Different fibre compositions (fine fibre, coarse fibre and coarse fibre sandwiched with glass fibre) of 15 % by weight were used in the present study. The tensile strength of composites made with fine fibres (15.1 MPa) was observed to be more than that of composites made with coarse fibres (10.8 MPa). Further improvement in tensile strength of composite panels made of coarse arecanut husk fibre layer sandwiched with two layers of glass fibre (24.8 MPa) was observed. The flexural strength of fine fibre composites was more when compared to that of the coarse fibre composites. The average flexural strength of composites reinforced with fine fibre, coarse fibre and coarse fibre sandwiched with glass fibre were observed as 85 MPa, 65 MPa and 240 MPa respectively. The coarse fibre composites resulted in higher impact strength when compared to fine fibre composites. Dynamic mechanical analysis, shows trend of storage modulus increased with increase in loading frequency and variation of increment in storage modulus decreased with increase in frequency. At room temperature, the values of storage modulus are 0.478 GPa, 0.573 GPa and 0.607 GPa for loading frequencies of 5 Hz, 10 Hz and 15 Hz respectively. The arecanut composite can retain its storage modulus up to 80 °C. The glass transition temperature of arecanut husk fibre composites is 105 °C.

Keywords: Arecanut husk fibre, Epoxy, Chemical retting, Composite panel preparation, Mechanical properties, Dynamic mechanical analysis.

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NOMENCLATURE

b : Width of the beam

d : Depth of the beam

d.b : Dry bulb

l : Support span length of the beam

E : Elastic Modulus

E' : Storage Modulus

E'' : Loss Modulus

L12 : Lapox epoxy resin

m : Slope of load-deflection curve

NaOH : Sodium hydroxide

pH : Potential of hydrogen

V_c : Volume of the composite mixture

V_f : Volume factor

V_p : Volume of the casting composite panel

W_a : Weight of arecanut

W_E : Weight of epoxy

W_G : Weight of glass fibre

W_H : Weight of hardener

W_A : Weight of arecanut husk fibre

W_P : Weight percentage of arecanut husk fibre

ρ_a : Density of arecanut husk fibre (fine fibre)

ρ_E : Density of epoxy resin

ρ_H : Density of hardener

δ : Phase lag

σ_f : Stress at outer surface of the beam at mid span (from ASTM-D790)

σ_{Ef} : Stress at outer surface of the beam at mid span (from Euler’s Bernoulli bending equation)

ε_f : Strain at outer surface of the beam at mid spam

ABBREVIATIONS

AHF : Arecanut Husk Fibre

ASTM : American Society for Testing and Materials

AP-O : Anti Parallel Orientation

BFRP : Betel Fibers Reinforced Polyester

BNF : Betel Nut Husk

Bn : Betel Nut

BIS : Bureau of Indian Standards

CBR : California Bearing Ratio

CF : Coarse fibre

DMA : Dynamic Mechanical Analyzer

FF : Fine fibre

FTIR : Fourier Transform Infrared Spectroscopy

GF : Glass fibre

HDPE : High Density Polyethylene

HSC : Hindusthan Speciality Chemicals

N-O : Normal Orientation

P-O : Parallel Orientation

PP : Polypropylene

PCL : Polycaprolactone

PWT : Processed Waste Tea Powder

SC : Clayey Sand

SEB : Stabilised Earthen Blocks

SEM : Scanning Electron Microscope

UCS : Unconfined Compressive Strength

CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

1.1 General

Rapid population growth leads to increased usage of resources and thereby results in enormous quantities of waste material. Waste management of agricultural by-products is vital to fast growing economies. Several researchers focused on utilization of organic waste materials and inorganic waste materials for the manufacture of composite panels and found improvement in physical, mechanical and thermal characteristics of composite panels. Organic waste materials such as bagasse, jute, coir and arecanut husk fibres are being used for manufacturing low-cost composite panels. Arecanut, obtained from arecanut palm, consists husk of 15% – 30% by weight of raw arecanut. Bonding between the natural fibre and epoxy resin depends on the quality of fibre which requires proper surface treatment of fibre (Pickering et al., 2016). Usually, natural fibres are treated with alkaline solution to remove the debris present on the fibre surface. Researchers used 2% – 10% NaOH solution by volume to treat arecanut husk fibre and concluded that treating arecanut husk fibre with 6% NaOH solution by volume resulted in obtaining optimum tensile strength of arecanut husk fibre. Several researchers performed static tests, dynamic tests and thermal tests to characterize composite panels reinforced with natural fibre. The mechanical properties of composite panels reinforced with natural fibre extracted from bagasse, coir and epoxy were investigated by conducting static and dynamic experiments. The authors observed tensile strength of composite panels containing three layers of (bagasse, coir, and bagasse) fibres was 27 MPa and Young’s modulus was 0.8 GPa. The organic waste materials such as grain straw and cotton waste (Hanifi Binici et al., 2014), processed tea waste (Ismail Demi et al., 2006), bamboo waste (Thwe et al., 2002), corn cob (Nkayem et al., 2016) and arecanut husk fibre (Lekha et al., 2015) were used for manufacturing composite panels. Currently, few agricultural waste materials are being used for commercial purposes and locally available agricultural waste materials are being studied across the globe (Kamath et al., 2017). Hence, detailed studies are essential for identifying the unutilized waste materials from which composite material can be produced and thereby increase utility value of agricultural by-products. Karnataka is a major cultivator of arecanut, contributing about 40% of India's overall production (Sasmal et al., 2011). India is the largest producer of arecanut in the world. The detailed study and research initiatives are required for the improving utilization of arecanut husk fibre. The current research work focuses on characterization of composites containing Arecanut Husk Fibre (AHF) and epoxy. Therefore, arecanut husk fibre could be effectively utilized for fabrication of structural components in engineering applications. The present work focuses on processing of arecanut husk fibre with 6% of sodium hydroxide solution by alkali treatment process, composite panel preparation and determination of mechanical properties (tensile properties, flexural properties and impact properties) of composite panels.

1.2 Motivation

Major problems of developing countries in the world are lag in management of waste produced in different industries (chemical industry, food production, material manufacturing industry) and utilization of agricultural waste materials. Improper dumping of waste materials produced from these industries leads to environmental pollution. The present world is moving towards manufacturing of various synthetic materials which can replace the existing materials having less weight comparatively. Polymer composites are the emerging materials in market to get better weight strength ratio. Being India is an agricultural based country, there is a scope for effective utilization of agricultural waste for manufacturing of polymer composites. Agricultural industries produce bio-degradable waste materials which are ecofriendly. Generally, fibrous (coir, jute fibre, sugarcane bagasse, bamboo fibre and arecanut fibre) materials from agricultural waste contains good mechanical properties and longer bio degradable period. So, utilizing these fibrous materials for manufacturing of polymer composites leads to effective agricultural waste management and reduces the use of synthetic materials. India is the largest arecanut cultivating country in the world, where as 40% of production from Karnataka state. Arecanut is a commercial crop, in which arecanut, leaf sheath and stems are being utilized in food industries. Arecanut husk fibre is the agricultural waste material which can be used for manufacturing of bio-composites. After removal of nuts from areca fruit, husk will be disposed in barren land. A proper utilization of husk is very vital as a revenue generating material for developing countries like India. Detailed studies on arecanut husk fibre are essential to utilize arecanut husk fibre for manufacturing of composite materials.

1.3 Literature review

The detailed literature survey on development of various composite materials from agricultural waste materials is presented in this section. Literature review includes study of static properties and dynamic mechanical properties of composite consisting agriculture waste materials. The arecanut husk fibre characteristics and uses are also studied in literature survey.

1.3.1 *Literature survey on composite materials manufactured using agricultural waste*

Taha et al. (2015) proposed on stabilization of composite with naturally available fibre. The composite was manufactured using clay, cement/gypsum with wheat/barley Straw fibre. The specimens of dimension 24 cm x 12 cm x 6 cm were manufactured using soil, cement and fibres of length 4 cm by applying compact load of 100 kN. The prepared specimens were dried at a room temperature of 21.7 ºC for 60 days. The addition of fibre to the composite resulted in decrease of thermal conductivity and increase in compressive strength. Thermal conductivity of composite was calculated using hot wire apparatus. The hot and cold plates maintain constant temperature of the external and internal surfaces of the specimen. Increase in wheat straw fibre content decreases the thermal conductivity of composite by 54.4% when compared with brick without fibre (0.961 W/mK).

Njeum et al. (2016) manufactured light weight clay brick using corn cob as pores forming agent. Series of 15 samples were prepared using Corn cob varying from 0%, 2%, 5%, 10% and 15% in weight of brick. The clay-corn cob slurry was molded under a hydraulic pressure of 3 MPa. The samples were fired at different temperature of 900 ºC, 950 ºC, 1000 ºC, 1050 ºC and 1100 ºC. The bulk density of brick decreased with increase in percentage of corn cob above 5% due to the porosity formation during firing of samples. It is also observed that flexural strength decreases with increase in corn cob, this behavior is due to pores in the brick. Pores in the brick, reduces the thermal conductivity and hence it can be used as thermal insulating material and also as sound proofing material. The optimum replacement of clay with corn cob is 10% which forms pores ranging from 33.4% to 45.4% at firing temperature of 1100 ºC.

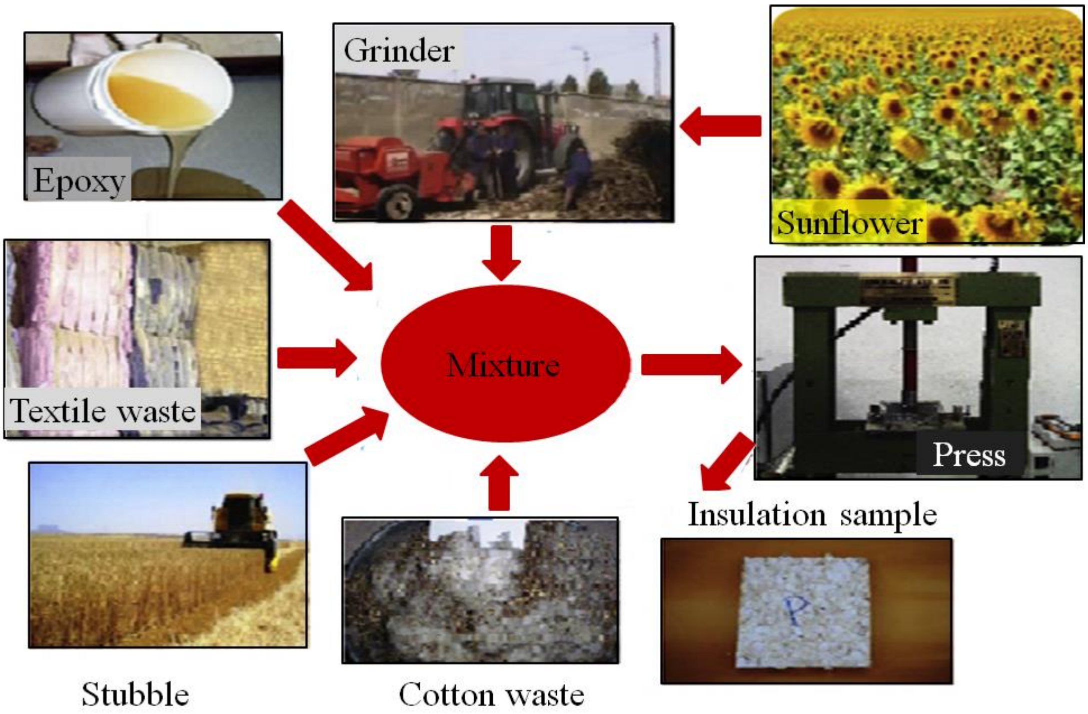


Figure 1.1 Graphical representation of insulation block manufacturing process (Hanifi Binici et. al, 2014).

Hanifi Binici et al. (2014) prepared the thermal insulation block samples of size 30 cm x 40 cm x 2.5 cm using combinations of Sunflower stalk, cotton waste, stubble fibres, and gypsum and urea formaldehyde under different pressures as shown in Figure 1.1. The coefficient of thermal conductivity of the insulation block was found to be 0.1642 W/mK. The water absorption and unit weight of blocks were found to be 71% and 720 kg/m^3 respectively, which satisfies the Turkish Standard (TS 805 EN 601).

Hanifi Binici and Orhan Aksogan (2014) studied on manufacturing of Light weight blocks using fly ash and heterogeneous cotton waste. The different proportions of cement, fly ash, cotton waste and water were mixed to form mortar and moulded by applying compressive force of 40 tons to produce blocks of size 5 cm x 9 cm x 19 cm and 10 cm x 20 cm x 40 cm and cured for 28 days. Co-efficient of thermal conductivity of these blocks was 29% lesser than that of concrete blocks (0.325 kcal/m^{2}h $^\circ$C). The density of light weight blocks was varying from 740 kg/m^3 to 799 kg/m^3. This decreases the building weight and reduces the damage and casualties due to earth quake load.

Ismail et al. (2006) investigated on the manufacture of bricks using clay and Processed Waste Tea (PWT) powder. Three series of composites were manufactured using various percentage of PWT powder (0%, 2.5% and 5%) and clay. Two groups of solid clay-PWT powder brick samples of size 40 mm x 70 mm x 100 mm were manufactured, one group of samples burnt at 900 ºC and other group of samples were not burnt. The PWT powder acts as an agent forming small pores in burnt composite and as binding material in composite which was not burnt. The shrinkage effect of samples was observed after burning them. The increase of PWT powder content decreases the bulk density of brick due to combustible nature of organic material PWT powder during burning period. The water absorption of burnt brick with 5% of PWT samples was 22.7% and for burnt brick without PWT samples was 15.5%. The maximum compressive strength of burnt brick was 22.7 N/mm^2 and un-burnt brick was 7.6 N/mm^2.

Paul et al. (2003) proposed reinforced polypropylene composite made with natural fibres (kenaf, sisal, jute, hemp and coir) using compression moulding process. The experimentally measured mechanical properties of these natural fibre composites were compared with the glass mat fibre reinforced polypropylene composite which was mentioned in existing literature. Composite panels manufactured with kenaf, hemp, flax and sisal fibre showed similar mechanical properties; these composites showed properties similar to that of glass mat fibre reinforced polypropylene composite. Hemp fibre composites exhibit the highest tensile strength of 52 MPa while coir fibre composites gave lowest tensile strength of 10 MPa. The tensile modulus of coir composites is 1.3 GPa which is very low when compared to hemp and kenaf composites (6.8 GPa). Impact strength can be improved by increasing the fibre weight varies from 30% to 50%. In this study, they have concluded that the natural fibre composites can be used for the applications which require very low load bearing capacity than that of composite containing glass fibre.

Chien Chua-Chil et al. (2012) investigated manufacturing of composites for decorative purpose using waste bamboo, charcoal, coal debris, fly ash, cement and water. Five mix proportions were used for preparation of specimen having dimension of 2.8 cm in diameter and 6.0 cm in height. The prepared specimens were cured for 6 days, 14 days and 28 days at room temperature. The specimens were tested for uniaxial compressive test and it was observed that mix proportion of bamboo waste and cement specimen were resulted in compressive strength of 24.402 MPa, 22.246 MPa and 27.636 MPa at 6 days, 14 days and 28 days respectively. Whereas the specimens made with mixture of bamboo-charcoal and cement were resulted in compressive strength of 1.103 MPa, 16.01 MPa and 22.481 MPa at above mentioned curing days respectively.

Sreekumar et al. (2013) worked on the utilization of coir fibre waste as reinforcement to laterite soil for manufacturing of Stabilized Earthen Blocks (SEB). SEB of dimension 190 mm x 110 mm x 100 mm were cast with and without fibre waste. These blocks were tested to compare mechanical properties. Addition of 0.5% coir waste in blocks showed improvement in compressive strength of 19% and tensile strength increased by 9% when compared with the reference block. It was also observed that blocks without coir exhibited brittle failure pattern and blocks with coir fibre exhibited ductile failure pattern. Addition of coir fibres improved the strength, ductility and durability characteristics of the blocks. These blocks are suitable for load bearing structure and for earthquake resistant construction.

Even though several agricultural waste materials are being used for manufacturing of composites, waste from arecanut plantation is not at used extensively for manufacturing of composites. Arecanut husk is the seasonal agricultural waste produced from the arecanut planation after removal of arecanut from areca fruit. The waste arecanut husk creates uncomfortable ambience when it places in the barren lands. Since India is the largest arecanut cultivating country in the world, effective usage of this agricultural waste is essential. Several researchers have started working on composites manufacturing using various waste materials produced from arecanut plantation. The present study deals with the usage of arecanut husk fibre for manufacturing of composite materials.

1.3.2 *Literature survey on physical properties of arecanut*

Ramchandra et al. (2004) made a detail assessment on bio-source availability in Karnataka. Assessment was based on the energy demand and bioenergy availability from domestic, agriculture, horticulture, forests and plantations. The horticulture crops of Karnataka are coconut, cashew nut and arecanut etc. Arecanut tree is tall palm trees grow at different height depending up on the environmental conditions. In Karnataka arecanut was cultivated about 0.78 lakh hectares with an average production of 5.48 lakh tonnes in 2004. The bio sources from arecanut trees are leaf sheath, arecanut, arecanut husk and arecanut stem. The total weight and volume of arecanut husk varies from 60% to 80% of the fresh fruit.

Akhila Rajan et al. (2005) studied on degradation of lignin in arecanut husk fibre for the production of bio softened fibre. The physicochemical properties of dry, ripe, and raw fibre are shown in Table 1.1. Experiments were conducted for 10 samples to measure length, thickness, moisture content and pH value. The average length of fibres was found in the range of 5.5 cm to 6 cm and thickness varies from 300 μm to 650 μm. The moisture contents of dry, ripe and raw fibre are 8.1%, 79.8% and 68.4% respectively. The pH value of the extract is of acidic nature, i.e. 3.0 for ripe nut (golden yellow) fibre, 5.5 for raw nut (green) fibre and 7.0 for dry nut (brownish) fibre.

Table 1.1 Physical and chemical properties of arecanut husk fibre (Akhila Rajan et al., 2005).

Physico-chemical properties of ANH Fibre			
Properties	Dry	Ripe	Raw
Length (cm)	5.5	5.8	5.9
Moisture content (%)	8.05	79.84	68.39
pH of extract	7.0	3.0	5.5

Kaleemullah et al. (2002) studied the moisture dependent physical properties of arecanut kernels. The arecanut kernels contain moisture content of 88.91% d.b at harvesting time and 10.51% d.b after drying. The bulk density increased from 662.14 to 695.91 kg/m^3 and the kernel density increased from 1139.16 kg/m^3 to 1152.48 kg/m^3 as the moisture content decreased from 88.91% to 10.51% d.b. The porosity decreased from 41.87% to 39.62% as the moisture content decreased from 88.91% to 10.51% d.b. The angle of repose decreased from 19.81° to 17.69° as the kernel moisture content decreased from 88.91% d.b. to 10.51% d.b. The mean values of roundness and sphericity of kernel were decreased as moisture content decreased from 88.91% d.b. to 10.51% d.b.

Binoj et al. (2016) studied the characterization of Areca Fruit Husk (AFH). Morphological, physical, mechanical, chemical and thermal properties of AFH were examined and detailed briefly. The obtained Physical properties of AFH fibres from anatomical studies are tabulated below.

Table 1.2. Physical properties of AFH fibres (Binoj et al., 2016).

Property	**Value**
Primary wall thickness (nm)	1074±113
Secondary wall thickness (nm)	402±74
Middle lamellae thickness (nm)	671±53
Cell lumen thickness (nm)	3462±223
Diameter of the fibre (μm)	396–476
Colour of the fibre	Dark brownish
Density of the fibre (g/cc)	0.7–0.8
Porosity of the fibre (%)	38.5–43.2

AFH fibres surfaces were analysed with Fourier Transform Infrared Spectroscopy (FTIR) and found cellulose of 57.35% and wax of 0.12% by weight. AFH Fibres with cellulose of 57.35 wt% were shown maximum tensile strength of 231.66 MPa. AFH fibres surface porous was 40.8 %, which improves interfacial reaction between matrix and fibre. Density of the AFH fibre was 0.78 g/cc which is less than hazardous synthetic fibres which are used to manufacture low density composite. The polymerization temperature of AFH composites shows stabilisation up to 240 ºC. Researchers concluded that AFH fibres can be replaced with synthetic fibres as a reinforcement material in polymer composites.

Raghupathy et al. (2002) had focused on utilization of arecanut leaf sheath for manufacture of paper boards. The various combinations of arecanut leaf sheath with waste paper, 1:1, 1:2, 1:3, 3:1, 2:1 and control (100% arecanut leaf sheath) were used to make paper boards. Tearing resistance, tensile strength, bursting strength, and water absorption tests were conducted as per BIS 1982. The tear strength of paper boards made with 1:3 and 1:2 ratios were best compared to all other combinations and they did not yield to tearing in the first attempt. The water resistance of paper board was increased by adding arecanut leaf sheath. The combination of arecanut leaf sheath and paper of ratio 2:1 and 3:1 improves the tensile and bursting strength.

From the above literature, it is found that arecanut husk fibre having physical properties like length varying from 1.8 cm to 6 cm, diameter 0.28 mm to 0.89 mm, density 0.38 to 1.25, and chemical constituents like hemi cellulose, cellulose, lignin and wax. Physical properties for manufacturing of any natural fibre composites are satisfied.

1.3.3 *Literature Survey on alkali treatment of Arecanut.*

Mohan Kumar et al. (2008) studied on characteristics of alkali treated fibres of arecanut and maize stalk and compared with the other known natural fibre. The arecanut fibre specimen of 50 mm wide and 75 mm long were prepared and soaked in alkali solution for a period of 2 to 3 months with controlled pH value to observe the changes in the specimen weight. It was observed that in initial stages the specimens showed increase in weight around one month, later they lost their weight due to biodegradability of fibres. Arecanut fibres were decomposing at slower rate when compare to other natural fibres. Alkali treated arecanut husk fibre had given maximum tensile strength of 123.36 MPa than untreated arecanut husk fibre i.e. 101.85 MPa. Tensile strength of alkaline treated maize fibre was 152 MPa which is higher than the treated arecanut fibre i.e. 123.36 MPa.

Dhanalakshmi et al. (2015) studied on chemically treated arecanut fibre. The treated arecanut fibres were used for manufacturing of fibre reinforced natural rubber composites. The arecanut fibres were treated with varying percentage of sodium hydroxide (2%, 4%, 6% and 8%) varies the tensile strength were tabulated in Table 1.3.

Table 1.3 Effect of alkali treatment on tensile strength of arecanut fibre (Dhanalakshmi et al., 2015).

Fibre type	Tensile Strength (N/mm^2)	Fibre Composite (N/mm^2)
Untreated	116.93	517.36
2% NaOH	109.33	626.40
4% NaOH	102.43	624.08
6% NaOH	100.13	634.52
8% NaOH	97.82	583.48

Yousif et al. (2008) studied on betel nut (arecanut) fibres for tribo-polyester composites in bearing applications. The hand lay-up technique was used to fabricate the betel fibres reinforced polyester composite (BFRP) is shown in Figure 1.2. BFRP was prepared by compression of fibres to a size of 10 mm x 10 mm x 12 mm with stell roller pressure of 50 kPa. The wear and friction studies were done with block on disk tribometer (Figure 1.3 a) at different normal loads (5 N to 30 N) and sliding distance (0 - 7 km). Wear and coefficient of friction were observed for different orientations of fibres with respect to sliding distance. The considered orientations are Parallel (P-O), anti-parallel (AP-O) and normal (N-O) as shown in Figure 1.3 (b). Observations were made that the coefficient of friction is not changed significantly for P-O and AP-O orientations; specific wear rate was reached after 5 km sliding distance. Unlike P-O and AP-O orientations, in N-O orientation wear rate and coefficient of friction were increased with increment in normal load due to poor support of fibres in this orientation.

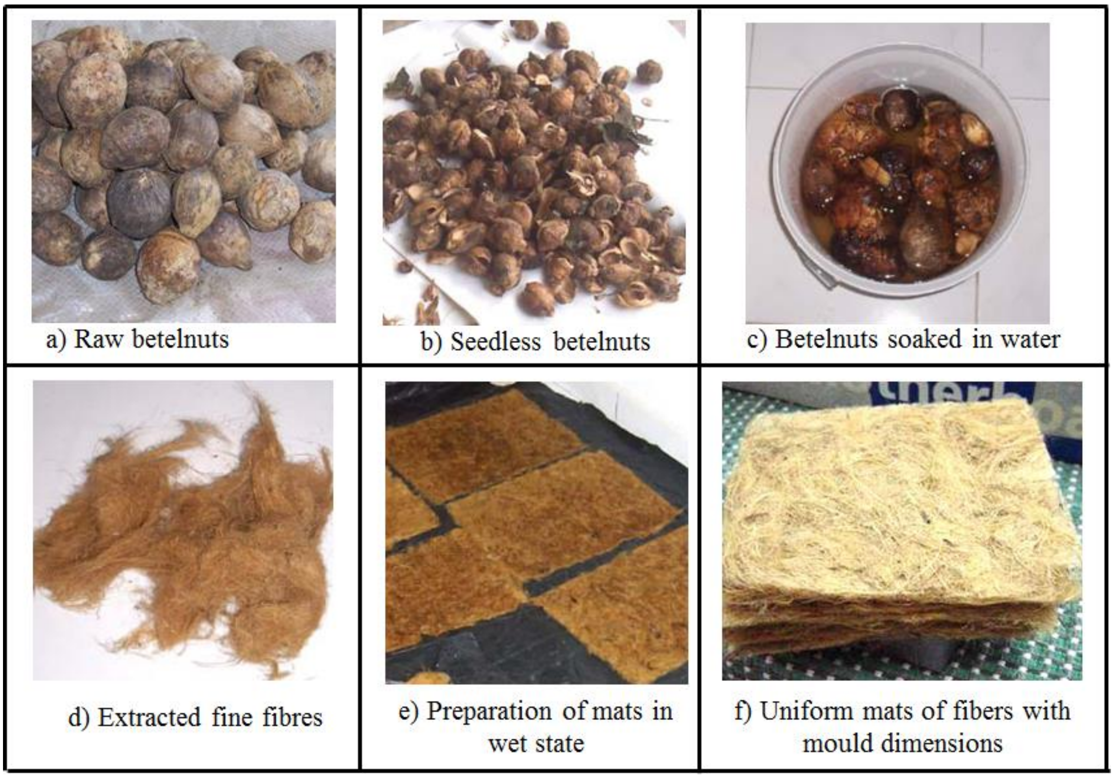

a) Raw betelnuts
b) Seedless betelnuts
c) Betelnuts soaked in water
d) Extracted fine fibres
e) Preparation of mats in wet state
f) Uniform mats of fibers with mould dimensions

Figure 1.2 Extraction process of fine fibres from arecanut (Yousif et al., 2008).

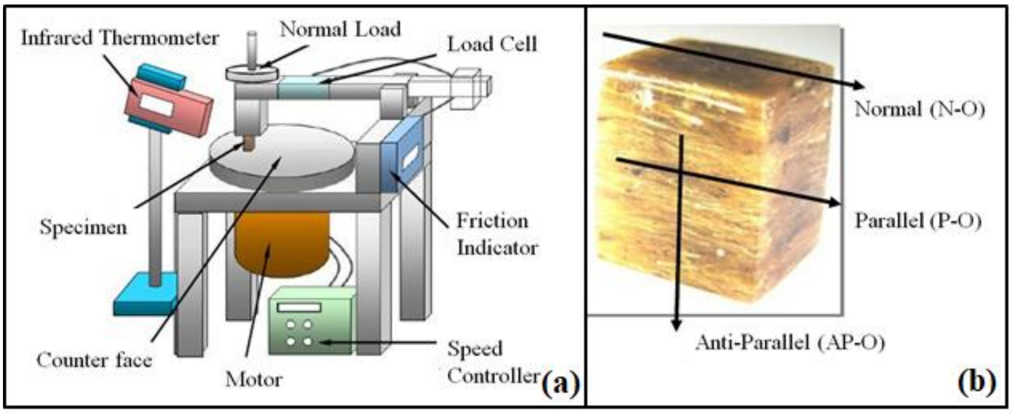


Figure 1.3 (a) block on disk tribometer and (b) the considered orientations (Yousif et al., 2008).

Lai W. L. et al. (2008) compared morphology, physical properties and mechanical properties of treated and untreated woven betel palm and kenaf fibres polyester composites. Woven betel palm and kenaf fibres were alkali treated with 6% NaOH solution, for surface clean and to improve surface roughness. Treated and untreated woven betel palm and kenaf composites were manufactured using fibres of 7% by volume using vacuum bagging technique for experimental studies. Morphological properties and mechanical properties are shown in Table 1.4. The average tensile strength of kenaf and betel palm fibres are 117.9 MPa and 31.6 MPa respectively.

Table 1.4 Chemical composition and tensile properties of betel palm and kenaf fibres (Lai W. L. et al., 2008).

Type of fibre	Cellulose (wt %)	Hemi-celluloses (wt %)	Lignin (wt %)	Moisture content (wt %)	Ash content (wt %)	Tensile strength (MPa)	Young's modulus (MPa)
Betel palm	35.9	26.6	16.6	11.7	9.2	31.6	1262
Kenaf (bast)	76	10.5	9	9	5.2	117.9	2434

Kenaf fibres composite consists of higher tensile and flexural strength compared to betel palm fibres. Researchers also concluded that 6% NaOH treated fibre composites improve the flexural properties than untreated fibre composites. Flexural strength for treated woven kenaf composites shows 161% increment than untreated fibre.

From the literature, researchers used different percentage of alkaline solutions (potassium hydroxide and sodium hydroxide) to remove soil particles and chemical traces on the surface of natural fibres. Natural fibres were treated with varying 2% to 10% of alkali solution and researchers concluded 6% of NaOH solution improves mechanical characteristics of natural fibre composites. Hence, 6% of NaOH solution is considered as optimum percentage for arecanut husk fibre alkali treatment.

1.3.4 *Literature survey on mechanical characterization of arecanut fibre composite materials*

Srinivasa et al. (2011) considered natural fibre (Arecanut husk fibre) to have potential usage like reinforcement in polymer composites. The dried arecanut husk which was soaked in deionized water for 5 days and then dried for 15 days was considered as untreated fibre. The fibre surface was treated with 10% potassium hydroxide solution for 36 hours at a temperature of 30 ºC, then neutralized with 2% of acetic solution and washed with running water. Composites were manufactured using 50% and 60% of alkali treated fibres with urea formaldehyde and melamine formaldehyde resin. The specimens of dimension 50 mm x 240 mm x 10 mm with fibre diameter varying from 0.028 mm to 0.89 mm, length of fibre varying from 18 mm to 38 mm and average density from 1.05 to 1.25 g/cm^3 were cast. The composites with modified surface (treated) of arecanut fibre show betterment in adhesion matrix and mechanical properties (flexural and impact) than untreated surface.

Chakrabarty et al. (2012) manufactured composites using Betel nut fiber (Bn) and polypropylene (PP) with ratios of 10:90, 20:80, 30:70, 40:60 (Bn wt%:PP wt%) using hot press mould method. Betel nut fruit shell was socked in 5% of detergent solution for half an hour and washed by distilled water to remove traces of detergent. Bn fibre were soaked in 20% of NaOH solution for one hour, then fibres were washed with 3% acidic acid to neutralise NaOH traces on the fibre surface. Composites were manufactured with different ratios of untreated, detergent treated and alkali treated fibres with polypropylene using hot-press machine at 180 ºC under 10 MPa pressure for 5 minutes. Mechanical properties of manufactured composites was determined using UTM testing machine and obtained results were given in Table 1.5.

Table 1.5 Mechanical properties of the Betel nut polypropylene (BnPP) composites (Chakrabarty et al., 2012).

Properties	Composites			
	Bn10	Bn20	Bn30	Bn40
Tensile strength (TS, MPa)	24.7	25.5	27	27.25
Elongation at break (Eb, %)	45	47	51	46
Bending strength (BS, N/mm2)	49	51	55	50
Impact strength (IS, kJ/mm2)	1.45	1.5	1.6	1.55
Tensile modulus (TM, MPa)	1480	1550	1600	1720
Bending modulus (BM, MPa)	1750	1800	1950	2100

From the study, researchers concluded Bn30:PP70 mixture composite shows improvement in strength compared to other mixtures. Alkali treated Betel nut fibre composites shows improvement in mechanical properties when compared to detergent washed fibre composite and untreated betel nut fibre composites.

Kamol Dey et al. (2013) utilized arecanut fibre (reinforcement) for manufacturing of bio composite materials with polycaprolactone by compression molding and detailed physical and chemical properties were studied. Surface of arecanut fibres were modified using six different combination of vinyl trimethoxy silane (1-6 wt %) along with methanol (97-92%) and photo-initiator Darocur-1173 (2%). Surface modified areca nut fibre were soaked for 15 min in different formulations and exposed for various dose of gamma radiation (250-1000 krad). Mechanical properties of the manufactured bio composites were tested and found improvement in strength compared to polycaprolactone (PCL) sheet is shown Table 1.6.

Table 1.6 Mechanical properties of the areca nut fibre reinforced PCL based unidirectional composite (50 wt% fibre) (Kamol Dey et al., 2013).

Mechanical Properties of the Composite Material				
	Tensile Strength	Tensile Modulus	Bending Strength	Bending Modulus
PCL Sheet	15 MPa	424 MPa	20 MPa	590 MPa
Composite	32 MPa	685 MPa	45 MPa	820 MPa

Areca nut fibre composites treated with 4% silane and at 500 krad dose of gamma radiation shown improvement in mechanical properties. Tensile strength and bending strength of arecanut fibre composites were found to be 43 MPa and 64 MPa respectively. Researchers concluded that by silane and gamma radiation treatment to composite can improve in mechanical properties of composite materials.

Dhanalakshmi et al. (2014) investigated on the arecanut husk fibre reinforced natural rubber composites. The arecanut fibre was extracted from dried arecanut husk fibre which was soaked in de-ionized water for about five days. Fibres were dried for 72 hours at a temperature of 30 ºC. The arecanut fibre reinforced natural rubber composites of size 300 mm x 300 mm x 5 mm was prepared with weight fraction of 40%, 50%, 60% and 70% of arecanut fibres and natural rubber granules. The composites were mould at a pressure of 5 MPa with varying temperature of 130 ºC, 140 ºC and 150 ºC for 30 minute. The effect of moulding temperature on tensile strength and percentage of elongation were given in Table 1.7.

Table 1.7 Effect of moulding temperature on tensile strength of arecanut fibre (Dhanalakshmi et al., 2014).

Moulding temperature	Tensile strength (MPa)	Elongation at Break (%)
130	126.02	15.48
140	130.25	17.42
150	125.24	18.48
160	127.68	16.94

Yusriah Lazim et al. (2014) had worked on effect of treatment to betel nut (arecanut) husk fibre on physical, chemical, thermal and mechanical properties of Raw, Ripe and Matured arecanut husk fibre. Polymer composites were reinforced using agricultural - waste material betel nut husk (BNH) fibre. BNH fibres are of good aspect ratio, low density and light weight characteristic. The composites made with treated BNH fibres were giving higher mechanical properties when compared with composites made with untreated BNH fibres as given in Table 1.8.

Table 1.8 Physical and mechanical properties of raw, ripe and mature arecanut fibre (Yusriah Lazim et al., 2014).

Type of fibre (BNH)	Fibre density (g/cm^3)	Fibre diameter (mm)	Tensile strength (MPa)		Young's modulus (N/mm^2)		Elongation at break (%)	
			Untreated	Treated	Untreated	Treated	Untreated	Treated
Raw	0.19	0.47	123.92	32.67	1285.66	375.30	22.49	46.42
Ripe	0.34	0.45	166.03	44.73	1381.31	616.03	23.21	32.50
Mature	0.38	0.41	128.79	30.74	2569.03	363.79	23.13	37.25

Scanning Electron Microscopic (SEM) results revealed the reason behind the loss of mechanical properties is due to formation of deep pores in BNH fibre which were caused by alkaline treatment but the interfacial shear strength is more due to high surface area and roughness.

Elammaran et al. (2014) explained chemical treatment effects on betelnut (arecanut) fibres. The composite material was prepared using combination of betelnut fibre and unsaturated polyester in different ratios of 5:95, 10:90, 15:85, 20:80 (betelnut fibre weight %: unsaturated polyester weight %) with cold press mould technique. The composite materials were tested for sound absorption properties as per ASTM Standards, where 20% weight of arecanut husk fibre was found good for sound absorption. The mechanical properties of composite is increased linearly with increase in fibre loading from 0% to 15% and decreased from 15% to 20% of fibre loading. Thermal stability of sodium hydroxide treated fibre composites exhibits lower than the untreated fibre composite.

Srinivas Shenoy Heckadka et al. (2014) studied on biodegradable composite manufactured using base material, binder, plasticizer and natural fibre (areca frond) as reinforcement. Composite mixture were compressed under pneumatic press and cured. Taguchi method with L8 orthogonal array was used to reduce the number of experiments. Maximum flexural strength of 16.97 MPa was obtained with a combination of base (170g), binder (10g), and plasticizer (5g). The obtained flexural strength was in the range of 2.81 MPa to 16.97 MPa. Analysis of the results indicated that plasticizer has the maximum effect on flexural strength of the biodegradable composites.

Lekha et al. (2015) studied on improvement in shear strength of lateritic soil using arecanut husk fibre and cement. Lateritic soil samples were collected from NITK Surathkal campus, Dakshina Kannada district, India. Geotechnical properties of laterite soil were determined as per Indian Standard and found that the soil belongs to SC group (clayey sand) constituent with 9% of gravel, 44% of sand, 32% of silt and 15% of clay and specific gravity of 2.45. Arecanut husk fibres having diameter of 0.35 mm, length of 28 mm were collected from Puttur, Dakshina Kannada district, Karnataka state, India. California Bearing Ratio (CBR) and Unconfined Compressive

Strength (UCS) tests were carried out to determine the optimum quantity of fibre by weight of soil. Fibre by the weight of 0.6% of soil is used as optimum percentage in lateritic soil for stabilization. Arecanut husk fibre with 3% of cement by weight of lateritic soil leads to increase in UCS and CBR.

Chethan et al. (2016) studied the effect of untreated arecanut fibre reinforced epoxy composite manufactured with 70% epoxy resin and 30% fibre was subjected to three point flexural analysis. The flexural strength of the specimens made with 30 mm long fibre was 50.34 N/mm^2.

Sakshi. S. Kamath et al. (2017) reviewed on the utilization of arecanut husk fibre for various composite materials. The chemical treatment of arecanut husk fibre resulted in better surface topography and crystallographic structure. Improvement of mechanical properties of composites depends on the interfacial bonding between fibre and epoxy, which would be more effective when the fibre is chemically treated.

Most of the researchers concentrated on mechanical properties of composites made with agricultural waste from arecanut plantation. For utilization of composites in industries, material properties such as dynamic characteristics and response of composites to environmental factors play an important role. Since polymer composites are sensitive to the environment conditions, variation in temperature, extensive studies on effect of temperature on mechanical properties of composites are essential. The present study focuses on dynamic characteristics such as glass transition temperature and Static characteristics such as tensile strength, flexural capacity and impact resistance of arecanut husk fibre composite panels.

1.4 Research gaps

Research summary highlights utilization of arecanut husk as a revenue generating material for developing countries like India. Detailed studies on arecanut husk fibre are essential to utilize arecanut husk fibre for manufacturing of composite materials. The strength of any composite material depends on the properties of reinforcing material. The uniformity in size of the reinforcing material used for manufacturing composite helps to get uniform strength in the composite panels. Therefore, proper de-husking of arecanut fibre is required to separate the coarse fibres and fine fibres. The study on composites manufactured with coarse fibre and fine fibre separately is essential to get composite panels of uniform strength. The strength of composite panel depends on the percentage of composition of reinforcing material. Studies on optimum percentage of reinforcing material are essential to enhance the strength of composite panel. In the present study, the properties of arecanut husk fibre reinforced epoxy composites is assessed by using conventional testing methods such as tensile testing, flexural testing and impact testing. Suitability of the manufactured composite panel at higher temperature was assessed using Dynamic Mechanical Analysis (DMA). Glass transition temperature of any polymer composite is essential to check the possibility of using the composite at higher temperatures. The glass transition temperature of the manufactured composite panel was observed from the DMA.

1.5 Aim and objectives

The aim of the present research is to investigate the applicability of arecanut husk fibre as reinforcing material for manufacturing composites.

The main objectives of this thesis are:

- Mechanical characterization of arecanut husk fibre composite panels under static loading condition.
- Dynamic mechanical characterization of epoxy composite reinforced with arecanut husk fibre.

The following sub objectives are required to accomplish the above given main objectives:

- Preparation of arecanut husk fibre reinforced composite panels using hand layup technique.
- To find the tensile strength, flexural strength and elastic modulus of arecanut husk fibre reinforced composites.
- Response of composite material reinforced with arecanut husk fibre in absorbing energy transferred is determined by conducting impact tests.
- To find the glass transition of arecanut husk fibre reinforced composite.

- To find the elastic modulus, secant modulus and loss modulus of arecanut husk fibre reinforced composite at various temperatures.

1.6 Structure of the thesis

Chapter 1 provides an introduction to the background of agricultural waste material utilization and management, different types of natural fibres from agricultural waste, manufacturing composite materials reinforced with natural fibres, arecanut husk fibre alkali treatment and utilization of arecanut husk fibre with epoxy for manufacturing of composite panels.

Literature the reviews on waste materials, agricultural waste materials, arecanut, alkali treatment, manufacturing process of composite using natural fibre, characterization of mechanical properties of composites made with natural fibre. This chapter also presents the research gaps, aims and objectives of the present study. Also, the chapter presents the organization of thesis.

Chapter 2 gives the details of arecanut husk fibre and its physical properties, epoxy resin and composite panel manufacturing process is explained in this section.

Chapter 3 Experimental results obtained from Dynamic Mechanical Analysis (DMA) are compared with those obtained from static experiments.

Chapter 4 characterization of mechanical properties of composites made with natural fibre. This chapter also presents the research gaps, aims and objectives of the present study.

Chapter 5 is devoted to conclusions arising from this research study, limitations of present study and scope of future work, followed by references.

CHAPTER 2

MATERIAL PREPERATION AND METHODOLOGY

This chapter deals with preprocessing of arecanut husk fibre for manufacturing of bio-composite, measurement of physical properties of arecanut husk fibre and manufacturing of composite using hand layup technique. Detailed process of fibre treatment and fibre extraction from dried arecanut is given in this chapter. Problems experienced during fabrication of composite panel using hand layup technique and methods followed to get uniform thickness of composite panel are explained in detail.

2.1 Materials

In the present study, the composite panels were manufactured using arecanut husk fibre and epoxy resin. Chemically treated arecanut husk fibre and epoxy resin HSC 7600 (1.16 g/cc) with epoxy hardener HSC 8210 (0.93 g/ cc) were utilized for the panel preparation. The arecanut husk fibre can withstand the tensile load acting on the composite material and the epoxy resin acts like a binding agent of these fibres. The arecanut husk fibres are also protected from environment due to epoxy resin.

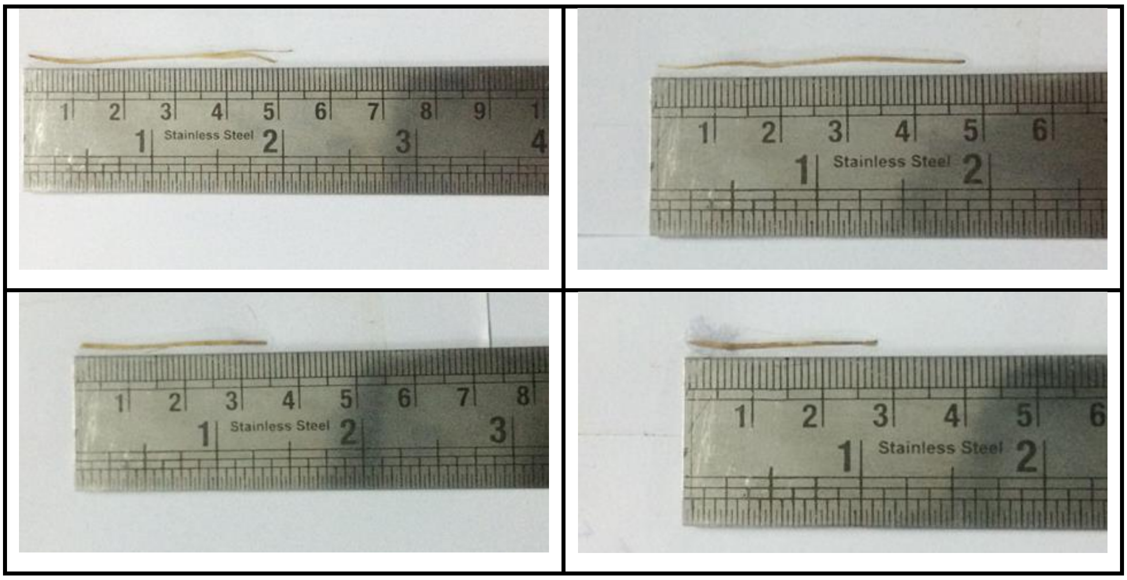
2.1.1 Arecanut husk fibre

Arecanut husk fibre is a non-toxic and eco-friendly material. The weight of areca fibre is less when compared to the weight of synthetic fibres (C.V. Srinivasa et al., 2011). The strength and durability of areca fibre is dependent on the amount of the cellulose content present in the fibre (Narendra Reddy et al., 2005). The moisture absorption of areca fibre increases with increase in hemicellulose content which decreases the fibre performance (Sakshi.S. Kamath et al., 2017). Arecanut husk fibre contains 53.2% cellulose content, 32.98% hemicellulose content and 7.2% lignin content (M.M. Hassan et al., 2010). Fibre obtained from matured arecanut husk was used for composite panel preparation due to its low moisture absorption when compared to fibre obtained from raw arecanut. The dried arecanut fibre contains fine soil particles and chemical substances on the surface of fibres. In the present study, the fibres were treated with alkali solution to remove unwanted substances on the fibre surface. The alkali-treated fibres of finer and coarser arecanut fibres are used for composite panel preparation.

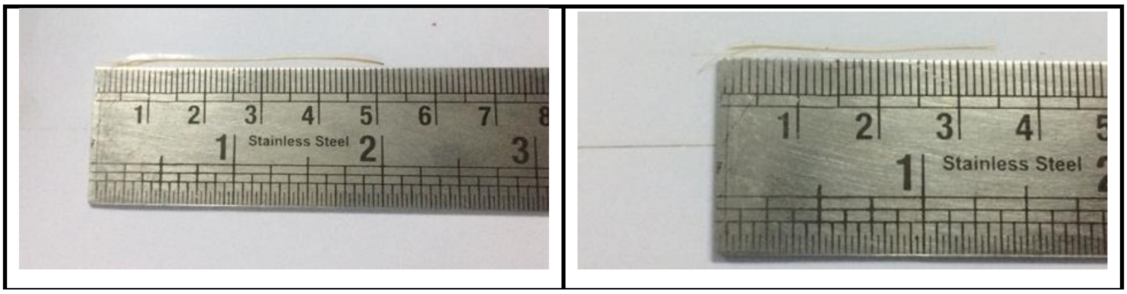
2.1.2 Physical properties of arecanut husk fibre

The performance of natural fibres depends upon physical properties such as length, diameter, density and orientation of the fibres. Dried and treated arecanut fibres were measured to find length, diameter and density of the fibres. Length of the arecanut husk fibres varies from 25 mm to 50 mm (Figure 2.1). Diameter of the treated arecanut husk fibres were measured as 50 µm - 200 µm using optical microscope. Five samples of each coarse fibre and fine fibre were used to measure the density of arecanut husk fibre. Density of the treated coarse arecanut husk fibres and fine arecanut husk fibres were observed as 1.11 g/cc and 0.907 g/cc respectively. The observed density was used to calculate the quantity of arecanut fibre required to cast the composite panels.

Coarse fibre



Fine fibre



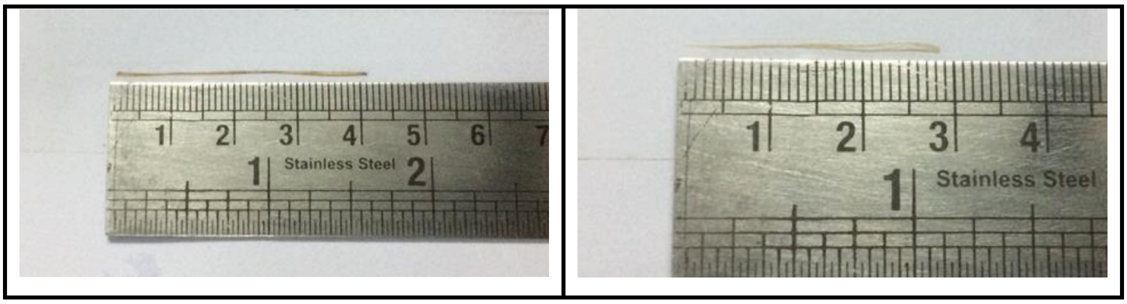


Figure 2.1 Length of coarse and fine arecanut husk fibres.

2.1.3 Model calculation of Density of arecanut husk fibre

The density of fibre was calculated by measuring the mass and volume of the fibre using water pycnometer method are shown in Figure 2.2 – Figure 2.5.

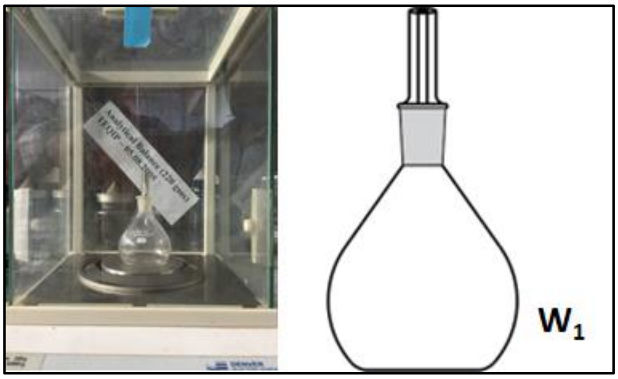


Figure 2.2 Weighing of empty pycnometer.

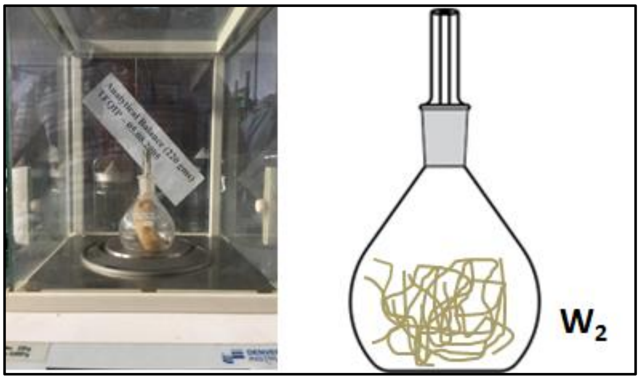


Figure 2.3 Weighing of empty pycnometer with arecanut husk fibre

Figure 2.4 Pycnometer with arecanut husk fibre and water.

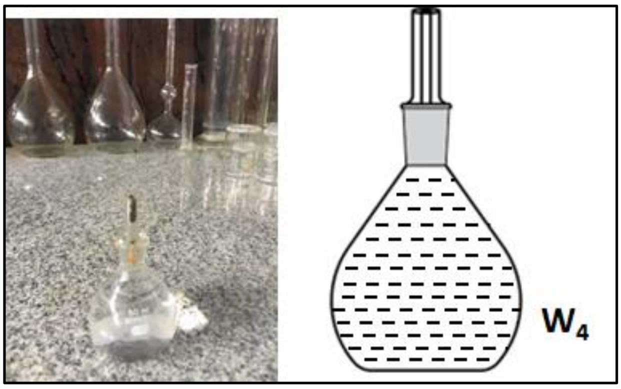


Figure 2.5 Pycnometer with water.

Model observations to calculate density of fibre are given below:

Volume of excess water in the pycnometer containing fibre (V_1) = (W_3-W_2)/density of water

V_1 = (79.124-32.100)/1

V_1 = 47.024 cc

Volume of empty pycnometer (V_2) = (W_4-W_1)/density of water

V_2 = (79.100-30.901)/1

V_2 = 48.199

Density of fibre = Mass of fibre/volume of fibre

Density of fibre = (W_2-W_1)/ (V_2-V_1)

Density of fibre = (32.100-30.901)/ (48.199-47.024)

Density of fibre = 1.020 g/cc

The detailed experimental observations to measure density of all the fibres are given in Appendix I.

2.1.4 Epoxy resin

Epoxy resins have been used in many industries due to its wide range of applications. Epoxy resins are belonging to polymers family. Epoxy resin is used in the present study for manufacturing composite panels due to the typical properties of the epoxy resin such as good adhesive capacity with wide variety of materials, fast curing, low shrinkage after curing, good mechanical properties, electrical resistance, chemical inertness and insoluble in water (J.L. Massingill Jr et al., 2000). Epoxy resin protects the areca fibres from the severe environmental conditions like marine environment, moisture content and chemicals. Due to the cost of the epoxy resin material, certain volume of the components made with pure epoxy can be replaced by a cheaper and strength enhancing material. In the present study, arecanut fibre is used as the volume filler and strength enhancing material of epoxy composites. Due to the wide advantages of epoxy resin material, composites manufactured with areca fibre and epoxy can be used for marine application, electrical insulating components, light weight components, automobile industry and chemical industry.

2.2 Preparation of composite panel with arecanut husk fibre

The manufacture of composite panels requires optimum mix proportion of arecanut husk fibre as reinforcement (filler) and epoxy resin as binder. Arecanut husk fibre (load carrying material), which strengthens the composites by interfacial bonding between arecanut husk fibre and epoxy resin. Interfacial and interphase bonding depends on the surface crystallographic properties of arecanut husk fibre. Since arecanut husk fibre are available in plantation lands, they consist of soil, debris, chemical traces. Arecanut husk fibre was treated with alkali solution for surface treatment to manufacture natural fibre reinforced composites.

The different phases in manufacturing of arecanut husk fibre composite panel and tests conducted for material characterization is explained with the help of flow chart depicted in Figure 2.6.

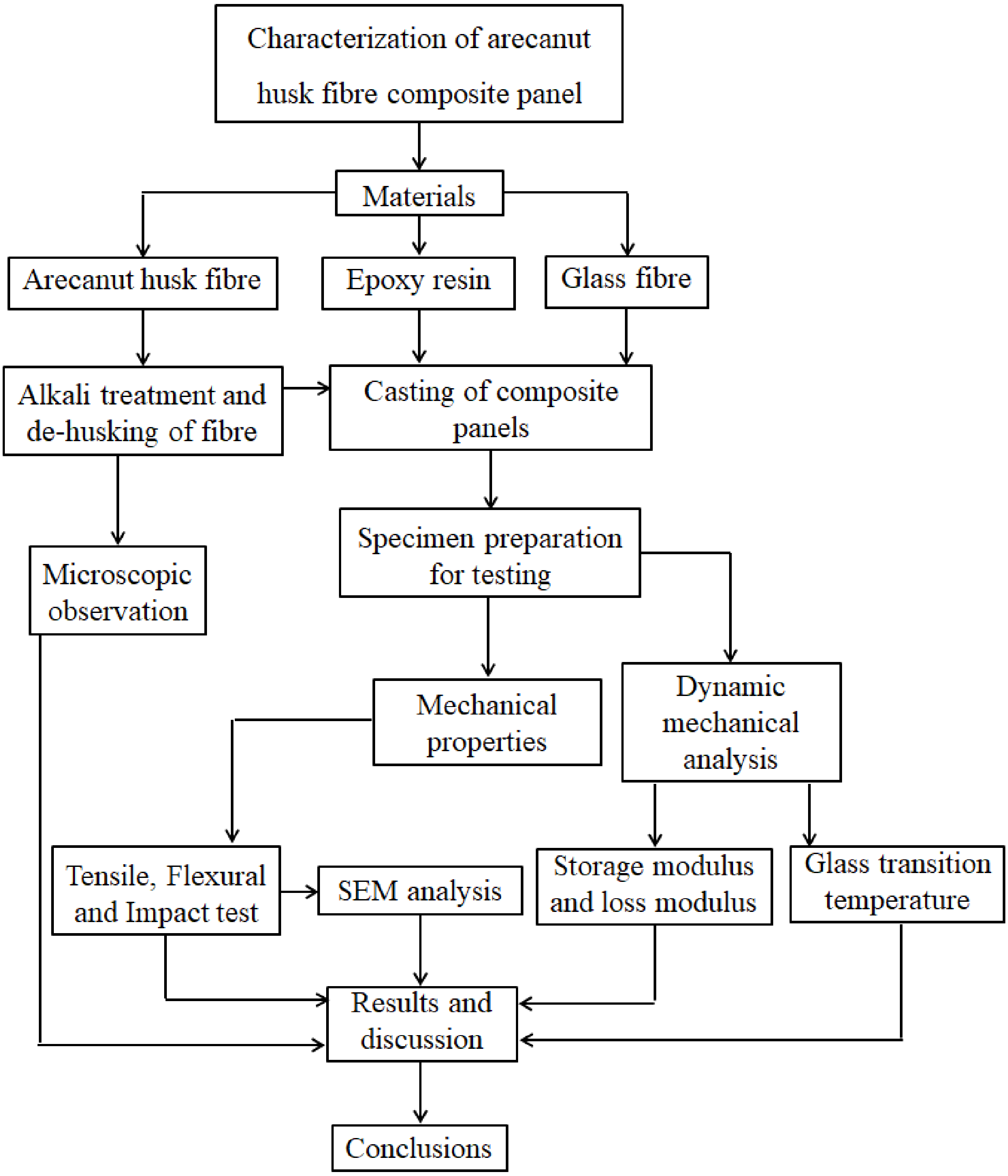


Figure 2.6 Flow chart of methodology for manufacturing and characterization of arecanut husk fibre composite panel.

2.2.1 Alkali treatment and fibre extraction

Dried husk of matured arecanut was collected from the plantation. Dried husk was soaked for 24 h in fresh water to loosen the fibres. Later, the water soaked arecanut husk was cleaned with freshwater to remove the soil particles attached to the fibres. Consequently, the arecanut husk was soaked in 6% by volume NaOH alkali solution for 24 hours at room temperature of 26 ± 2 °C to perform the chemical retting process. The alkali-treated husk was washed with distilled water to remove the chemical traces on surface of the fibres. The washed arecanut husk was sun dried for 2 days to reduce the absorbed moisture content from the arecanut fibres. Fibres were extracted from the sun dried arecanut husk and stored in airtight covers to avoid the moisture absorption. The process of treated areca husk fibre extraction is shown in Figure 2.7 - Figure 2.11.

Figure 2.7 Dried arecanut husk collected from field.

Figure 2.8 Arecanut husk cleaning with water

Figure 2.9 Soaking arecanut husk in alkaline solution.

Figure 2.10 Drying of arecanut husk.

Figure 2.11 Extracted fibre from arecanut husk.

2.2.2 Microscopic observation of arecanut fibre

The extracted fibres from alkali-treated and untreated arecanut husk were separated as coarser and finer fibres. They were examined using optical microscope to observe the average diameter of coarser fibres and finer fibres and their surface texture. From Figure 2.12, the untreated fibres were observed to have light brown colour, whereas the treated fibres were having silky texture. Smooth surface with presence of foreign particles was observed on coarse untreated fibres, while the surface of treated fibres was undulated due to the chemical treatment process. The undulated surfaces may give better bonding between epoxy and fibres. The fibre diameter of untreated fibres was observed more than that of treated fibres. The chemical treatment process reduces the diameter of the fibre due to removal of lignin content from the surface of the fibre (M.T. Paridah et al., 2011). The average fibre diameter of coarse fibres of untreated fibres and treated fibres are in the range of 300-400 µm and 150-200 µm, respectively. The average diameter of fine fibres of both untreated fibres and treated fibres is in the range of 50 - 80 µm. The detailed surface morphology of arecanut fibres observed using optical microscope is given in Figure 2.12 - Figure 2.15.

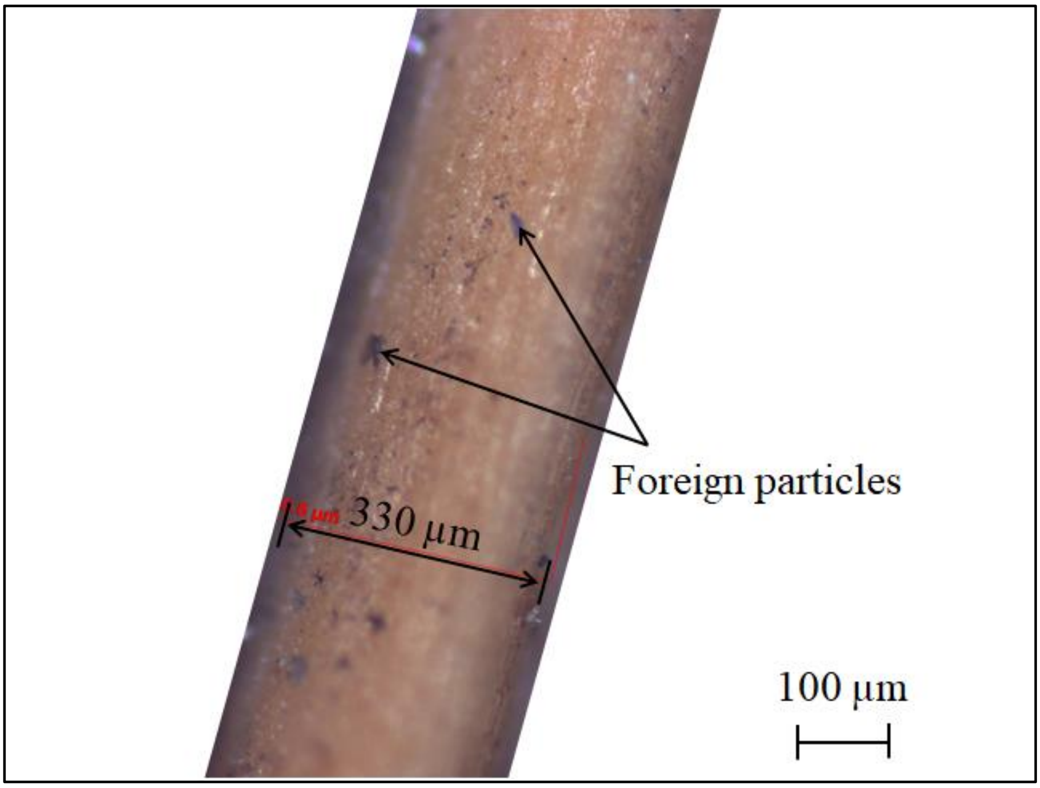


Figure 2.12 Micromorphology of untreated coarse arecanut husk fibre

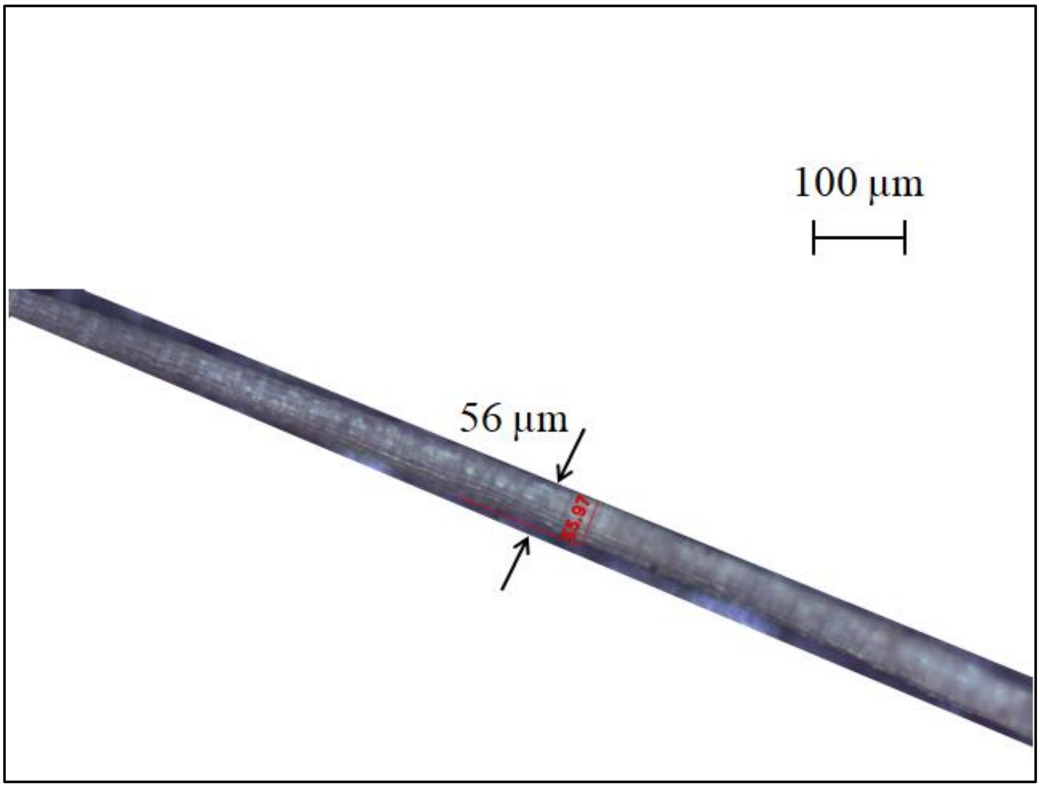


Figure 2.13 Micromorphology of untreated fine arecanut husk fibre

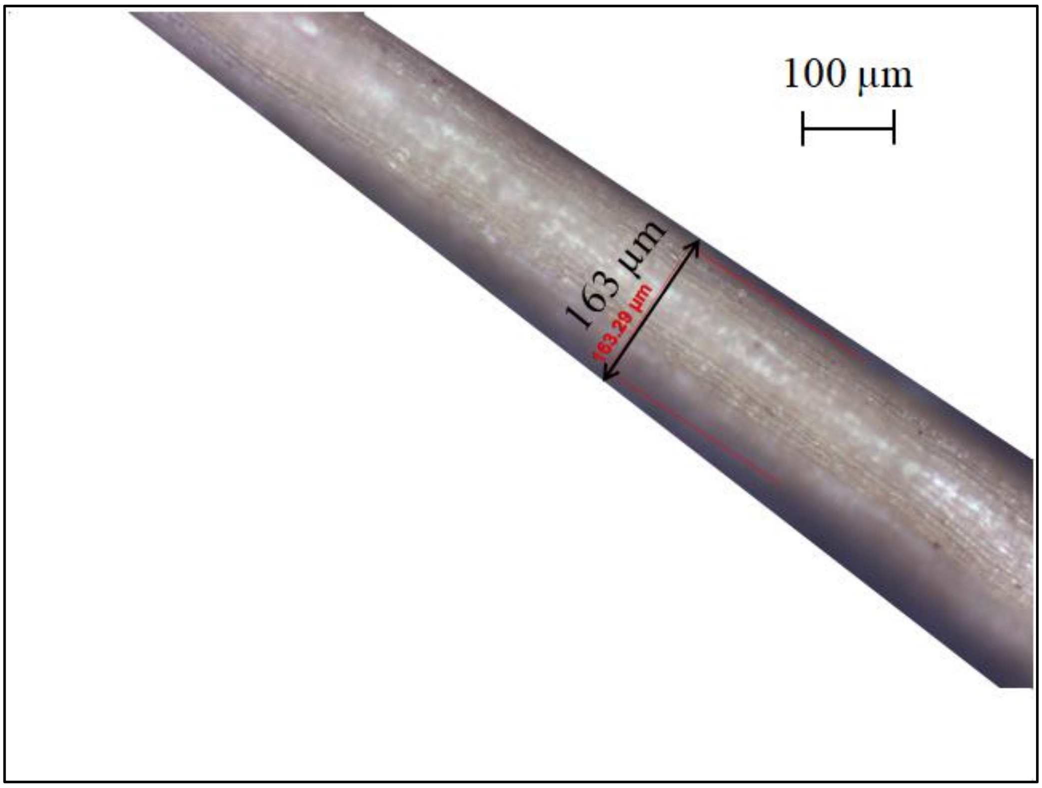


Figure 2.14 Micromorphology of treated coarse arecanut husk fibre

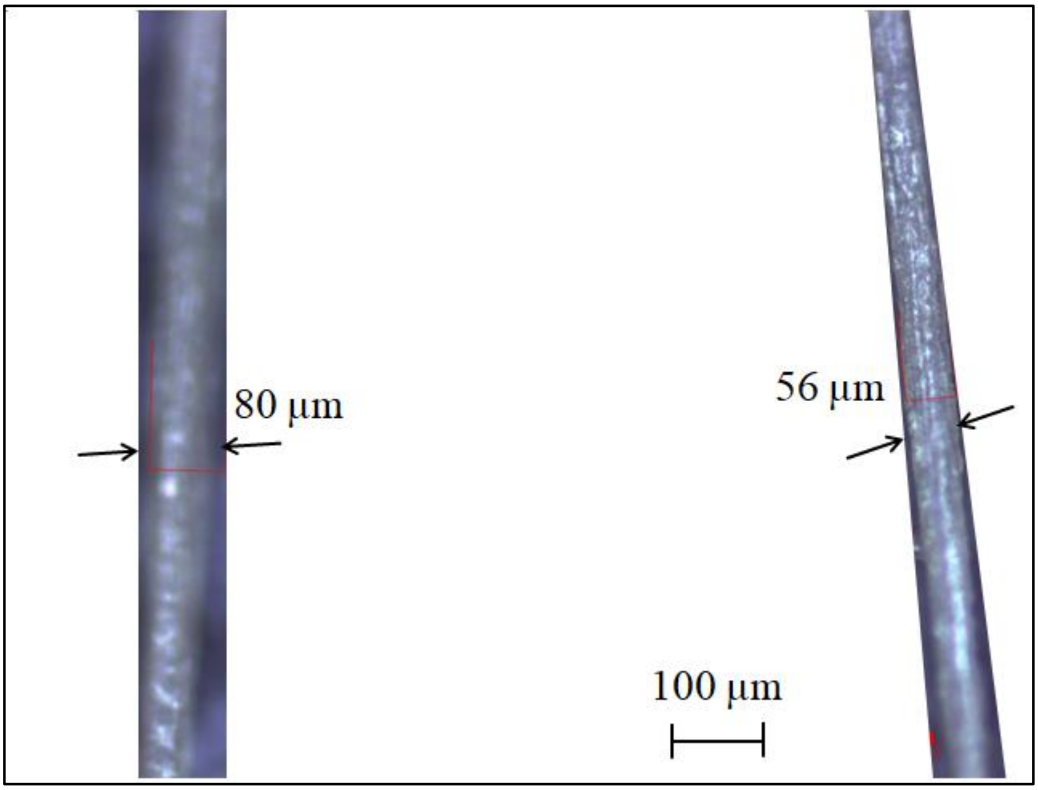


Figure 2.15 Micromorphology of treated fine arecanut husk fibre.

2.2.3 Material constituents content calculation

The weight of fibre required to prepare composite mixture with 100 g epoxy, 10 g hardener and arecanut husk fibre was calculated as below:

Weight percentage of arecanut husk fibre = W_P

The weight of arecanut husk fibre = W_F

The composition of W_P fibre contains arecanut husk fibre of mass, 100 g epoxy and 10 g hardener.

$$W_a = \frac{W_p}{100}\left(W_a + 100 + 10\right)$$

$$W_a = \frac{W_p \text{x} 110}{100 - W_p}$$, For 15 % by weight of the fibre $W_P = 15$

$$W_a = \frac{15\text{x}110}{100-15} = 19.412 \text{ g}$$

Volume of the composite mixture (V_c) = $\frac{W_a}{\rho_a} + \frac{100}{\rho_E} + \frac{10}{\rho_H}$

Density of arecanut husk fibre (fine fibre) (ρ_a) = 1.11 g/cc

Density of epoxy resin (ρ_E) = 1.16 g/cc, Density of hardener (ρ_H) = 0.93 g/cc

$$V_c = \frac{19.412}{1.11} + \frac{100}{1.16} + \frac{10}{0.93} = 114.45 \text{ cm}^3$$

Dimensions of the panel casting mould are 30 cm x 30 cm x 4 mm.

The volume of the casting composite panel (V_p) = 30 x 30 x 0.4 = 360 cm^3

The volume factor (V_f) = $\frac{V_p}{V_c} = \frac{360}{114.45} = 3.145$

$V_p = V_f \text{ x } V_c$

$$360 = V_f \text{ x } \frac{W_a}{\rho_a} + \frac{100}{\rho_E} + \frac{10}{\rho_H}$$

$360 = \frac{V_f W_a}{\rho_a} + \frac{V_f 100}{\rho_E} + \frac{V_f 10}{\rho_H}$ = (volume of arecanut + volume of epoxy + volume of hardener).

The weight of compositions required to cast the given panel dimension with 15% by weight of arecanut husk fibre epoxy composite panel were calculated as given below:

Weight of arecanut (W_A) = Vf x wa = 3.145 x 19.421 = 61.08 g

Weight of epoxy (W_E) = Vf x 100 = 3.145 x 100 = 314.5 g

Weight of hardener (W_H) = Vf x 10 = 3.145 x 10 = 31.45 g

The weight of glass fibre (two sheets) (W_G) = 35 g

The weight of arecanut husk fibre used to fabricate arecanut husk fibre epoxy composites sand witched with glass fibre was considered as W_A – 35 g.

Table 2.1 Weight of materials (arecanut husk fibre, glass fibre and epoxy resin) used for composite panel casting.

Composite type	Weight percentage of fibre	Weight of arecanut (W_A)	Weight of glass fibre (W_G)	Weight of epoxy (W_E)	Weight of hardener (W_H)
Coarse fibre epoxy composite	15%	59.04 g	-	304.15 g	30.42 g
Fine fibre epoxy composite	15%	61.06 g	-	314.55 g	31.45 g
Coarse fibre sandwiched with glass fibre epoxy composite	15% (W_a = 6.1%; W_g = 8.9%)	24 g	35 g	304.15 g	30.42 g

2.2.4 Composite panel casting

The first stage of composite panel preparation was made by arranging the fibres in mould and by pouring the epoxy resin on the top of fibres (Figure 2.16). The mould was cured using hot press moulding for 30 minutes. In this process thermal hardener was used for preparation of panel. The resulted panel from hot press moulding process is given in Figure 2.17. Uneven distribution of fibre was observed due to flow of fibre in the mould during hot moulding process. So, the second stage of panel preparation was decided to cast the panel using room temperature hardener. Arecanut husk fibre was arranged in the casting mould and epoxy resin was poured on the top of the fibre as shown in Figure 2.16. The resin was allowed to flow to the bottom part of the mould by gravity. The mould was closed with covering plate held with C-clamp mechanism as shown in Figure 2.18.The mould was allowed for curing of 6 hours and then the casted panel was removed from the mould. The resulted composite panel was very poor and contains uneven distribution of resin. The failed composite panel in second stage of casting is given in Figure 2.19.

Figure 2.16 Addition of epoxy resin to the fibre.

Figure 2.17 Failure of AHF composite panel due to hot press moulding.

Figure 2.18 Holding cover plate of cast mould with C-clamps.

Figure 2.19 Failed cast panel due to uneven distribution of epoxy resin.

Later, the fibres were wetted with resin and arranged in casting mould resulting in observation of more pores in this stage due to presence of air bubbles in the fibre epoxy mixture. The air bubbles were removed by pouring extra resin and applying uniformly distributed load on the covering plate of the mould. Finally, the composite panel prepared thus is shown in Figure 2.23.

The matrix used to fabricate composite panels is epoxy resin HSC 7600 with hardener HSC 8210 and treated AHF of 15 % by weight were used as reinforcement. AHF composite panels were cast using a mould and it’s covering plate made of mild steel. Composite panels were prepared with dimensions of 320 mm x 320 mm x 3.5 mm. Covering plate of thickness 3 mm was used to avoid bending of the cover plate and to obtain a uniform thickness of the composite panel. The inner surface of the mould and covering plate were cleaned with acetone solution and coated with thin layer of wax (Figure 2.20). Hand lay-up technique was used to prepare the composite panels. A layer of a matrix was poured into the mould to provide clear cover between fibre and mould. Subsequently, fibres were dipped in the matrix and arranged on mould randomly (Figure 2.21). A uniform load of 150 kg is applied on the cover plate to get a uniform thickness of the composite panel (Figure 2.22). Panels were cured for a period of 6 hours at room temperature. The same procedure was followed for the AHF sandwiched with glass fibre composites. While casting the glass fibre composite panel the bottom and top layer of arecanut fibres were covered with glass fibre sheets of 0.2 mm thickness as shown in Figure 2.24 and Figure 2.25. The coarse fibre sandwiched with glass fibre composite was cast with 6.1% of coarse fibre, 8.9% of glass fibre, by weight of composite.

While casting the composite panels care has been taken to arrange the fibre layers uniformly. After casting the composite panels, the non-uniform fibre dispersion portions of the cast panel were neglected for testing.

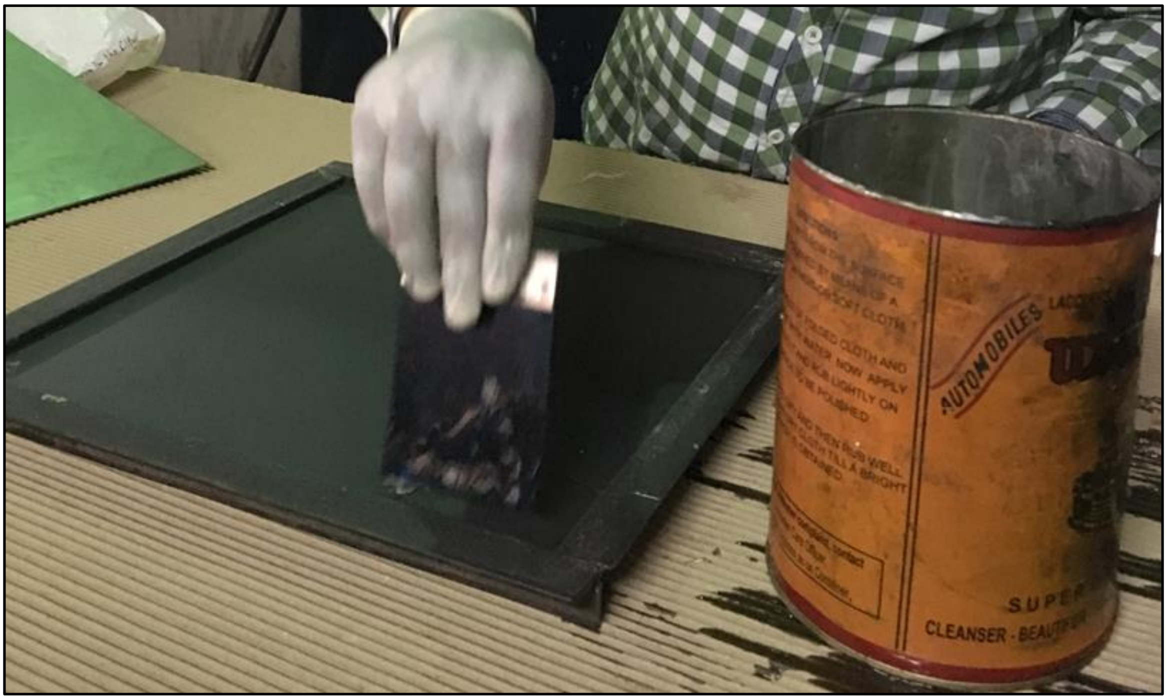


Figure 2.20 Waxing of mould before casting the composite panel.

Figure 2.21 Random arrangement of fibre in mould.

Figure 2.22 Application of uniformly distributed load on mould.

Figure 2.23 AHF composite panel after unmould.

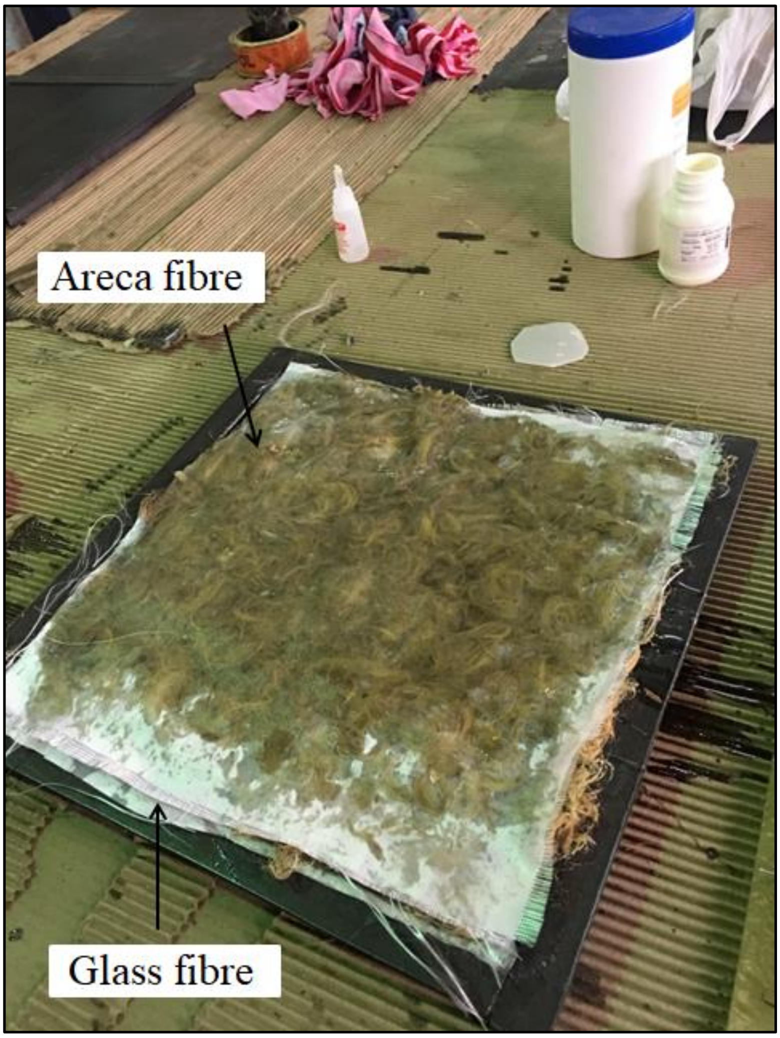


Figure 2.24 Arrangement of AHF and glass fibre while casting AHF sandwiched with glass fibre composites.

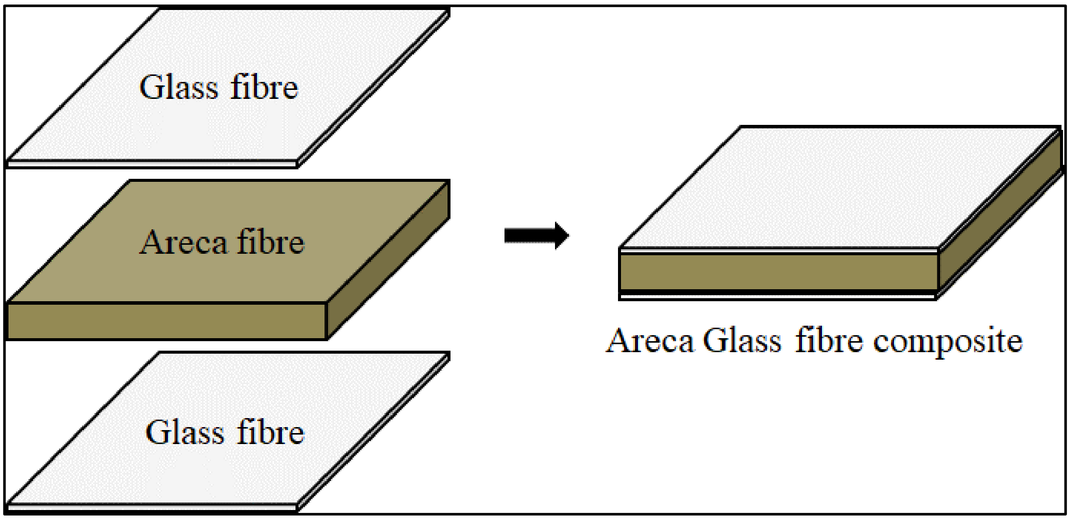


Figure 2.25 Schematic of fibre layer arrangement AHF sandwiched with glass fibre composites.

CHAPTER 3

DYNAMIC MECHANICAL ANALYSIS

The main aim of this chapter is to find out the glass transition temperature, storage modulus, loss modulus and elastic modulus of arecanut husk fibre reinforced epoxy composites using Dynamic Mechanical Analyzer (DMA). Studies on dynamic mechanical characteristics of any new material is essential for industrial application which are subjected to vibration loads. Due to viscoelastic nature of polymers, understanding the effect of temperature on moduli (elastic modulus, storage modulus and loss modulus) of polymer composites and glass transition temperature is essential.

3.1 Materials

Composite panels were manufactured using AHF obtained from arecanut plantation in the present research work. To fabricate AHF composite panels, a fibre reinforcement of 15% by weight, epoxy resin (L12) and epoxy hardener (camcure-2386) were used as matrix to bind AHF reinforcement. Fibres were chemically treated to improve surface roughness, and thereby adhesion between fibre and matrix was improved. Arecanut husk fibres are short fibres which give stiffness to composite panel (Umar Nirmal et al., 2015). Epoxy is the thermoset resin, having properties such as low curing time, good mechanical properties, low shrinkage affect, chemical inertness, low electrical conductivity and insoluble in water (Massingill JR. J.L. and Bauer R.S, 2000). Matrix, acts as continuous phase in the composite panel, binds the fibres together, distributes load to the fibres and protects fibres from environmental affects.

3.1.1 Physical properties of arecanut husk fibre

The performance of the natural fibre composites depends upon physical properties like length, diameter, density and orientation of the fibres. Dried and treated arecanut fibres were considered to find length, diameter and density of the fibres. Length of the arecanut husk fibres varies from 25 mm to 65 mm. Diameter of the treated arecanut husk fibres was measured as 50 µm - 300 µm using optical microscope. Density of the fibres was measured using water pycnometer method. Average density of the treated arecanut husk fibres was 0.947 g/cc (Appendix I). This density of AHF was used to calculate the quantity of arecanut fibre required to cast the composite panels.

3.2 Composite panel preparation

3.2.1 Fibre surface treatment, extraction and thread formation

AHF was soaked in clean water for 24 hours for removing soil particles attached to the fibres. Soaking process loosens the fibres and makes the fibre extraction easier. Water-soaked fibres were treated by soaking the fibres for 24 hours in 6% NaOH alkali solution under room temperature of 26 ± 2 °C. Fibres treated with alkaline solution were cleaned with fresh water to remove foreign substances and alkali traces on fibre surface. Cleaned fibres were dried for two days to reduce moisture in the fibres. Fibres were extracted from treated arecanut husk to cast AHF composite panels. The extracted fibres were made into threads by using hand spin yarning process (Figure 3.1).

Figure 3.1 Preparation of arecanut husk threads using hand spin yarning process.

3.2.2 Fabrication of Composite panel

The matrix used to fabricate composite panels was epoxy resin (L12) with hardener (camcure-2386) and treated AHF of 15% by weight was used as reinforcement (Elammaran Jayamania et al., 2014). AHF composite panels were cast using a mould and it’s covering plate made of mild steel. Composite panels with dimensions of 150 mm x 120 mm x 5 mm were cast for present research work. Covering plate of thickness 3 mm was used during casting process for uniform distribution of load and to resist for bending. Load of 150 kg was placed over the cover plate of the mould to get a uniform composite panel thickness of 5 mm. The inner surface of the mould and covering plate were cleaned with acetone solution and coated with thin layer of wax. Hand lay-up technique was used to prepare the composite panels. A layer of a matrix was poured into the mould to provide clear cover between fibre and mould. Subsequently, fibre threads were dipped in the matrix and arranged on mould in three-layered form (two layers in the longitudinal direction of the panel and middle layer in the transverse direction of the panel) as shown in Figure 3.2 and Figure 3.3. A uniform load of 150 kg was applied on the cover plate to get a uniform thickness of the composite panel. Panels were cured for a period of 6 hours at room temperature. Fabricated panels (Figure 3.4) were cut into specimen of dimensions 80 mm x 10 mm x 5 mm for dynamic flexural experiments using diamond cutter. The specimen cutting process is given in Figure 3.5.

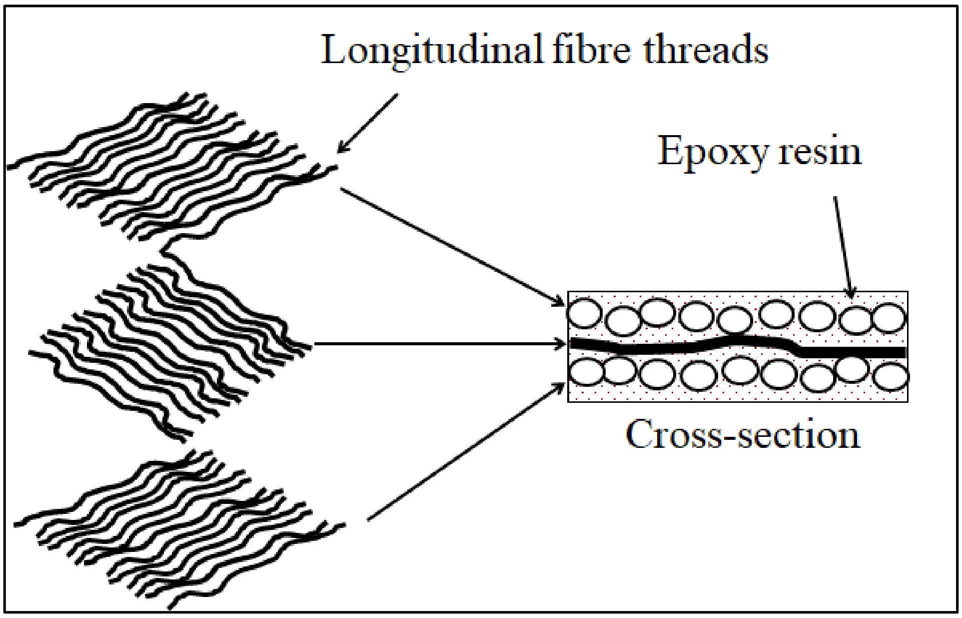


Figure 3.2 Schematic of longitudinal and transverse fibre threads arrangement used for the composite panel fabrication.

Figure 3.3 Arecanut husk fibre threads orientation in the form of mat for specimen preparation.

Figure 3.4 Cast arecanut husk fibre epoxy composite panel.

Figure 3.5 Specimen cutting process using diamond cutter.

3.3 Dynamic flexural experiments

Arecanut husk fiber composite specimens were subjected to dynamic loading at a temperature range of 28 ºC - 120 ºC, at a heating rate of 3 ºC/min. using DMA 50N equipment (Figure 3.6). Tests were conducted according to the standards ASTM D5418 – 15. The double cantilever mode (Figure 3.7 and Figure 3.8) bending was used to test the composite samples at a cyclic loading frequency of 5 Hz, 10 Hz and 15 Hz. Generally, polymers have both elastic and viscous properties. The modulus obtained by testing polymers is a complex modulus which contains real component (elastic modulus) and imaginary component (viscous modulus). The elastic properties of the polymer materials can be obtained by dynamic mechanical analyzer (DMA). DMA applies force at required frequency on the specimen and observes the response of the materials with respect to time. Generally, DMA applies force on specimen in sinusoidal wave form of constant amplitude and collects the response in sinusoidal manner (Figure 3.9). The polymers exhibit some phase lag (δ) between force curve and response curve. Pure elastic materials exhibit zero phase lag whereas the pure viscous materials exhibit phase change of 90°.

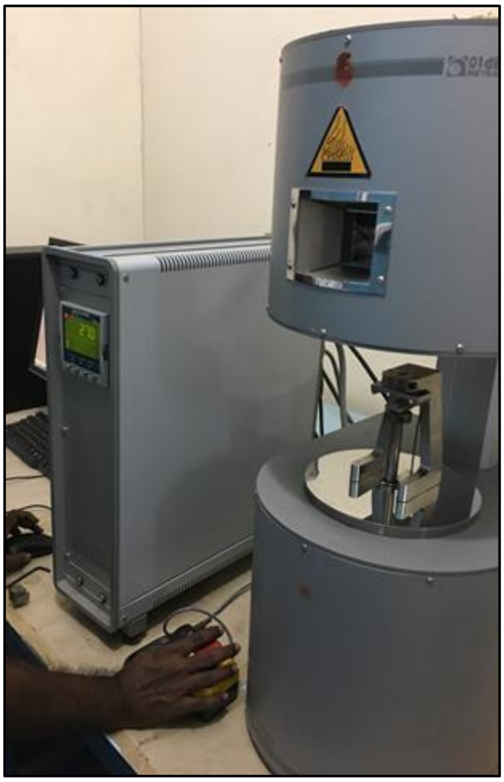


Figure 3.6 DMA 50N equipment.

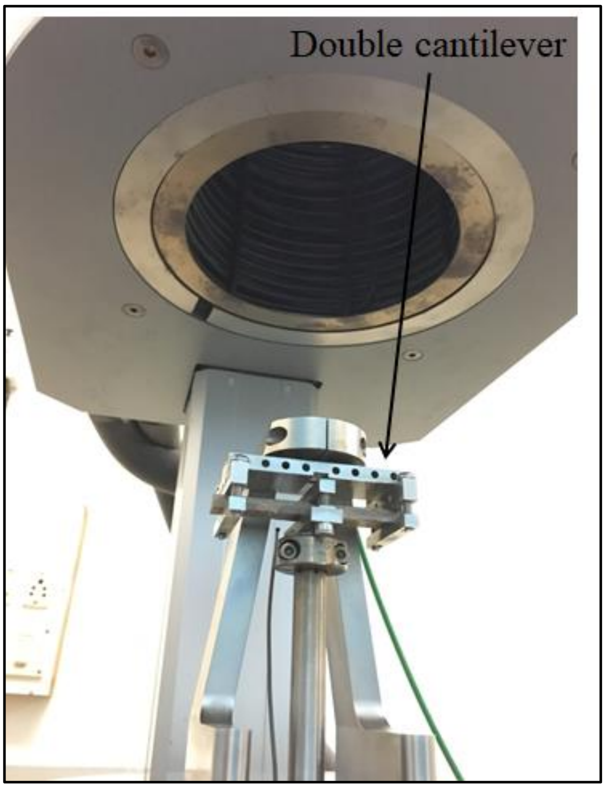


Figure 3.7 Double cantilever beam arrangement in DMA.

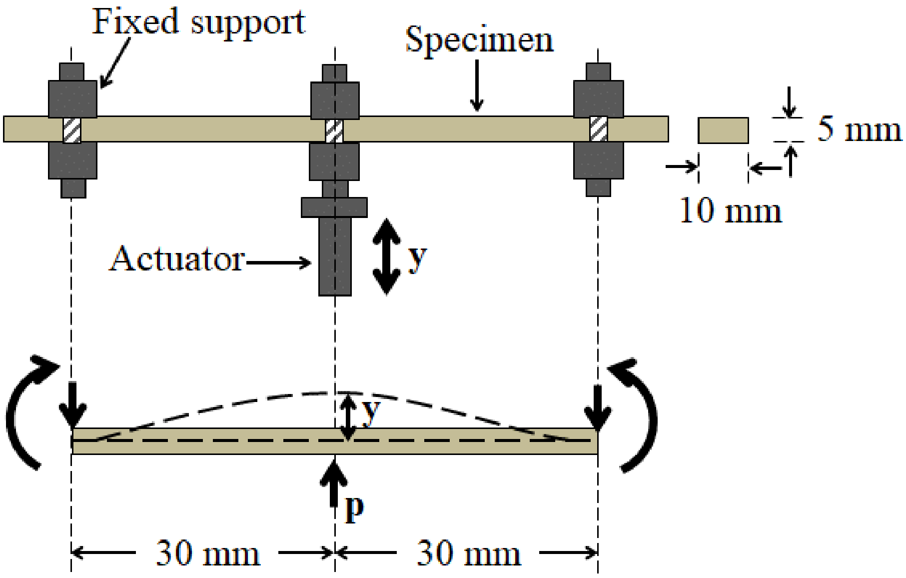


Figure 3.8 Schematic diagram of double cantilever beam arrangement in DMA.

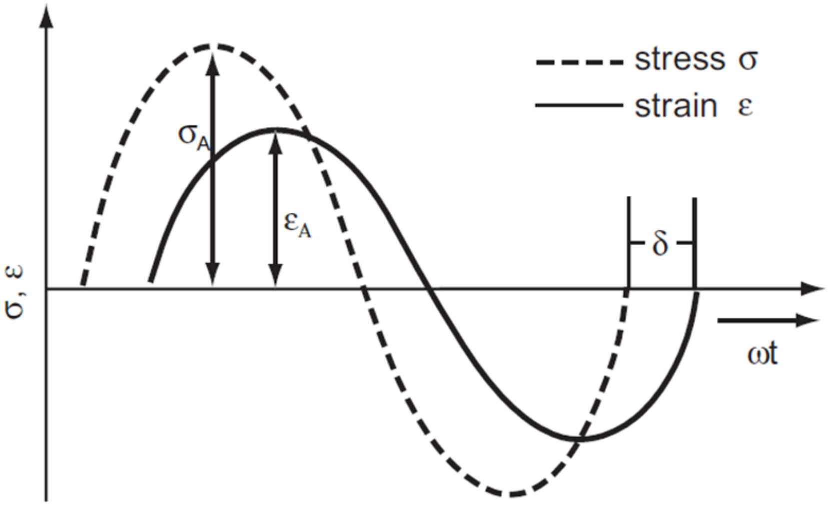


Figure 3.9 Schematic picture of applied load and response curves from the DMA (Hevin P. Menard, 2008).

The schematic diagram of sinusoidal stress and sinusoidal strain curves are given in Figure 3.9. The information of amplitudes of stress and strain curves and phase lag (δ) over a period of time are the base quantities required for the calculation of moduli of the material. The storage modulus (E'), loss modulus (E") and tan (δ) were calculated by using the equations (3.1), (3.2) and (3.3) respectively (Hevin P. Menard, 2008).

$$E' = \frac{\sigma_A}{\varepsilon_A}\cos(\delta) \tag{3.1}$$

$$E'' = \frac{\sigma_A}{\varepsilon_A}\sin(\delta) \tag{3.2}$$

$$\mathrm{Tan}(\delta) = \frac{E''}{E'} \tag{3.3}$$

3.3.1 Storage modulus (E')

The ability of material to store energy and release energy during loading and unloading process represents the storage modulus (E'). The storage modulus represents the elastic property of the material (Hevin P. Menard, 2008). The storage modulus of the arecanut husk fiber composites increased (0.478 GPa, 0.573 GPa and 0.607 GPa) with increase in loading frequency (5 Hz, 10 Hz and 15 Hz) as shown in Figure 3.10. The material is able to retain its elastic property upto a temperature of 80 °C and later it transforms to viscous material, which shows decrease in storage modulus. From Figure 3.10, consistency in storage modulus upto 80 °C temperature represents the persistence of good bonding between fiber and epoxy (Shanmugam D. and Thiruchitrambalam M., 2013; Vimalanathan P. et al., 2018). At higher loading frequencies, the composite does not have enough time to deform fully, which results in higher elastic modulus (Obada D.O., 2018). Therefore the storage modus increases with increase in loading frequency (Figure 3.10). The arecanut husk fiber composites exhibit better elastic properties at higher loading frequency. At lower temperature, composites exhibit higher elastic nature due to immobilization of polymer chains and strong interlocking of fibre and matrix (Obada D.O., 2018). As the temperature increases, the polymer chains move easily and the fibre-matrix interlocking diminishes which leads to decrease in storage modulus. At higher temperature, the specimens subjected to 10 Hz and 15 Hz frequency resulted similar storage modulus.

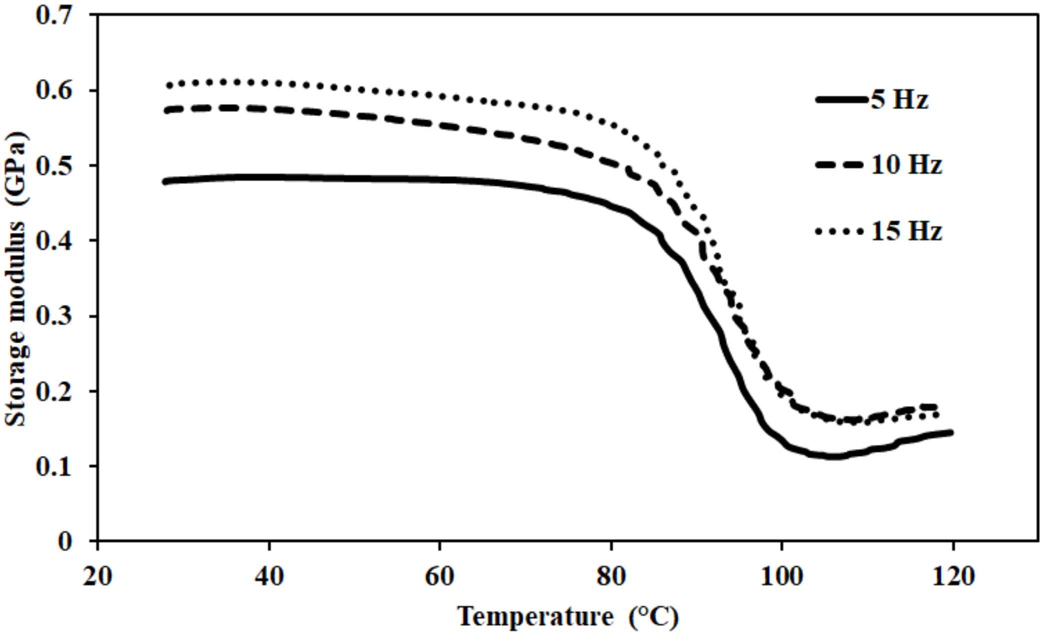


Figure 3.10 The storage modulus variation at different loading frequencies.

3.3.2 Loss modulus (E'')

The ability of material to absorb energy (non-recoverable energy) represents the loss modulus (E''). The loss modulus gives the viscous property of the material and hence is referred to as viscous modulus. The viscous property of the material depends on phase lag between stress curve and strain curve. At 80 ºC, the loss modulus has increased suddenly which indicates the change in material behavior from elastic material to viscous material. Up to 70 ºC, loss modulus decreases with increase in temperature. Later, sudden increase in loss modulus is due to dissipation of energy in intermolecular frictional forces (Dipa Ray, 2002). The stored energy in the material dissipates suddenly in the glass transition region which results in rapid increase of loss modulus and rapid decrease of storage modulus. The peak of loss modulus curves (Figure 3.11) increases with increase in loading frequency.

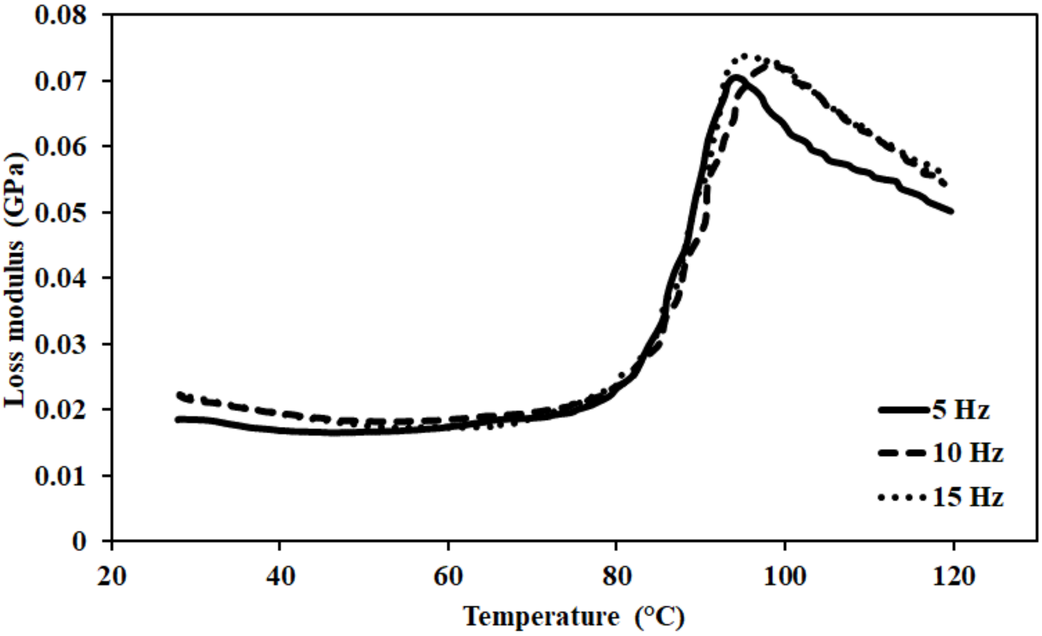


Figure 3.11 The loss modulus variation at different loading frequencies.

3.3.3 Damping factor (Tan-delta)

Tan-delta is the ratio of loss modulus to storage modulus. The storage modulus and loss modulus depend on geometry of the test specimens, but the tan-delta (δ) is a constant which does not depend on geometry of the test specimens (Rajini N. et al., 2016). The peak of the tan-delta (δ) curve represents the glass transition temperature of the material (Dipa Ray et al., 2002; Vimalanathan P. et al., 2016). From the experimental study, it is observed that the glass transition temperature of the arecanut husk fiber panels is not affected by the loading frequency and the glass transition temperature is observed as 105 ºC (Figure 3.12). The peak of tan-delta (δ) curve characterizes the damping nature of a material (Pothan LA, Z Oommen and S Thomas, 2003). The peak of tan-delta (δ) curve represents the internal molecular motion and dissipation of energy at fiber matrix interactions (Pothan LA, Z Oommen and S Thomas, 2003; Huda MS, 2008). In the present study, arecanut husk fiber epoxy composite has better damping characteristics at 5 Hz loading frequency (Figure 3.12) when compared to 10 Hz and 15 Hz loading frequencies.

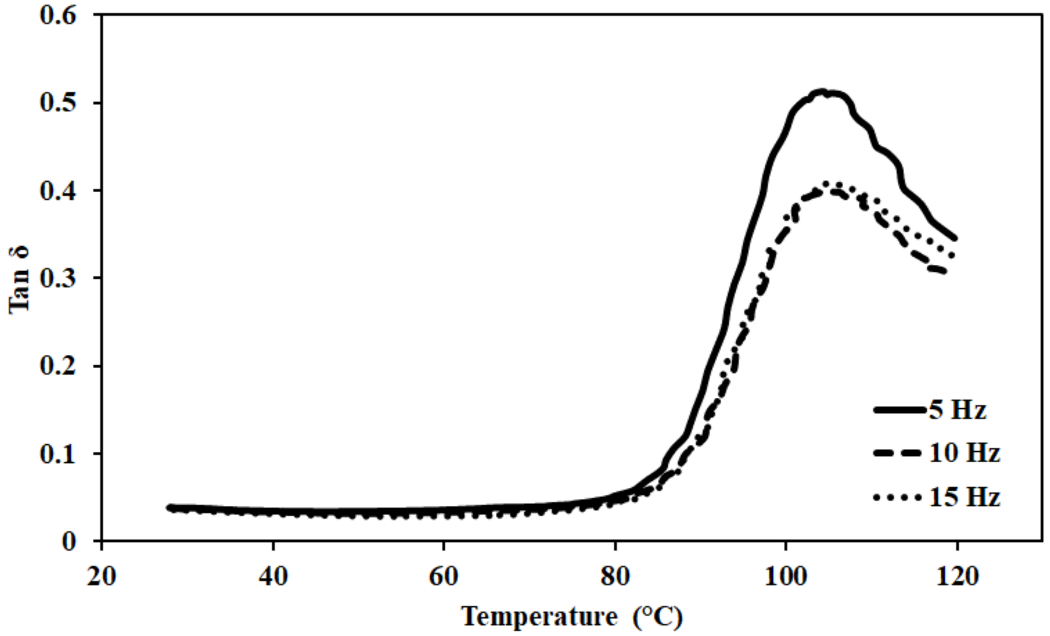


Figure 3.12 The tan (δ) variation at different loading frequencies.

3.3.4 Elastic modulus calculation

Dynamic flexural experiments were conducted by applying maximum deflection of 0.1 mm at mid-span of double cantilever beam. Force required to give 0.1 mm deflection at an instant of time was acquired through DMA data acquisition system. The tests were conducted at ambient temperature ranging from 28 ºC to 120 ºC. The schematic representation of test specimen and the forces acting on the specimen during testing is shown in Figure 3.13. The force required to give 0.1 mm deflection at various temperatures is given in Figure 3.14. The elastic modulus of the composite material is calculated by equating the known central deflection (y = 0.1 mm) with the theoretical deflection (Equation 3.7) derived from Euler - Bernoulli bending theory (Gere and Timoshenko, 1984). The elastic modulus of the composite at different ambient temperatures is calculated and given in Figure 3.15. The calculated elastic modulus decreases with increase in temperature. At lower temperatures (from 28 °C to 80 °C), the elastic modulus is more for higher loading frequency when compared to that of the lower loading frequency. Significant drop in elastic modulus at all loading frequencies is observed at 80 °C temperature. At room temperature (28 °C), the elastic modulus is observed as 3.4 GPa, 2.95 GPa and 2.7 GPa for loading frequencies of 15 Hz, 10 Hz and 5 Hz respectively (Figure 3.16).

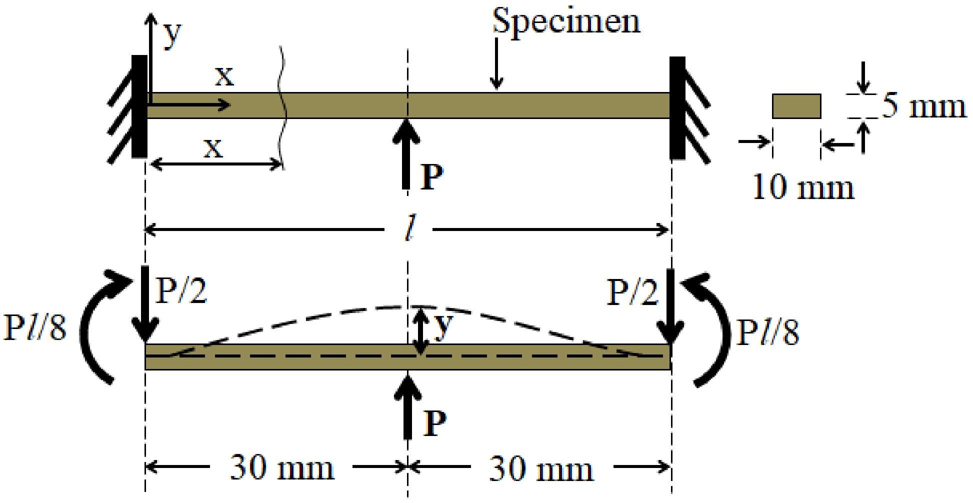


Figure 3.13 Schematic picture of double cantilever beam and free body diagram of the beam.

$$EI\frac{d^2y}{dx^2} = \frac{-Px}{2} + \frac{Pl}{8} \qquad (0 \le x \le l) \tag{3.4}$$

By performing two times integration

$$EIy = \frac{-Px^3}{12} + \frac{Plx^2}{16} + C_1x + C_2 \qquad (0 \le x \le l)$$

Where; C_1 and C_2 are integral constants which can be obtained from the boundary conditions:

$y = 0$ at $x = 0 \Rightarrow C_2 = 0$ and

$dy/dx = 0$ at $x = 0 \Rightarrow C_1 = 0$

$$EIy = \frac{-Px^3}{12} + \frac{Plx^2}{16} \qquad (0 \le x \le l) \tag{3.5}$$

$$\text{at } x = l/2 \Rightarrow y = \frac{Pl^3}{192EI} \tag{3.6}$$

$$y = \frac{pl^3}{192EI} \tag{3.7}$$

$$E = \frac{pl^3}{192yI} \tag{3.8}$$

$$E = 108p \tag{3.9}$$

Where;

y = Applied vertical deflection at mid span of the double cantilever beam (0.1 mm)

p = Measured reaction force at mid span of the double cantilever beam (N)

l = Length of the double cantilever beam (60 mm)

I = Moment of inertia of the section (104.17 mm^4)

E = Elastic modulus of the material (MPa)

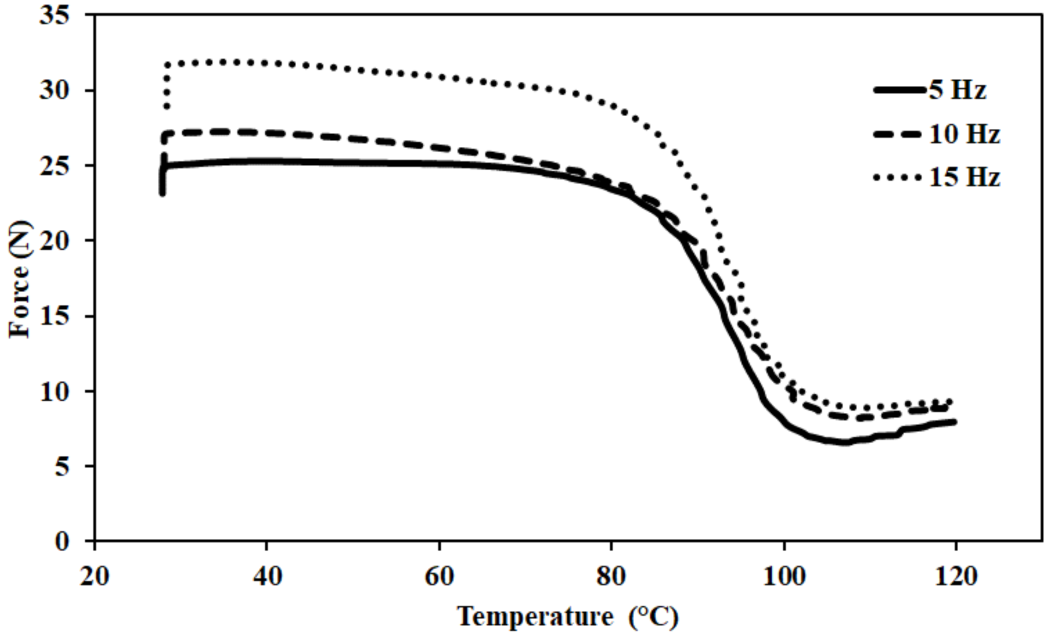


Figure 3.14 Reaction force at mid span of the double cantilever beam at different temperatures.

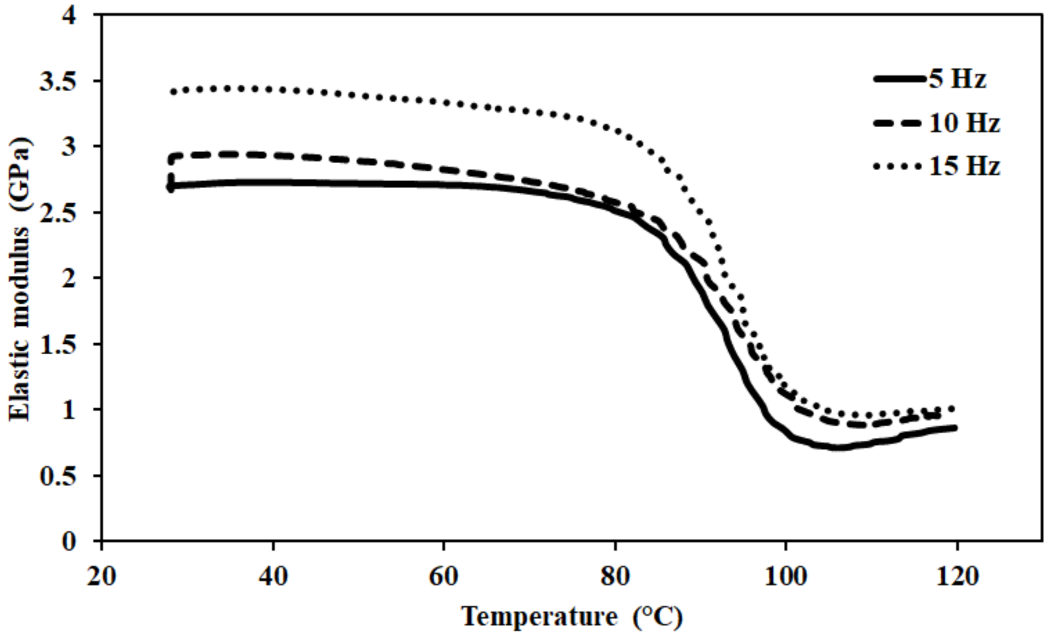


Figure 3.15 Variation in elastic modulus with change in ambient temperature.

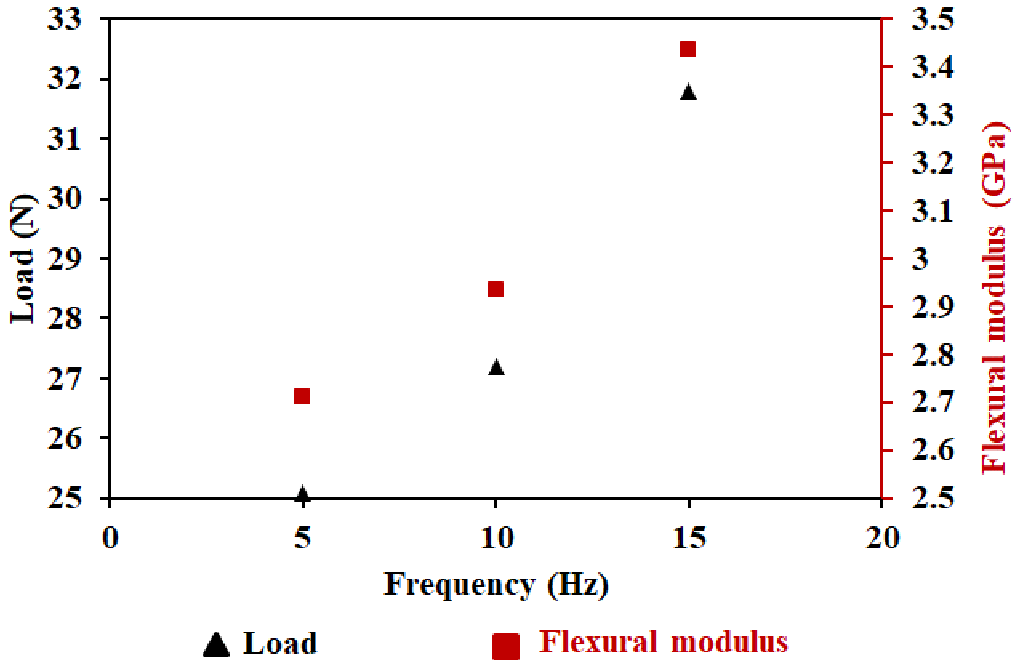


Figure 3.16 The reaction force at the mid-span of the beam obtained from DMA and calculated flexural modulus at different frequencies and room temperature.

3.4 Static three point bending test

The elastic modulus calculated from the DMA data is confirmed from the results of static flexural tests at room temperature. Specimens were tested using three point bending test at midpoint deflection rate of 0.5 mm/min. Specimen of dimensions 150 mm x 25 mm x 3.5 mm were used for static flexural test. All the static flexural tests were conducted at support span length (l) of 100 mm. Three specimens of the composite were tested at same loading rate. The load-deflection curves plotted from the experimental data are given in Figure 3.17. The elastic modulus of the composite was calculated from the derived equation (Equation 3.10) from Euler - Bernoulli bending theory. The elastic modulus of the composite specimens calculated from static flexural test data is given in Table 3.1. Elastic modulus obtained from the static flexural tests at room temperature is in the range of 3 GPa to 3.63 GPa.

$$E = \frac{l^3 m}{4bd^3} \tag{3.10}$$

Where;

E = Elastic modulus.

m = Slope of load-deflection curve

b = Width of the beam (mm)

d = Depth of the beam (mm)

l = Support span length of the beam (mm)

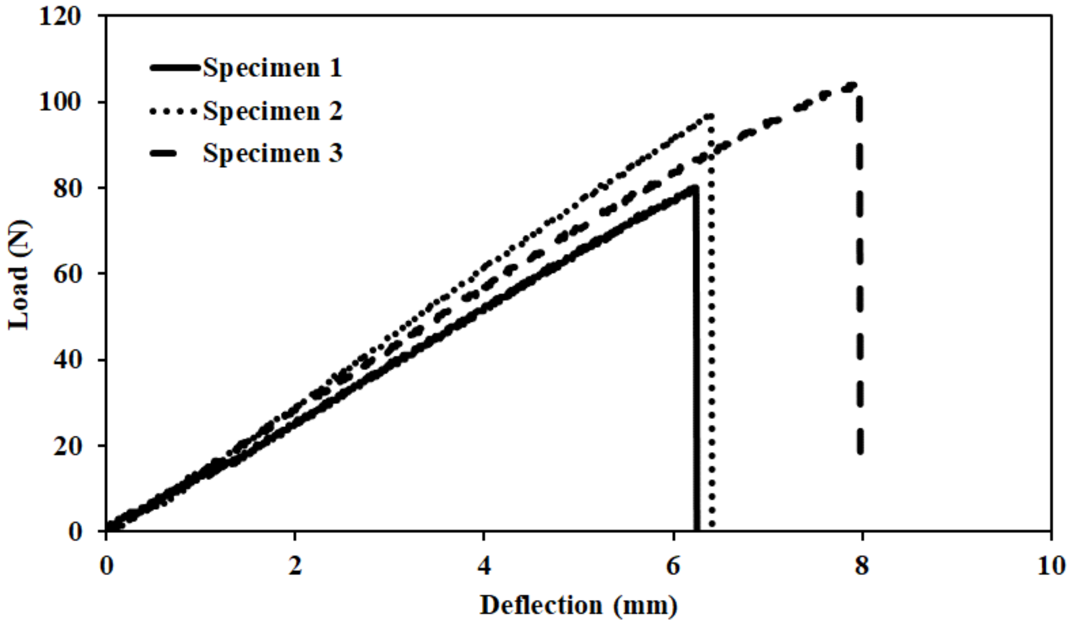


Figure 3.17 Load-deflection curves of the static flexural experiments.

Table 3.1 Elastic modulus (GPa) of composite specimens obtained from static flexural experiments.

	Elastic modulus (GPa)
Specimen 1	3.00
Specimen 2	3.63
Specimen 3	3.13

CHAPTER 4

MECHANICAL CHARACTERIZATION OF ARECANUT HUSK FIBRE

Static mechanical properties of arecanut husk fibre epoxy composite are discussed in this chapter. Static mechanical properties of any material are important to design engineering components. Tensile, flexural and impact tests were conducted using standard material testing procedures. Effect of glass fibre on mechanical properties (tensile strength, flexural strength and impact energy absorption) of arecanut husk fibre epoxy composite is given in this chapter. The failure mechanisms in composites due to tensile, flexural and impact loads were explained using Scanning Electron Microscopy (SEM) image technique.

4.1 Tensile Strength

Specimens for tensile testing were prepared by cutting the cast arecanut husk fibre panel with dimensions of 280 mm x 25 mm x 3 mm. Griping portions of tensile specimens were pasted with knurled aluminium sheets (50 mm x 25 mm x 2 mm) as shown in Figure 4.1 to avoid the slip between holding grips and specimen while conducting the experiments. Araldite was used for pasting knurled aluminium sheets to tensile specimens. Experiments were conducted on specimens made with coarse fibre (CF), fine fibre (FF) and coarse fibre with glass fibre (CF + GF) according to the standards of ASTM D3039 using tensile testing machine shown in Figure 4.2. Each test was repeated with three samples to observe the consistency of the results.

Figure 4.1 Test specimen pasted with knurled aluminium sheet.

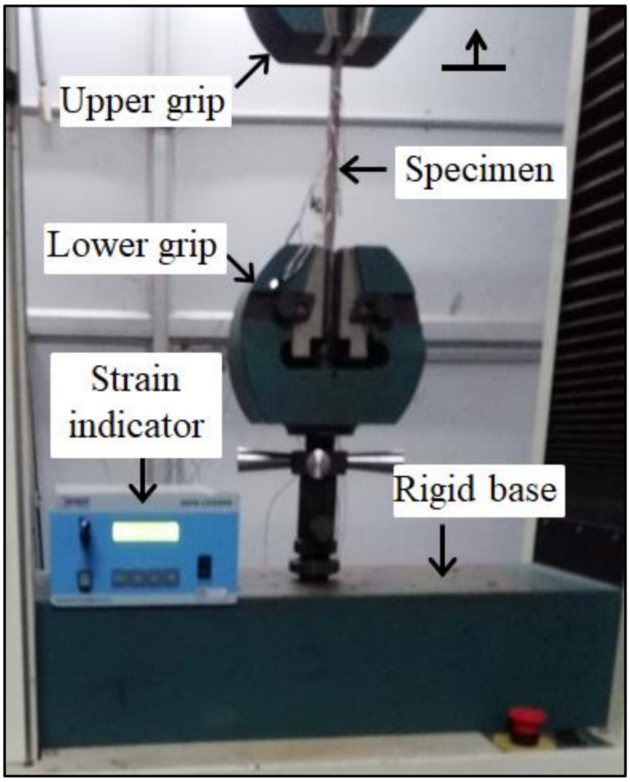


Figure 4.2 Tensile testing setup used for the study.

Tensile strength, elastic modulus and percentage of elongation of composite specimens made of treated arecanut coarse fibre, fine fibre and coarse fibre with glass fibre were observed by conducting tensile tests. The typical stress versus strain curves of the three different fibre composites are shown in Figure 4.3. Experiments were conducted with loading rate of 0.5 mm per minute. From the experimental results, all the composite specimens display linear trend and fail suddenly at particular load. The composites made with coarse fibre and fine fibre had shown lower tensile strength when compared to that of composites made of coarse arecanut husk fibre with glass fibre. The average mechanical properties observed from the experiments were given in Table 4.1. The composites made with finer fibre had displayed marginally higher tensile strength when compared to the composites made with coarser fibre. The composites made with coarser fibre had given marginal increase in elastic modulus and percentage of elongation when compared to the composites made with fine fibre. Error bars for tensile strength of all the composites are drawn from three test samples of each type of composite and given in Figure 4.3a.

Table 4.1 The average mechanical properties of the composite specimen.

Fibre Composition	Tensile Strength (MPa)	Young's modulus (GPa)	Percentage of Elongation
Fine Fibre	15.1	3.2	0.321
Coarse Fibre	10.80	3.54	0.435
Coarse Fibre + Glass Fibre	24.80	4.4	0.809

The increase in tensile strength of composites made with fine fibres is due to the increase in interaction between fibre surface and epoxy matrix. The tensile strength, elastic modulus and percentage of elongation of composites made with coarser fibre were increased by adding two layers of glass fibre.

The model calculation for Young's modulus of CF+GF composite is given below:

From Figure 4.3, Young's modulus = The slope of CF+GF line

= (14 - 7.73) / (0.0039 - 0.0019) = 3.135 GPa

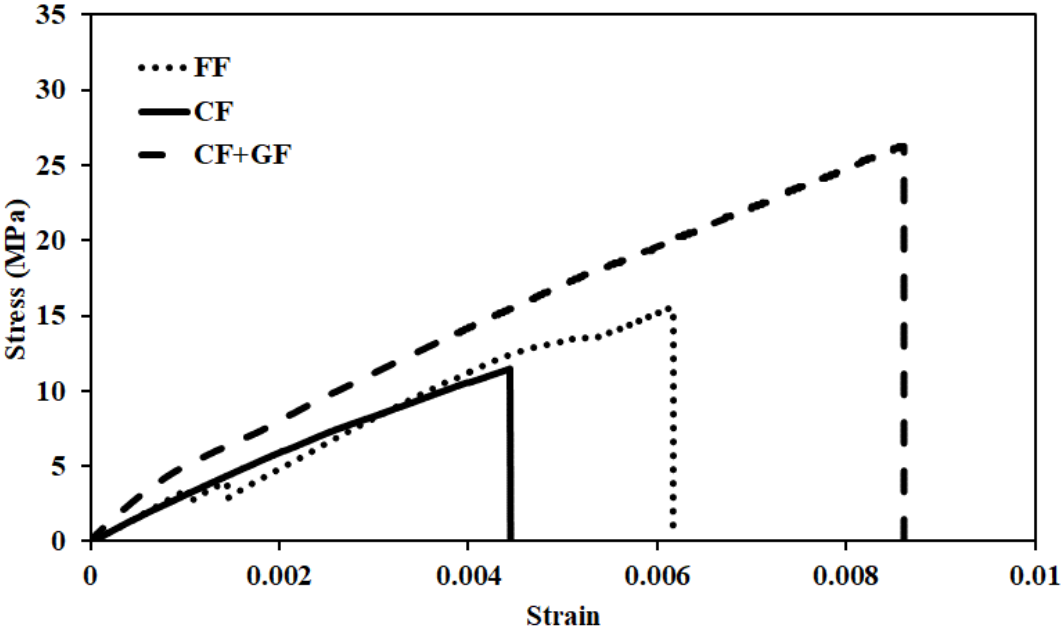


Figure 4.3 Stress-Strain curves of composites made with fine fibre, coarse fibre and coarse fibre with glass fibre.

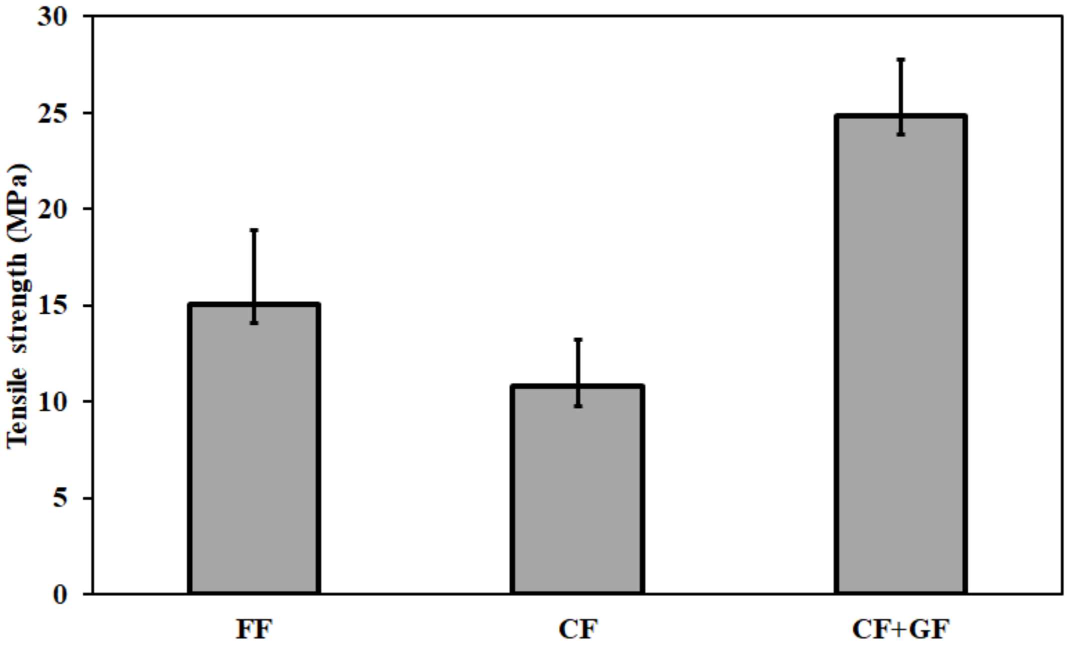


Figure 4.3a Error bars drawn for tensile strength of all the composites from three test samples in each composite.

4.1.1 Failure analysis of tensile specimens

The specimens, which failed during tensile test, were analyzed to find the mode of failure through micro-level and macro-level observations. From the macro-level observations, most of the tensile test specimens failed closer to mid-length of the span and the crack propagation was transverse to the loading direction (Figure 4.4). One specimen out of all the casted samples failed with propagation of crack along the fibre direction where a bunch of fibres was stacked (Figure 4.5). The stacked fibre bunch creates weaker plane, when stacked fibres got arranged in transverse direction and has weaker bonding between matrix material and fibres. So, proper de-husking is required to avoid such failures caused due to stacked fibre bunches. From the load deflection curves of tensile testing samples and the physical observation of failed specimen, the failure was observed as brittle failure.

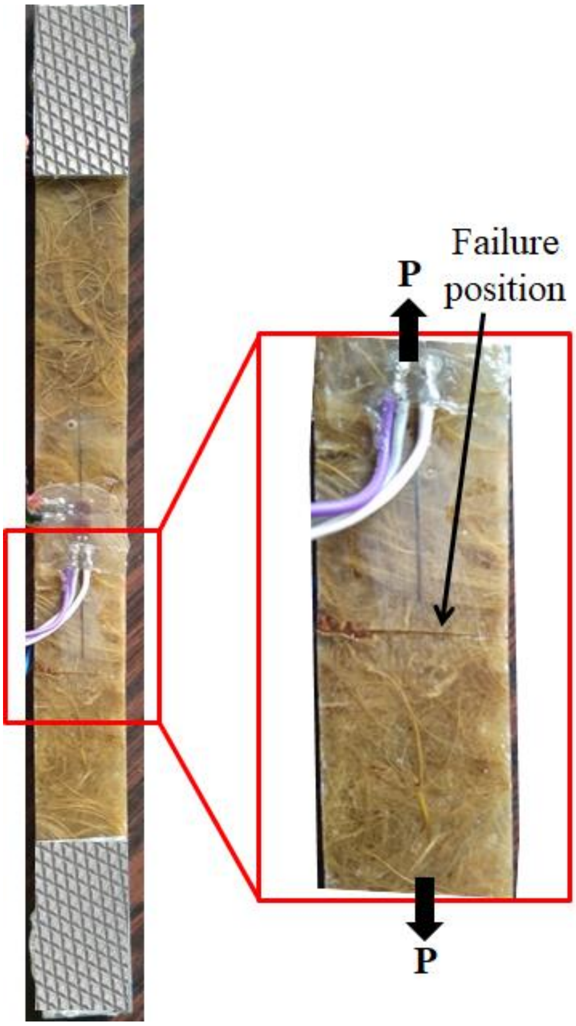


Figure 4.4 Transverse crack propagation in specimens subjected to tensile test.

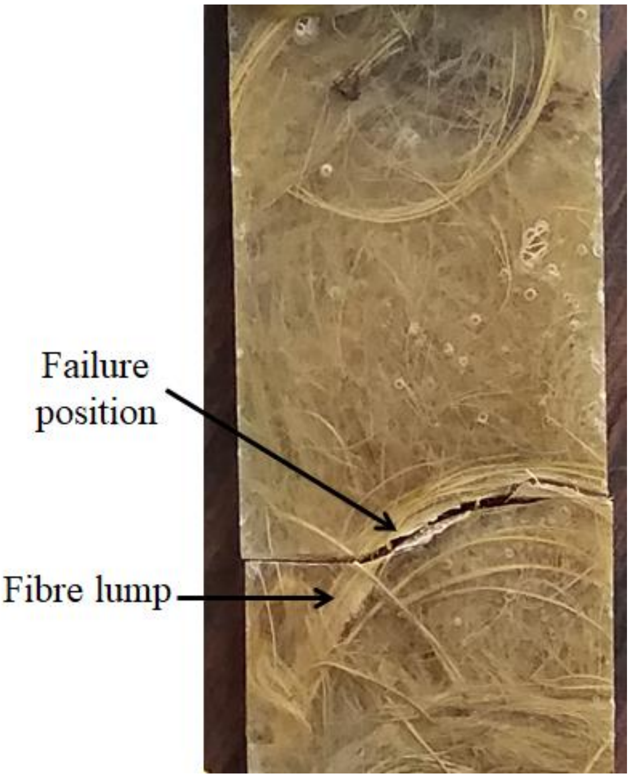


Figure 4.5 Crack propagation along stacked fibre bunch of specimens subjected to tensile test.

Micro-level observation of composite specimens failed due to tension was carried out using optical microscope. The cross-section images of tensile test specimens at failure positions were captured using optical microscopy. From these images, crack propagation from longitudinal fibre surface into the epoxy matrix and bonding failure between transverse fibres and epoxy matrix were observed. The cross-section of a fibre with crack propagation into the epoxy matrix is given in Figure 4.6. The failed transverse fibres due to de-bonding of fibre and epoxy matrix and failed cross-section of longitudinal fibres are given in Figure 4.7. From Figure 4.7, air bubbles with diameter of 40 micro-meters were observed on the cross-sections of failed tensile specimens. The concentration of air bubbles leads to decrease in strength of composites. The drawback of hand lay-up technique of composite casting is the formation of air bubbles in the composites which cannot be avoided completely using hand lay-up technique.

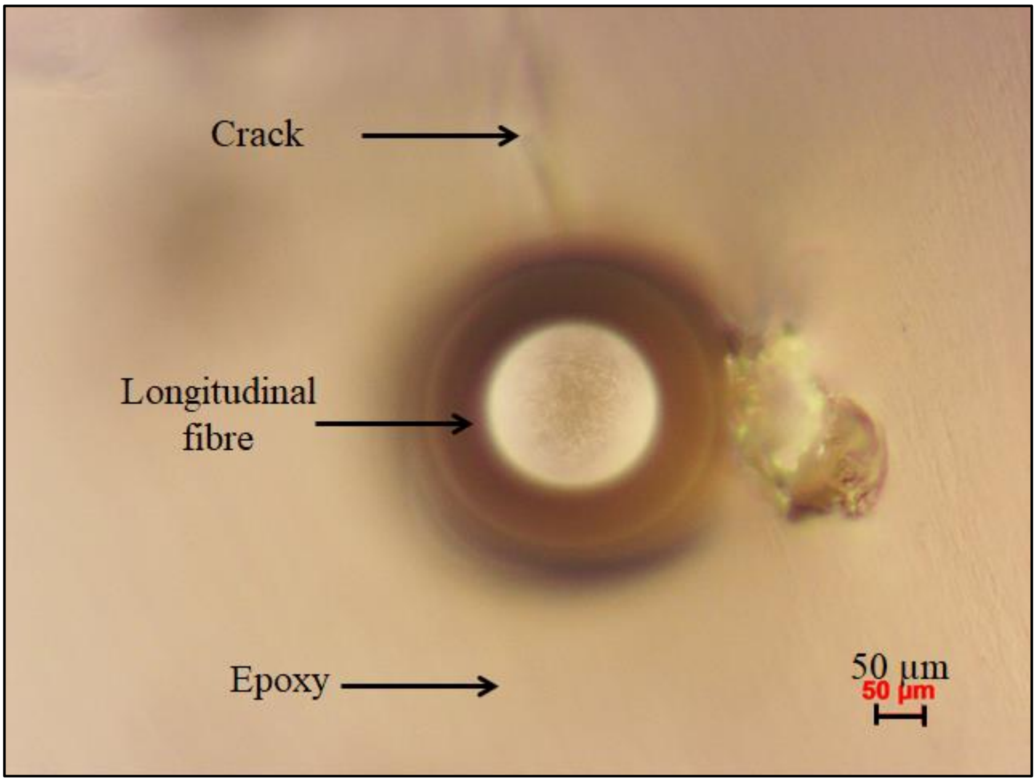


Figure 4.6 Crack propagation in cross-section of failed tensile specimen.

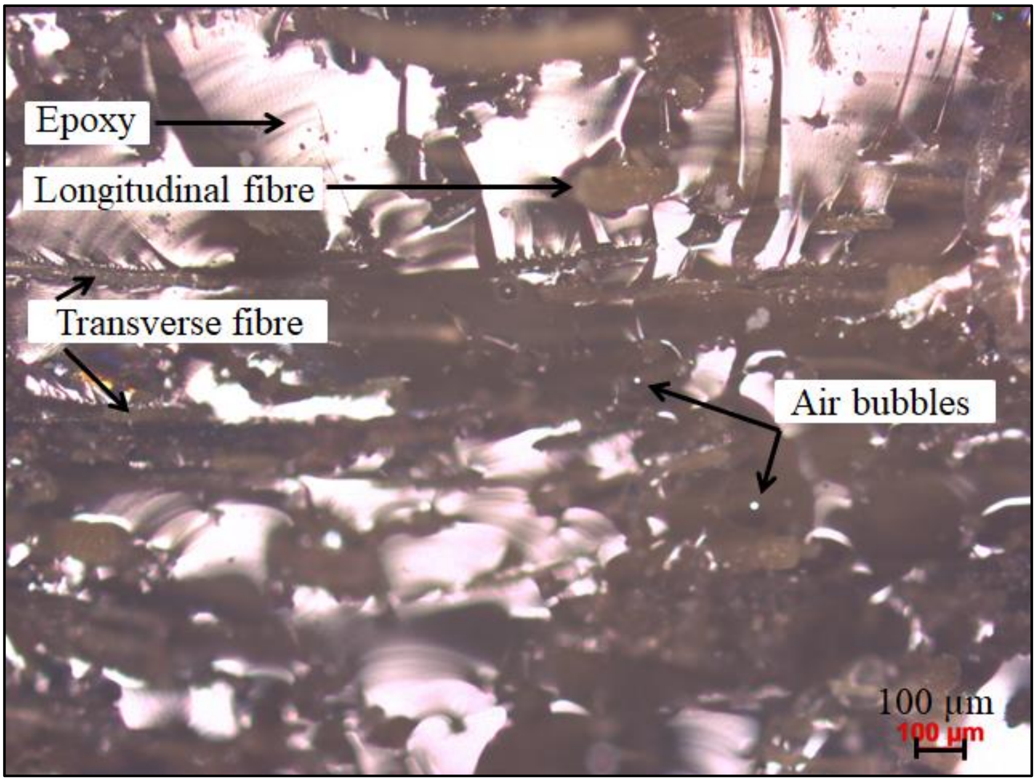


Figure 4.7 Air bubbles in cross-section of failed tensile specimen.

Surfaces of all the composites before conducting the tensile tests were captured. Voids of different sizes (maximum of 1 mm diameter) were observed (Figure 4.8) on surfaces of all the samples, those cannot avoid in hand lay-up technic of composite panel casting. The specimens failed at the cross-sections, where longitudinal fibre density is less. In all the composites cracks were observed on the cross-section. These cracks started from the periphery of the longitudinal fibres (Figure 4.9 - 4.11) and propagated radially outward from the fibre in epoxy matrix. From the failure patterns of tensile specimens, arecanut husk fibre failed before the epoxy matrix. The periphery of failed fibre resulted in a circular hollow in epoxy matrix and the crack formation at the periphery of failed areca fibre is due to high stress concentration at the periphery of failed areca fibre. These cracks propagated along the weak planes where the failure of adjacent areca fibres was observed (Figure 4.10).

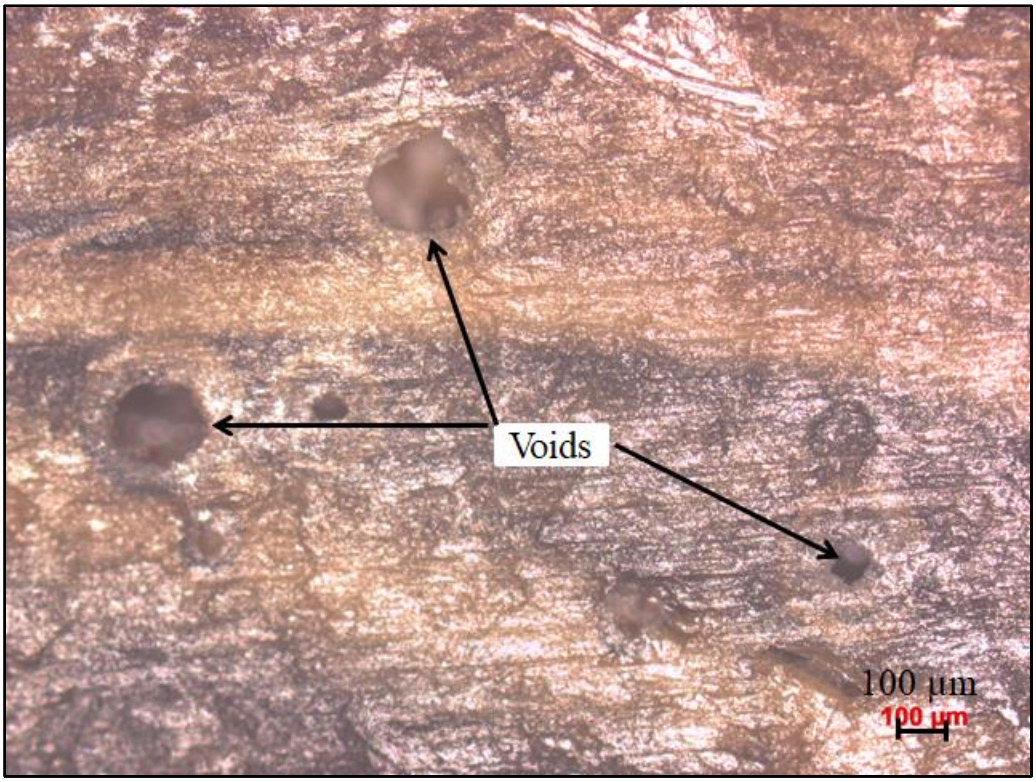


Figure 4.8 Voids on the surface of cast composite panels.

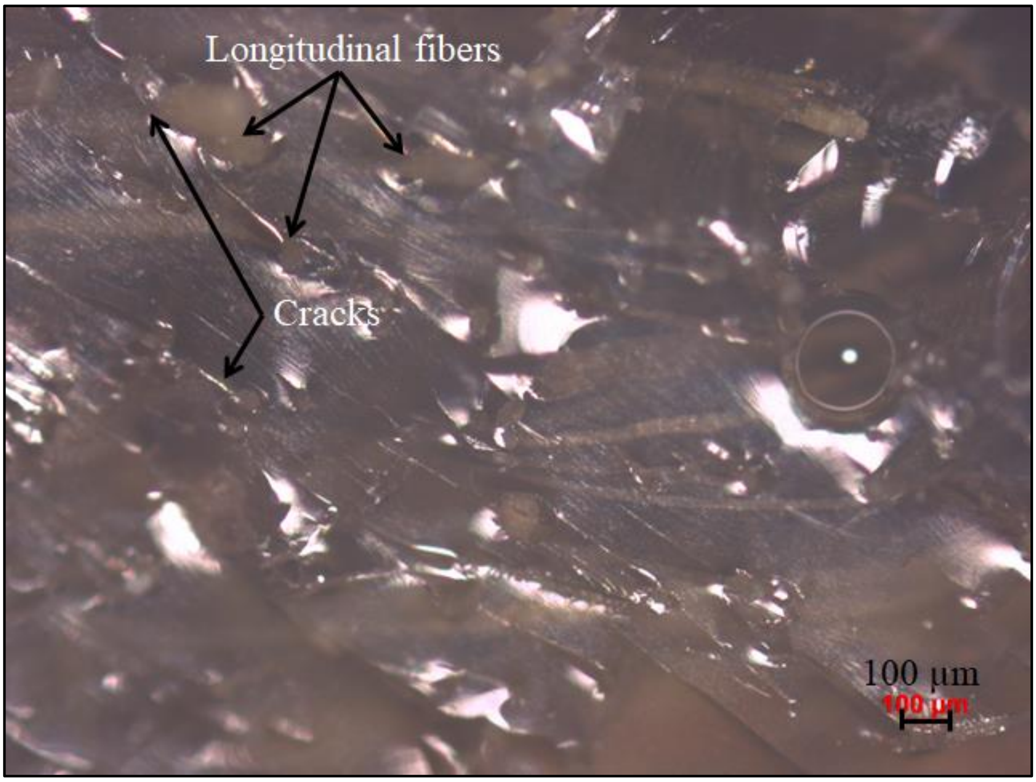


Figure 4.9 Cross-section of composites made with fine fibre.

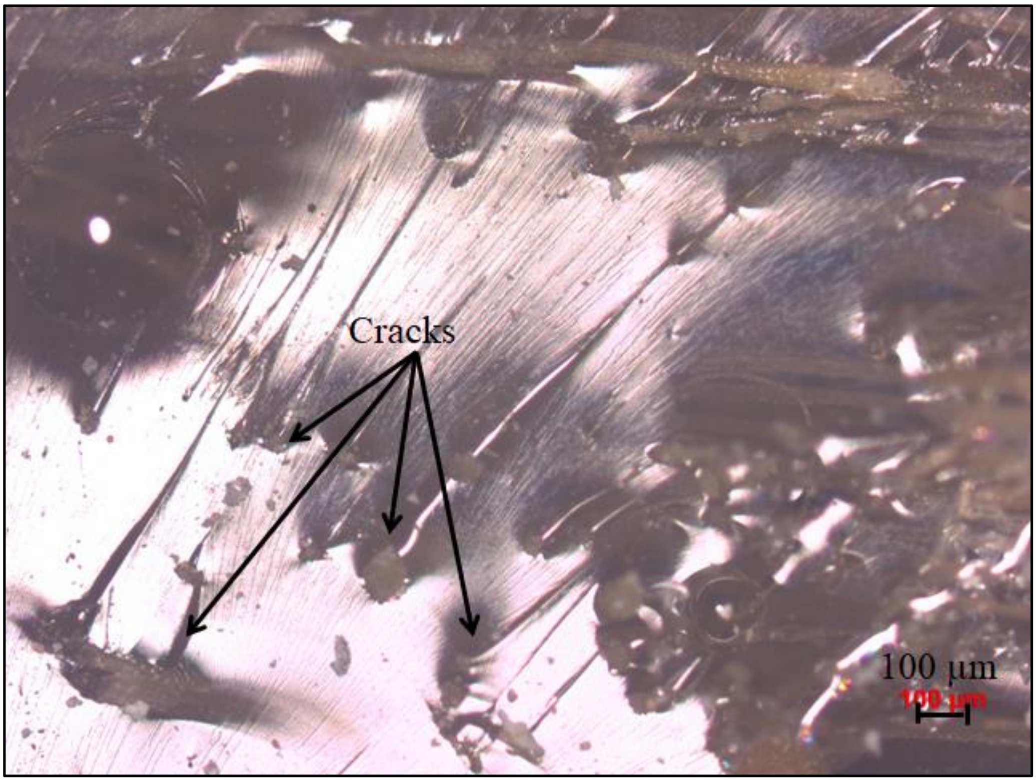


Figure 4.10 Cross-section of composites made with coarse fibre.

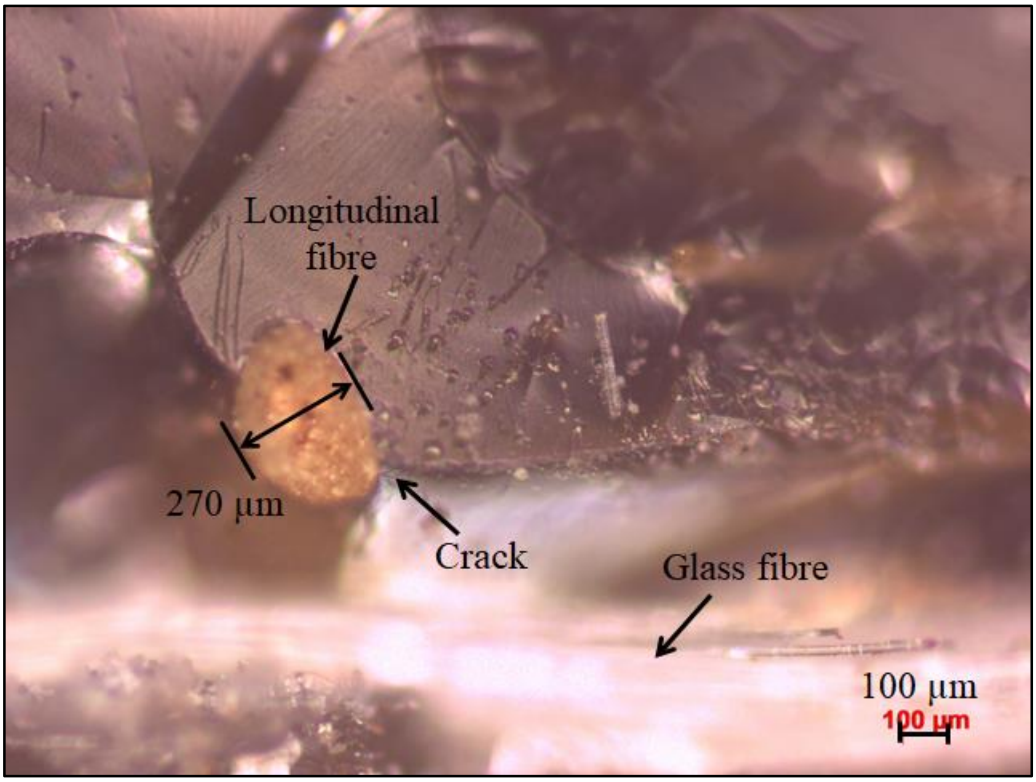


Figure 4.11 Cross-section of composites made with coarse fibre sandwiched with glass fibre.

4.2 Flexural strength

Experiments were conducted to analyze flexural properties of composites containing arecanut husk fibre, according to relevant standards enlisted in ASTM-D790. The composite panel was cut into a specimen of dimensions 150 mm length, 25 mm width and 4 mm thickness. Three-point bending experiments were conducted with effective span length of 100 mm. All the experiments were conducted with a mid-span deflection rate of 0.5 mm per minute. Flexural tests were conducted on composites made with FF, CF and CF sandwiched with two layers of glass fibre (CF+GF). Three samples of each composite type were tested to verify the consistency of the results. The experimental setup used for the study is given in Figure 4.12. The schematic of flexural test loading conditions and specimen dimensions are given in Figure 4.13.

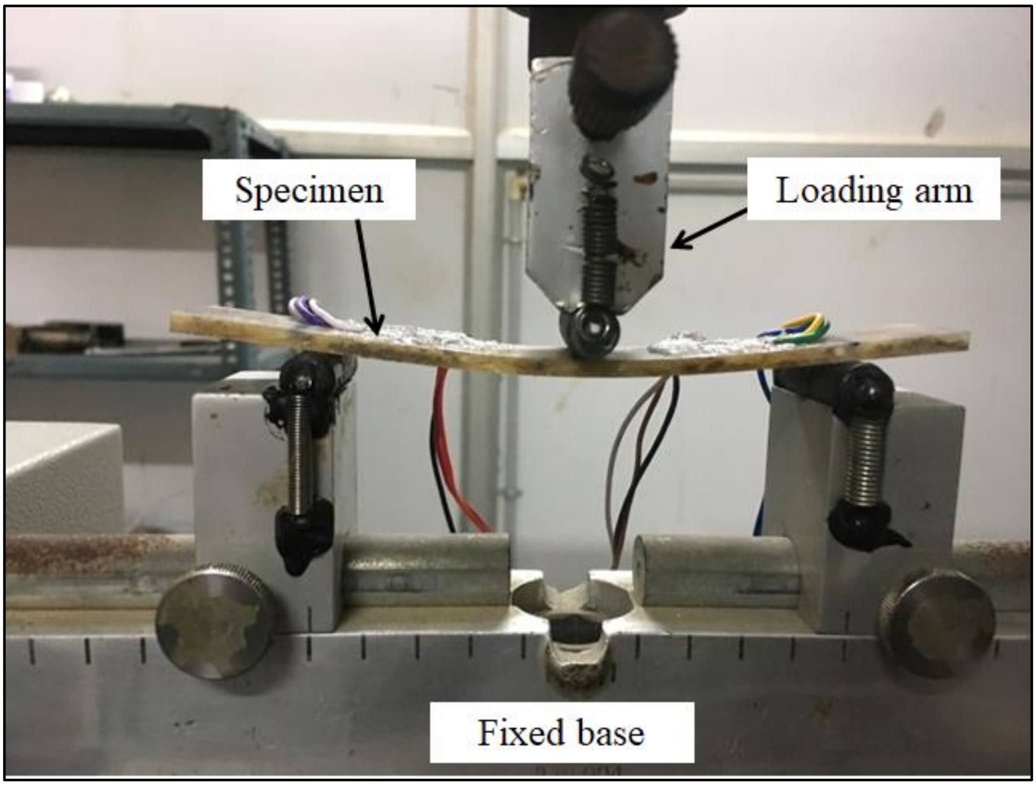


Figure 4.12 Three-point bending experimental setup used for the study.

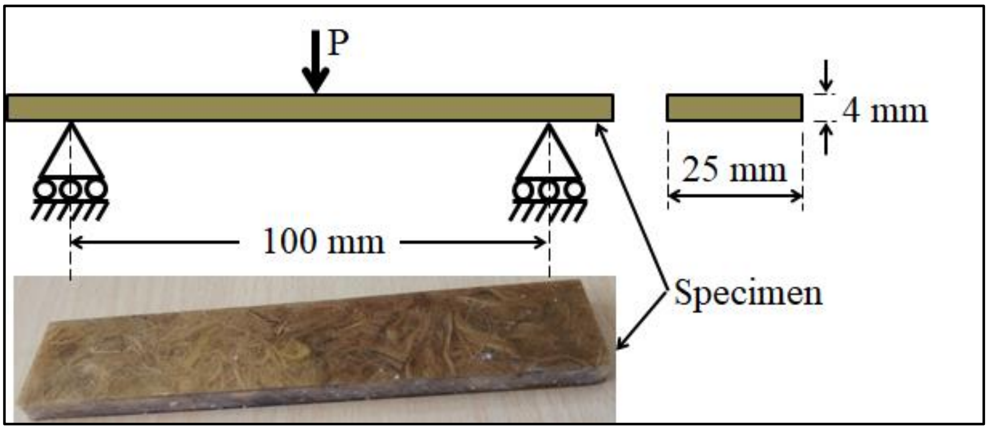


Figure 4.13 Schematic of loading conditions of three-point bending test and specimen dimensions.

The load-deflection curves are plotted using the data obtained from three-point flexure tests are given in Figure 4.14. The load increases linearly with increase in vertical deflection at loading point on beam for all three types of composites. From the observation of load-deflection relationship of composites made with fine fibre and coarse fibre, the composites fail at transverse deflection of 2 mm. The flexural strength of composites was calculated using the guidelines provided in ASTM-D790. The relationship of flexural stress and flexural strain at outer most layers of the composites is plotted in Figure 4.15. The average flexural strength of composites reinforced with FF, CF and coarse fibre sandwiched with glass fibre (CF+GF) are given in Table 4.2. The improvement in flexural strength of fine fibre composites is due to increase in surface area of fine fibre, which resulted in better bonding between fibre and epoxy. Considerable improvement in flexural strength of CF+GF composites is due to the presence of glass fibre, which has higher strength than areacnut husk fibre, at outer layers of the composites where higher stress occurs in composite during flexural test. Error bars for flexural strength of all the composites are drawn from three test samples of each type of composite and given in Figure 4.15a.

Table 4.2 The average flexural strength of the composite specimen.

Type of Fibre Composition	**Flexural Strength (MPa)**
Fine Fibre	73
Coarse Fibre	66.7
Coarse Fibre + Glass Fibre	284

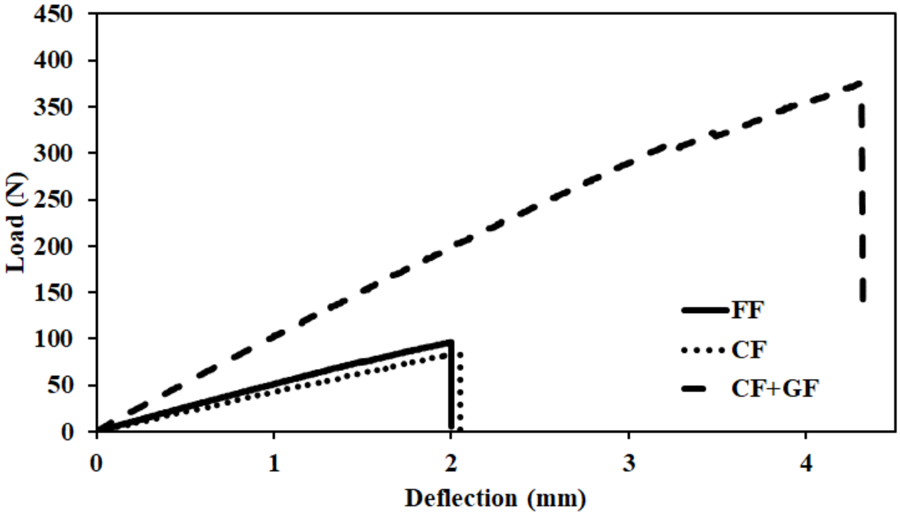


Figure 4.14 Load-deflection curves of epoxy composites reinforced with FF, CF and CF with glass fibre sheets (CF+GF).

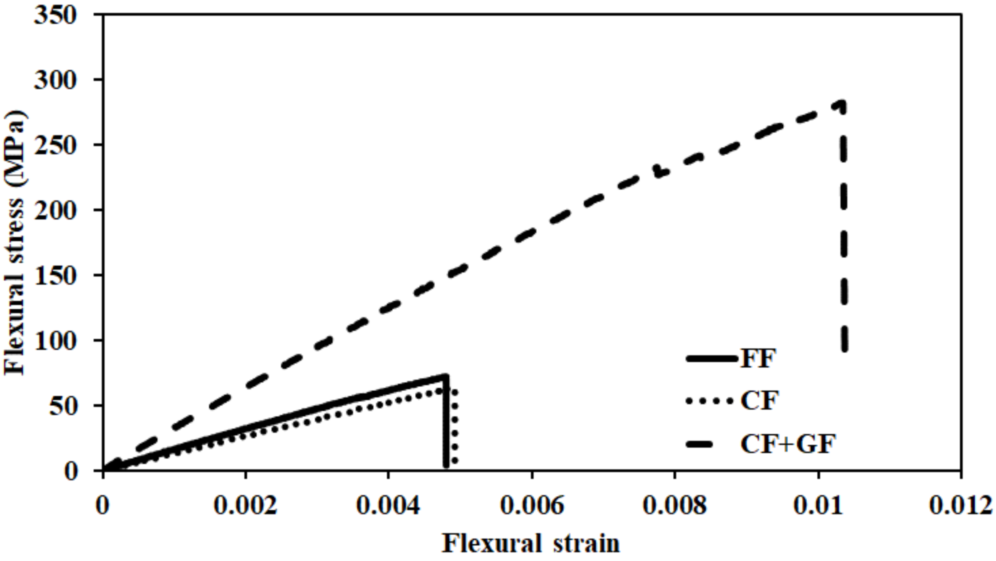


Figure 4.15 Flexural stress-strain curves of epoxy composites reinforced with FF, CF and CF with glass fibre sheets (CF+GF).

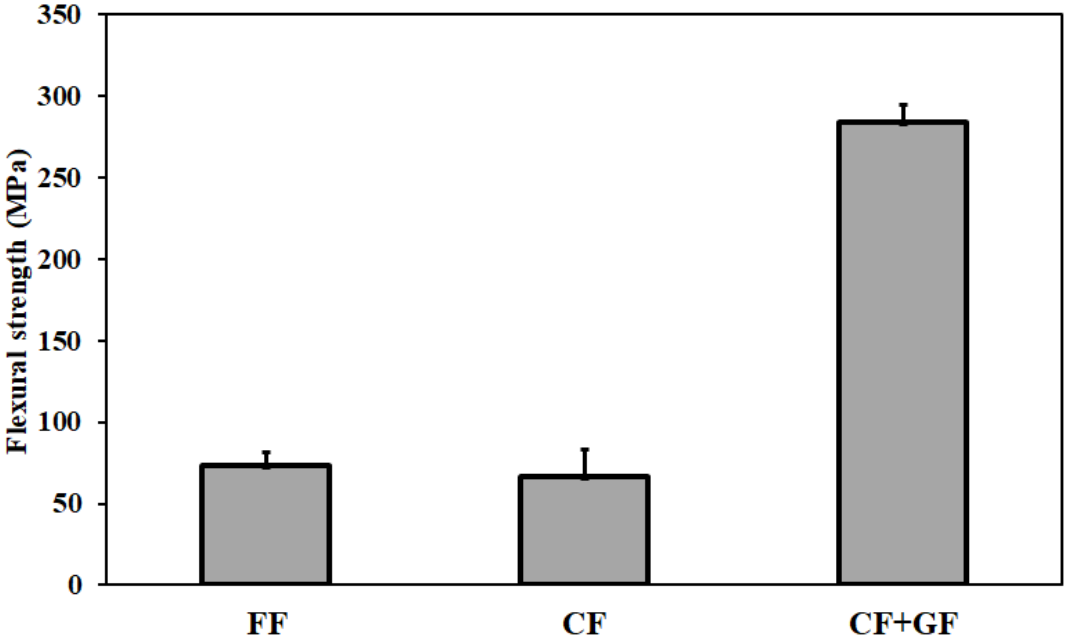


Figure 4.15a Error bars drawn for flexural strength of all the composites from three test samples in each composite.

The flexural strength of reinforced composites was calculated using the guidelines provided in ASTM-D790. The flexural stress at outer most layers of anisotropic materials having free span length to depth ratio more than sixteen can be calculated using equation (4.1). In the present study, the maximum strength at failure of flexural member was calculated using the equation (4.1). The strain at outer most layers of composite was calculated using simple Euler- Bernoulli bending theory (equation 4.2). From the experimental observations (Figure 4.14), all the specimens were failed suddenly at particular stress. The sudden material failure represents the brittle failure nature. Similar brittle failure nature was observed by Ajith Gopinath et al. (2014) in jute-epoxy composites, E Kara et al. (2015) in glass fibre epoxy composites and Shabbir Ahmed and Chad A. Ulven (2018) in individual Flax Fibres.

$$\sigma_f = \frac{3Pl}{2bd^2}\left[1+\left(\frac{6D^2}{l^2}\right)-\left(\frac{4dD}{l^2}\right)\right] \tag{4.1}$$

$$\varepsilon_f = \frac{6dD}{l^2} \tag{4.2}$$

$$\sigma_{Ef} = \frac{3Pl}{2bd^2} \tag{4.3}$$

Where;

P = Load applied at an instant (N)

D = Mid span deflection at an instant (mm)

b = Width of the beam (mm)

d = Depth of the beam (mm)

l = Support span length of the beam (mm)

σ_f = Stress at outer surface of the beam at mid span (from ASTM-D790)

σ_{Ef} = Stress at outer surface of the beam at mid span (from Euler’s Bernoulli bending equation)

ε_f = Strain at outer surface of the beam at mid span

The flexural strength of composites is also calculated using Euler’s Bernoulli bending equation (4.3) and the average flexural strength of fine arecanut husk fibre, coarse arecanut husk fibre and coarse arecanut husk fibre sandwiched with glass fibre are observed as 36 MPa, 32 MPa and 140 MPa respectively. The flexural strength curves obtained by using Euler- Bernoulli bending theory are depicted in Figure 4.16.

The flexural strength of epoxy composites reinforced with treated arecanut fibre (at fibre to epoxy weight ratio of 0.6 and at curing period of 30 days) was observed as 50 MPa by Srinivasa CV et al. (2011). In the present study, the flexural strength of areca epoxy composites calculated using guidelines provided in ASTM-D790 is comparable with the same observed by Srinivasa CV et al. (2011). The flexural strength of any material includes both tensile and compressive strength of material. The arecanut husk fibre cannot contribute to the compressive strength of the composite. Therefore, lower variation in the flexural strength between FF and CF composites were observed.

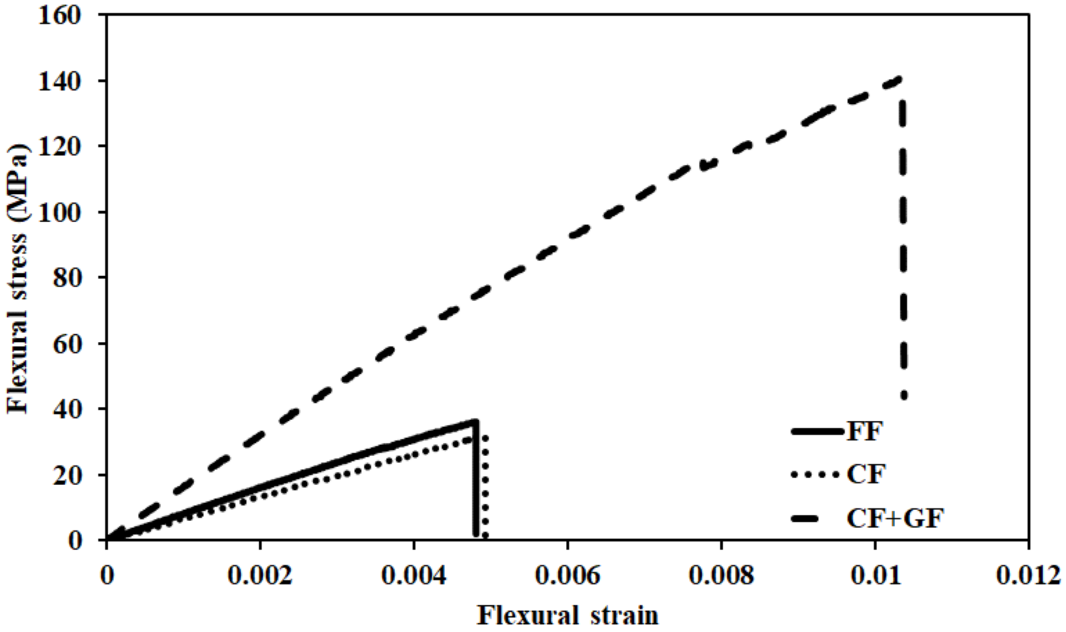


Figure 4.16 composites reinforced with AHF sandwiched with glass fibre sheets (according to Euler's Bernoulli bending equation).

4.3 Impact strength

Impact experiments were performed to determine the response of composite materials to shock loads. Experiments were conducted using Fractovis Plus drop weight impact testing machine (Figure 4.17), as per ASTM-D5628 standard. The schematic diagram of specimen arrangement and loading details are given in Figure 4.18.

Figure 4.17 Fractovis plus drop weight impact testing machine.

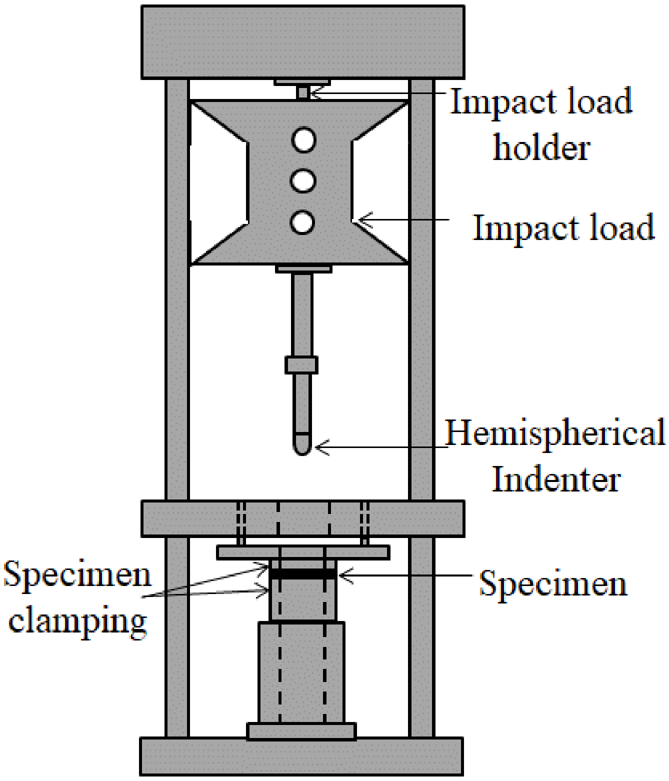


Figure 4.18 Schematic diagram of specimen arrangement and load frame.

The composite panel of thickness 4 mm was cut into specimen of dimensions 60 mm length and 60 mm width to conduct impact test. A hemispherical impactor of diameter 12.7 mm was used for the experiments. The impact test conditions are specified in Table 4.3.

Table 4.3 Experimental conditions for the drop weight impact test.

Impact velocity (m/s)	Drop weight (kg)	Impact energy (J)	Test height (m)	Clamping force (N)
3.0	1.92	8.64	0.459	50

Impact tests were conducted on composites cast with FF, CF and CF + GF. Three samples of each composite type (FF, CF and CF + GF) were tested to verify the consistency of results. For each sample, the impact force, impact energy absorbed, deformation, and velocity of impactor were recorded and analyzed. Figure 4.19 – 4.22 shows the result of the impact test for composites made with FF, CF and CF + GF. In all the tested composites, impact force increases with time in first 2-ms duration, and then, it decreases to zero. From Figure 4.19, the fall in force curves represents the initiation of failure of the fibre composites. The coarse fibre composites resist higher impact force when compared to that of the fine fibre composites. The coarse fibre sandwiched with glass fibre composite material increases the impact force resistance by a factor of one and half times that of the coarse fibre composites. From the force deflection curves displayed in Figure 4.20, the gradual increase and decrease in impact force indicates resistance of material and failure of material, respectively. The typical decrease in displacement after failure of coarse fibre sandwiched with glass fibre composite material is due to partial failure of composite and bouncing of impactor after impact. Figure 4.21 shows energy absorbed during the impact test. All absorbed energy profiles of the three types of composites increased linearly up to some point before it changes its gradient. This change in gradient is due to the initiation of internal damages in the composite material, these internal damages are due to cracks in the matrix or other forms of internal damages like delamination, these internal damages are invisible during physical examination of specimen. These internal damages cause reduction in material stiffness. The fine fibres in composite material fail easily than the coarse fibres during impact due to high stress concentration induced by the impactor on composite. So, the coarse fibre composites can resist more impact loads than fine fibre composites. The velocity of impactor during impact test was observed and plotted in Figure 4.22.

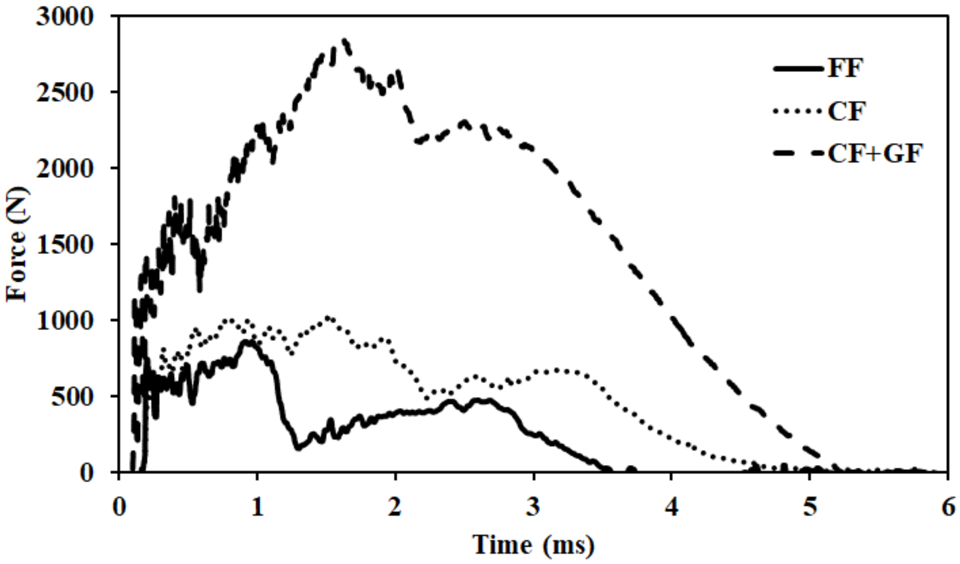


Figure 4.19 Force–time curves, recorded during impact tests of epoxy composites reinforced with FF, CF and CF+GF.

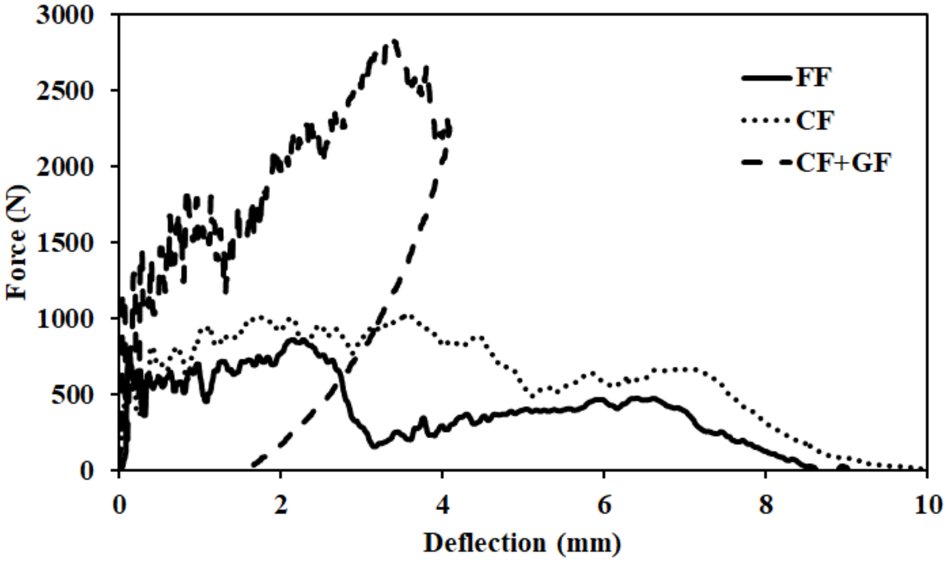


Figure 4.20 Force–deflection curves, recorded during impact tests of epoxy composites reinforced with FF, CF and CF+GF.

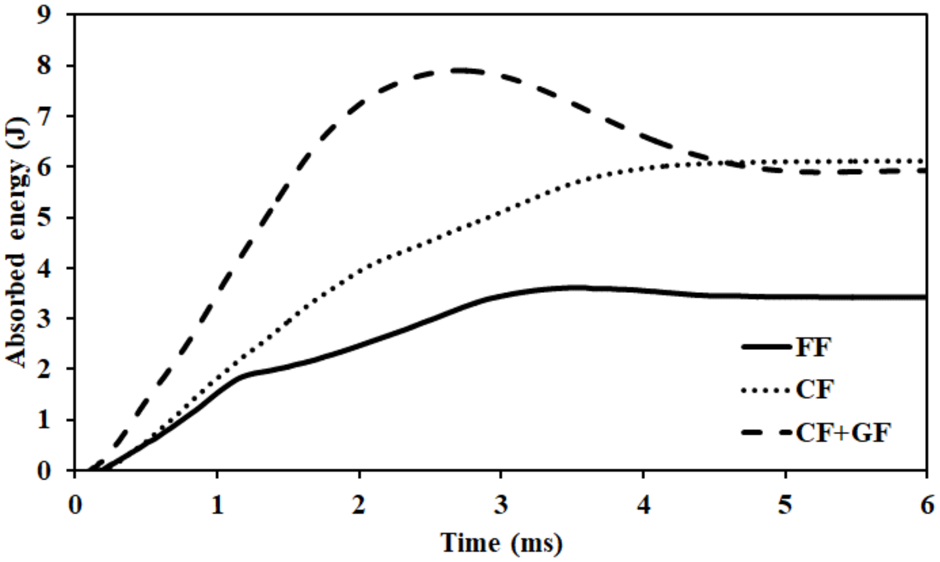


Figure 4.21 Energy-time curves recorded during impact tests of epoxy composites reinforced with FF, CF and CF+GF.

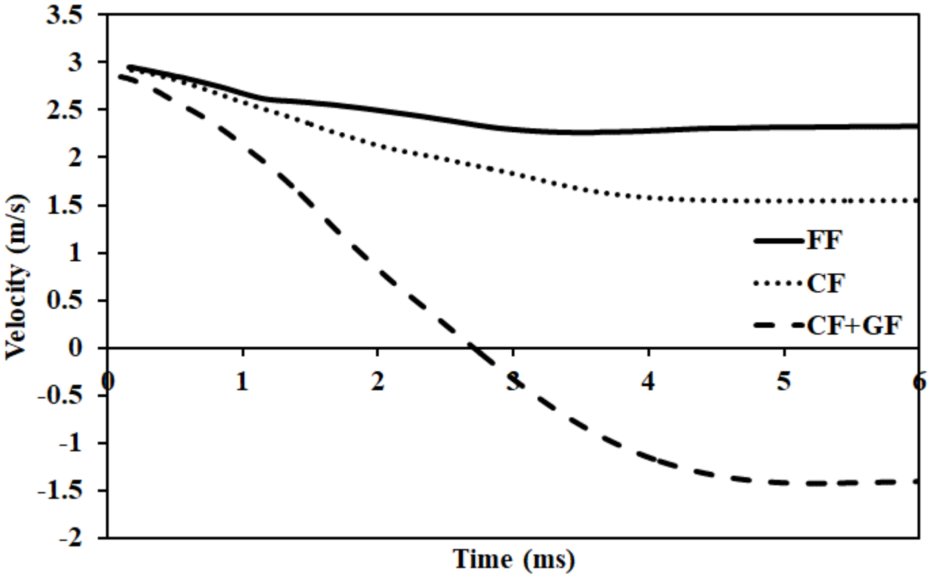


Figure 4.22 Velocity–time curves recorded during impact tests of epoxy composites reinforced with FF, CF and CF+GF.

The decrease in velocity of impactor represents the increase in the absorbed impact energy. In fine fibre composites and coarse fibre composites, velocity of impactor decreased gradually and then stabilized after complete failure of specimen. The negative velocity in coarse fibre sandwiched with glass fibre composite is due to bouncing of impactor after impact. From the macroscopic observations (Figure 4.23 – 4.26) of failed impact test specimens, the fine fibre composites failed with radial cracks (Figure 4.23), punching failure mode without radial cracks is observed in coarse fibre composites (Figure 4.24), delamination of glass fibre sheet at the bottom side of the failed coarse fibre sandwiched with glass fibre specimens is observed (Figure 4.26). The fine fibre composites and coarse fibre composites failed fully and the coarse fibre sandwiched with glass fibre composite failed partially (Figure 4.25) for the loading conditions given in Table 4.3. The two glass fibre layers added to the coarse fibre layer improved the impact strength of areca fibre epoxy composites.

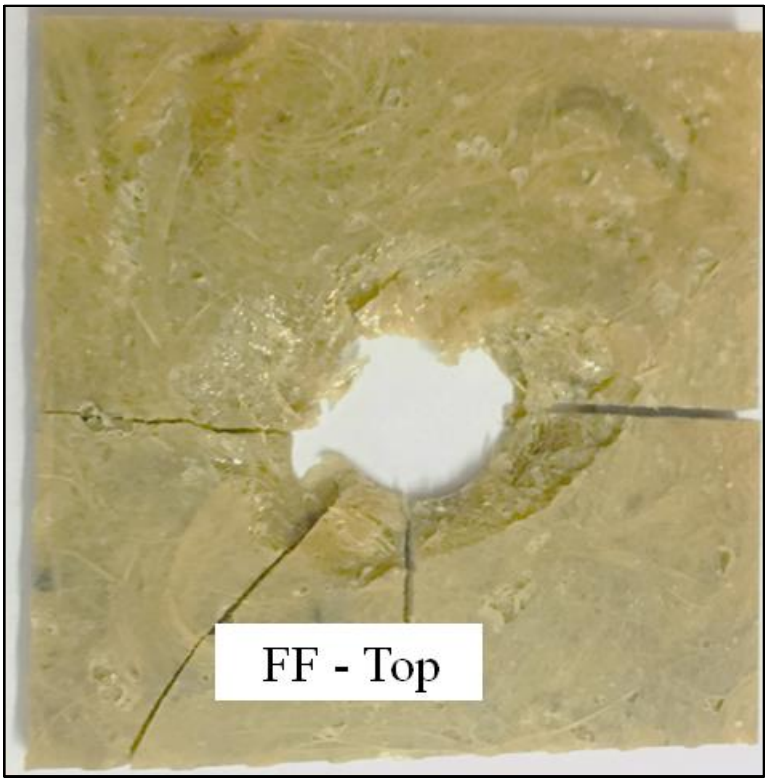


Figure 4.23 Radial cracks in FF composites.

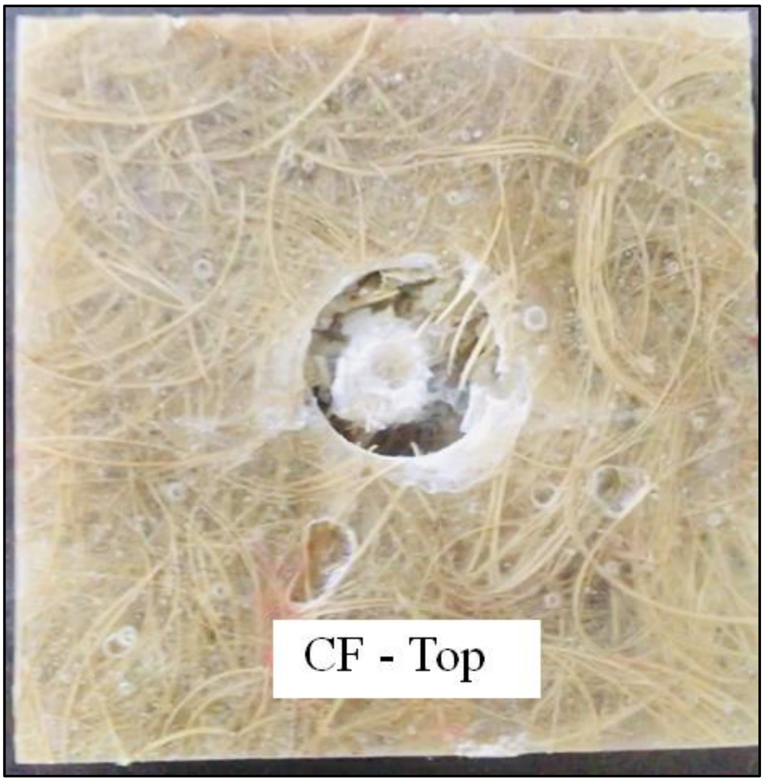


Figure 4.24 Punching failure in CF composites.

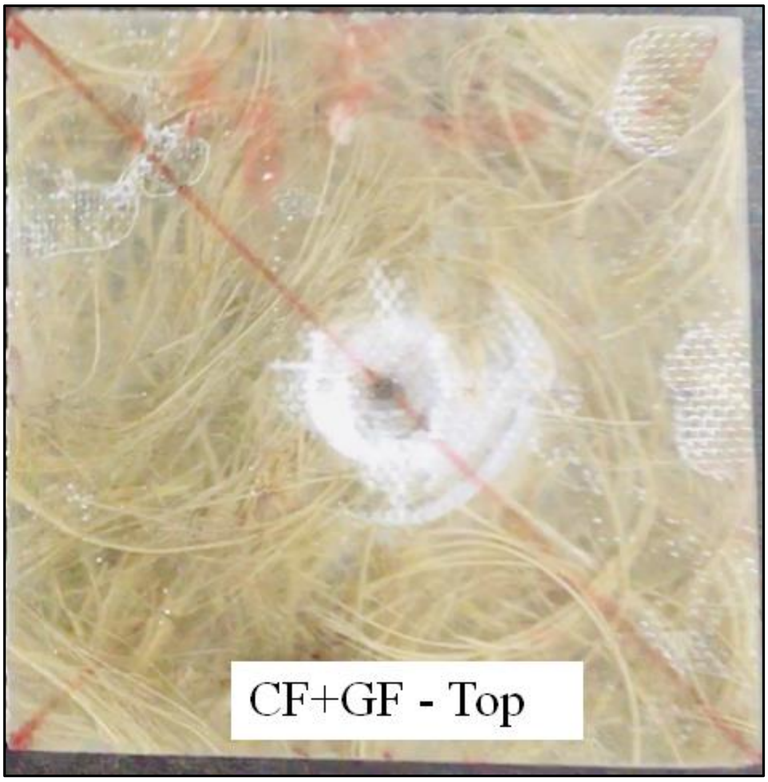


Figure 4.25 Top side of failed CF + GF composites.

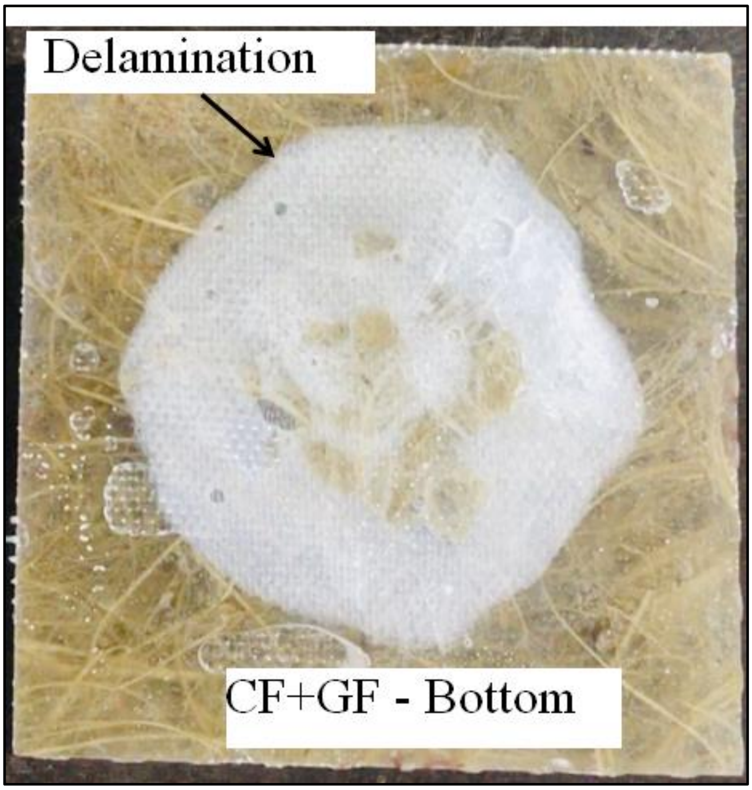


Figure 4.26 Delamination at bottom side of failed CF + GF composites.

4.4 Scanning Electron Microscope (SEM) analysis

VEGA3 TESCAN Scanning Electron Microscope (SEM) (Figure 4.27) was used for capturing images of fractured surface of arecanut husk fibre composites. Specimens were sputter coated with gold using sputter coater to improve conductivity and prevent charging of the specimen with the electron beam (Figure 4.28).

Figure 4.27 Scanning Electron Microscope (SEM).

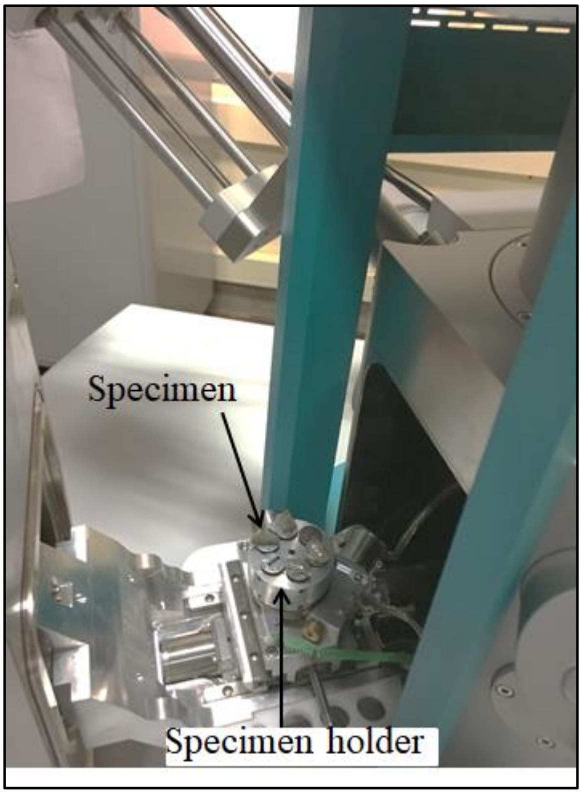


Figure 4.28 Specimen arrangement in Scanning Electron Microscope (SEM).

Figure 4.29 Specimens arranged for sputter coating.

Figure 4.30 Sputter coater during coating process.

Scanning Electron Micrographs of fractured surfaces of the FF, CF and CF + GF composite panels are shown in Figure 4.31 - 4.39. Figure 4.31 - 4.33 represents the tensile fracture surfaces of composites containing FF, CF and CF + GF, respectively. Good bonding between fine fibre and matrix is observed in Figure 4.31, and no cracks are observed on the failure cross section. De-bonding of coarse fibre with epoxy matrix and crack formation in matrix from periphery of the coarse fibres are observed in Figure 4.32. After tensile test, glass fibres were pulled out from epoxy due to debonding of fibre and epoxy as observed in Figure 4.33. Figure 4.34 - 4.36 represent the fracture surfaces of composites containing FF, CF and CF + GF, respectively, after conducting flexural test. Pullout of fibres and crack formation in matrix at periphery of fibres are observed in both fine fibre and coarse fibre composite specimens after flexural failure (Figure 4.34 and Figure 4.35). Figure 4.37 - 4.39 represents the fracture surfaces of composites containing FF, CF and CF + GF, respectively, after conducting impact test. All the composite specimens failed due to de-bonding mechanism during the impact test (Figure 4.37 - 4.39) (Ktaz et al., 2008).

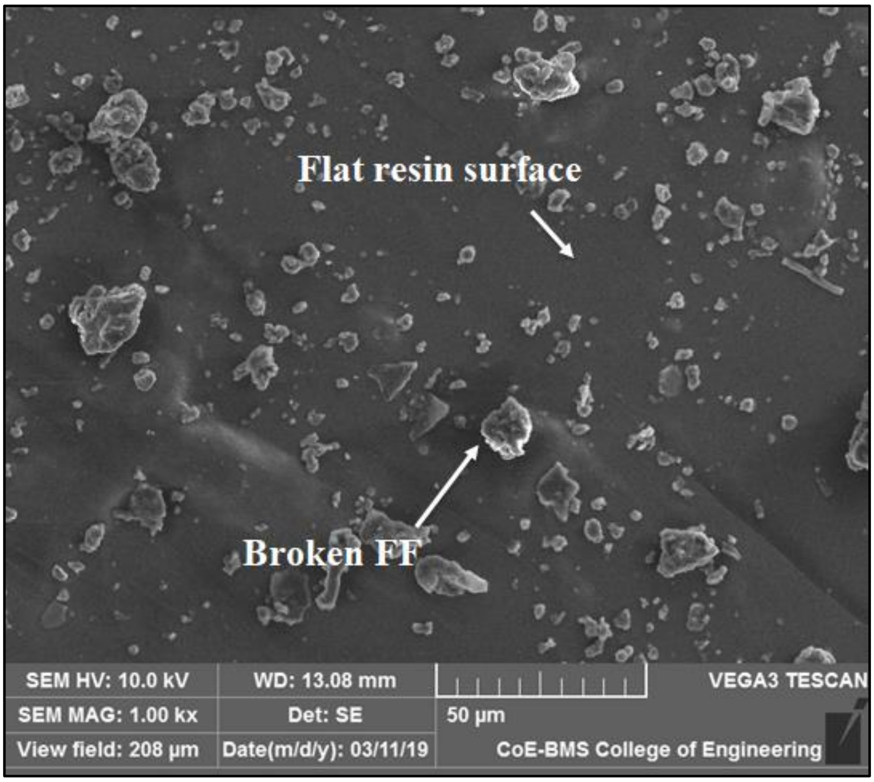


Figure 4.31 SEM micrographs of composites made with FF after tensile test.

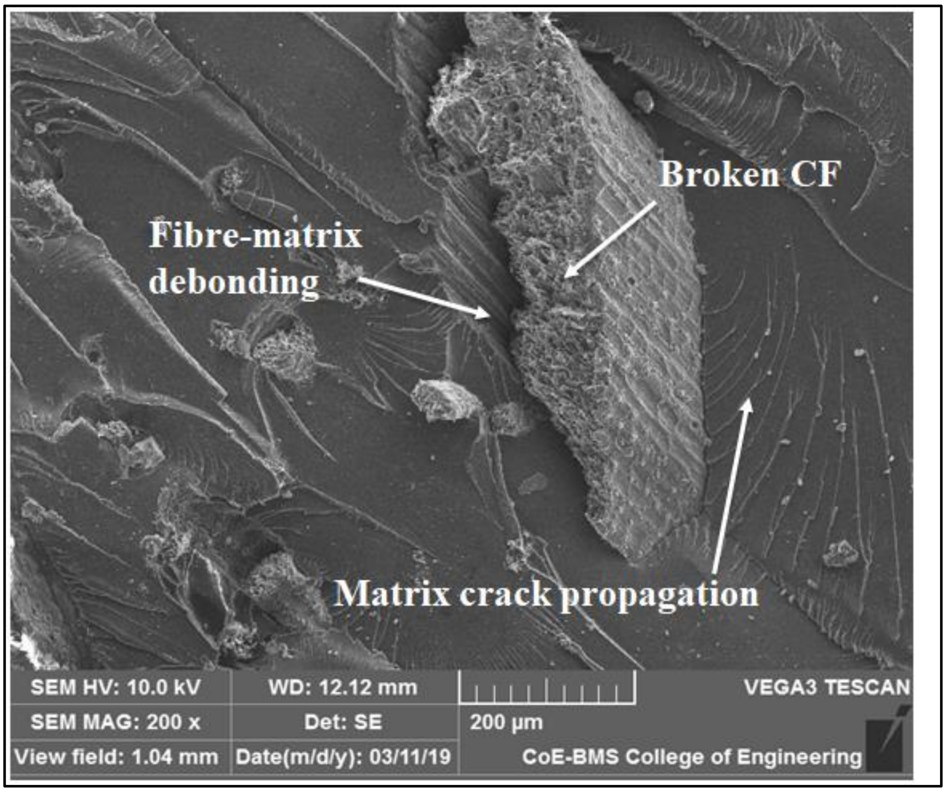


Figure 4.32 SEM micrographs of composites made with CF after tensile test.

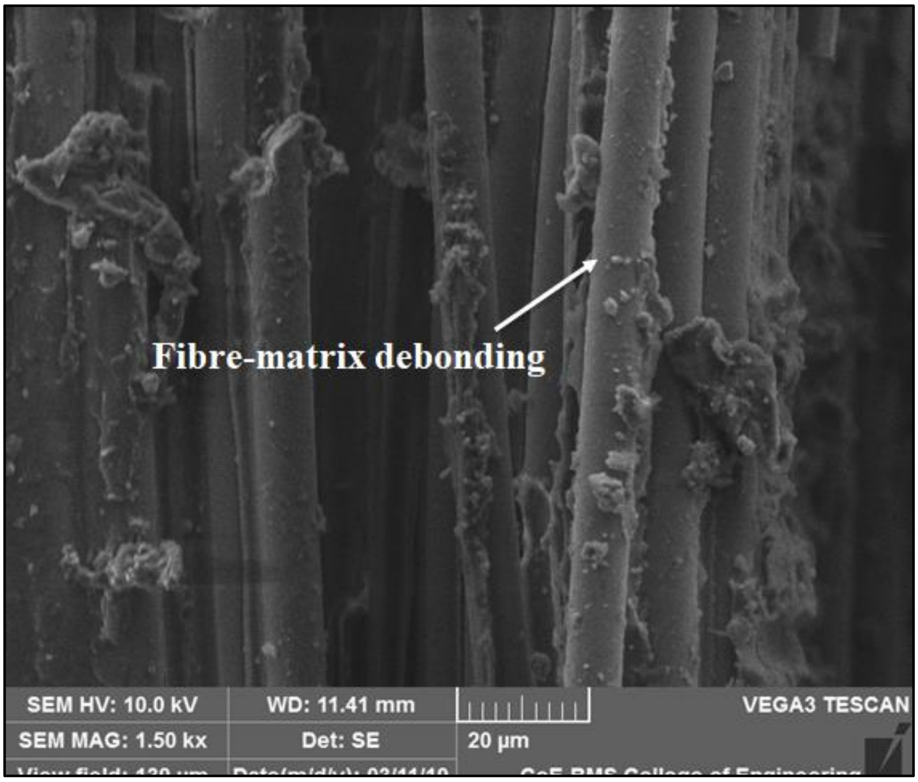


Figure 4.33 SEM micrographs of composites made with CF+GF after tensile test.

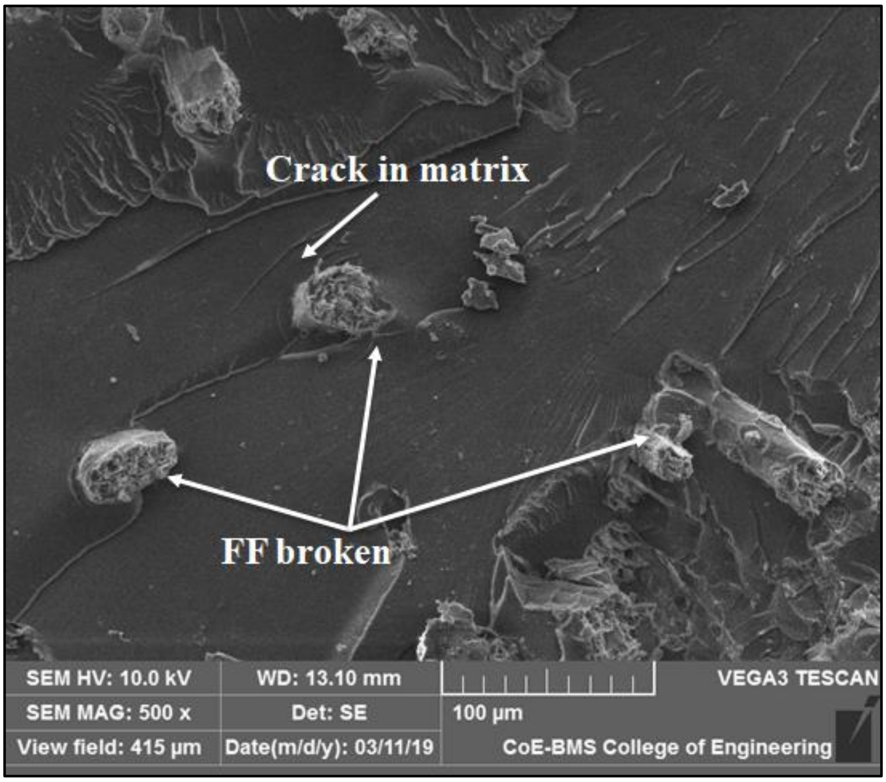


Figure 4.34 SEM micrographs of composites made with FF after flexure test.

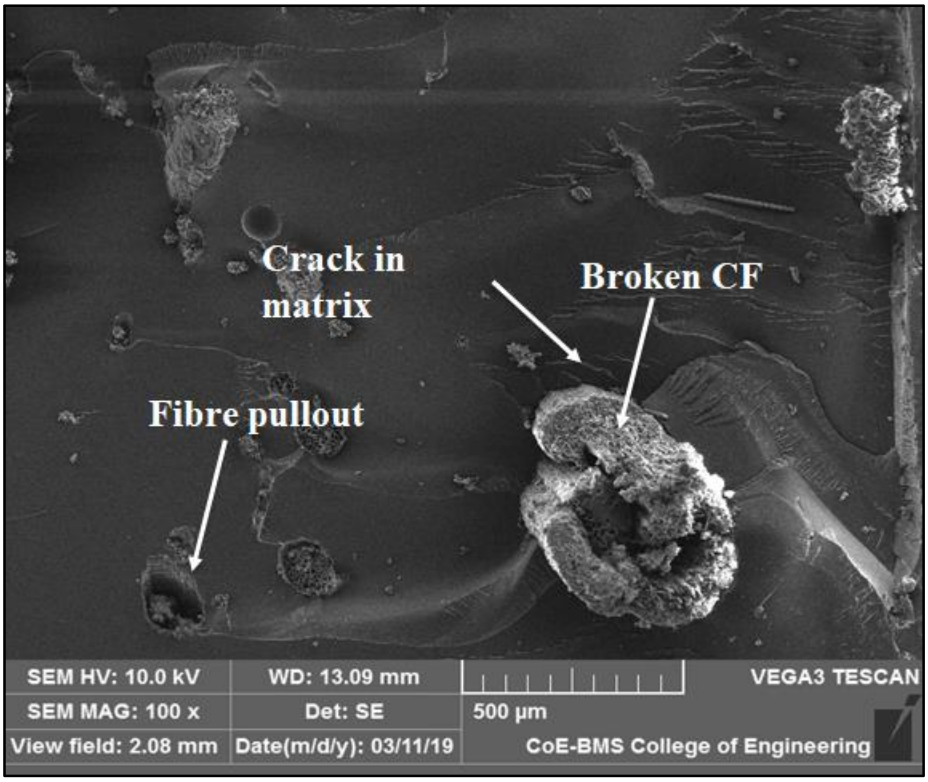


Figure 4.35 SEM micrographs of composites made with CF after flexure test.

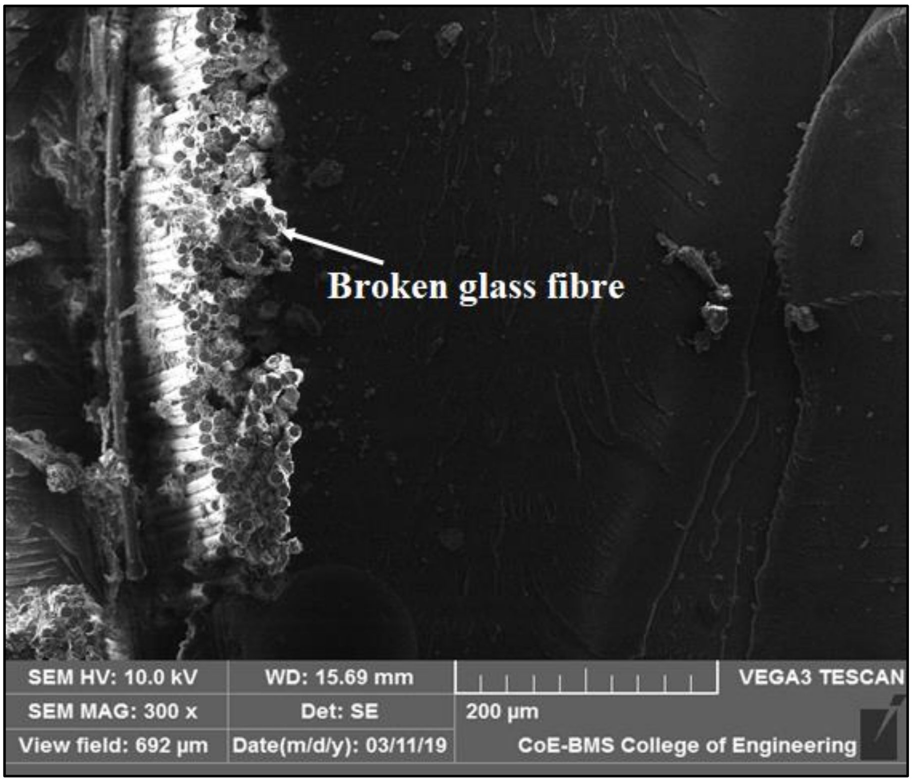


Figure 4.36 SEM micrographs of composites made with CF+GF after flexure test.

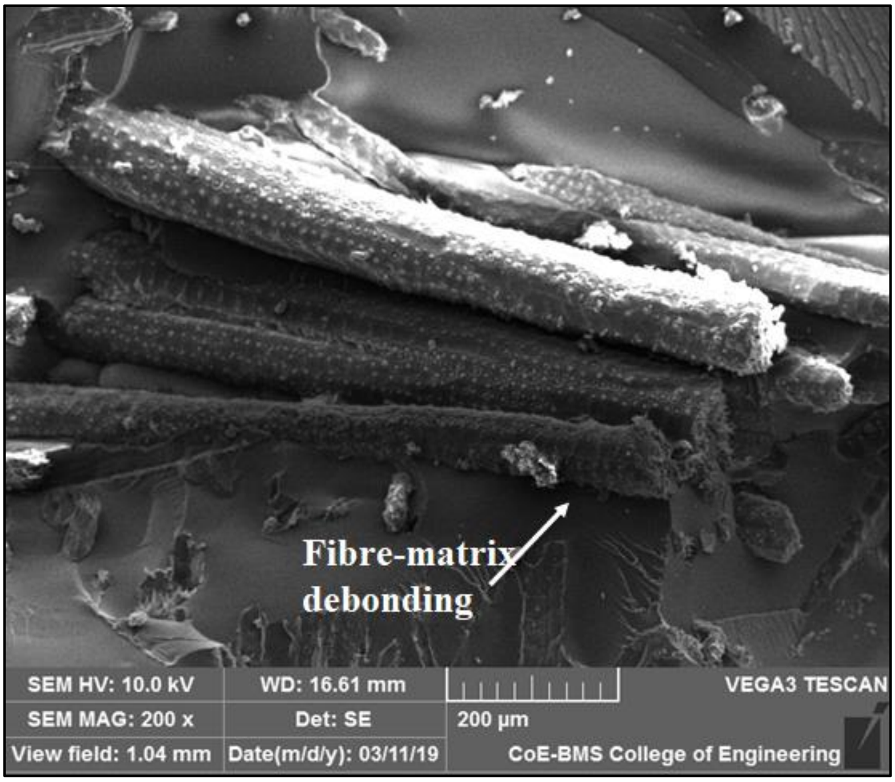


Figure 4.37 SEM micrographs of composites made with FF after impact test.

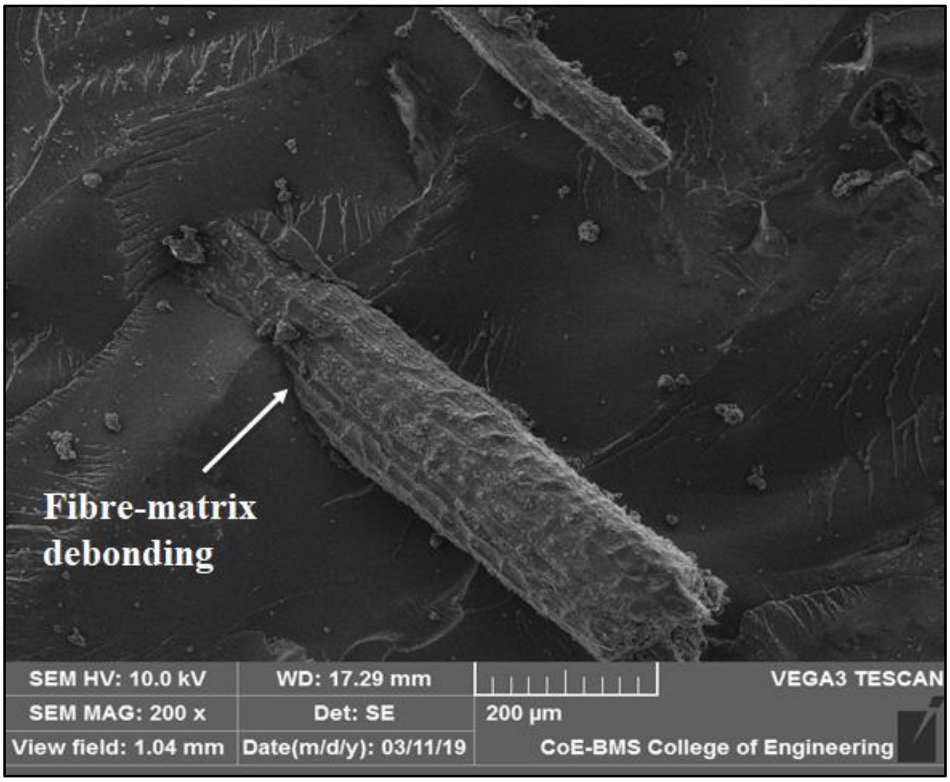


Figure 4.38 SEM micrographs of composites made with CF after impact test.

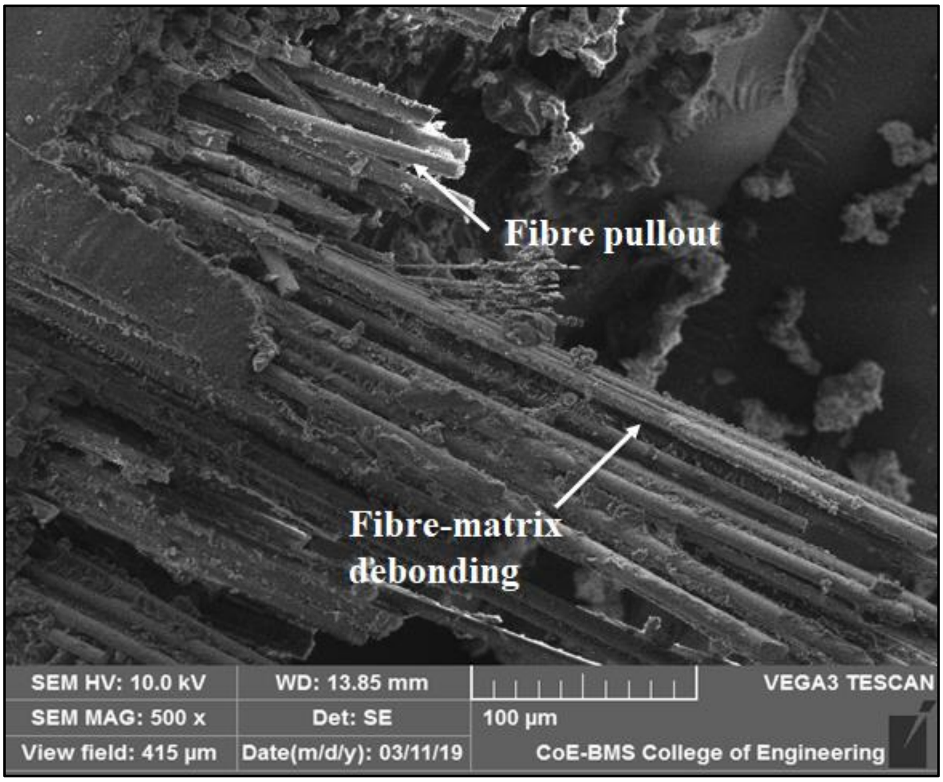


Figure 4.39 SEM micrographs of composites made with CF+GF after impact test.

4.5 Comparative study of static mechanical properties of different natural fibre composites.

The material densities and static mechanical properties of different natural fibre composites are given in Table 4.4, Table 4.5 and Table 4.6. The densities of Coir, Oil palm, Sisal, Jute, Flax, Bambo fibres are given in Table 4.4. The density of areca fibre is comparable with Bambo fibre and densities of rest of the fibre given in Table 4.4 are higher than density of areca fibre. Researchers (Nguyen Minh Hai et al. (2012), Omar Faruk et al. (2012) and VikasDhawan et al. (2013)) tried with different fibre materials at different fibre weight percent. The static mechanical properties of different natural fibres with different matrix materials are given in Table 4.5. From Table 4.5, Young's modulus of arecanut husk fibre reinforced epoxy composites, obtained from the present study, is greater than the coir - poly propylene composite and less than the Jute - poly propylene composite. The tensile strength of arecanut husk fibre reinforced composites are less than that of both coir - poly propylene composite and Jute - poly propylene composite. The flexural strength of arecanut husk fibre reinforced epoxy composites are comparable with the flexural strength of Hemp – polyester composites. The static mechanical properties of natural fibre along with glass fibre reinforced composites are given in Table 4.6. The tensile strength of coarse arecanut husk fibre along with glass fibre reinforced epoxy composites are less compared to the literature values due to less percentage of glass fibre used in the present study.

Table 4.4 Densities of different fibres.

Fibre type	Density (g/cm^3)	Reference
Coir	1.2	Vikas Dhawan et al., 2013
Oil palm	0.7-1.55	
Sisal	1.5	
Jute	1.3	
Flax	1.5	
Bambo	0.6-1.1	

Table 4.5 Static mechanical properties of different fibre reinforced composite materials.

Fibre type	Matrix material	Tensile strength (MPa)	Young's modulus (GPa)	Flexural strength (MPa)	Impact strength (kJ/m^2)	Reference
Coir (50 wt%)	Poly propylene	21	0.49	-----	-----	Nguyen Minh Hai et al., 2012
Jute (50 wt%)	Poly propylene	90	4.5	-----	-----	
Flax (30 wt%)	PLA	75				Omar Faruk et al., 2012
Hemp (20 vol%)	polyester	33	1.42	54	4.8	
Glass fibre (20 vol%)	polyester	85	1.72	176	61	

Table 4.6 Static mechanical properties of glass fibre reinforced composites with different matrix material and second filler material.

Fibre type	Matrix material	Tensile strength (MPa)	Compressive strength (MPa)	Impact strength (MPa)	Reference
No fill	epoxy	398	351	263	Vikas Dhawan et al., 2013
Coir	epoxy	372	289	215	
Wheat husk	epoxy	353	222	206	
Rice	Epoxy	307	280	234	
No fill	Polyester	352	213	234	
Coir	Polyester	315	224	279	
Wheat husk	Polyester	283	174	246	
Rice	Polyester	325	199	257	

CHAPTER 5

CONCLUSIONS

5.1 Introduction

The following conclusions were drawn from composite material manufacturing process, static and dynamic experimental studies on composite panels cast with fine arecanut husk fibre, coarse arecanut husk fibre and coarse arecanut husk fibre sandwiched with glass fibre layers.

5.2 Conclusions from static analysis

- The chemical treatment of arecanut husk fibres resulted in undulated surface of fibres which improves mechanical bonding between fibres and epoxy matrix.
- Tensile strength of epoxy composites made with fine arecanut husk fibres (15.1 MPa) was observed to be more when compared to that of epoxy composites made with coarse arecanut husk fibres (10.8 MPa) due to higher surface interaction of fine fibres with epoxy matrix.
- Elastic modulus of composites made with coarse fibre (3.54 GPa) and fine fibre (3.2 GPa) have not changed significantly. Elastic modulus of coarse fibre sandwiched with glass fibre composites (4.4 GPa) is more when compared to that of pure areca fibre composites.
- The average flexural strength of composites reinforced with fine fibre, coarse fibre and coarse fibre sandwiched with glass fibre are found to be 73 MPa, 66.7 MPa and 284 MPa, respectively.
- The improvement in tensile strength and flexural strength of composites with fine fibre is due to increase in surface area of fibre which results in better interaction between fibre and matrix.
- Coarse fibre composites (absorbed impact energy 6 J) absorb higher impact load than the fine fibre composites (absorbed impact energy 3.6 J).

- Addition of two glass fibre layers to coarse arecanut husk fibre composites improves the mechanical properties (tensile, flexural and impact) of the composites.

5.3 Conclusions from dynamic analysis

- The storage modulus increased with increase in loading frequency and variation of increment in storage modulus decreased with increase in frequency.
- At room temperature, the values of storage modulus are 0.478 GPa, 0.573 GPa and 0.607 GPa for loading frequencies of 5 Hz, 10 Hz and 15 Hz respectively.
- The arecanut composite can retain its storage modulus up to 80 ºC.
- The glass transition temperature of arecanut husk fibre composites is 105 ºC. Glass transition temperature of arecanut husk fibre composite is independent of loading frequency.
- The elastic modulus, obtained from the dynamic analysis at room temperature, is ranging from 2.7 GPa to 3.4 GPa at loading frequencies of 5 Hz, 10 Hz and 15 Hz. Whereas the elastic modulus obtained from static flexural test at room temperature is in the range of 3 GPa to 3.63 GPa.

From the static tensile tests, average elastic modulus of epoxy composite reinforced with randomly arranged arecanut husk fibre was observed as 3.2 GPa and 3.54 GPa for fine arecanut husk fibre composites and coarse arecanut husk fibre composites respectively. From static flexural test of the elastic modulus of composite made with mixed fibres (coarse and fine arecanut husk fibres) and threaded form was ranging from 3 GPa to 3.63 GPa. The elastic modulus of arecanut husk fibre epoxy composites obtained from different tests are given in Table 5.1.

Table 5.1 Modulus of composite specimens obtained from different experiments.

	Dynamic flexural test			Static test		
				Flexural	Tensile	
	5 Hz	10 Hz	15 Hz	Mixed fibre	(Fine fibre composite)	(Coarse fibre composite)
Elastic modulus (GPa)	2.7	2.94	3.4	3 - 3.63	3.2	3.54

5.4 Limitations of the study

- Avoiding pore formation during casting of arecanut husk fibre epoxy composites using hand lay-up technique is difficult which creates weaker sections of the composite panels.
- Uniform distribution of epoxy resin with arecanut husk fibre can be achieved using Light Resin Transfer Molding (LRTM) manufacture process to avoid air voids in the composite.
- From the failed specimens after testing, the weaker sections of the composites are due to stacked of fibre bunches. Proper dehusking is required to avoid the stacking of fibre bunches in the composite.
- Proper thread forming procedure is need to adopt for arecanut husk fibre as compare to other natural fibres to obtain uniform diameter of threads.

5.5 Scope for future work

- The present study can be extended with different percentage of arecanut husk fibre to optimize the fibre weight percentage.
- Characterization of arecanut husk fibre composite with different types of epoxy resin can be studies based on the applications of product.

- Characterization of arecanut husk fibre composite under different environmental conditions such as humid environment, marine environment, thermal environment.
- Life of arecanut husk fibre composites for fatigue loads.

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APPENDIX I

Table A1 Experimental observations to measure density of fine arecanut husk fibre.

Sample No.	Pycnometer weight (g)	Pycnometer + fibre weight (g)	Pycnometer + fibre + water weight (g)	Pycnometer + water weight (g)	Volume of excess water in the pycanomer containing fibre (cc)	Volume of empty pycnometer (g)	Density of fibre (g/cc)
	(A)	(B)	(C)	(D)	V_1 = (C-B)/density of water	V_2 = (D-A)/density of water	(B-A)/(V_2-V_1)
1	30.901	32.100	79.124	79.100	47.024	48.199	1.020
2	29.512	29.810	79.335	79.310	49.525	49.798	1.092
3	30.000	31.210	79.540	79.400	48.330	49.400	1.131
4	31.210	32.011	79.600	79.500	47.589	48.290	1.143
5	31.110	32.021	79.800	79.671	47.779	48.561	1.165
Average density							1.110

Table A2 Experimental observations to measure density of coarse arecanut husk fibre.

Sample No.	Pycnometer weight (g)	Pycnometer + fibre weight (g)	Pycnometer + fibre + water weight (g)	Pycnometer + water weight (g)	Volume of excess water in the pycanomer containing fibre (cc)	Volume of empty pycnometer (g)	Density of fibre (g/cc)
	(A)	(B)	(C)	(D)	V_1 = (C-B)/density of water	V_2 = (D-A)/density of water	(B-A)/(V_2-V_1)
1	30.900	32.120	79.534	79.650	47.414	48.750	0.913

2	29.512	29.795	79.471	79.500	49.676	49.988	0.907
3	30.100	31.500	79.491	79.650	47.991	49.550	0.898
4	31.210	31.854	79.650	79.721	47.796	48.511	0.901
5	31.110	31.997	79.698	79.779	47.701	48.669	0.916
Average density							0.907

Table A3 Experimental observations to measure density of mixed arecanut husk fibre (coarse and fine fibre).

Sample No.	Pycnometer weight (g)	Pycnometer + fibre weight (g)	Pycnometer + fibre + water weight (g)	Pycnometer + water weight (g)	Volume of excess water in the pycanomer containing fibre (cc)	Volume of empty pycnometer (g)	Density of fibre (g/cc)
	(A)	(B)	(C)	(D)	V_1 = (C-B)/density of water	V_2 = (D-A)/density of water	(B-A)/(V_2-V_1)
1	30.900	32.120	79.931	79.980	47.811	49.080	0.961
2	30.100	30.211	79.699	79.750	49.488	50.250	0.933
3	31.110	31.958	79.560	79.680	47.602	49.580	0.939
4	31.210	31.859	79.850	79.890	47.991	48.680	0.942
5	29.500	31.801	79.743	79.774	47.942	48.664	0.957
Average density							0.947

Table A4: Data from Dynamic Mechanical Analysis of arecanut husk fibre composite at 5Hz frequency.

Time (s)	Temperature (°C)	E" (Pa)	E' (Pa)	Tan delta (δ)	dyn. Force (N)	dyn. Displacement (m)
5.71E-07	27.9	1.85E+07	4.78E+08	0.038723	23.1613	9.28E-05
15.438	27.9	1.86E+07	4.79E+08	0.03874	24.1447	9.66E-05
30.8752	27.95	1.86E+07	4.79E+08	0.03882	24.8364	9.93E-05
46.3123	28.45	1.86E+07	4.80E+08	0.03879	24.9857	9.97E-05
61.7494	29.6	1.86E+07	4.81E+08	0.038586	25.053	9.99E-05
77.1866	30.85	1.85E+07	4.82E+08	0.03842	25.095	9.99E-05
92.6237	31.75	1.84E+07	4.82E+08	0.038152	25.1302	9.99E-05
108.061	32.45	1.83E+07	4.83E+08	0.037833	25.1632	9.99E-05
123.498	33.15	1.81E+07	4.83E+08	0.037419	25.1902	9.99E-05
138.935	33.95	1.79E+07	4.84E+08	0.036978	25.2179	9.99E-05
154.372	34.75	1.77E+07	4.84E+08	0.036622	25.2409	1.00E-04
169.809	35.4	1.76E+07	4.84E+08	0.036319	25.2548	1.00E-04
185.246	36	1.74E+07	4.85E+08	0.035985	25.2682	1.00E-04
200.684	36.75	1.73E+07	4.85E+08	0.035679	25.2784	1.00E-04
216.121	37.75	1.72E+07	4.85E+08	0.035461	25.2841	1.00E-04
231.558	38.6	1.71E+07	4.85E+08	0.035275	25.2854	1.00E-04
246.995	39.2	1.70E+07	4.85E+08	0.035113	25.2892	1.00E-04
262.432	39.9	1.69E+07	4.85E+08	0.034871	25.29	0.0001
277.869	40.75	1.69E+07	4.85E+08	0.034763	25.2887	0.0001
293.306	41.5	1.68E+07	4.85E+08	0.034595	25.2863	0.0001
308.744	42.25	1.67E+07	4.84E+08	0.03455	25.2793	0.0001
324.181	43.2	1.67E+07	4.84E+08	0.034492	25.2689	0.0001
339.618	44.05	1.66E+07	4.84E+08	0.03438	25.2631	0.0001
355.055	44.7	1.66E+07	4.84E+08	0.034392	25.2555	0.0001
370.492	45.4	1.66E+07	4.84E+08	0.034319	25.2496	0.0001
385.929	46.05	1.66E+07	4.84E+08	0.034256	25.2403	0.0001
401.366	46.65	1.66E+07	4.83E+08	0.034285	25.2302	0.0001
416.803	47.7	1.66E+07	4.83E+08	0.034335	25.2171	0.0001
432.241	48.8	1.66E+07	4.83E+08	0.034416	25.2069	0.0001
447.678	49.4	1.67E+07	4.83E+08	0.034509	25.2004	0.0001
463.115	49.95	1.67E+07	4.83E+08	0.03457	25.1969	0.0001
478.552	50.75	1.67E+07	4.83E+08	0.034607	25.193	0.0001
493.989	51.6	1.67E+07	4.83E+08	0.034661	25.1846	0.0001
509.426	52.25	1.68E+07	4.83E+08	0.034732	25.1798	0.0001
524.863	52.95	1.68E+07	4.83E+08	0.034791	25.1747	0.0001
540.3	54	1.68E+07	4.82E+08	0.034903	25.1702	0.0001
555.738	54.75	1.69E+07	4.82E+08	0.035028	25.1646	0.0001
571.175	55.6	1.69E+07	4.82E+08	0.035145	25.1608	0.0001

586.612	56.5	1.70E+07	4.82E+08	0.035303	25.1542	0.0001
602.049	56.85	1.71E+07	4.82E+08	0.035405	25.1506	0.0001
617.486	57.65	1.71E+07	4.82E+08	0.035587	25.1467	0.0001
632.923	58.75	1.72E+07	4.82E+08	0.035786	25.1357	0.0001
648.36	59.45	1.73E+07	4.82E+08	0.036005	25.129	0.0001
663.798	59.85	1.74E+07	4.81E+08	0.036222	25.123	0.0001
679.235	60.8	1.76E+07	4.81E+08	0.03651	25.1092	0.0001
694.672	61.9	1.77E+07	4.81E+08	0.036876	25.0944	0.0001
710.109	62.45	1.78E+07	4.80E+08	0.037135	25.0809	0.0001
725.546	63.15	1.80E+07	4.80E+08	0.037482	25.0646	0.0001
740.983	64.1	1.82E+07	4.80E+08	0.037845	25.0399	0.0001
756.42	64.7	1.83E+07	4.79E+08	0.038196	25.017	0.0001
771.857	65.3	1.84E+07	4.78E+08	0.038553	24.9916	0.0001
787.295	66.3	1.86E+07	4.78E+08	0.038889	24.9577	0.0001
802.732	67	1.86E+07	4.77E+08	0.039074	24.9182	0.0001
818.169	67.6	1.87E+07	4.76E+08	0.039225	24.8801	0.0001
833.606	68.5	1.87E+07	4.75E+08	0.039335	24.8345	0.0001
849.043	69.35	1.87E+07	4.74E+08	0.039512	24.7797	0.0001
864.48	70.1	1.88E+07	4.73E+08	0.039794	24.7177	0.0001
879.917	71.2	1.89E+07	4.71E+08	0.040134	24.6473	0.0001
895.355	72	1.90E+07	4.70E+08	0.040541	24.5702	0.0001
910.792	72.2	1.92E+07	4.68E+08	0.04094	24.5068	0.0001
926.229	73.1	1.94E+07	4.67E+08	0.041514	24.4309	0.0001
941.666	74.35	1.96E+07	4.65E+08	0.042059	24.3388	0.0001
957.103	74.95	1.98E+07	4.64E+08	0.042683	24.2607	0.0001
972.54	75.3	2.01E+07	4.62E+08	0.043452	24.1758	0.0001
987.977	76.1	2.04E+07	4.60E+08	0.044353	24.0836	0.0001
1003.41	77.05	2.08E+07	4.58E+08	0.045399	23.9722	0.0001
1018.85	77.8	2.13E+07	4.55E+08	0.046713	23.8587	0.0001
1034.29	78.75	2.18E+07	4.52E+08	0.048227	23.7249	0.0001
1049.73	79.45	2.25E+07	4.50E+08	0.04996	23.587	0.0001
1065.16	79.95	2.33E+07	4.46E+08	0.052126	23.4469	0.000101
1080.6	80.95	2.42E+07	4.42E+08	0.054736	23.2716	0.000101
1096.04	82	2.53E+07	4.38E+08	0.057744	23.069	0.000101
1111.47	82.6	2.66E+07	4.34E+08	0.061225	22.8605	0.000101
1126.91	83.15	2.81E+07	4.29E+08	0.065493	22.6345	0.000101
1142.35	83.85	2.99E+07	4.23E+08	0.07073	22.3629	0.000101
1157.79	84.85	3.20E+07	4.16E+08	0.077106	22.0411	0.000101
1173.22	85.7	3.45E+07	4.08E+08	0.084456	21.6728	0.000102
1188.66	86	3.73E+07	3.99E+08	0.093544	21.2782	0.000102
1204.1	86.85	4.09E+07	3.86E+08	0.106049	20.7888	0.000103
1219.53	88.2	4.47E+07	3.73E+08	0.119801	20.1238	0.000103
1234.97	88.8	4.84E+07	3.60E+08	0.134347	19.4737	0.000103
1250.41	89.45	5.26E+07	3.46E+08	0.152221	18.8456	0.000103

1265.85	90.25	5.68E+07	3.30E+08	0.171929	18.0991	0.000104
1281.28	90.85	6.10E+07	3.13E+08	0.194743	17.3377	0.000104
1296.72	91.85	6.48E+07	2.95E+08	0.219594	16.4784	0.000105
1312.16	92.8	6.77E+07	2.77E+08	0.243974	15.5764	0.000105
1327.59	93.2	6.96E+07	2.60E+08	0.267671	14.7244	0.000105
1343.03	93.95	7.05E+07	2.40E+08	0.293705	13.8628	0.000106
1358.47	94.9	7.03E+07	2.21E+08	0.318516	12.8573	0.000106
1373.91	95.5	6.94E+07	2.01E+08	0.344645	11.8747	0.000107
1389.34	96.45	6.86E+07	1.84E+08	0.371871	10.9074	0.000106
1404.78	97.25	6.74E+07	1.71E+08	0.39512	10.0793	0.000105
1420.22	97.65	6.63E+07	1.59E+08	0.41684	9.42303	0.000105
1435.65	98.45	6.50E+07	1.48E+08	0.440324	8.85436	0.000105
1451.09	99.55	6.39E+07	1.39E+08	0.459298	8.29089	0.000104
1466.54	100.15	6.29E+07	1.33E+08	0.472744	7.88767	0.000103
1481.97	100.8	6.18E+07	1.26E+08	0.489877	7.60108	0.000104
1497.4	102.15	6.10E+07	1.21E+08	0.502952	7.2506	0.000103
1512.85	102.75	6.04E+07	1.20E+08	0.504392	7.0226	0.0001
1528.28	103.2	5.95E+07	1.17E+08	0.510508	6.96336	0.000102
1543.71	104.4	5.90E+07	1.15E+08	0.513103	6.79525	0.000101
1559.16	104.8	5.85E+07	1.15E+08	0.509399	6.71761	9.99E-05
1574.59	105.35	5.79E+07	1.13E+08	0.51129	6.71586	0.000101
1590.03	106.65	5.75E+07	1.13E+08	0.50856	6.61046	1.00E-04
1605.48	107.55	5.72E+07	1.15E+08	0.49882	6.60848	9.89E-05
1620.9	107.9	5.69E+07	1.17E+08	0.487879	6.69511	9.90E-05
1636.34	108.6	5.64E+07	1.18E+08	0.480058	6.77377	9.96E-05
1651.79	109.75	5.61E+07	1.19E+08	0.470502	6.80866	9.91E-05
1667.21	110.25	5.58E+07	1.22E+08	0.457566	6.89045	9.85E-05
1682.65	110.65	5.54E+07	1.23E+08	0.449416	7.01618	9.97E-05
1698.1	111.9	5.50E+07	1.24E+08	0.442588	7.05319	9.95E-05
1713.52	113.15	5.48E+07	1.28E+08	0.42856	7.10038	9.80E-05
1728.96	113.45	5.43E+07	1.32E+08	0.411991	7.28083	9.80E-05
1744.41	113.8	5.36E+07	1.33E+08	0.402014	7.4606	9.95E-05
1759.83	114.75	5.32E+07	1.35E+08	0.39377	7.51597	9.93E-05
1775.27	115.8	5.27E+07	1.37E+08	0.384708	7.58727	9.91E-05
1790.72	116.5	5.22E+07	1.40E+08	0.373843	7.67671	9.87E-05
1806.15	117	5.17E+07	1.41E+08	0.365939	7.79778	9.95E-05
1821.58	117.85	5.12E+07	1.43E+08	0.359099	7.85186	9.94E-05
1837.03	118.8	5.07E+07	1.44E+08	0.352309	7.90931	9.94E-05
1852.46	119.7	5.02E+07	1.45E+08	0.345917	7.96506	9.95E-05

Table A5: Data from Dynamic Mechanical Analysis of arecanut husk fibre composite at 10Hz frequency.

Time (s)	Temperature (°C)	E" (Pa)	E' (Pa)	Tan delta (δ)	dyn. Force (N)	dyn. Displacement (m)
5.83E-07	28.1	2.22E+07	5.73E+08	0.038694	24.7669	0.0001
7.92257	28.1	2.23E+07	5.73E+08	0.038986	26.2332	0.0001
15.8442	28.1	2.23E+07	5.73E+08	0.038959	26.9102	0.0001
23.7659	28.15	2.22E+07	5.74E+08	0.038695	27.057	0.0001
31.6876	28.3	2.20E+07	5.75E+08	0.038314	27.1157	0.0001
39.6093	28.6	2.18E+07	5.75E+08	0.037954	27.1458	0.0001
47.531	29.05	2.16E+07	5.75E+08	0.037627	27.1653	0.0001
55.4527	29.65	2.15E+07	5.76E+08	0.037289	27.1803	0.0001
63.3744	30.35	2.14E+07	5.76E+08	0.037107	27.19	0.0001
71.2961	30.9	2.13E+07	5.76E+08	0.036908	27.1977	0.0001
79.2177	31.4	2.12E+07	5.76E+08	0.03678	27.2091	0.0001
87.1394	31.9	2.12E+07	5.76E+08	0.036705	27.2176	0.0001
95.0611	32.3	2.11E+07	5.76E+08	0.036567	27.2246	0.0001
102.983	32.65	2.10E+07	5.77E+08	0.036439	27.2299	0.0001
110.905	33	2.09E+07	5.77E+08	0.036205	27.2351	0.0001
118.826	33.35	2.08E+07	5.77E+08	0.036065	27.2405	0.0001
126.748	33.7	2.07E+07	5.77E+08	0.035837	27.243	0.0001
134.67	34.05	2.06E+07	5.77E+08	0.035747	27.2445	0.0001
142.591	34.4	2.06E+07	5.77E+08	0.035637	27.2457	0.0001
150.513	34.8	2.05E+07	5.77E+08	0.035475	27.2474	0.0001
158.435	35.2	2.04E+07	5.77E+08	0.035376	27.2474	0.0001
166.356	35.6	2.03E+07	5.77E+08	0.035205	27.2464	0.0001
174.278	36	2.02E+07	5.77E+08	0.035065	27.2431	0.0001
182.2	36.4	2.01E+07	5.77E+08	0.034908	27.2397	0.0001
190.121	36.75	2.01E+07	5.77E+08	0.034804	27.2379	0.0001
198.043	37.05	2.00E+07	5.76E+08	0.034721	27.2331	0.0001
205.965	37.45	1.99E+07	5.76E+08	0.034598	27.2256	0.0001
213.886	37.9	1.98E+07	5.76E+08	0.034441	27.2215	0.0001
221.808	38.25	1.98E+07	5.76E+08	0.034298	27.2157	0.0001
229.73	38.7	1.97E+07	5.76E+08	0.034235	27.2053	0.0001
237.651	39.25	1.97E+07	5.76E+08	0.034185	27.1972	0.0001
245.573	39.7	1.96E+07	5.75E+08	0.034025	27.1855	0.0001
253.495	40.1	1.95E+07	5.75E+08	0.033985	27.1777	0.0001
261.417	40.5	1.94E+07	5.75E+08	0.033807	27.1641	0.0001
269.338	40.85	1.94E+07	5.75E+08	0.033758	27.1567	0.0001
277.26	41.25	1.93E+07	5.75E+08	0.03367	27.1451	0.0001
285.182	41.7	1.93E+07	5.74E+08	0.033554	27.1362	0.0001
293.103	42	1.92E+07	5.74E+08	0.033467	27.1247	0.0001

301.025	42.15	1.91E+07	5.74E+08	0.03335	27.1125	0.0001
308.947	42.4	1.91E+07	5.73E+08	0.033268	27.1013	0.0001
316.868	42.9	1.90E+07	5.73E+08	0.033165	27.0839	0.0001
324.79	43.4	1.89E+07	5.73E+08	0.033056	27.0673	0.0001
332.712	43.95	1.89E+07	5.72E+08	0.032975	27.0543	0.0001
340.633	44.65	1.88E+07	5.72E+08	0.032905	27.035	0.0001
348.555	45.1	1.88E+07	5.72E+08	0.032851	27.0186	0.0001
356.477	45.35	1.87E+07	5.72E+08	0.03271	27.0061	0.0001
364.398	45.65	1.86E+07	5.71E+08	0.032641	26.9946	0.0001
372.32	45.85	1.86E+07	5.71E+08	0.032564	26.978	0.0001
380.242	46.1	1.85E+07	5.71E+08	0.032494	26.9641	0.0001
388.164	46.55	1.85E+07	5.70E+08	0.032486	26.9464	0.0001
396.085	47.1	1.85E+07	5.70E+08	0.032388	26.9292	0.0001
404.007	47.65	1.84E+07	5.69E+08	0.032328	26.9084	0.0001
411.929	48.1	1.84E+07	5.69E+08	0.032329	26.8944	0.0001
419.85	48.45	1.84E+07	5.69E+08	0.032327	26.8743	0.0001
427.772	48.75	1.84E+07	5.68E+08	0.032342	26.8581	0.0001
435.694	49.05	1.83E+07	5.68E+08	0.032265	26.8406	0.0001
443.615	49.3	1.83E+07	5.68E+08	0.032292	26.8231	0.0001
451.537	49.6	1.83E+07	5.67E+08	0.032234	26.8056	0.0001
459.459	50	1.83E+07	5.67E+08	0.032245	26.7858	0.0001
467.38	50.45	1.83E+07	5.66E+08	0.032264	26.7637	0.0001
475.302	51.05	1.83E+07	5.66E+08	0.032278	26.7408	0.0001
483.224	51.65	1.83E+07	5.65E+08	0.032294	26.718	0.0001
491.145	52.15	1.83E+07	5.65E+08	0.032322	26.6964	0.0001
499.067	52.35	1.83E+07	5.64E+08	0.032365	26.675	0.0001
506.989	52.45	1.83E+07	5.64E+08	0.032384	26.656	0.0001
514.911	52.9	1.83E+07	5.63E+08	0.032401	26.631	0.0001
522.832	53.6	1.82E+07	5.63E+08	0.03241	26.6045	0.0001
530.754	54.25	1.82E+07	5.62E+08	0.032442	26.5831	0.0001
538.676	54.5	1.83E+07	5.62E+08	0.032497	26.5619	0.0001
546.597	54.55	1.83E+07	5.62E+08	0.032581	26.5431	0.0001
554.519	54.75	1.83E+07	5.61E+08	0.03253	26.5193	0.0001
562.441	55.15	1.83E+07	5.61E+08	0.032646	26.4985	0.0001
570.362	55.7	1.83E+07	5.60E+08	0.032696	26.4704	0.0001
578.284	56.2	1.83E+07	5.59E+08	0.032732	26.4434	0.0001
586.206	56.65	1.84E+07	5.59E+08	0.03285	26.4176	0.0001
594.127	57.05	1.84E+07	5.58E+08	0.032869	26.3921	0.0001
602.049	57.4	1.84E+07	5.58E+08	0.03297	26.3677	0.0001
609.971	57.9	1.84E+07	5.57E+08	0.032989	26.3404	0.0001
617.892	58.45	1.84E+07	5.57E+08	0.033076	26.3123	0.0001
625.814	58.75	1.84E+07	5.56E+08	0.033166	26.284	0.0001
633.736	58.9	1.85E+07	5.55E+08	0.033256	26.2606	0.0001
641.658	59.2	1.85E+07	5.55E+08	0.033306	26.2319	0.0001

649.579	59.65	1.85E+07	5.54E+08	0.033434	26.2032	0.0001
657.501	60.15	1.86E+07	5.54E+08	0.033586	26.171	0.0001
665.423	60.6	1.86E+07	5.53E+08	0.03363	26.1418	0.0001
673.344	61.05	1.87E+07	5.52E+08	0.033788	26.1111	0.0001
681.266	61.55	1.87E+07	5.52E+08	0.033908	26.0801	0.0001
689.188	61.9	1.87E+07	5.51E+08	0.033935	26.0477	0.0001
697.109	62.2	1.88E+07	5.50E+08	0.03415	26.0176	0.0001
705.031	62.55	1.89E+07	5.50E+08	0.034302	25.9886	0.0001
712.953	62.9	1.89E+07	5.49E+08	0.034414	25.9584	0.0001
720.874	63.35	1.89E+07	5.48E+08	0.034497	25.9268	0.0001
728.796	63.85	1.90E+07	5.48E+08	0.034676	25.8974	0.0001
736.718	64.25	1.90E+07	5.47E+08	0.0348	25.8664	0.0001
744.639	64.55	1.91E+07	5.47E+08	0.034936	25.838	0.0001
752.561	64.95	1.91E+07	5.46E+08	0.034974	25.81	0.0001
760.483	65.35	1.91E+07	5.45E+08	0.035057	25.7809	0.0001
768.405	65.7	1.91E+07	5.45E+08	0.035115	25.752	0.0001
776.326	66.05	1.92E+07	5.44E+08	0.035256	25.7198	0.0001
784.248	66.35	1.92E+07	5.43E+08	0.035371	25.6843	0.0001
792.17	66.7	1.92E+07	5.42E+08	0.035459	25.6488	0.0001
800.091	67.2	1.93E+07	5.42E+08	0.035641	25.6129	0.0001
808.013	67.95	1.94E+07	5.41E+08	0.035827	25.5752	0.0001
815.935	68.5	1.94E+07	5.40E+08	0.035927	25.5351	0.0001
823.856	68.65	1.94E+07	5.39E+08	0.036029	25.5042	0.0001
831.981	68.75	1.95E+07	5.39E+08	0.03619	25.4727	0.0001
839.903	69.15	1.95E+07	5.38E+08	0.036357	25.4365	0.0001
847.825	69.7	1.96E+07	5.37E+08	0.036434	25.3907	0.0001
855.746	69.95	1.97E+07	5.36E+08	0.036667	25.3527	0.0001
863.668	70.3	1.97E+07	5.35E+08	0.036887	25.3125	0.0001
871.59	70.9	1.98E+07	5.34E+08	0.037068	25.2674	0.0001
879.511	71.35	1.99E+07	5.33E+08	0.037325	25.2225	0.0001
887.433	71.6	2.00E+07	5.32E+08	0.037524	25.1777	0.0001
895.355	72	2.00E+07	5.31E+08	0.037684	25.1348	0.0001
903.276	72.6	2.01E+07	5.30E+08	0.037871	25.0845	0.0001
911.198	73.05	2.02E+07	5.29E+08	0.038155	25.0409	0.0001
919.12	73.25	2.03E+07	5.28E+08	0.038429	24.9931	0.0001
927.041	73.65	2.04E+07	5.27E+08	0.038714	24.9444	0.0001
934.963	74.25	2.05E+07	5.26E+08	0.039049	24.8902	0.0001
942.885	74.6	2.07E+07	5.25E+08	0.039371	24.8366	0.0001
950.806	74.6	2.08E+07	5.24E+08	0.03967	24.7891	0.0001
958.728	74.9	2.09E+07	5.22E+08	0.040074	24.735	0.0001
966.65	75.75	2.11E+07	5.21E+08	0.040429	24.6688	0.0001
974.571	76.35	2.12E+07	5.20E+08	0.040748	24.609	0.0001
982.493	76.45	2.13E+07	5.19E+08	0.041162	24.5526	0.0001
990.415	76.65	2.15E+07	5.17E+08	0.041634	24.4922	0.0001

998.337	77.15	2.18E+07	5.16E+08	0.042175	24.4271	0.0001
1006.26	77.6	2.19E+07	5.14E+08	0.042641	24.3554	0.0001
1014.18	78.05	2.21E+07	5.13E+08	0.043147	24.2844	0.0001
1022.1	78.55	2.24E+07	5.11E+08	0.043755	24.2158	0.0001
1030.02	78.85	2.26E+07	5.10E+08	0.044415	24.1419	0.0001
1037.94	78.9	2.29E+07	5.08E+08	0.045035	24.0672	0.0001
1045.87	79.3	2.32E+07	5.06E+08	0.045792	23.9912	0.0001
1053.79	79.95	2.35E+07	5.04E+08	0.046694	23.8957	0.0001
1061.71	80.45	2.39E+07	5.02E+08	0.047613	23.8002	0.0001
1069.63	81.15	2.43E+07	5.00E+08	0.048544	23.7037	0.0001
1077.55	81.85	2.46E+07	4.98E+08	0.049489	23.6055	0.0001
1085.48	82.05	2.51E+07	4.96E+08	0.050576	23.5162	0.0001
1093.4	82.05	2.55E+07	4.94E+08	0.051624	23.4251	0.0001
1101.32	82.15	2.60E+07	4.92E+08	0.052836	23.3344	0.0001
1109.24	82.25	2.65E+07	4.89E+08	0.054235	23.2282	0.0001
1117.16	82.8	2.72E+07	4.86E+08	0.055964	23.1049	0.0001
1125.08	83.45	2.79E+07	4.83E+08	0.057632	22.9629	0.0001
1133.01	84	2.87E+07	4.80E+08	0.059687	22.8342	0.0001
1140.93	84.7	2.95E+07	4.77E+08	0.06176	22.6775	0.0001
1148.85	85.15	3.03E+07	4.74E+08	0.063906	22.539	0.0001
1156.77	85.3	3.12E+07	4.71E+08	0.066181	22.4003	0.0001
1164.69	85.5	3.21E+07	4.67E+08	0.068713	22.2521	0.0001
1172.61	85.65	3.32E+07	4.64E+08	0.071625	22.0898	0.0001
1180.54	85.95	3.44E+07	4.59E+08	0.074938	21.9065	0.0001
1188.46	86.7	3.57E+07	4.54E+08	0.078519	21.7019	0.0001
1196.38	87.25	3.70E+07	4.50E+08	0.082141	21.4866	0.0001
1204.3	87.5	3.82E+07	4.45E+08	0.085861	21.2725	0.0001
1212.22	87.75	3.96E+07	4.40E+08	0.090066	21.0533	0.0001
1220.14	87.95	4.11E+07	4.33E+08	0.094863	20.7954	0.0001
1228.07	88.3	4.28E+07	4.27E+08	0.100357	20.5072	0.0001
1235.99	89	4.46E+07	4.20E+08	0.106367	20.1924	0.0001
1243.91	89.85	4.65E+07	4.12E+08	0.112822	19.8624	0.0001
1251.83	90.5	4.84E+07	4.05E+08	0.11954	19.5313	0.0001
1259.75	90.65	5.02E+07	3.98E+08	0.126064	19.2021	0.0001
1267.67	90.7	5.19E+07	3.91E+08	0.132946	18.8843	0.0001
1275.6	90.75	5.37E+07	3.82E+08	0.140521	18.5462	0.0001
1283.52	91.1	5.57E+07	3.73E+08	0.14939	18.1682	0.0001
1291.44	91.9	5.77E+07	3.63E+08	0.158871	17.7402	0.0001
1299.36	92.45	5.95E+07	3.54E+08	0.168128	17.2974	0.0001
1307.28	92.75	6.11E+07	3.45E+08	0.17706	16.8676	0.0001
1315.2	93.3	6.26E+07	3.35E+08	0.186833	16.4609	0.0001
1323.13	93.9	6.41E+07	3.27E+08	0.19602	16.0277	0.0001
1331.05	94.05	6.53E+07	3.19E+08	0.204776	15.6663	0.0001
1338.97	94.15	6.66E+07	3.10E+08	0.214504	15.3086	0.0001

1346.89	94.4	6.77E+07	3.01E+08	0.225071	14.9135	0.0001
1354.81	94.95	6.88E+07	2.92E+08	0.235714	14.4923	0.0001
1362.73	95.65	6.96E+07	2.83E+08	0.245563	14.0777	0.0001
1370.66	95.9	7.01E+07	2.75E+08	0.254731	13.699	0.0001
1378.58	96	7.06E+07	2.67E+08	0.264594	13.3383	0.0001
1386.5	96.45	7.13E+07	2.59E+08	0.275792	12.9683	0.0001
1394.42	97.2	7.19E+07	2.50E+08	0.287023	12.5937	0.0001
1402.34	97.6	7.22E+07	2.43E+08	0.296685	12.2318	0.0001
1410.26	97.75	7.24E+07	2.36E+08	0.306221	11.9239	0.0001
1418.19	98.15	7.25E+07	2.30E+08	0.31583	11.6127	0.0001
1426.11	98.4	7.24E+07	2.23E+08	0.324889	11.3014	0.0001
1434.03	98.7	7.23E+07	2.16E+08	0.335114	11.0056	0.0001
1441.95	99.25	7.21E+07	2.09E+08	0.34504	10.6792	0.0001
1449.87	100	7.19E+07	2.03E+08	0.354555	10.3769	0.0001
1457.79	100.8	7.16E+07	1.99E+08	0.36043	10.0986	0.0001
1465.72	101.1	7.12E+07	1.95E+08	0.365326	9.92655	0.0001
1473.64	101.1	7.08E+07	1.92E+08	0.369398	9.76367	0.0001
1481.56	101	7.04E+07	1.88E+08	0.374194	9.61964	0.0001
1489.48	101.1	7.00E+07	1.84E+08	0.381365	9.44706	0.0001
1497.4	101.9	6.96E+07	1.79E+08	0.389368	9.23166	0.0001
1505.32	102.85	6.92E+07	1.76E+08	0.394167	9.01188	0.0001
1513.25	103.5	6.88E+07	1.74E+08	0.396233	8.87638	0.0001
1521.17	103.85	6.83E+07	1.72E+08	0.397218	8.78968	0.0001
1529.09	103.95	6.78E+07	1.71E+08	0.397861	8.71789	0.0001
1537.01	104.3	6.74E+07	1.69E+08	0.398302	8.64884	0.0001
1544.93	104.6	6.70E+07	1.68E+08	0.397939	8.58615	0.0001
1552.85	104.75	6.65E+07	1.67E+08	0.397917	8.53986	0.0001
1560.78	105.05	6.61E+07	1.66E+08	0.39836	8.48387	0.0001
1568.7	105.55	6.57E+07	1.65E+08	0.398666	8.42176	0.0001
1576.62	106.3	6.53E+07	1.64E+08	0.398091	8.36377	0.0001
1584.54	106.6	6.50E+07	1.64E+08	0.395991	8.33053	0.0001
1592.46	106.75	6.46E+07	1.64E+08	0.39439	8.33109	0.0001
1600.38	107	6.43E+07	1.63E+08	0.393361	8.31248	0.0001
1608.31	107.45	6.39E+07	1.62E+08	0.393277	8.2788	0.0001
1616.23	108.35	6.36E+07	1.62E+08	0.392305	8.23252	0.0001
1624.15	109.05	6.33E+07	1.63E+08	0.38903	8.21356	0.0001
1632.07	108.95	6.29E+07	1.64E+08	0.384241	8.23807	0.0001
1639.99	109.05	6.25E+07	1.64E+08	0.381811	8.28729	0.0001
1647.91	109.75	6.22E+07	1.64E+08	0.379839	8.27411	0.0001
1655.84	110.3	6.19E+07	1.64E+08	0.376534	8.2689	0.0001
1663.76	110.7	6.15E+07	1.65E+08	0.372039	8.29745	0.0001
1671.68	110.85	6.12E+07	1.66E+08	0.367898	8.33965	0.0001
1679.6	111.2	6.09E+07	1.67E+08	0.364638	8.3745	0.0001
1687.52	111.7	6.05E+07	1.68E+08	0.360715	8.39517	0.0001

1695.44	112	6.02E+07	1.69E+08	0.356566	8.42805	0.0001
1703.37	112.4	5.99E+07	1.69E+08	0.353462	8.46853	0.0001
1711.29	113.05	5.96E+07	1.70E+08	0.350232	8.48565	0.0001
1719.21	113.45	5.92E+07	1.71E+08	0.345693	8.51119	0.0001
1727.13	113.7	5.89E+07	1.73E+08	0.341203	8.56549	0.0001
1735.05	114.15	5.85E+07	1.74E+08	0.337322	8.61603	0.0001
1742.98	114.3	5.82E+07	1.75E+08	0.33339	8.65448	0.0001
1750.9	114.5	5.79E+07	1.75E+08	0.330459	8.6926	0.0001
1758.82	115.1	5.76E+07	1.75E+08	0.328126	8.70659	0.0001
1766.74	115.65	5.72E+07	1.76E+08	0.325049	8.71768	0.0001
1774.66	116.3	5.69E+07	1.77E+08	0.32143	8.74785	0.0001
1782.58	116.75	5.66E+07	1.78E+08	0.317695	8.78681	0.0001
1790.51	116.45	5.62E+07	1.79E+08	0.313482	8.83256	0.0001
1798.43	116.5	5.59E+07	1.79E+08	0.311857	8.88117	0.0001
1806.35	117.65	5.56E+07	1.79E+08	0.310976	8.86271	0.0001
1814.27	118.55	5.54E+07	1.80E+08	0.307869	8.84479	0.0001
1822.19	118.7	5.50E+07	1.81E+08	0.30389	8.89465	0.0001
1830.11	118.6	5.47E+07	1.82E+08	0.301192	8.94367	0.0001
1838.04	118.9	5.44E+07	1.82E+08	0.299753	8.95667	0.0001

Table A6: Data from Dynamic Mechanical Analysis of arecanut husk fibre composite at 15Hz frequency.

Time (s)	Temperature (°C)	E" (Pa)	E' (Pa)	Tan delta (δ)	dyn. Force (N)	dyn. Displacement (m)
5.83E-07	28.4	2.22E+07	6.07E+08	0.036569	28.9649	9.15E-05
9.75066	28.4	2.27E+07	6.06E+08	0.03752	31.4073	9.93E-05
19.5004	28.4	2.26E+07	6.07E+08	0.037147	31.6467	9.99E-05
24.3753	28.45	2.24E+07	6.08E+08	0.036913	31.6853	9.99E-05
34.1251	28.7	2.22E+07	6.09E+08	0.036429	31.7391	1.00E-04
39	28.95	2.21E+07	6.09E+08	0.036315	31.7581	1.00E-04
48.7497	29.65	2.19E+07	6.09E+08	0.035977	31.7873	1.00E-04
53.6246	30.1	2.18E+07	6.10E+08	0.035798	31.797	1.00E-04
63.3744	30.85	2.17E+07	6.10E+08	0.035519	31.8179	1.00E-04
68.2493	31.15	2.16E+07	6.10E+08	0.035398	31.8253	1.00E-04
77.999	31.75	2.14E+07	6.10E+08	0.035111	31.8395	1.00E-04
82.8739	32.05	2.14E+07	6.11E+08	0.035043	31.848	1.00E-04
92.6237	32.5	2.12E+07	6.11E+08	0.03478	31.8565	1.00E-04
97.4986	32.7	2.12E+07	6.11E+08	0.034665	31.8639	1.00E-04
107.248	33.1	2.10E+07	6.11E+08	0.034442	31.871	1.00E-04
112.123	33.3	2.10E+07	6.11E+08	0.034314	31.8759	1.00E-04
121.873	33.75	2.08E+07	6.11E+08	0.034109	31.8818	1.00E-04
126.748	34	2.08E+07	6.11E+08	0.034041	31.8854	1.00E-04
136.498	34.45	2.07E+07	6.11E+08	0.033822	31.8877	1.00E-04

141.373	34.65	2.06E+07	6.11E+08	0.033747	31.8892	1.00E-04
151.122	35.15	2.05E+07	6.11E+08	0.033563	31.8917	0.0001
155.997	35.45	2.05E+07	6.11E+08	0.033483	31.8881	0.0001
165.747	36	2.03E+07	6.11E+08	0.033262	31.8845	0.0001
170.622	36.2	2.03E+07	6.11E+08	0.033156	31.8833	0.0001
180.372	36.7	2.02E+07	6.11E+08	0.033002	31.8785	0.0001
185.247	36.95	2.01E+07	6.11E+08	0.032849	31.8763	0.0001
194.996	37.45	2.00E+07	6.11E+08	0.032732	31.8713	0.0001
199.871	37.75	1.99E+07	6.11E+08	0.032638	31.8678	0.0001
209.621	38.2	1.98E+07	6.11E+08	0.03247	31.8607	0.0001
214.496	38.4	1.98E+07	6.11E+08	0.032395	31.858	0.0001
224.246	38.85	1.97E+07	6.10E+08	0.032191	31.846	0.0001
229.12	39.15	1.96E+07	6.10E+08	0.032114	31.8424	0.0001
238.87	39.65	1.95E+07	6.10E+08	0.032007	31.8305	0.0001
248.62	40.2	1.94E+07	6.10E+08	0.031821	31.8209	0.0001
253.495	40.4	1.93E+07	6.10E+08	0.031721	31.816	0.0001
263.245	40.85	1.93E+07	6.10E+08	0.0316	31.8049	0.0001
268.12	41.1	1.92E+07	6.10E+08	0.031492	31.8003	0.0001
277.869	41.45	1.91E+07	6.09E+08	0.031357	31.7884	0.0001
282.744	41.6	1.91E+07	6.09E+08	0.031326	31.7811	0.0001
292.494	42.15	1.90E+07	6.09E+08	0.03116	31.7639	0.0001
297.369	42.45	1.89E+07	6.09E+08	0.031062	31.7567	0.0001
307.119	43.1	1.88E+07	6.08E+08	0.030964	31.7386	0.0001
311.994	43.35	1.88E+07	6.08E+08	0.030864	31.7251	0.0001
321.743	43.65	1.87E+07	6.08E+08	0.030765	31.7061	0.0001
326.618	44	1.86E+07	6.08E+08	0.030677	31.6975	0.0001
336.368	44.6	1.85E+07	6.07E+08	0.030531	31.6756	0.0001
341.243	44.85	1.85E+07	6.07E+08	0.030491	31.6648	0.0001
350.993	45.4	1.84E+07	6.06E+08	0.03038	31.643	0.0001
355.868	45.65	1.84E+07	6.06E+08	0.030331	31.6333	0.0001
365.617	46.1	1.83E+07	6.06E+08	0.030187	31.6122	0.0001
370.492	46.25	1.83E+07	6.06E+08	0.030184	31.6015	0.0001
380.242	46.45	1.82E+07	6.05E+08	0.030031	31.58	0.0001
385.117	46.6	1.82E+07	6.05E+08	0.030005	31.5692	0.0001
394.867	47.35	1.81E+07	6.05E+08	0.029888	31.5441	0.0001
399.741	47.8	1.80E+07	6.04E+08	0.029825	31.528	0.0001
409.491	48.3	1.80E+07	6.04E+08	0.029748	31.5029	0.0001
414.366	48.45	1.79E+07	6.04E+08	0.029682	31.4881	0.0001
424.116	48.9	1.78E+07	6.03E+08	0.029578	31.4655	0.0001
428.991	49.1	1.78E+07	6.03E+08	0.029507	31.4521	0.0001
438.741	49.6	1.77E+07	6.02E+08	0.029443	31.427	0.0001
443.615	49.85	1.77E+07	6.02E+08	0.02944	31.4124	0.0001
453.365	50.35	1.76E+07	6.01E+08	0.029306	31.3859	0.0001
458.24	50.6	1.76E+07	6.01E+08	0.029235	31.3702	0.0001

467.99	50.95	1.75E+07	6.01E+08	0.029184	31.3451	0.0001
472.865	51.3	1.75E+07	6.00E+08	0.029173	31.3315	0.0001
482.615	51.95	1.74E+07	6.00E+08	0.02908	31.3051	0.0001
492.364	52.35	1.74E+07	6.00E+08	0.02901	31.285	0.0001
497.239	52.45	1.74E+07	5.99E+08	0.029041	31.2716	0.0001
506.989	52.75	1.73E+07	5.99E+08	0.028945	31.251	0.0001
511.864	52.95	1.74E+07	5.99E+08	0.028983	31.2392	0.0001
521.614	53.35	1.73E+07	5.98E+08	0.028989	31.2146	0.0001
526.489	53.8	1.73E+07	5.98E+08	0.028948	31.2039	0.0001
536.238	54.95	1.73E+07	5.98E+08	0.029027	31.1822	0.0001
541.113	55.3	1.74E+07	5.98E+08	0.029038	31.1725	0.0001
550.863	55.25	1.74E+07	5.97E+08	0.029083	31.1594	0.0001
555.738	55.2	1.74E+07	5.97E+08	0.029101	31.1486	0.0001
565.488	55.8	1.74E+07	5.97E+08	0.029114	31.1277	0.0001
570.362	56.15	1.73E+07	5.96E+08	0.029086	31.1159	0.0001
580.112	56.85	1.74E+07	5.96E+08	0.029127	31.0929	0.0001
584.987	57	1.74E+07	5.96E+08	0.029156	31.0821	0.0001
594.737	57.35	1.73E+07	5.95E+08	0.029126	31.0588	0.0001
599.612	57.6	1.73E+07	5.95E+08	0.02914	31.0482	0.0001
609.362	58.2	1.74E+07	5.95E+08	0.029184	31.0213	0.0001
614.236	58.6	1.74E+07	5.94E+08	0.029207	31.0083	0.0001
623.986	59.2	1.73E+07	5.94E+08	0.029215	30.9829	0.0001
628.861	59.4	1.73E+07	5.94E+08	0.0292	30.9708	0.0001
638.611	59.55	1.74E+07	5.93E+08	0.029283	30.9466	0.0001
643.486	59.65	1.73E+07	5.93E+08	0.029259	30.9311	0.0001
653.236	60.25	1.73E+07	5.92E+08	0.029282	30.9033	0.0001
658.11	60.35	1.73E+07	5.92E+08	0.029287	30.8866	0.0001
667.86	60.7	1.73E+07	5.91E+08	0.029311	30.8516	0.0001
672.735	61.2	1.74E+07	5.91E+08	0.029381	30.8326	0.0001
682.485	62.2	1.74E+07	5.90E+08	0.029439	30.7966	0.0001
687.36	62.45	1.74E+07	5.90E+08	0.029454	30.7817	0.0001
697.109	62.65	1.74E+07	5.89E+08	0.029536	30.7519	0.0001
701.984	62.85	1.74E+07	5.89E+08	0.029526	30.7335	0.0001
711.734	63.15	1.74E+07	5.88E+08	0.029621	30.6985	0.0001
716.609	63.35	1.74E+07	5.88E+08	0.029639	30.6797	0.0001
726.359	63.9	1.74E+07	5.87E+08	0.029653	30.6413	0.0001
736.109	64.6	1.75E+07	5.86E+08	0.029805	30.6037	0.0001
740.983	65.05	1.75E+07	5.86E+08	0.029832	30.5881	0.0001
750.733	65.7	1.75E+07	5.86E+08	0.029944	30.5627	0.0001
755.608	65.75	1.76E+07	5.86E+08	0.030028	30.5506	0.0001
765.358	65.55	1.77E+07	5.85E+08	0.030174	30.5304	0.0001
770.233	65.6	1.77E+07	5.85E+08	0.030223	30.5172	0.0001
779.982	66.1	1.78E+07	5.84E+08	0.030426	30.4859	0.0001
784.857	66.5	1.78E+07	5.84E+08	0.030557	30.4687	0.0001

794.607	67.55	1.80E+07	5.83E+08	0.030815	30.4328	0.0001
799.482	67.95	1.80E+07	5.83E+08	0.030874	30.4205	0.0001
809.232	68.4	1.82E+07	5.82E+08	0.031185	30.3932	0.0001
814.107	68.65	1.82E+07	5.82E+08	0.031267	30.3794	0.0001
823.857	68.95	1.84E+07	5.82E+08	0.03155	30.3519	0.0001
828.731	69.2	1.84E+07	5.81E+08	0.031712	30.3374	0.0001
838.481	69.6	1.86E+07	5.81E+08	0.032091	30.3099	0.0001
843.356	69.75	1.87E+07	5.80E+08	0.0322	30.295	0.0001
853.106	70.4	1.88E+07	5.80E+08	0.032506	30.2586	0.0001
857.981	70.7	1.90E+07	5.80E+08	0.032731	30.2445	0.0001
867.73	71.05	1.92E+07	5.79E+08	0.033079	30.2118	0.0001
872.605	71.15	1.92E+07	5.79E+08	0.033231	30.1977	0.0001
882.355	71.9	1.95E+07	5.78E+08	0.033691	30.1615	0.0001
887.23	72.2	1.96E+07	5.78E+08	0.033871	30.143	0.0001
896.98	72.6	1.98E+07	5.77E+08	0.034291	30.1058	0.0001
901.855	72.85	1.99E+07	5.76E+08	0.034463	30.0854	0.0001
911.604	73	2.01E+07	5.75E+08	0.034911	30.0416	0.0001
916.479	73.1	2.02E+07	5.75E+08	0.035146	30.0185	0.0001
926.229	73.85	2.04E+07	5.74E+08	0.035608	29.963	0.0001
931.104	74.45	2.05E+07	5.73E+08	0.03582	29.9316	0.0001
940.854	75.1	2.08E+07	5.72E+08	0.036276	29.8856	0.0001
945.729	75.15	2.09E+07	5.72E+08	0.036541	29.8563	0.0001
955.478	75.65	2.11E+07	5.71E+08	0.037015	29.801	0.0001
960.353	76.05	2.12E+07	5.70E+08	0.037259	29.7673	0.0001
970.103	76.2	2.14E+07	5.69E+08	0.037683	29.7053	0.0001
979.853	76.55	2.17E+07	5.67E+08	0.038236	29.639	0.0001
984.728	76.65	2.18E+07	5.67E+08	0.038541	29.6003	0.0001
994.477	77.3	2.21E+07	5.65E+08	0.039097	29.5192	0.0001
999.352	77.7	2.22E+07	5.64E+08	0.039428	29.4792	0.0001
1009.1	78.25	2.25E+07	5.63E+08	0.040073	29.391	0.0001
1013.98	78.45	2.28E+07	5.62E+08	0.040525	29.3434	0.0001
1023.73	78.6	2.32E+07	5.60E+08	0.041371	29.248	0.0001
1028.6	79.15	2.34E+07	5.58E+08	0.04182	29.191	0.0001
1038.35	80.05	2.38E+07	5.56E+08	0.042746	29.0774	0.0001
1043.23	80	2.40E+07	5.55E+08	0.04318	29.0217	0.0001
1052.98	80.45	2.45E+07	5.53E+08	0.044216	28.9074	0.0001
1057.85	80.55	2.47E+07	5.52E+08	0.044761	28.8485	0.0001
1067.6	80.55	2.52E+07	5.49E+08	0.045926	28.723	0.0001
1072.48	80.75	2.55E+07	5.48E+08	0.046648	28.6528	0.0001
1082.23	82.05	2.63E+07	5.44E+08	0.048258	28.4823	0.0001
1087.1	82.5	2.66E+07	5.43E+08	0.049021	28.3892	0.0001
1096.85	82.55	2.74E+07	5.39E+08	0.050759	28.2227	0.0001
1101.72	82.75	2.77E+07	5.37E+08	0.05162	28.1336	0.0001
1111.47	83.3	2.87E+07	5.33E+08	0.053735	27.9358	0.0001

1116.35	83.7	2.92E+07	5.31E+08	0.054883	27.8258	0.0001
1126.1	84.05	3.01E+07	5.27E+08	0.057115	27.6177	0.0001
1130.97	84.25	3.07E+07	5.25E+08	0.058429	27.5075	0.0001
1140.71	85	3.18E+07	5.20E+08	0.061071	27.2664	0.0001
1145.79	85.3	3.24E+07	5.18E+08	0.062576	27.1511	0.0001
1155.54	85.5	3.36E+07	5.13E+08	0.065598	26.9052	0.0001
1160.41	85.35	3.43E+07	5.10E+08	0.067249	26.7727	0.0001
1170.16	85.65	3.60E+07	5.04E+08	0.071396	26.4779	0.000101
1175.04	86.05	3.69E+07	5.00E+08	0.073843	26.3077	0.000101
1184.79	87.15	3.89E+07	4.93E+08	0.078912	25.9444	0.000101
1189.66	87.6	3.99E+07	4.90E+08	0.081549	25.7712	0.000101
1199.41	87.9	4.19E+07	4.83E+08	0.086786	25.4232	0.000101
1204.29	87.8	4.30E+07	4.80E+08	0.089683	25.2563	0.000101
1214.03	88.3	4.54E+07	4.72E+08	0.096351	24.8702	0.000101
1218.91	88.45	4.67E+07	4.67E+08	0.099964	24.6609	0.000101
1228.66	88.95	4.93E+07	4.58E+08	0.107692	24.2107	0.000101
1238.41	89.35	5.20E+07	4.48E+08	0.116041	23.7396	0.000101
1243.28	89.85	5.33E+07	4.43E+08	0.120337	23.4736	0.000101
1253.03	90.75	5.58E+07	4.32E+08	0.129164	22.935	0.000101
1257.91	91	5.71E+07	4.27E+08	0.133753	22.6735	0.000101
1267.66	91.25	5.95E+07	4.16E+08	0.143204	22.1249	0.000101
1272.53	91.4	6.07E+07	4.10E+08	0.147938	21.8426	0.000101
1282.28	91.9	6.30E+07	3.98E+08	0.158237	21.2708	0.000101
1287.16	92.05	6.42E+07	3.92E+08	0.163791	20.9696	0.000101
1296.91	92.45	6.65E+07	3.79E+08	0.175231	20.3383	0.000101
1301.78	92.5	6.75E+07	3.73E+08	0.18116	20.0168	0.000101
1311.53	92.75	6.98E+07	3.58E+08	0.194836	19.3244	0.000102
1316.41	92.95	7.09E+07	3.50E+08	0.202342	18.9495	0.000102
1326.16	93.95	7.29E+07	3.33E+08	0.21874	18.1469	0.000102
1331.03	94.55	7.35E+07	3.25E+08	0.226209	17.6984	0.000102
1340.78	95.1	7.39E+07	3.10E+08	0.237901	16.9346	0.000102
1345.66	94.95	7.38E+07	3.03E+08	0.243716	16.561	0.000102
1355.41	95.15	7.38E+07	2.87E+08	0.256962	15.7704	0.000102
1360.28	95.65	7.38E+07	2.80E+08	0.263616	15.3785	0.000102
1370.03	96.45	7.36E+07	2.67E+08	0.275881	14.6802	0.000102
1374.91	96.85	7.34E+07	2.61E+08	0.281291	14.3623	0.000102
1384.66	96.9	7.30E+07	2.50E+08	0.29147	13.8006	0.000102
1389.53	96.8	7.29E+07	2.45E+08	0.297565	13.5394	0.000102
1399.28	97.8	7.30E+07	2.34E+08	0.312334	12.9791	0.000102
1404.16	98.2	7.31E+07	2.29E+08	0.318721	12.7154	0.000101
1413.91	98	7.29E+07	2.21E+08	0.329594	12.3099	0.000101
1418.78	98.3	7.28E+07	2.16E+08	0.336593	12.0954	0.000102
1428.53	99.55	7.26E+07	2.09E+08	0.346581	11.6727	0.000101
1433.4	99.95	7.24E+07	2.07E+08	0.350503	11.5202	0.000101

1443.15	100	7.19E+07	2.01E+08	0.357198	11.2445	0.000101
1448.03	99.75	7.17E+07	1.99E+08	0.360837	11.1129	0.000101
1457.78	100.1	7.12E+07	1.92E+08	0.370319	10.8169	0.000101
1462.65	100.7	7.09E+07	1.89E+08	0.374597	10.6548	0.000101
1472.4	101.5	7.04E+07	1.85E+08	0.380916	10.3857	0.000101
1482.15	102	6.98E+07	1.81E+08	0.385222	10.1915	0.000101
1487.03	101.95	6.95E+07	1.79E+08	0.387594	10.1055	0.000101
1496.78	102.2	6.90E+07	1.75E+08	0.392967	9.91416	0.000101
1501.65	102.45	6.87E+07	1.74E+08	0.395865	9.80845	0.000101
1511.4	103.55	6.82E+07	1.70E+08	0.401072	9.61065	0.000101
1516.28	103.75	6.80E+07	1.69E+08	0.402214	9.54	0.0001
1526.03	103.75	6.74E+07	1.67E+08	0.404713	9.42014	0.000101
1530.9	104.05	6.72E+07	1.65E+08	0.406393	9.35933	0.000101
1540.65	105	6.67E+07	1.63E+08	0.408453	9.23759	0.0001
1545.53	105.45	6.65E+07	1.63E+08	0.408725	9.18835	0.0001
1555.28	105.65	6.60E+07	1.62E+08	0.407371	9.14007	0.0001
1560.15	105.75	6.58E+07	1.61E+08	0.407246	9.11209	0.0001
1569.9	106.15	6.53E+07	1.61E+08	0.406713	9.05725	0.0001
1574.78	106.4	6.51E+07	1.60E+08	0.406502	9.03191	0.0001
1584.53	106.85	6.47E+07	1.60E+08	0.405248	8.98981	0.0001
1589.4	107.15	6.45E+07	1.59E+08	0.404375	8.97723	0.0001
1599.15	107.55	6.41E+07	1.59E+08	0.402396	8.95452	0.0001
1604.03	107.85	6.39E+07	1.59E+08	0.401434	8.94331	0.0001
1613.78	108.3	6.35E+07	1.59E+08	0.399152	8.92993	0.0001
1618.65	108.45	6.33E+07	1.59E+08	0.398249	8.92273	0.0001
1628.4	109	6.29E+07	1.59E+08	0.395381	8.91238	9.99E-05
1633.27	109.15	6.27E+07	1.59E+08	0.394462	8.91807	0.0001
1643.02	109.9	6.23E+07	1.59E+08	0.392292	8.89733	1.00E-04
1647.9	110.4	6.22E+07	1.59E+08	0.390758	8.8975	9.99E-05
1657.65	110.85	6.18E+07	1.60E+08	0.385721	8.9291	9.98E-05
1662.52	110.9	6.15E+07	1.60E+08	0.383636	8.95123	9.99E-05
1672.27	111.1	6.12E+07	1.61E+08	0.379449	8.98423	9.99E-05
1677.15	111.4	6.10E+07	1.61E+08	0.377762	8.99286	1.00E-04
1686.9	111.75	6.06E+07	1.62E+08	0.374492	9.00913	1.00E-04
1691.77	112.2	6.04E+07	1.62E+08	0.372784	9.0141	9.99E-05
1701.52	112.85	6.01E+07	1.63E+08	0.368639	9.04349	9.99E-05
1711.27	113.3	5.97E+07	1.64E+08	0.36474	9.07426	9.99E-05
1716.15	113.5	5.95E+07	1.64E+08	0.3628	9.08742	9.99E-05
1725.9	113.9	5.92E+07	1.65E+08	0.358427	9.13231	9.99E-05
1730.77	114.1	5.90E+07	1.65E+08	0.356386	9.14613	9.99E-05
1740.52	114.4	5.86E+07	1.66E+08	0.353455	9.1684	0.0001
1745.4	114.8	5.85E+07	1.66E+08	0.352269	9.16845	1.00E-04
1755.15	115.2	5.81E+07	1.66E+08	0.349298	9.18723	1.00E-04
1760.02	115.5	5.80E+07	1.66E+08	0.348458	9.19312	0.0001

1769.77	116.45	5.77E+07	1.67E+08	0.345652	9.19561	9.99E-05
1774.65	116.8	5.75E+07	1.67E+08	0.343906	9.2051	9.99E-05
1784.4	116.85	5.71E+07	1.68E+08	0.340159	9.24266	9.99E-05
1789.27	117.05	5.70E+07	1.68E+08	0.338684	9.25483	9.99E-05
1799.02	117.45	5.67E+07	1.69E+08	0.336341	9.26688	1.00E-04
1803.9	117.7	5.66E+07	1.69E+08	0.335247	9.27188	9.99E-05
1813.65	118.55	5.63E+07	1.69E+08	0.332867	9.27901	9.99E-05
1818.52	119.1	5.61E+07	1.69E+08	0.33119	9.29093	9.99E-05
1828.27	119.3	5.57E+07	1.70E+08	0.327046	9.33246	9.98E-05
1833.15	119.55	5.56E+07	1.71E+08	0.325307	9.35436	9.99E-05

Table A7: Model data from Tensile tests of composites made with different fibre reinforcements.

Fine fibre				Coarse fibre				Coarse fibre + Glass fibre			
Position (mm)	**Force (N)**	**Strain**	**stress (Mpa)**	**Position (mm)**	**Force (N)**	**strain**	**stress (Mpa)**	**Position (mm)**	**Force (N)**	**strain**	**stress (Mpa)**
-0.0364	-53	-0.0002	-0.70667	-0.00325	-11.6	-1.8E-05	-0.15467	-0.0038	-0.961	-2.1E-05	-0.01281
-0.0349	-50.2	-0.00019	-0.66933	-0.00332	-11.6	-1.8E-05	-0.15467	-0.00419	-3.27	-2.3E-05	-0.0436
-0.0337	-48	-0.00019	-0.64	-0.00323	-11.6	-1.8E-05	-0.15467	-0.0025	-1.15	-1.4E-05	-0.01533
-0.0327	-46.5	-0.00018	-0.62	-0.00195	-10.2	-1.1E-05	-0.136	-0.00054	5.64	-3E-06	0.0752
-0.0315	-45.1	-0.00018	-0.60133	-0.00096	-8.69	-5.3E-06	-0.11587	0.00104	10.1	5.78E-06	0.134667
-0.0303	-42.9	-0.00017	-0.572	-0.0002	-7.17	-1.1E-06	-0.0956	0.00259	13.9	1.44E-05	0.185333
-0.0292	-41.6	-0.00016	-0.55467	0.00062	-5.76	3.44E-06	-0.0768	0.00425	18.2	2.36E-05	0.242667
-0.0281	-40	-0.00016	-0.53333	0.00148	-4.49	8.22E-06	-0.05987	0.00578	22.1	3.21E-05	0.294667
-0.027	-38.3	-0.00015	-0.51067	0.00224	-3.22	1.24E-05	-0.04293	0.00728	25.7	4.04E-05	0.342667
-0.0258	-36.1	-0.00014	-0.48133	0.00311	-2.24	1.73E-05	-0.02987	0.00893	30.6	4.96E-05	0.408
-0.0246	-34.9	-0.00014	-0.46533	0.00393	-1.33	2.18E-05	-0.01773	0.0104	33.7	5.78E-05	0.449333
-0.0235	-32.9	-0.00013	-0.43867	0.00471	0.274	2.62E-05	0.003653	0.012	38.4	6.67E-05	0.512
-0.0225	-31.3	-0.00013	-0.41733	0.00549	1.45	3.05E-05	0.019333	0.0136	41.5	7.56E-05	0.553333
-0.0213	-29	-0.00012	-0.38667	0.00629	2.66	3.49E-05	0.035467	0.0152	45.4	8.44E-05	0.605333
-0.0201	-27.7	-0.00011	-0.36933	0.00718	3.93	3.99E-05	0.0524	0.0167	50.4	9.28E-05	0.672
-0.019	-26.3	-0.00011	-0.35067	0.00792	5.47	0.000044	0.072933	0.0182	53.9	0.000101	0.718667
-0.0179	-24.9	-9.9E-05	-0.332	0.00869	6.56	4.83E-05	0.087467	0.0197	57.2	0.000109	0.762667
-0.0167	-22.6	-9.3E-05	-0.30133	0.00952	7.87	5.29E-05	0.104933	0.0213	61.1	0.000118	0.814667
-0.0155	-21.2	-8.6E-05	-0.28267	0.0103	8.42	5.72E-05	0.112267	0.0229	65	0.000127	0.866667
-0.0144	-20	-0.00008	-0.26667	0.0112	10.3	6.22E-05	0.137333	0.0244	68.3	0.000136	0.910667
-0.0133	-17.5	-7.4E-05	-0.23333	0.0121	11	6.72E-05	0.146667	0.026	72.5	0.000144	0.966667
-0.0121	-16.4	-6.7E-05	-0.21867	0.0128	12.2	7.11E-05	0.162667	0.0276	76	0.000153	1.013333

-0.0109	-14.4	-6.1E-05	-0.192	0.0136	13.3	7.56E-05	0.177333	0.0291	79.6	0.000162	1.061333
-0.00981	-12.7	-5.5E-05	-0.16933	0.0143	14.8	7.94E-05	0.197333	0.0306	83.1	0.00017	1.108
-0.00863	-11	-4.8E-05	-0.14667	0.0152	15.9	8.44E-05	0.212	0.0321	86.8	0.000178	1.157333
-0.00748	-9.77	-4.2E-05	-0.13027	0.016	17.4	8.89E-05	0.232	0.0338	91.2	0.000188	1.216
-0.00639	-8.26	-3.6E-05	-0.11013	0.0168	18.5	9.33E-05	0.246667	0.0353	94.8	0.000196	1.264
-0.00524	-6.08	-2.9E-05	-0.08107	0.0176	19.9	9.78E-05	0.265333	0.0368	98.3	0.000204	1.310667
-0.00409	-4.78	-2.3E-05	-0.06373	0.0184	20	0.000102	0.266667	0.0383	102	0.000213	1.36
-0.00293	-3.18	-1.6E-05	-0.0424	0.0192	21.9	0.000107	0.292	0.0399	106	0.000222	1.413333
-0.00178	-1.53	-9.9E-06	-0.0204	0.0201	23.3	0.000112	0.310667	0.0414	109	0.00023	1.453333
-0.00065	0.684	-3.6E-06	0.00912	0.0208	24.3	0.000116	0.324	0.043	113	0.000239	1.506667
0.000518	1.89	2.88E-06	0.0252	0.0217	24.7	0.000121	0.329333	0.0447	117	0.000248	1.56
0.00163	3.56	9.06E-06	0.047467	0.0224	26.5	0.000124	0.353333	0.0462	121	0.000257	1.613333
0.00283	5.39	1.57E-05	0.071867	0.0232	27.7	0.000129	0.369333	0.0477	124	0.000265	1.653333
0.00393	6.73	2.18E-05	0.089733	0.024	28.8	0.000133	0.384	0.0492	128	0.000273	1.706667
0.00514	8.44	2.86E-05	0.112533	0.0248	29.5	0.000138	0.393333	0.0509	132	0.000283	1.76
0.00624	10.5	3.47E-05	0.14	0.0256	31.2	0.000142	0.416	0.0524	135	0.000291	1.8
0.0074	12.3	4.11E-05	0.164	0.0264	32.3	0.000147	0.430667	0.054	139	0.0003	1.853333
0.0085	13.5	4.72E-05	0.18	0.0272	33.6	0.000151	0.448	0.0554	143	0.000308	1.906667
0.00965	15.5	5.36E-05	0.206667	0.028	34.6	0.000156	0.461333	0.057	146	0.000317	1.946667
0.0108	16.9	0.00006	0.225333	0.0288	36	0.00016	0.48	0.0586	150	0.000326	2
0.012	18.4	6.67E-05	0.245333	0.0296	37.1	0.000164	0.494667	0.0603	153	0.000335	2.04
0.0131	20.2	7.28E-05	0.269333	0.0304	37.5	0.000169	0.5	0.0617	157	0.000343	2.093333
0.0142	21.7	7.89E-05	0.289333	0.0312	39.7	0.000173	0.529333	0.0633	161	0.000352	2.146667
0.0153	23.6	0.000085	0.314667	0.032	39.9	0.000178	0.532	0.065	164	0.000361	2.186667
0.0165	25.4	9.17E-05	0.338667	0.0329	41.3	0.000183	0.550667	0.0665	167	0.000369	2.226667
0.0176	27.3	9.78E-05	0.364	0.0337	42.7	0.000187	0.569333	0.068	171	0.000378	2.28
0.0187	28.3	0.000104	0.377333	0.0345	43.5	0.000192	0.58	0.0698	175	0.000388	2.333333

0.0199	30.8	0.000111	0.410667	0.0353	45	0.000196	0.6	0.0713	178	0.000396	2.373333
0.021	32.1	0.000117	0.428	0.0361	46	0.000201	0.613333	0.0728	182	0.000404	2.426667
0.0222	33.5	0.000123	0.446667	0.0369	47.3	0.000205	0.630667	0.0743	185	0.000413	2.466667
0.0234	34.8	0.00013	0.464	0.0377	47.9	0.000209	0.638667	0.0758	188	0.000421	2.506667
0.0246	35.9	0.000137	0.478667	0.0385	49.1	0.000214	0.654667	0.0774	192	0.00043	2.56
0.0256	37.2	0.000142	0.496	0.0393	50.7	0.000218	0.676	0.0789	195	0.000438	2.6
0.0268	37.8	0.000149	0.504	0.0401	52	0.000223	0.693333	0.0805	199	0.000447	2.653333
0.028	38.3	0.000156	0.510667	0.0409	53.2	0.000227	0.709333	0.0821	202	0.000456	2.693333
0.0291	39.6	0.000162	0.528	0.0417	53.8	0.000232	0.717333	0.0836	205	0.000464	2.733333
0.0302	40.8	0.000168	0.544	0.0425	54.7	0.000236	0.729333	0.0853	209	0.000474	2.786667
0.0314	42	0.000174	0.56	0.0433	56.5	0.000241	0.753333	0.0868	212	0.000482	2.826667
0.0325	43.2	0.000181	0.576	0.0442	57	0.000246	0.76	0.0884	216	0.000491	2.88
0.0337	43.7	0.000187	0.582667	0.0449	58.4	0.000249	0.778667	0.09	219	0.0005	2.92
0.0348	44.8	0.000193	0.597333	0.0457	59.2	0.000254	0.789333	0.0915	222	0.000508	2.96
0.036	45.7	0.0002	0.609333	0.0466	60.6	0.000259	0.808	0.093	225	0.000517	3
0.0371	46.9	0.000206	0.625333	0.0474	61.7	0.000263	0.822667	0.0946	228	0.000526	3.04
0.0382	48.2	0.000212	0.642667	0.0482	62.9	0.000268	0.838667	0.0961	232	0.000534	3.093333
0.0394	49.3	0.000219	0.657333	0.049	64	0.000272	0.853333	0.0977	235	0.000543	3.133333
0.0406	50.4	0.000226	0.672	0.0498	65.2	0.000277	0.869333	0.0993	238	0.000552	3.173333
0.0417	52.4	0.000232	0.698667	0.0506	66.9	0.000281	0.892	0.101	242	0.000561	3.226667
0.0429	53.8	0.000238	0.717333	0.0514	67.4	0.000286	0.898667	0.102	245	0.000567	3.266667
0.044	55.1	0.000244	0.734667	0.0522	67.9	0.00029	0.905333	0.104	247	0.000578	3.293333
0.0451	56.3	0.000251	0.750667	0.053	69.7	0.000294	0.929333	0.105	250	0.000583	3.333333
0.0463	58.4	0.000257	0.778667	0.0538	71.2	0.000299	0.949333	0.107	253	0.000594	3.373333
0.0474	59.6	0.000263	0.794667	0.0547	72.2	0.000304	0.962667	0.109	256	0.000606	3.413333
0.0487	61.8	0.000271	0.824	0.0554	73	0.000308	0.973333	0.11	259	0.000611	3.453333
0.0497	63	0.000276	0.84	0.0562	74.3	0.000312	0.990667	0.112	263	0.000622	3.506667

Table A8: Model Data from Flexural tests of composites made with different fibre reinforcements.

Fine fibre				Coarse fibre				Coarse fibre + Glass fibre			
Position (mm)	**Force (N)**	**Strain**	**Stress (MPa)**	**Position (mm)**	**Force (N)**	**Strain**	**Stress (MPa)**	**Position (mm)**	**Force (N)**	**Strain**	**Stress (MPa)**
0.000958	-0.32	2.3E-06	-0.24	0.00357	-0.0332	8.57E-06	-0.0249	0.000776	1.16	1.86E-06	0.869999
0.00102	-0.0356	2.45E-06	-0.0267	0.00575	-0.0332	1.38E-05	-0.0249	0.00218	1.16	5.23E-06	0.869997
0.00396	-0.398	9.5E-06	-0.2985	0.00783	-0.0332	1.88E-05	-0.0249	0.00716	1.16	1.72E-05	0.86999
0.00604	-0.222	1.45E-05	-0.1665	0.00986	-0.0332	2.37E-05	-0.0249	0.0115	2.51	2.76E-05	1.882466
0.00821	1.12	1.97E-05	0.839989	0.0121	-0.0332	2.9E-05	-0.0249	0.0157	2.55	3.77E-05	1.912452
0.0103	1.13	2.47E-05	0.847486	0.0141	-0.0332	3.38E-05	-0.0249	0.02	2.55	0.000048	1.912439
0.0121	1.13	2.9E-05	0.847484	0.0161	1.11	3.86E-05	0.832479	0.0242	3.36	5.81E-05	2.519903
0.0141	1.13	3.38E-05	0.847481	0.0179	1.23	4.3E-05	0.922474	0.0286	3.75	6.86E-05	2.812373
0.016	1.13	3.84E-05	0.847478	0.0201	1.23	4.82E-05	0.922471	0.033	3.94	7.92E-05	2.954846
0.0181	1.13	4.34E-05	0.847476	0.0223	1.23	5.35E-05	0.922467	0.0374	4.97	8.98E-05	3.72728
0.0201	1.13	4.82E-05	0.847473	0.0242	1.23	5.81E-05	0.922465	0.0415	4.97	9.96E-05	3.727256
0.0222	1.13	5.33E-05	0.84747	0.0264	1.23	6.34E-05	0.922461	0.0456	4.97	0.000109	3.727233
0.024	1.13	5.76E-05	0.847468	0.0284	1.23	6.82E-05	0.922459	0.0502	6.47	0.00012	4.852118
0.026	1.13	6.24E-05	0.847465	0.0305	1.23	7.32E-05	0.922455	0.0545	6.47	0.000131	4.852086
0.0282	1.13	6.77E-05	0.847462	0.0326	1.23	7.82E-05	0.922452	0.0589	6.47	0.000141	4.852053
0.0301	2.04	7.22E-05	1.529927	0.0342	1.23	8.21E-05	0.92245	0.0631	7.59	0.000151	5.691939
0.0322	2.22	7.73E-05	1.664915	0.0366	1.23	8.78E-05	0.922447	0.0675	7.59	0.000162	5.691901

0.0341	2.22	8.18E-05	1.66491	0.0385	1.8	9.24E-05	1.349918	0.0717	8.76	0.000172	6.569267
0.036	2.22	8.64E-05	1.664905	0.0406	2.42	9.74E-05	1.814884	0.0758	8.76	0.000182	6.569226
0.0383	2.22	9.19E-05	1.664899	0.0427	1.34	0.000102	1.004932	0.0805	9.91	0.000193	7.431572
0.0402	2.22	9.65E-05	1.664895	0.0446	1.66	0.000107	1.244913	0.0848	10.4	0.000204	7.798975
0.0422	2.22	0.000101	1.664889	0.0468	1.53	0.000112	1.147416	0.089	10.4	0.000214	7.798926
0.0443	2.22	0.000106	1.664884	0.0487	1.89	0.000117	1.417392	0.0934	10.4	0.000224	7.798875
0.0461	2.22	0.000111	1.664879	0.0507	2.56	0.000122	1.919847	0.0975	11.5	0.000234	8.623704
0.048	2.22	0.000115	1.664874	0.0529	2.72	0.000127	2.039831	0.102	11.5	0.000245	8.623646
0.0502	2.22	0.00012	1.664869	0.0549	2.72	0.000132	2.039824	0.106	11.5	0.000254	8.623595
0.052	3.47	0.000125	2.602288	0.057	2.72	0.000137	2.039818	0.11	12.8	0.000264	9.59838
0.0543	3.48	0.00013	2.609778	0.0591	2.72	0.000142	2.039811	0.115	12.8	0.000276	9.59831
0.0563	3.72	0.000135	2.789754	0.0611	2.72	0.000147	2.039805	0.119	12.8	0.000286	9.598254
0.058	2.68	0.000139	2.009818	0.0632	2.72	0.000152	2.039799	0.123	14.5	0.000295	10.87296
0.06	3.53	0.000144	2.647252	0.0652	2.72	0.000156	2.039792	0.128	14.5	0.000307	10.87288
0.0623	3.55	0.00015	2.662241	0.0673	2.72	0.000162	2.039786	0.132	14.5	0.000317	10.87282
0.0643	3.96	0.000154	2.969702	0.0691	2.72	0.000166	2.03978	0.137	15.6	0.000329	11.69757
0.0663	4.15	0.000159	3.112178	0.0714	2.72	0.000171	2.039773	0.141	15.6	0.000338	11.6975
0.0684	4.15	0.000164	3.112168	0.0733	2.84	0.000176	2.129757	0.145	15.6	0.000348	11.69743
0.0702	4.15	0.000168	3.11216	0.0754	2.82	0.000181	2.114752	0.15	16.7	0.00036	12.52216
0.0723	4.15	0.000174	3.11215	0.0776	3.87	0.000186	2.90215	0.154	16.7	0.00037	12.52209
0.0744	4.15	0.000179	3.11214	0.0796	3.88	0.000191	2.90964	0.158	17.9	0.000379	13.42181
0.0763	4.15	0.000183	3.112131	0.0818	3.88	0.000196	2.909631	0.162	17.9	0.000389	13.42173
0.0784	4.15	0.000188	3.112121	0.0837	3.88	0.000201	2.909623	0.167	18	0.000401	13.49662
0.0799	4.15	0.000192	3.112114	0.0858	3.88	0.000206	2.909613	0.171	19	0.00041	14.24635
0.0822	4.15	0.000197	3.112103	0.0877	3.88	0.00021	2.909605	0.175	19	0.00042	14.24627
0.0843	4.21	0.000202	3.157088	0.0899	3.88	0.000216	2.909596	0.18	19	0.000432	14.24617
0.0862	4.15	0.000207	3.112085	0.0919	3.88	0.000221	2.909587	0.184	20.3	0.000442	15.22083

0.0883	5.38	0.000212	4.034449	0.094	3.88	0.000226	2.909578	0.188	20.3	0.000451	15.22074
0.09	4.67	0.000216	3.502013	0.096	3.88	0.00023	2.909569	0.192	21.6	0.000461	16.19538
0.0923	5.44	0.000222	4.079418	0.0981	4.97	0.000235	3.726936	0.197	21.5	0.000473	16.12029
0.0943	5.44	0.000226	4.079406	0.1	4.96	0.00024	3.719427	0.201	21.6	0.000482	16.19518
0.0962	5.44	0.000231	4.079395	0.102	5.17	0.000245	3.876891	0.206	22.7	0.000494	17.01982
0.0983	5.44	0.000236	4.079382	0.104	5.17	0.00025	3.87688	0.21	22.7	0.000504	17.01973
0.1	5.44	0.00024	4.079372	0.106	5.17	0.000254	3.876869	0.214	22.7	0.000514	17.01964
0.102	5.44	0.000245	4.07936	0.108	4.64	0.000259	3.479423	0.219	24	0.000526	17.99421
0.104	5.59	0.00025	4.19183	0.11	5.21	0.000264	3.906841	0.223	24	0.000535	17.99411
0.106	5.51	0.000254	4.131827	0.112	5.54	0.000269	4.154287	0.227	25.1	0.000545	18.81874
0.108	6.29	0.000259	4.716718	0.114	5.54	0.000274	4.154275	0.232	25.1	0.000557	18.81862
0.11	5.53	0.000264	4.1468	0.116	5.54	0.000278	4.154262	0.236	25.1	0.000566	18.81852
0.112	6	0.000269	4.499227	0.118	5.54	0.000283	4.15425	0.24	26.3	0.000576	19.71811
0.114	6.7	0.000274	5.024123	0.12	5.54	0.000288	4.154238	0.245	26.3	0.000588	19.71798
0.116	6.7	0.000278	5.024108	0.123	5.54	0.000295	4.15422	0.249	26.3	0.000598	19.71788
0.118	6.7	0.000283	5.024093	0.125	5.54	0.0003	4.154208	0.253	27.4	0.000607	20.54247
0.12	6.7	0.000288	5.024079	0.127	5.54	0.000305	4.154196	0.257	27.4	0.000617	20.54236
0.122	6.7	0.000293	5.024064	0.129	5.54	0.00031	4.154184	0.262	28	0.000629	20.99206
0.124	6.7	0.000298	5.024049	0.131	5.54	0.000314	4.154172	0.266	28.7	0.000638	21.51675
0.126	6.7	0.000302	5.024035	0.133	5.54	0.000319	4.15416	0.27	28.7	0.000648	21.51664
0.128	6.7	0.000307	5.02402	0.135	5.54	0.000324	4.154148	0.275	29.8	0.00066	22.34118
0.13	7.63	0.000312	5.721368	0.137	5.54	0.000329	4.154136	0.279	29.8	0.00067	22.34107
0.132	7.55	0.000317	5.661363	0.139	5.54	0.000334	4.154124	0.283	29.8	0.000679	22.34095
0.134	7.82	0.000322	5.863806	0.141	6.76	0.000338	5.068917	0.287	31.1	0.000689	23.31544
0.136	7.86	0.000326	5.893783	0.143	6.77	0.000343	5.076401	0.292	31.1	0.000701	23.3153
0.138	7.86	0.000331	5.893766	0.145	6.77	0.000348	5.076386	0.296	31.1	0.00071	23.31518
0.141	7.86	0.000338	5.89374	0.147	6.77	0.000353	5.076372	0.301	32.6	0.000722	24.43955

PUBLICATIONS BASED ON PRESENT RESEARCH WORK

International Journals

1. **N. Muralidhar**, K. Vadivuchezhian, V. Arumugam and I. Srinivasula Reddy., (2019) "A Study on Arecanut Husk Fibre Extraction, Composite Panel Preparation and Mechanical Characteristics of the Composites", *J. Inst. Eng. India Ser. D*, 100, 1-11. https://doi.org/10.1007/s40033-019-00186-1.

2. **N. Muralidhar**, K. Vadivuchezhian, V. Arumugam and I. Srinivasula Reddy., (2019) "Flexural modulus of Epoxy Composite Reinforced with Arecanut Husk Fibre: a mechanics approach", *Mater Today: Proc*. https://doi.org/10.1016/j.matpr.2019.09.109

3. **N. Muralidhar**, K. Vadivuchezhian, V. Arumugam and I. Srinivasula Reddy., (2019) "Dynamic mechanical characterization of epoxy composite reinforced with Arecanuthusk fiber", *Int J of Polym Anal Ch*. (**Under Review**).

International Conferences

1. **Muralidhar N**., Vadivuchezhian K., and Arumugam V., (2018) "Mechanical Properties of Arecanut Husk Fibre Composite panels", *7th International Engineering Symposium - IES* 2018, Kumamoto University, Japan, March 7-9, 2018.

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