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Investigations on Mechanical and Thermal Behaviour of Fiber Reinforced Polymer Composites

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Submitted by

Parmar VijayKumar Mohanlal
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Supervised by

Dr. Piyush Gohil
Associate Professor,
Department of Mechanical Engineering, Faculty of Technology and Engineering,
The Maharaja Sayajirao University of Baroda,
Vadodara

Submitted to
Department of Mechanical Engineering, Faculty of Technology and Engineering,
The Maharaja Sayajirao University of Baroda

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NOMENCLATURE

NF	Natural Fibers
SF	Synthetic Fibers
PCC	Post Process Curing
IPC	In Process Curing
FRC	Fiber Reinforced Composite
Tg	Glass Transition Temperature
RTD	Resistance Temperature Detector
PID	Proportional Integral Derivative Controller
ASTM	American Society For Testing And Materials
UTM	Universal Testing Machine
TWD	Teak Wood Dust
JVC	Jute Vinyl ester Composites
BVC	Basalt Vinyl ester Composites
CVC	Carbon Vinyl ester Composites
K	Thermal Conductivity

1. INTRODUCTION

1.1 Composite Materials

The development of composite materials as well as the related design and manufacturing technologies is one of the most important advances in the history of materials. Composites are multifunctional materials having unprecedented mechanical and physical properties that can be tailored to meet the requirements of a particular application. These unique characteristics provide the mechanical engineer with design opportunities not possible with conventional monolithic (unreinforced) materials. Further, many manufacturing processes for composites are well adapted to the fabrication of large, complex structures, which allows consolidation of parts, reducing manufacturing costs.

1.2 Characteristics and Classification of the Composite Materials

Composites are strongly heterogeneous materials. That is, the properties of a composite vary considerably from point to point in the material, depending on which material phase the point is located in. Many artificial composites, especially those reinforced with fibers, are anisotropic, which means their properties vary with direction (the properties of isotropic materials are the same in every direction).

Composite materials are classified according to their content, i.e. base material and filler material. The base material, which binds or holds the filler material in structures, is termed as a matrix or a binder material, while filler material is present in the form of sheets, fragments, particles, fibers or whiskers of natural or synthetic material. As represented in Figure 1.1 composites are classified into three main categories based on their structure. Uzay(2017).

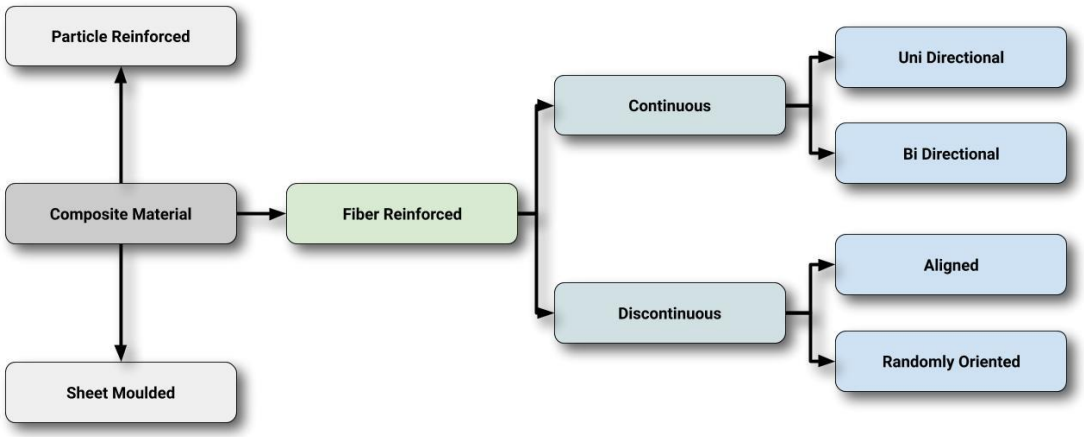

Figure 1.1 Classification of composites

1.3 Synthetic Fibers

Human-made fibers that are produced by chemical synthesis are called synthetic fibers (SFs) and further classified as organic or inorganic based on their content. Kim et al. (2004). Generally, the strength and stiffness of fiber materials are much higher than that of the matrix material, making them a load-bearing element in the composite structure. Nielsen and Landel (1994).

1.4 Natural Fibers

Natural fibers (NFs) are very easy to obtain, extensively available in nature. They reveal some outstanding material properties like biodegradability, low cost per unit volume, high strength, and specific stiffness. Composites made of NF reinforcements seem to carry some diverse properties over synthetic fibers, such as reduced weight, cost, toxicity, environmental pollution, and recyclability.

1.5 Polymers-Resins

The primary functions of the resin are to transfer stress between the reinforcing fibers, act as a glue to hold the fibers together, and protect the fibers from mechanical and environmental damage. Resins are divided into two major groups known as thermoset and thermoplastic. Thermoplastic resins become soft when heated, and may be shaped or molded while in a heated semi-fluid state and become rigid when cooled. Thermoset resins, on the other hand, are usually liquids or low melting point solids in their initial form. When used to produce finished goods, these thermosetting resins are “cured” by the use of a catalyst, heat or a combination of the two. Once cured, solid thermoset resins cannot be converted back to their original liquid form.

1.6 Mechanical and Thermal Behaviour of Fiber Reinforced composites

1.6.1 Mechanical Behaviour of Fiber Reinforced composites

Innovative composite materials are frequently used in designing aerospace, naval and automotive components. In the typical structure of composites, multiple layers are stacked together with a particular sequence to give specific mechanical properties. Layers are organized with different angles, different sequences, and different technological process to obtain a new and innovative material. From the standpoint of engineering designers, it is useful to consider the single layer of the composite as a macroscopically homogeneous material. However, composites are non-homogeneous material. Therefore, the real behaviour of composite materials is quite different from the predictions coming from the traditional material. Due to the increasing structural performance required for innovative composites, the knowledge of the mechanical properties for different loading cases is a fundamental source of concern. Experimental characterization of materials and structures in different environmental conditions is extremely important to understand the mechanical behaviour of these new materials. The purpose of the present work is to characterize a composite material developed for such applications considering the effect of load, temperature and time during the development of composites.

1.6.2 Thermal Behaviour of Fiber Reinforced composites

The behaviour of composite materials is often sensitive to changes in temperature. This arises for two main reasons. Firstly, the response of the matrix to an applied load is temperature-dependent and, secondly, changes in temperature can cause internal stresses to be set up as a result of differential thermal contraction and expansion of the two constituents. moreover, significant stresses are normally present in the material at ambient temperatures, since it has in most cases been cooled at the end of the fabrication process. Changes in internal stress state on altering the temperature can be substantial and may strongly influence the response of the material to an applied load. Creep behaviour is affected by this, particularly under thermal cycling conditions. Finally, the thermal conductivity of composite materials is of interest, since many applications and processing procedures involve heat flow of some type. This property can be predicted from the conductivities of the constituents, although the situation may be complicated by poor thermal contact across the interfaces.

2. LITERATURE REVIEW

This section outlines some of the recent research published in the literature on the mechanical behaviour of fiber-reinforced polymer composites with special emphasis on the effect of pressure(load), temperature, and time as one of the parameters during post-process curing.

Many products are made from thermosetting resins because fiber-reinforced plastics, lacquers, and adhesives based on these resins generally have improved mechanical and chemical properties. They exhibit good mechanical and thermal stability and resist a wide variety of highly reactive chemicals. As with many other polymeric materials, development and control of the manufacturing process require monitoring of the degree of cure.

Polymeric composite is evaluated in a simple, rapid, and non-destructive manner by heating a surface portion of the polymeric composite to substantially curing temperature, over a predetermined period, and continuously monitoring with a contact type temperature sensor of the heated surface portion during the predetermined period.

Every material has an individual post-cure process that depends on raw materials. Post curing variables include temperature, duration of cure, the time between initial curing and post-curing and temperature profile gradient. There are several ways to determine the cure state of a polymer. It can be evaluated based on the mechanical and physical properties, glass transition temperature, etc.

2.1 Effect of post-process curing (PPC) and in-process curing (IPC) on the mechanical behaviour of the composite plates

Uzay (2017) worked on the post-cure heat treatment on the impact toughness and tensile properties of fiber-reinforced composites. The laminates were prepared by utilizing the hand layup vacuum bag moulding of woven carbon and glass fiber fabric plies. At three distinct temperatures, the post-curing was done for one hour i.e. 25, 62.5 and 100°C. The impact (Charpy) and tensile tests were conducted along with the statistical analysis to know the effect of post-curing and different types of hybrid plies. The results revealed that post-curing has a positive effect on energy absorption capacity and tensile properties of FRC

The curing cycle has a strong impact on the thermal and mechanical behavior of thermosetting polymers. The extent of cross-linking which is a strong function of curing temperature and time is directly linked to the glass transition temperature (Tg) of the thermosetting polymer. This transition temperature speaks about the transformation of the polymer from a glassy state to a rubbery state, hence decides the applicability of the material at a certain temperature with a certain degree of safety and reliability. D S Kumar et al. (2015) emphasized the impact of post-curing parameters on the thermal as well as mechanical behavior of glass fiber reinforced polymer (GFRP) composite. Post curing was carried out at 3 different temperatures (80° C, 110° C and 140° C) for different periods (2h, 4h, 6h, 8h, and 12h). it was observed that post-curing at 140°C for 6 hrs gave better thermal and mechanical properties as compared to post-curing at different temperatures and periods.

Chavan et al. (2018) conducted experiments that studied the effect of post-curing on GFRP hybrid composites. The result reveals that the samples only with natural fiber have more

promising results compared with synthetic fiber. The synthetic fibers get wrinkled due to post-curing were as no such visuals in the natural fibers.

Furtos et al. (2012) investigated that mechanical properties were improved by post-polymerization curing and by increasing the amount of glass fiber in the composites. SEM micrographs indicate strong interfacial interaction between glass fibers and polymer matrix.

Bourchak et al (2013) revealed that preheating epoxy resin for a longer duration can weaken the material ultimate tensile strength and increase its stiffness whereas post-curing the epoxy resin for two hours at 80°C slightly increased ultimate tensile strength but made the material significantly stiffer due to a large decrease in the material ultimate tensile strain

The mechanical properties of woven carbon, woven glass and hybrid FRP composites such as impact energy, tensile strength, and percent elongation were investigated by Uzay et al.(2017) under the post-curing heat treatment process temperature of 25^{o} C, 62.5^{o}C and 100^{o} C. The results showed that post-curing heat treatment process has a positive effect on mechanical properties of FRP composites in terms of impact toughness, tensile strength and percent elongation. This is because, during post-curing, the epoxy polymer matrix makes the composite stronger due to improved formation of cross-linking.

Elleuch et al (1999) investigated that upon the post-curing by heat, it was confirmed that the mechanical properties of the woven glass-polyester composites were increased moderately and the cure performance of the composite was also improved. Micro indentation tests were applied to study the quality of the fiber-matrix interface by using both post cured and non-post-cured. Composites. The result of the micro-indentation test was in agreement of the monotonic and fatigue test and confirmed that post-cure improves the resistance of the fiber-matrix interface.

Systematic research work based on in-process curing of a polymer-based composite is not observed in the literature.

2.2 Effect of fiber properties on Mechanical and Thermal Properties of composites

The heat conduction mainly depends on thermal transport property called thermal conductivity. The measured numerical value of thermal conductivity gives an idea about the use of the material as a heat conductor or insulator. Various investigations on the thermal properties of polymer-based composites with varying core materials and fillers have been published. A primary correlation between various composites is not so easy as different manufacturing technique is used by each researcher. Also, the correlation between the same materials, base, and filler might be useless as there might be a difference of crystal structure, size, and shape between the same type of filler. Some of the properties of fibers affecting the thermal properties of the polymer composites are discussed in the table No.2.1

Table No. 2.1 Effect of fiber properties on Mechanical and Thermal Properties of composites

Sr. No	**Study**	**Author/s**	**Materials**	**Remarks**
1	Volume Fraction (V_f)	Sair et al. (2018)	Composite made from polyurethane (PU) and hemp fiber	Around 15% in fiber content is better than other compositions for thermal insulation.

			at different loading rates.	
2		Gudapati et al. (2018)	Areca Palm fibers extracted from its stalk using the retting process were reinforced with polyester resin.	Thermal conductivity was inversely proportional to the volume fraction of the fiber.
3	Size of the Fibers (SF)	Das (2016)	Composite made from epoxy and short fibers of banana. Teak wood dust is used as filler material	TWD particles reduced the strength of epoxy. SBF enhanced the tensile, compressive and flexural strength of the composite. TWD reduced the thermal conductivity of epoxy. A blending of SBF also reduced the Thermal Conductivity of epoxy.
4	The cross-sectional shape of the fibers and weave pattern (CSF)	Karaca, et al. (2012)	Polyester multifilament yarn produced from semi-dull polyethylene terephthalate by melt spinning process	The Thermal conductivity increased in the fabrics woven with hollow fibers compared to those woven with solid fibers.
5	Fibers' Particles Size (FP)	Raju and Kumarappa (2012)	Specimens prepared from randomly distributed groundnut shell particles in a polymer matrix.	The particle size had a major effect on thermal properties.
6	Fibers 'Length (FL)	Supreeth S et al. (2014)	Specimens from Bisphenol-A (BPA) as a matrix and the short PALF fiber of different length were prepared by hand lay-up technique.	The thermal behavior of PALF reinforced Bisphenol-A composites greatly depends on fiber length.
7	Fibers 'Orientation (FO)	Gudapati et al. (2018)	The results are achieved at different volume fraction, temperature and also fiber angles (0^o,45^o,90^o).	The thermal conductivity of the composites increases with increasing fiber angle
8	Surface Treatments of Fibers (STF)	Ravi et al. (2018)	Various natural and synthetic fibers	Surface treatment provides a better increment in mechanical, adhesion.
9		Adekunle (2015)	Natural Fibers	Fiber surface treatments improve interfacial adhesion between fiber surface and matrix which enhances good

				mechanical properties of polymer-based composites.

2.3 Effect of Filler Material On Thermal And Mechanical Properties Of Composites

Polymer matrix composites are manufactured as per requirement through adding filler in a matrix material. These fillers' function is to enhance the various properties such as wear-resistance and hardness, cost reduction, control of thermal expansion, density control. In recent time ceramic or metal particles used as hard fillers whereas glass is used as the fiber filler to improve the wear resistance up to two to three times Sawyer et al. (2003) . In the various application of industry such as a heater, electrodes, thermal durability at high temperatures polymer matrix composite with metal particulate filler are used Jung-il et.al. (2004). Silica particles when used to form composite it improves considerable change in thermal, electrical and mechanical properties of fabricated composite Nielsen L.E and Landel R.F., (1994). Srivastava et al(1988), researched about the fracture toughness of the epoxy resin and concluded that as there is the addition of fly ash particles as filler there is some improvement in the toughness. It also affects the tensile characteristic according to size and interfacial bonding.

3. RESEARCH STATEMENT AND OBJECTIVES

3.1 Research Motivation

Fiber Reinforced Composites (FRC) have been in use in place of metals for various industrial and other applications where weight reduction is the primary criterion without compromising the strength. The synthetic fibers have taken the FRP composites to a level where the strength is often superior to some of the metals and thus are becoming a popular choice for specific applications.

Many researchers investigated that polymer composites are one of the most important applications of polymers, whether natural or synthetic. Polymer matrix composites are the most advanced composites; these composites have different types of fibers (natural and synthetic) as reinforced material in different types of polymers such as thermoplastic or thermoset polymers, which can mould in different shapes and sizes, and make different types of fashioned materials The polymer composites have very good mechanical strength and stiffness, along with resistance to corrosion. Polymer materials have advantages over conventional materials that are used in different aerospace components.

It is well known that polymers are insulators, which limit their usages in applications where thermal conductivity is essential for heat to be efficiently dissipated or stored. According to the studies conductive composites are frequently used in wide applications such as heating elements, temperature-dependent sensors, self-limiting electric heaters, switching devices, antistatic materials for electromagnetic interferences and shielding of electronic devices etc. Hence there is a need of time to tailor polymer-based fiber composites to be mechanically strong and thermally conductive/insulative as per demand by using appropriate matrix and reinforcement materials selecting proper filler material.

FRC has gained much interest among technologists and scientists for applications in civil, military, industrial, spacecraft and biomedical sectors. In the past two decades, the growing interest for FRC has resulted in extensive research. The driving forces are (i) cost reduction, (ii) weight reduction and (iii) marketing (application of renewable materials). Technical requirements were of less importance; hence application remained limited to non-structural parts for a long time. Recent research, however, showed that significant improvements of these properties are possible. There is a scope of research for improvement in the properties of FRC in the area of mechanical strength considering effect of post-process curing and in-process curing as well as its effect on their thermal behaviour. The mechanical and thermal behaviour of the fiber-reinforced polymer composites are future challenges and discussed in the following section.

Studies also emphasized the effect of post-curing on the mechanical characterization of fiber-reinforced polymer (FRP) composite. The curing cycle has a strong impact on the mechanical properties of thermosetting polymers. The extent of cross-linking which is a strong function of curing temperature and time is directly linked to the glass transition temperature (Tg) of the thermosetting polymer.

Investigations reveal that there is a lack of information in the area of impact of in-process curing and post-process curing on the mechanical strength of the composite material. Also, there is a need of user-friendly laboratory set up to measure the thermal conductivity of composite. Research survey reflects that only few studies are available in the direction of incorporation of filler material during the fabrication of composites to improve its thermal properties and its effect on mechanical strength.

3.2 Research Objectives

The present study is emphasized on the effect of post-curing and in-process curing parameters on mechanical as well as thermal behaviour of fiber-reinforced polymer (FRP) composite. The curing cycle has a strong impact on the mechanical and thermal behaviour of thermosetting polymers. The extent of cross-linking which is a strong function of curing temperature and time is directly linked to the glass transition temperature (Tg) of the thermosetting polymer. The improvement in the thermal conductivity of the polymer with conductive filler and its effect on mechanical strength. The following objectives have been identified and addressed in the present research work.

- To gain an understanding of natural and synthetic fiber-reinforced polymer composites, and to gain an insight into the work previously done by other researchers in this particular area.
- To develop mould and punch set up for preparing the composite specimen with a facility to cure at a different set of pressure and temperature.
- To develop hot plate set up and hot air oven with temperature controllers and indicators for preparing the composite specimen to facilitate in-process curing and post-process curing respectively.
- To carry out a systematic experimental study based on the design of experiments (DOE) for the composites of jute, basalt and carbon fibers as reinforcements and vinyl ester as matrix for post-process curing and in-process curing parameters.
- To carry out the experimental investigations to study the effect of applied load, in post-curing of the composites considering post-curing temperature and time. Also to propose statistics based correlation to predict tensile and flexural strength.
- To carry out the experimental investigations to study the effect of applied load and temperature during in-process curing to propose statistics based correlation to predict tensile and flexural strength.
- To develop a laboratory set up for measuring the thermal conductivity of the composites material using the guarded hot plate and calorimeter principle. Also to determine the thermal conductivity of developed composites
- To carry out the experimental investigation to study the effect of conductive filler material (e.g. Copper (Cu), Aluminium(Al) and silicon carbide(SiC)) in jute- Polyester composite on mechanical and thermal behaviour.

3.3 Research Scheme

Figure 3.1 shows the schematic flow chart of the research work carried out.

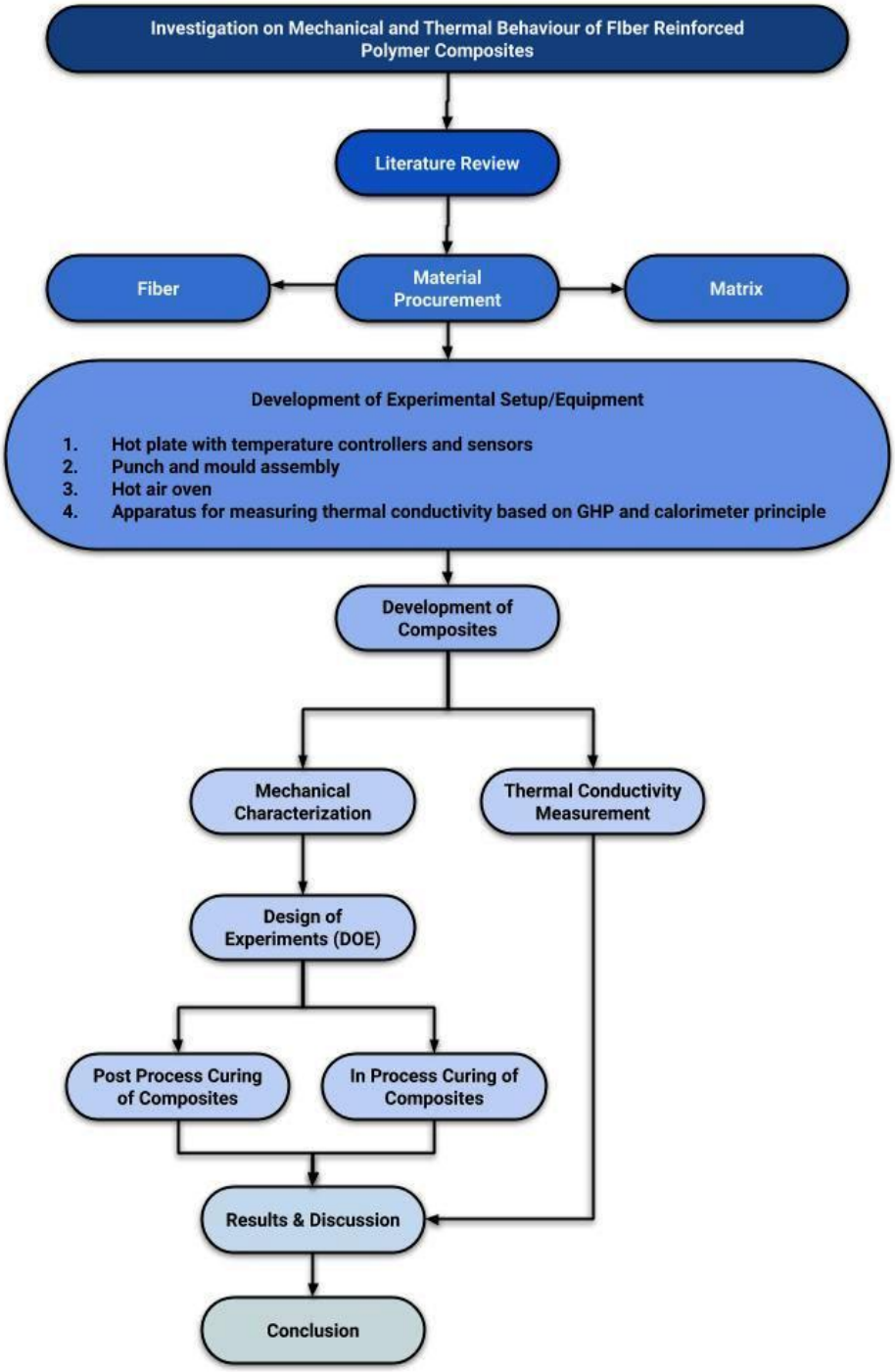

Figure 3.1 Research Scheme

4. EXPERIMENTAL SETUP AND METHODOLOGY

4.1 Mechanical Behaviour of composite material

The purpose of this investigation is to find correlations between mechanical strength and the effect of temperature on the curing process during fabrication (in process curing) and a correlation between mechanical strength and the effect of temperature after the fabrication process with time variable (post-process curing). Different mechanical tests have been carried out as per ASTM guidelines.

Mechanical Characterisation was carried out using Universal Testing Machine (TINIUS OLSEN / LSeries H50KL).

4.1.1 Tensile Strength

The most commonly used specimen geometries are the dog-bone specimen and straight-sided specimen with end tabs. The test-pieces of mechanical tests were used of dog bone type and having dimensions according to the ASTM standards. The tension test was performed as per ASTM D638 test standards. The test is repeated five times on five specimens (Refer: Tables 1, 2 and 3) made from each type of composite of different pressure, temperature and time combination and the mean value is reported as the tensile strength and flexural strength of that composite.

The dimensions of the specimen as per standards are shown in figures 4.3(a) and 4.3(b).

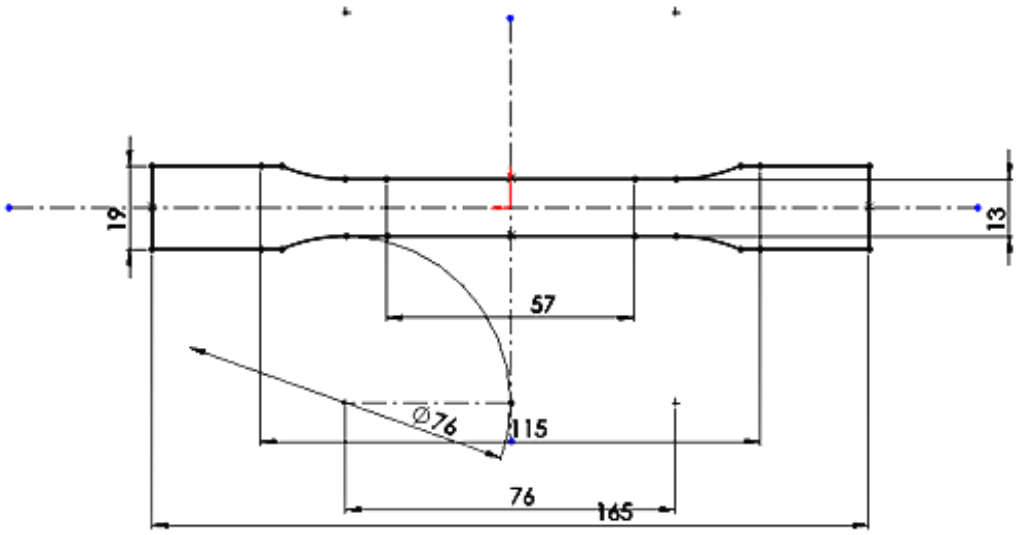

Figure 4.1 Specimen dimension as per ASTM D638

4.1.2 Flexural Strength

The determination of flexural strength is an important characterization of any structural material. A material can withstand the bending before reaching the breaking point as shown in

Figure 4.4(a). Conventionally a three-point bend test is conducted for finding out this material property. In the present investigation specimens of composites were subjected to flexural test as per ASTM D790 standards. The dimensions of the specimen as per standards are shown in the figures 4.4(a) and 4.4(b)

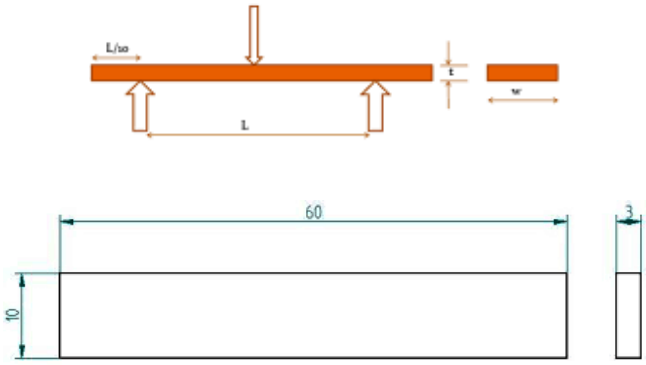

Figure 4.2 Specimen dimensions as per ASTM D790

4.2 Post-process curing of Composite Material

The curing process plays a major role in achieving FRC's mechanical properties and thermal properties. State of polymer resin is liquid (soft) before the fabrication of composite, which then changes to solid matrix (hard) after curing. For the fabrication of composite, two types of resins are used (i) primary resin (matrix) and (ii) secondary resin (hardener). During cross-linking, the state of matrix changes from liquid to gel and then transforms into solid. Curing can be done at room temperature as well as at elevated temperatures. Polymer matrix composites are post cured at an elevated temperature to increase the amount of cross-linking to achieve better chemical and heat resistance and mechanical properties. For the determination of the suitable post-cure parameters, plates were fabricated and post cured with varying time and temperature in a developed hot air oven. The effect of post-curing on mechanical properties of composites have been studied. The figure shows developed hot air oven used for post-process curing

Figure 4.3 Developed Hot Air Oven for post-process curing

4.3 In-process curing of Composite Material

An experimental set up of hot plate with a temperature controller and sensors with punch and mould (Fig 4.3) was prepared to know the effect of load applied during the fabrication process and to fabricate composite at controlled temperature (in process curing). Hot air oven was developed for the post-process curing of the specimens. Investigations were made to know the effect of in-process curing and post-process curing on mechanical characterization.

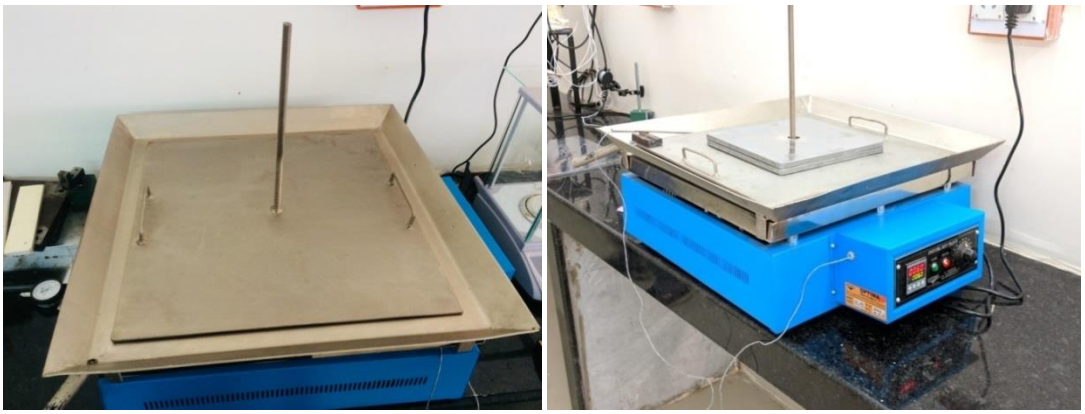

Figure 4.4 Developed Punch and Mould Assembly with hot plate for In – process curing

Hand layup method was used in the laboratory for the fabrication of fiber-reinforced polymer composites.

4.4 Taguchi Method

In any experimental research, since test procedures are generally expensive and time-consuming, the need to satisfy the design objectives with the least number of tests is an important requirement. In this context, the Taguchi method provides the designer with a systematic and efficient approach for experimentation to determine near optimum settings of design parameters for performance and cost. This method involves laying out the experimental conditions using specially constructed tables known as 'orthogonal arrays'. The use of orthogonal arrays significantly reduces the number of experimental configurations to be studied. The conclusions drawn from small scale experiments are valid over the entire experimental region spanned by the control factors and their settings. The most important stage in the design of the experiment lies in the selection of the control factors. Therefore, three factors pressure (load), temperature and time are included as control factors for a tensile and flexural test which are given in Table 1 and Table 2

Table 4.1 Parameter Setting for the test

Control parameters	**Fixed parameters**
Load (Pressure)	Fiber
Temperature	Resin
Time	Accelerator
	Hardener

Table 4.2 Levels for various control factors

Control parameters	**Levels**			**Units**
	I	II	III	
Load (Pressure)	180	230	280	Newton (N)

Temperature	40	60	80	Centigrade ^{0}C
Time	60	120	180	Minutes

The tests are conducted as per the experimental design given in Table 3 for a different set of pressure, temperature and time.

Table 4.3 Combination of the three parameters selected for the study (L_9 Orthogonal Array)

Sr No	**Load (Pressure) (N)**	**Temperature (^{O}C)**	**Time (Minutes)**
1	180	40	60
2	180	60	120
3	180	80	180
4	230	40	120
5	230	60	180
6	230	80	60
7	280	40	180
8	280	60	60
9	280	80	120

4.5 Mechanical Characterisation

The tensile strength of the composites was measured with a computerized universal testing machine (Model: TINIUS OLSEN/LSeries H50KL) following the ASTM D638 procedure at a crosshead speed of 5mm/min as shown in fig. 4.4

Figure 4.5 Tensile Testing in Universal Testing Machine (UTM) (Model: TINIUS OLSEN/LSeries H50KL)

The flexural tests were performed on the same universal testing machine, using the three-point bending fixture according to ASTM D790 with the crosshead speed of 5mm/min. Flexure testing is often done on relatively flexible materials such as polymers, wood and composites. The three-point flexure test is the most common for polymers. Specimen deflection is usually measured by the crosshead position. Test results include flexural strength and flexural modulus.

In a three-point test, the area of uniform stress is quite small and concentrated under the center loading point. (figure 4.5)

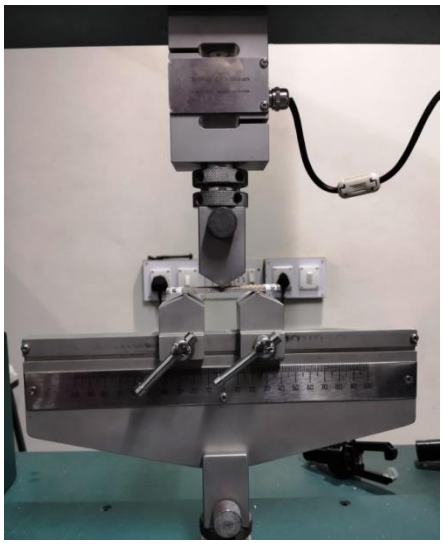

Figure 4.6 Flexural Testing in Universal Testing Machine (Model: TINIUS OLSEN/LSeries H50KL)

Composite plates were prepared from jute, basalt and carbon fibers with vinyl ester as a matrix. Plates were prepared in different combination of load, temperature and time (as per Taguchi L9 Orthogonal array) to study the effect of post-process curing on the mechanical strength of the composites whereas to study the effect of in-process curing on mechanical strength, plate were prepared with a different set of load and temperature. (Refer fig. 4.6)

Figure 4.7 (a) Post cured Plate of Carbon-vinyl ester post cured

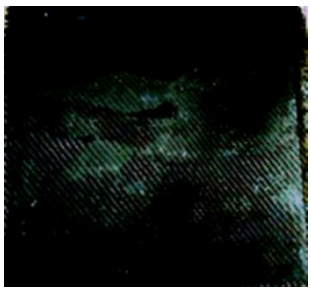

Figure 4.7 (b) Post cured Plate of Basalt-vinyl ester post cured

Figure 4.7 (c) post cured Plate of Jute – vinyl ester post cured

Table 4.4 Designation of the Codes for The Prepared Jute Fibers -Vinyl Ester Composite Specimens

TEST	JUTE- VINYL-ESTER																											
	LOAD	TEMP	TIME	LOAD	TEMP	TIME	LOAD	TEMP	TIME	LOAD	TEMP	TIME	LOAD	TEMP	TIME	LOAD	TEMP	TIME	LOAD	TEMP	TIME	LOAD	TEMP	TIME	LOAD	TEMP	TIME
	180	40	60	180	60	120	180	80	180	230	40	120	230	60	180	230	80	60	280	40	180	280	60	60	280	80	120
TENSILE	JT1804060/1			JT18060120/1			JT18080180/1			JT23040120/1			JT23060180/1			JT2308060/1			JT28040180/1			JT2806060/1			JT28080120/1		
	JT1804060/2			JT18060120/2			JT18080180/2			JT23040120/2			JT23060180/2			JT2308060/2			JT28040180/2			JT2806060/2			JT28080120/2		
	JT1804060/3			JT18060120/3			JT18080180/3			JT23040120/3			JT23060180/3			JT2308060/3			JT28040180/3			JT2806060/3			JT28080120/3		
	JT1804060/4			JT18060120/4			JT18080180/4			JT23040120/4			JT23060180/4			JT2308060/4			JT28040180/4			JT2806060/4			JT28080120/4		
	JT1804060/5			JT18060120/5			JT18080180/5			JT23040120/5			JT23060180/5			JT2308060/5			JT28040180/5			JT2806060/5			JT28080120/5		
FLEXURAL	JF1804060/1			JF18060120/1			JF18080180/1			JF23040120/1			JF23060180/1			JF2308060/1			JF28040180/1			JF2806060/1			JF28080120/1		
	JF1804060/2			JF18060120/2			JF18080180/2			JF23040120/2			JF23060180/2			JF2308060/2			JF28040180/2			JF2806060/2			JF28080120/2		
	JF1804060/3			JF18060120/3			JF18080180/3			JF23040120/3			JF23060180/3			JF2308060/3			JF28040180/3			JF2806060/3			JF28080120/3		
	JF1804060/4			JF18060120/4			JF18080180/4			JF23040120/4			JF23060180/4			JF2308060/4			JF28040180/4			JF2806060/4			JF28080120/4		
	JF1804060/5			JF18060120/5			JF18080180/5			JF23040120/5			JF23060180/5			JF2308060/5			JF28040180/5			JF2806060/5			JF28080120/5		

Abbreviation:

JF- Jute Flexural Test

Load = 180, 230 and 280 N

Temperature = 40 C, 60 C,80 C.

Time = 60 minutes,120 minute,180 minutes.

Total 5 specimens of each combination

Eg. JT18080180/4 means Carbon Tensile test of 180 N load at 80 C temp kept for 180 minutes ...4th specimen amongst total of 5

Similarly, codes are given to the plates made from basalt and carbon fibers with vinyl ester resin.

Composite plates were fabricated by hand lay-up process in the laboratory as per the details of table 4.3 mentioned above and specimens cut to the size and dimensions for tensile strength and tested as per ASTM D638 standards and for flexural strength, specimens were cut as per ASTM D790 standards. Five sample specimens were prepared from each plate.(Refer Tables 4.4, 4.5 and 4.6)

Figure 4.8 Post cured Specimens of jute, basalt, and Carbon fibers with vinyl ester as per ASTM 638 for tensile tests

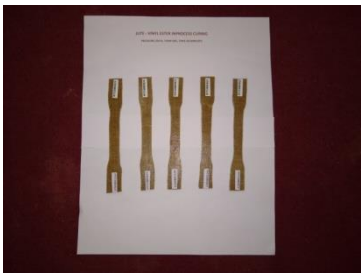

Figure 4.9 Specimens of in-process curing for tensile test as per ASTM 638 standards

Figure 4.10 (a) Specimens with SiC Filler (b) Specimens with AL Filler (c) Specimens with Cu Filler

Figure 4.11 Post cured Specimens of jute, basalt and Carbon fibers with vinyl ester as per ASTM 790 for flexural test

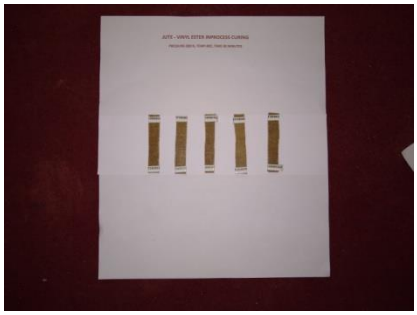

Figure 4.12 Specimens of in-process curing process Jute-Vinyl ester composite for Flexural test as per ASTM 790 for flexural tests


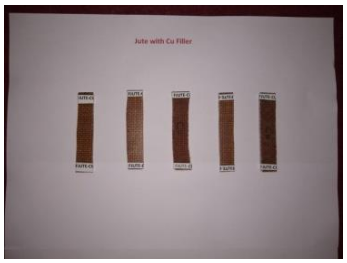


Figure 4.13 (a) Specimens with SiC Filler (b) Specimen with Cu Filler (c) Specimen with Al Filler
as per ASTM 790 for flexural tests

4.6 Tensile Properties of the composites prepared with post-process curing (PPC)

The depicted tensile strength values in table 4.6 are the average of five specimens values.

Table 4.5 Tensile Properties of the composites prepared with post-process curing (PPC)

Load	**Temperature**	**Time**	**TENSILE STRENGTH (JUTE)**	**TENSILE STRENGTH (BASALT)**	**TENSILE STRENGTH (CARBON)**
180	40	60	30.0000	246.5000	228.3333
180	60	120	34.4666	255.6666	238.3333
180	80	180	35.7000	263.0000	321.0000
230	40	120	39.4500	275.7500	264.3333
230	60	180	39.6500	301.7500	285.3333
230	80	60	40.5333	308.2500	327.0000
280	40	180	41.2500	315.000	289.2500
280	60	60	41.6000	321.6000	292.2500
280	80	120	42.8000	331.0000	337.2500

4.7 Flexural Properties of the composites prepared with post-curing

The depicted flexural strength values in table 4.7 are the average of five specimens' values.

Table 4.6 Flexural Properties of the composites prepared with post-curing

Load	Temperature	Time	Flexural Strength (JUTE)	Flexural Strength (BASALT)	Flexural Strength (CARBON)
180	40	60	57.0500	270.0000	193.5000
180	60	120	58.6500	280.7500	236.8000
180	80	180	71.3750	294.5000	270.6667
230	40	120	72.3000	306.2500	269.6667
230	60	180	74.3666	335.7500	303.7500
230	80	60	79.2000	365.0000	313.5000
280	40	180	80.5200	364.4000	321.6667
280	60	60	84.8500	399.4000	335.3333
280	80	120	88.0800	406.0000	370.0000

4.8 Tensile and Flexural Properties of the composites prepared with in-process curing.

The depicted tensile and flexural strength values in table 4.8 are the average of five specimens values.

4.7 Tensile and Flexural Properties of the composites prepared with in-process curing.

Load (N)	Temperature (Celsius)	Tensile Strength (MPa)	Flexural Strength (MPa)
180	40	32.5000	71.1400
180	60	37.6000	77.7500
180	80	39.9333	80.2750
230	40	35.1500	75.0333
230	60	34.9666	75.4000
230	80	40.4333	80.3333
280	40	36.0500	77.3000
280	60	36.7000	75.6000
280	80	43.3500	84.0333

4.9 Thermal Characterisation

The heat conduction depends on thermal transport property called thermal conductivity. The measured numerical value of thermal conductivity gives an idea about the use of the material as a heat conductor or insulator. To measure the thermal conductivity of materials for a wide range of temperatures, a laboratory model was fabricated which works based on Guarded Hot Plate using the principle of a calorimeter. Experiments were performed for measuring the thermal conductivity of insulating and other groups of materials over a limited range of temperatures. By adding highly conductive fillers in composite polymer we can achieve significant improvement in thermal conductivity without major effect on mechanical

properties. Experiments are conducted to measure the thermal conductivity of different specimens of composite fabricated by adding different conductive filler materials during the fabrication process.

4.10 Development of Apparatus for Measuring Thermal Conductivity based on GHP Method

The guarded hot plate is a standard technique for measuring thermal conductivity in low range of solid materials. Insulation materials and mid-range conductors as well may be tested by GHP method and many laboratories and organizations have developed their apparatuses based on this method. The device is developed in this research is based on a single specimen type of guarded hot plate apparatus.

4.10.1 Components and Materials

Hot plate – it is made of aluminum in the form of cylindrical plates in two halves; of which lower thinner cylinder is 10mm and upper cylinder is 18mm thick. A square slot of 80mm is cut at the center in both plates in such a way that a recess of 8mm total depth is formed when both the parts are bought together. The heater is sandwiched between two halves in this recess. Aluminum plates are electrically insulated from the electric circuit by a thin layer of thermal adhesive. For the temperature measuring sensor, a hole of 4mm diameter and 40mm length is drilled on the peripheral wall of the upper plate 3mm below the top surface.

The hot plates and the heater are clamped and bolted together to restrict the lateral movement between the two.

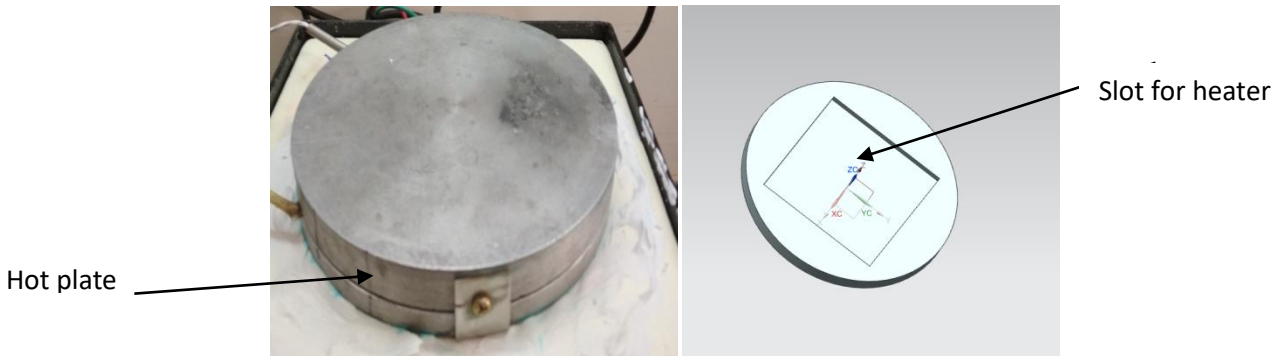

Figure 4.14 Hot plate

Cold plate assembly – It is also made from aluminum with a cylindrical base plate 10mm thick together with a coolant tank above in one piece. The thickness of tank wall is 6mm and its height from base plate is 70mm. Hole for sensor of diameter 4mm and 40mm length is drilled on the peripheral wall of the base plate in radial direction 3mm above the bottom surface. Two holes, one just above the base plate and other 5mm from top are drilled for coolant inlet and outlet connections respectively.

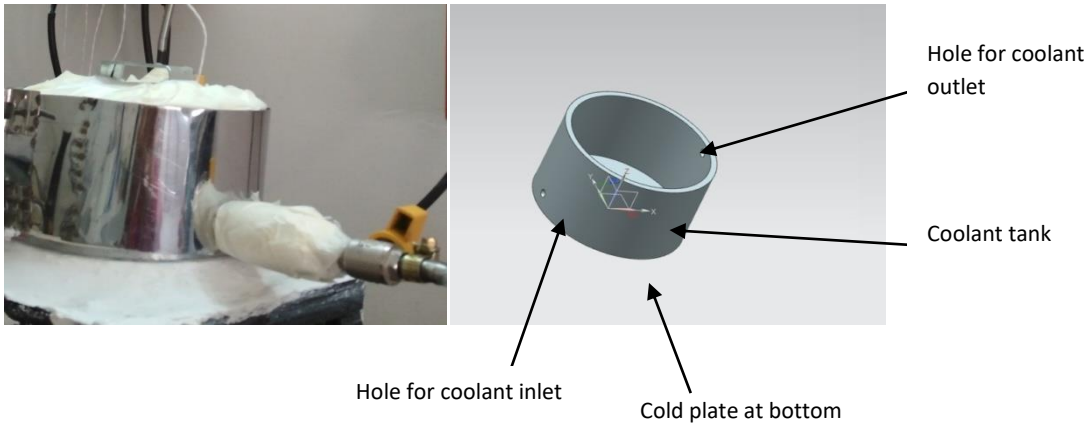

Figure 4.15 Cold plate

To get the isothermal conditions both the plates are made of good conducting material aluminum which also has good machinability. The plates and other components used in the apparatus are rated at high temperatures to satisfy the demands. Materials selected for heater and plates are dimensionally and chemically stable in the operating temperature range. The heat capacity of the hot plate affects the time required to reach the steady-state. The thick plates help in reducing lateral temperature distributions but reduce responsiveness. So thickness is selected as to balance these requirements.

Here thermal steady-state said to achieve when temperature of the plates and coolant do not vary with time. This varies considerably with the apparatus design, specimen to be measured and test conditions.

Heater plate – it is S.S.-mica type strip heater made up of several layers. The heating wire used is kanthol of gauge 20 wrapped on and covered with mica. It is of 1kW rating.

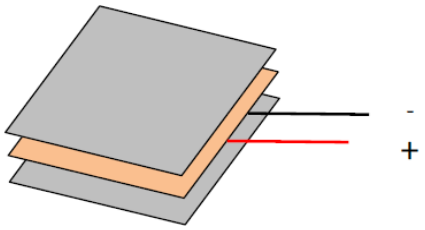

Figure 4.16 Heater

Overhead tank – a tank at an appropriate height for storing coolant is required as to supply it at constant head and temperature and act as heat sink.

Coolant inlet and outlet valves – made of brass of size 1/4” are connected at the inlet and outlet ports for flow regulation.

Figure 4.17 Control/Display unit

Temperature sensors – for measuring the temperature at different locations, resistance temperature detector (RTD) of type PT100 properly calibrated using a certified thermometer are installed. Sensors S1, S2, S3 and S4 are used to get the temperature of hot plate, cold plate, coolant inlet and coolant outlet respectively. The probe is 40mm long of diameter 4mm made of S.S. They must be in good contact with the plates. So epoxy is used as contact medium to reduce its thermal contact resistance with the plates. The fine wire of 0.2mm thickness is used in making of the sensor. The teflon insulated wires used do not come in contact with the plates as sensors are installed on the outer peripheral wall of the plates so there is no heat flow along them. This is to get correct plate temperature and reduce the error in measurement. The wires for the heater sensor and heater are connected to solid state relay and terminal block and then connected to the power supply and display unit.

Temperature indicator – It is a digital type. The electrical readings from the temperature sensors are converted to temperature using a mathematical equation based on sensor's calibration curve or an appropriate reference. The specifications are as below:

Table 4.8: Specification of temperature indicator

Model	Multispan Model MDI38
Supply	230V AC $\pm$ 10%, 50Hz
Input	PT-100/3W (RTD)
Range	0-200.0 °C
Display	4-Digit, 0.8 inch, Red color

The specifications of the temperature controller are as below:

Table 4.9 Specification of temperature controller

Model	Multispan PID temperature controller Model UTC 121P
Display	Upper: 4 digit, 0.56”, red LED display Lower: 4 digit, 0.4”, green LED display
Input	J, K, PT-100 (selectable)
Temperature Range	PT-100: -99 to 400 °C
Control Action	PID/ON-OFF (selectable)
Power Supply	100 to 250V AC, 50/60 Hz, Approx 4VA

Assembly of Hot and Cold Plate

Two aluminum plates with the same dimension of the specimen are placed on either side of the specimen to create a uniform heating profile and prevent any convective thermal loss directly from sample to the environment. The heater is sandwiched and fitted in the inbuilt groove made in the two halves of the hot aluminum plate.

The coolant tank of the cold plate assembly with valve operated inlet and outlet ports is affixed on the hot plate to make the heat flow vertically in an upward direction through the specimen sandwiched in between the hot plate and the cold plate assembly. The coolant is made to flow in the coolant tank as to sustain the upward heat flow.

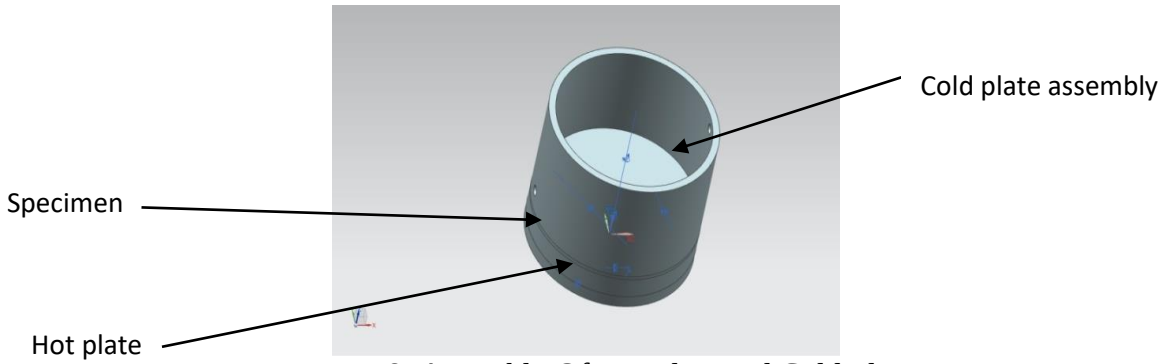

Figure 4.18: Assembly Of Hot Plate and Cold Plate

Resistance temperature detector PT 100 type sensors are installed for measuring the temperature of the plates, coolant inlet and outlet. These sensors are installed by accordingly drilling the holes of adequate size on the peripheral surface of the plates as described above.

The whole of the cold plate assembly is insulated by a layer of ceramic wool packed beneath the S.S. sheet to prevent the heat loss and to assure one-dimensional heat flow. The hot plate and hence the whole assembly is made to rest on the tripod supporting stand with a bowl that has a layer of insulation on the inside wall that envelops the hot plate to prevent the heat loss. This restricts the edge heat loss which is normally the source of greatest measurement errors.

The bottom face of the hot plate is insulated with calcium silicate plate and plaster of paris for protecting from backward heat loss.

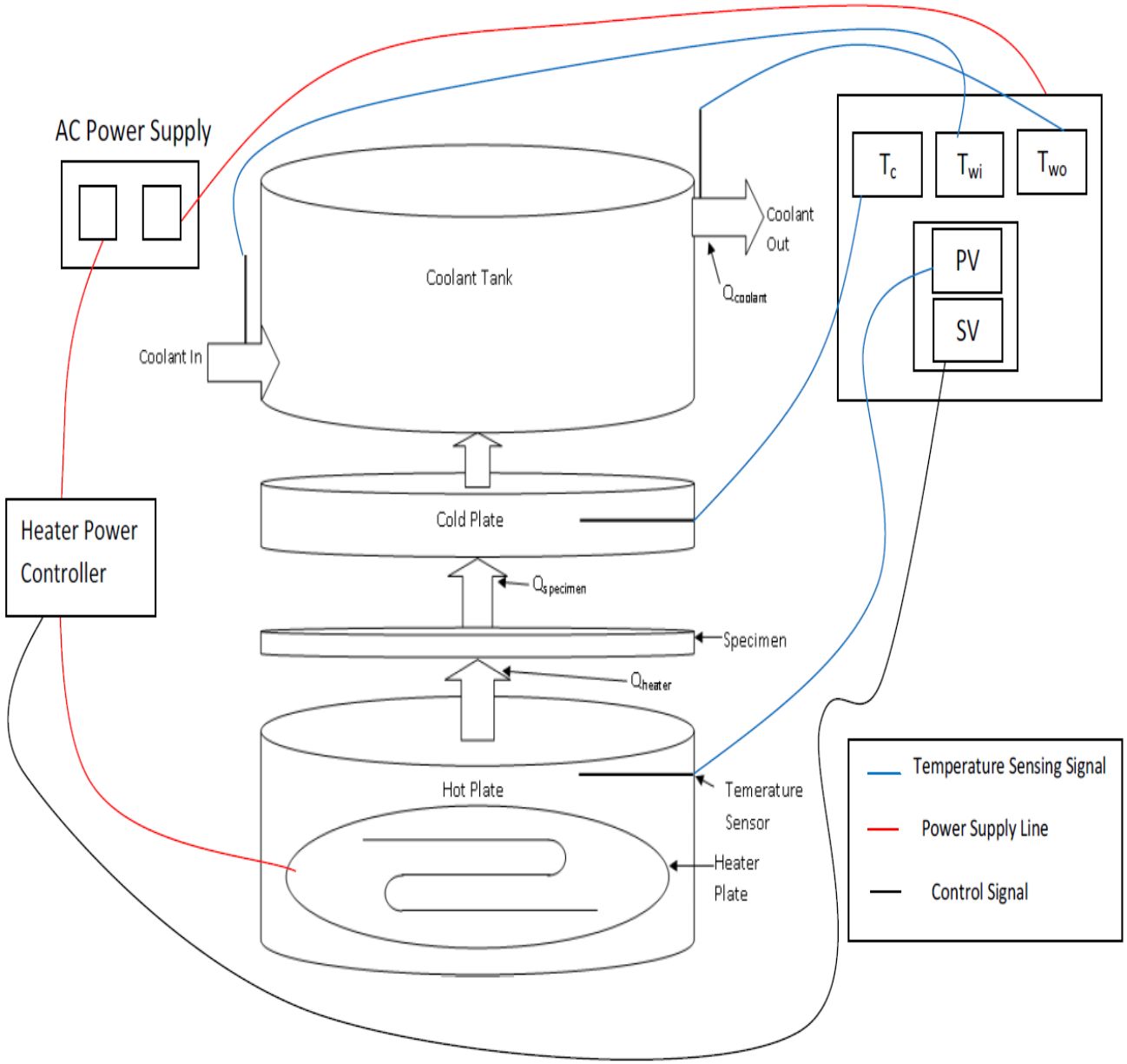

Figure 4.19: Schematic diagram of apparatus

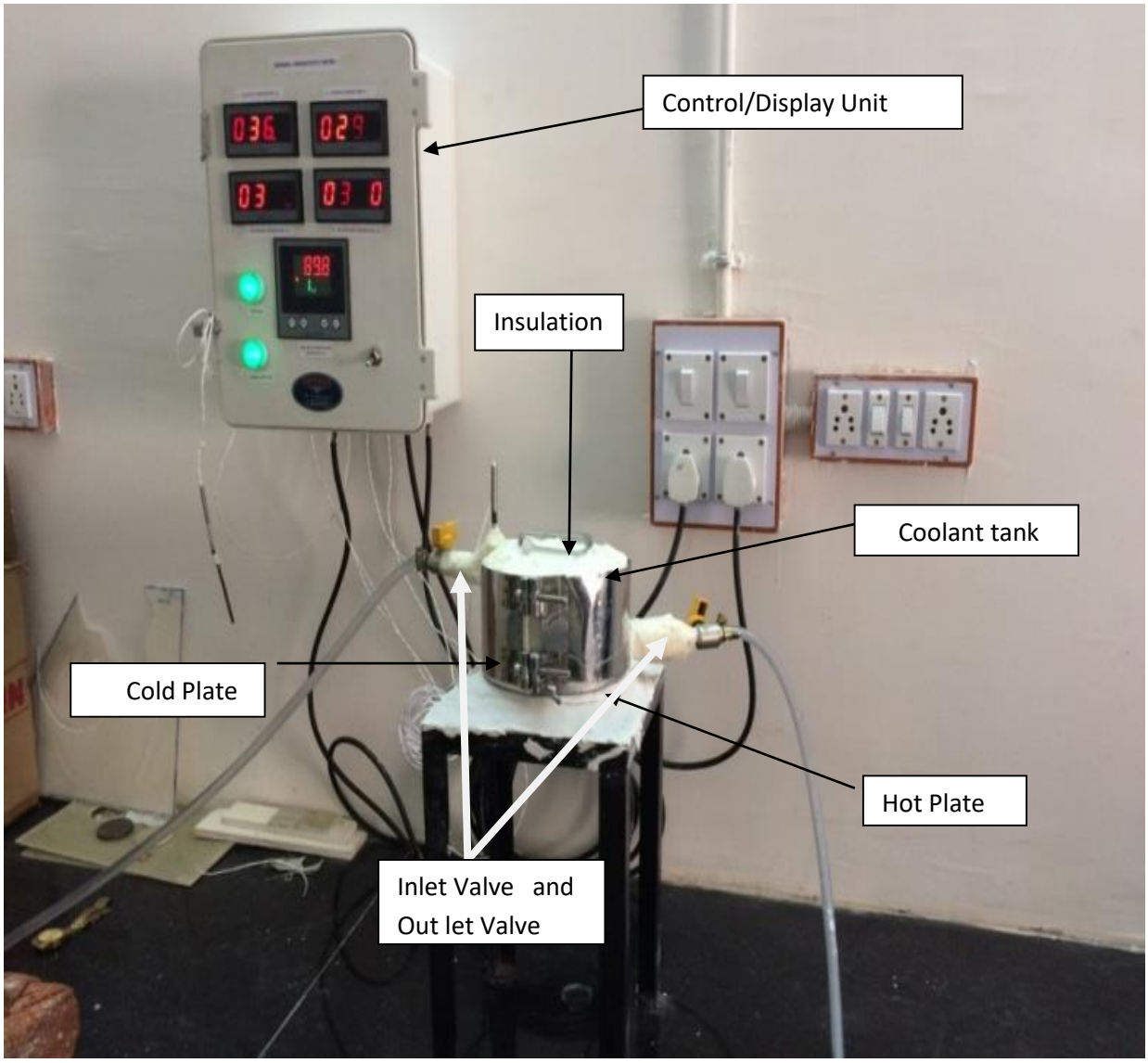

Figure 4.20 Developed Experimental set up for measuring thermal conductivity

The hot plate and cold plate surface should remain planar during the experimentation process of the apparatus. Also the surface of the specimen should be such that they are parallel with and have uniform thermal contact with the two plates. It is necessary to smooth the specimen surfaces to have a better plate to specimen contact. This is to be ensured because the measured heat flux will be greater than the heat flux obtained in the absence of voids if the apparent thermal conductivity of the contact void is greater than that of the specimen. The weight of the cold plate assembly here acts as the inertia force to maintain accurate spacing and have good thermal contact between the hot and cold plates.

The specimen size of 50.8mm diameter and 0.5 to 25.4mm thick was selected as per ASTM C1530. The composite specimens were prepared by hand lay-up technique (Figure 4.19 and Fig 4.20)

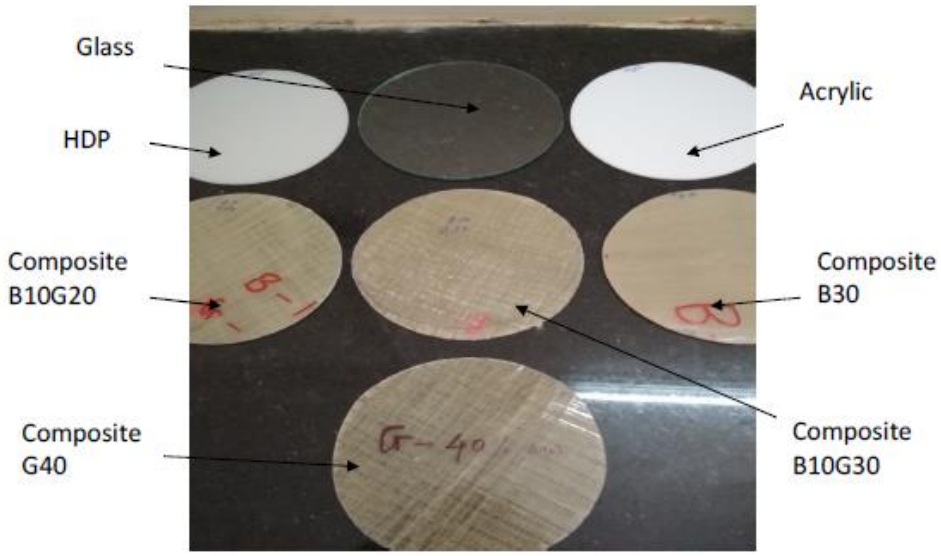

Figure 4.21 specimens prepared as per ASTM C1530 with a different combination of Bamboo and Glass fibers

Figure 4.22 Specimen for testing thermal conductivity of Jute-Polyester composite as per ASTM C1530 (a) with Cu Filler (b) with SiC Filler (c) with Al Filler

5. RESULT AND DISCUSSION

5.1 Tensile strength of Jute-Vinyl ester Composite (PPC)

The main effect plot of tensile strength for Jute is shown in Fig. 5.1. It was observed that as the load and temperature increase the tensile strength is increased. There is little increment in tensile strength is observed with increase in time.

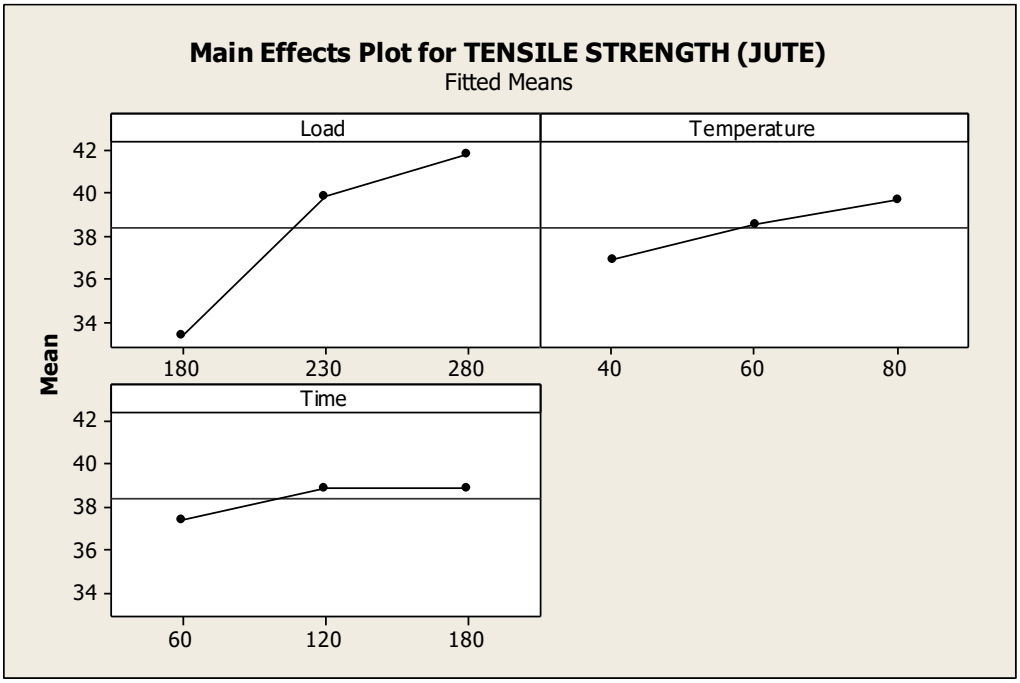

Figure 5.1 Main effects plot for tensile strength for Jute-Vinyl ester composite (PPC)

ANOVA was carried out for the tensile strength of jute-vinyl ester composites. Table 5.1 shows the ANOVA results for the tensile strength. The p-value from the ANOVA results represents that the load has significant effects on the tensile strength of jute-vinyl ester composites (PPC). The adjusted R2 value for the tensile strength of jute-vinyl ester composites (89.33%) suggests an acceptable fitting of the model.

Table 5.1 ANOVA table for tensile strength of jute-vinyl ester composites(PPC)

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Load	2	118.284	118.284	59.142	32.08	**0.03**
Temperature	2	11.735	11.735	5.867	3.18	0.239
Time	2	4.552	4.552	2.276	1.23	0.447
Error	2	3.687	3.687	1.843		
Total	8	138.257				
S = 1.35769		**R-Sq = 97.33%**		**R-Sq(adj) =89.33%**		

5.2 Tensile strength of Basalt-Vinyl ester Composite (PPC)

The main effect plot of tensile strength for basalt is shown in Fig. 5.2. It was observed that as the load increases the tensile strength is increases. There is a little increment in tensile strength is observed with an increase in temperature while there is no effect of time on the tensile strength of basalt vinyl ester composites.

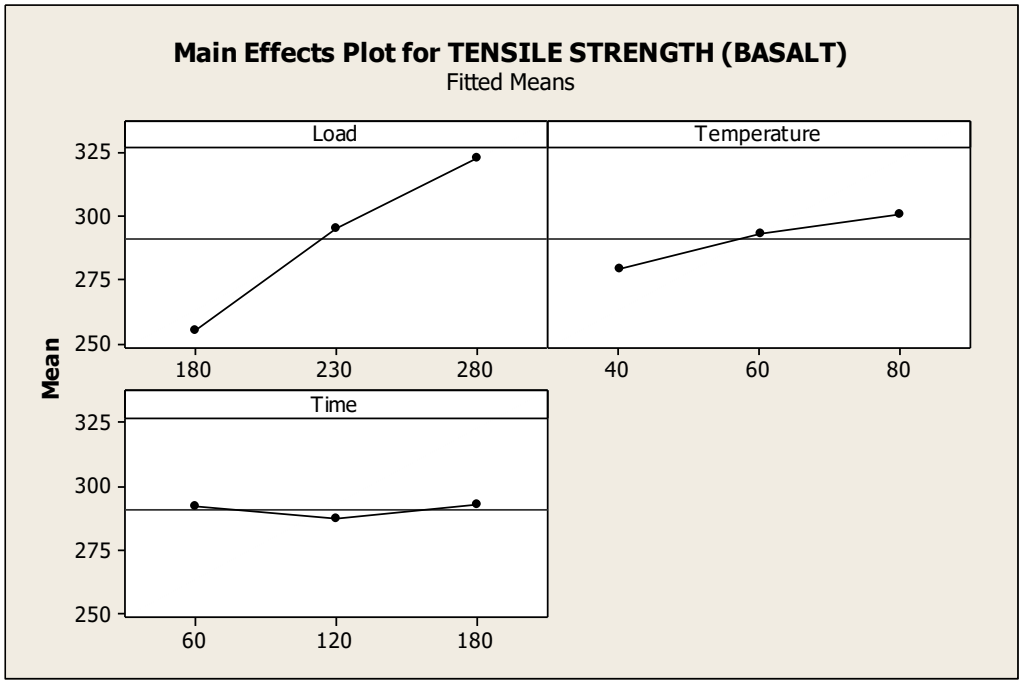

Figure 5.2 Main effect plot for tensile strength of basalt-vinyl ester composites (PPC)

ANOVA was carried out for the tensile strength of basalt-vinyl ester composites. Table 5.2 shows the ANOVA results for the tensile strength. The p-value from the ANOVA results represents that the load has significant effects on the tensile strength of basalt-vinyl ester composites. The adjusted R^2value for the tensile strength of basalt-vinyl ester composites (95.98%) suggests an acceptable fitting of the model.

Table5.2 ANOVA table for tensile strength of basalt-vinyl ester composites

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Load	2	6913.2	6913.2	3456.6	88.63	0.011
Temperature	2	723.2	723.2	361.6	9.27	0.097
Time	2	56.2	56.2	28.1	0.72	0.581
Error	2	78	78	39		
Total	8	7770.7				
S = 6.24519		**R-Sq = 99.00%**		**R-Sq(adj) = 95.98%**		

5.3 Tensile strength of Carbon-Vinyl ester Composite (PPC)

The main effect plot of tensile strength for carbon-vinyl ester is shown in Fig. 5.3.It was observed that as the load and temperature increase the tensile strength is increased. There is a little increment in tensile strength is observed with an increase in time.

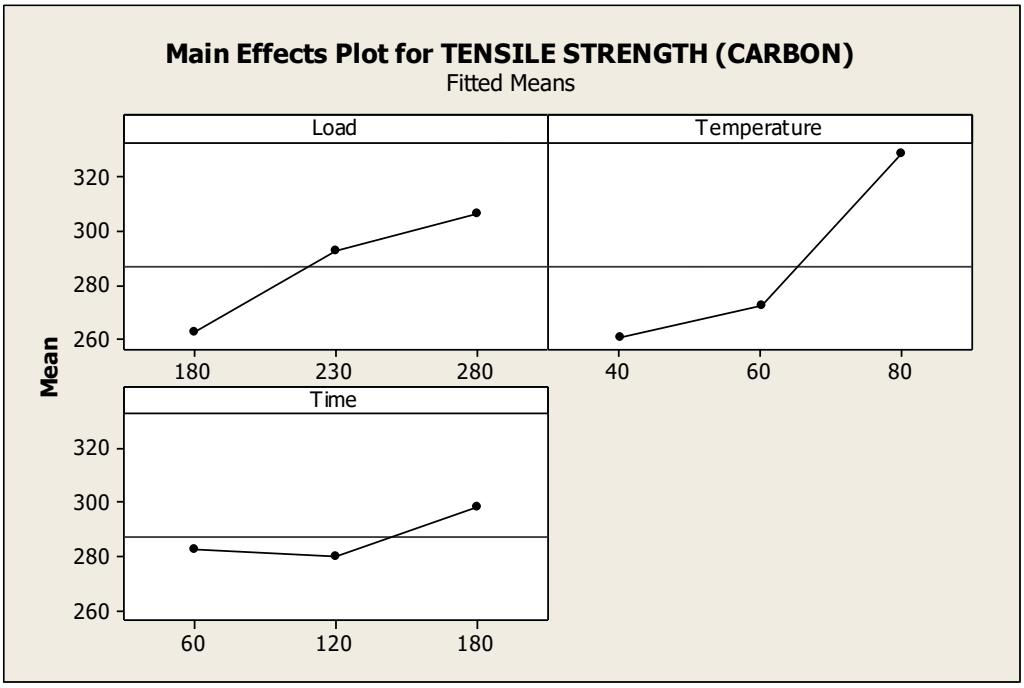

Figure 5.3 Main effect plot for tensile strength of Carbon-vinyl ester composites (PPC)

ANOVA was carried out for the tensile strength of carbon-vinyl ester composites. Table 5.3 shows the ANOVA results for the tensile strength. The p-value from the ANOVA results represents that the load and temperature have significant effects on the tensile strength of carbon-vinyl ester composites. The adjusted R^2 value for the tensile strength of carbon-vinyl ester composites (95.21%) suggests an acceptable fitting of the model.

Table 5.3 ANOVA table for tensile strength of carbon-vinyl ester composites

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Load	2	2986.1	2986.1	1493	21.44	0.045
Temperature	2	7908.2	7908.2	3954.1	56.78	0.017
Time	2	606.8	606.8	303.4	4.36	0.187
Error	2	139.3	139.3	69.6		
Total	8	11640.5				
S = 8.34518		**R-Sq = 98.80%**		**R-Sq(adj) = 95.21%**		

5.4 Flexural strength of Jute-vinyl ester Composites (PPC)

The main effects plot of flexural strength for Jute is shown in Fig. 5.4. It was observed that as the load and temperature increase the flexural strength is increased. There is no effect on flexural strength is observed with an increase in time

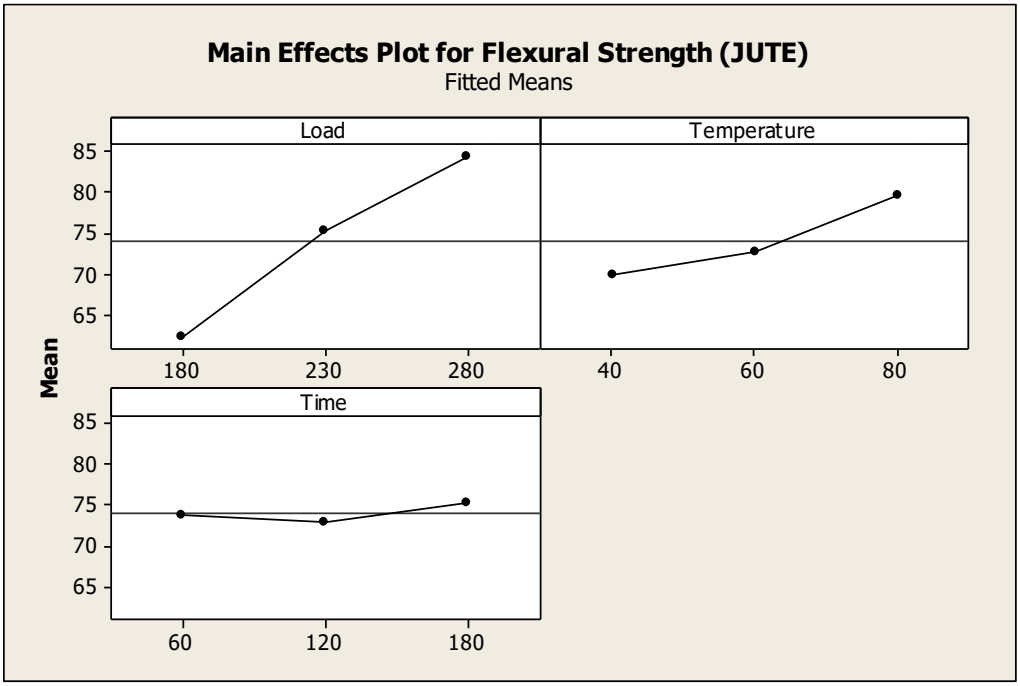

Figure 5.4 Main effects plot for Flexural strength of Jute-vinyl ester composites (PPC).

ANOVA was carried out for the flexural strength of jute-vinyl ester composites. Table 5.4 shows the ANOVA results for the flexural strength. The p-value from the ANOVA results represents that the load has significant effects on the flexural strength of jute-vinyl ester composites. The adjusted R^2 value for the flexural strength of jute-vinyl ester composites (91.00%) suggests an acceptable fitting of the model.

Table 5.4 ANOVA table for flexural strength of jute-vinyl ester composites

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Load	2	741.25	741.25	370.63	35.89	0.027
Temperature	2	147.19	147.19	73.59	7.13	0.123
Time	2	9.25	9.25	4.62	0.45	0.691
Error	2	20.66	20.66	10.33		
Total	8	918.34				
S = 3.21372		**R-Sq = 97.75%**			**R-Sq(adj) =91.00%**	

5.5 Flexural strength of Basalt-vinyl ester Composites (PPC)

The main effect plot of flexural strength for basalt is shown in Fig. 5.5 It was observed that as the load and temperature increase the flexural strength is increased. There is no effect of time on the flexural strength of basalt vinyl ester composites

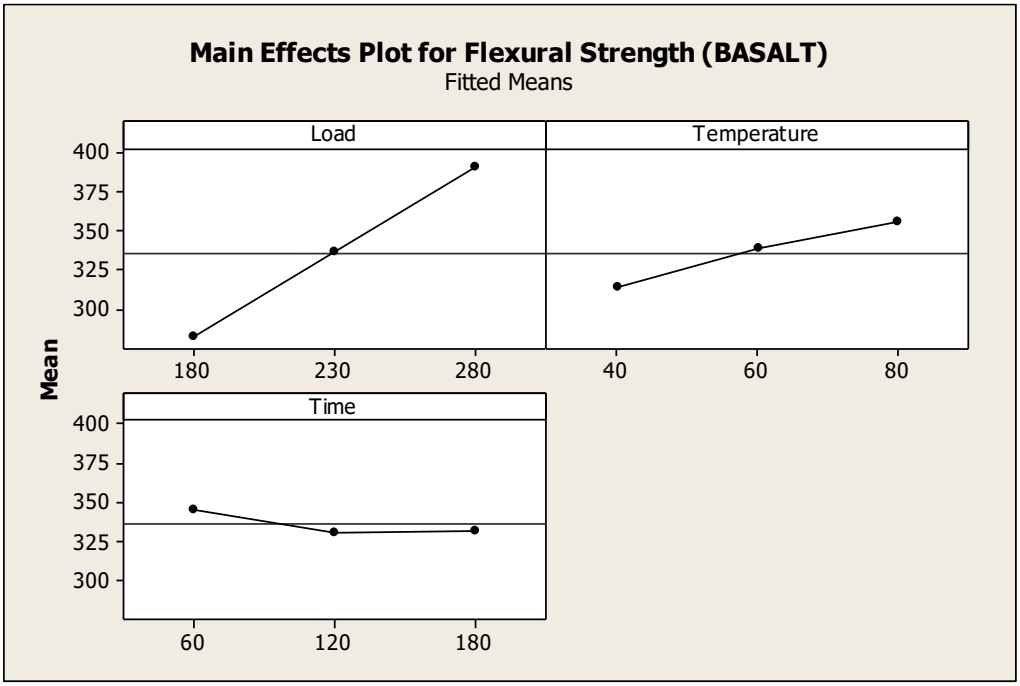

Figure 5.5 Main effects plot for flexural strength of basalt-vinyl ester composites(PPC)

ANOVA was carried out for the flexural strength of basalt-vinyl ester composites. Table 5.5 shows the ANOVA results for the flexural strength. The p-value from the ANOVA results represents that the load and temperature have significant effects on the flexural strength of basalt-vinyl ester composites. The adjusted R^2value for the flexural strength of basalt-vinyl ester composites (99.49%) suggests an acceptable fitting of the model.

Table 5.5 ANOVA table for flexural strength of Basalt-vinyl ester composites

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Load	2	17555.5	17555.5	8777.8	666.33	0.001
Temperature	2	2634.5	2634.5	1317.2	99.99	0.01
Time	2	366.3	366.3	183.2	13.9	0.067
Error	2	26.3	26.3	13.2		
Total	8	20582.6				
S = 3.62951		**R-Sq = 99.87%**			**R-Sq(adj) = 99.49%**	

5.6 Flexural strength of Carbon-vinyl ester Composites (PPC)

The main effect plot of flexural strength for a carbon-vinyl ester is shown in Fig. 5.6 It was observed that as the load and temperature increase the flexural strength is increased. There is a little increment in flexural strength is observed with increase in time.

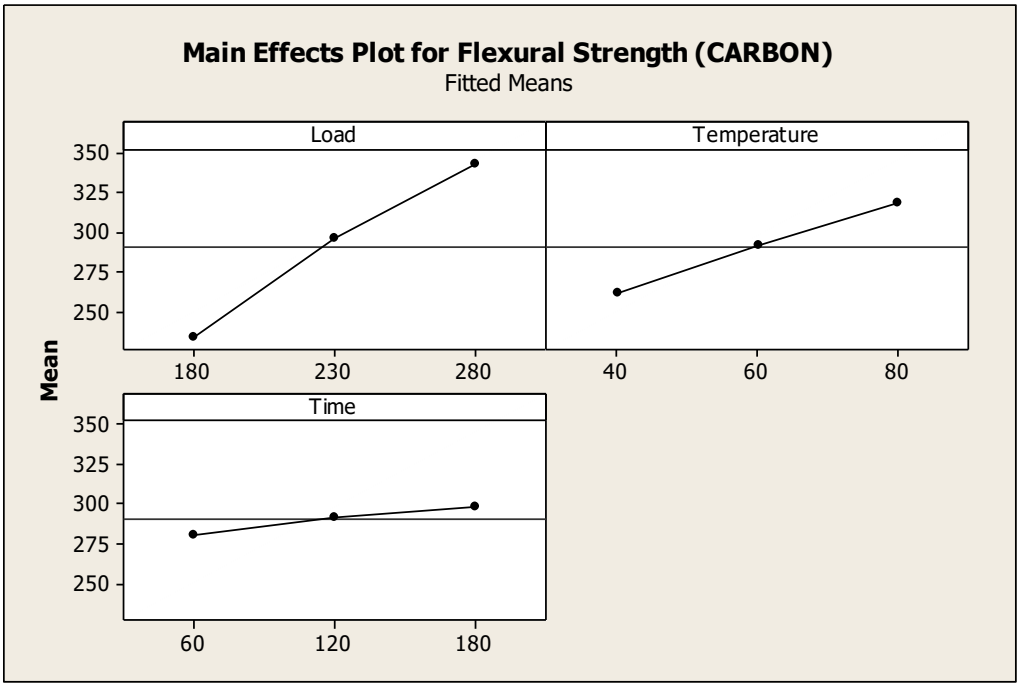

Figure 5.6 Main effects plot for flexural strength of Carbon-vinyl ester composites(PPC)

ANOVA was carried out for the flexural strength of carbon-vinyl ester composites. Table 5.6 shows the ANOVA results for the flexural strength. The p-value from the ANOVA results represents that the load, temperature and time have significant effects on the flexural strength of carbon-vinyl ester composites. The adjusted R^2 value for the flexural strength of carbon-vinyl ester composites (99.79%) suggests an acceptable fitting of the model.

Table 5.6 ANOVA table for flexural strength of carbon-vinyl ester composites

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Load	2	17833.2	17833.2	8916.6	1503.12	0.001
Temperature	2	4788	4788	2394	403.57	0.002
Time	2	493.2	493.2	246.6	41.57	0.023
Error	2	11.9	11.9	5.9		
Total	8	23126.3				
S = 2.43558			**R-Sq = 99.95%**		**R-Sq(adj) = 99.79%**	

5.7 Tensile strength of Jute-vinyl ester Composites (IPC)

The main effect plot of tensile strength for Jute is shown in Fig. 5.7. It was observed that as the load and temperature increase the tensile strength is increased.

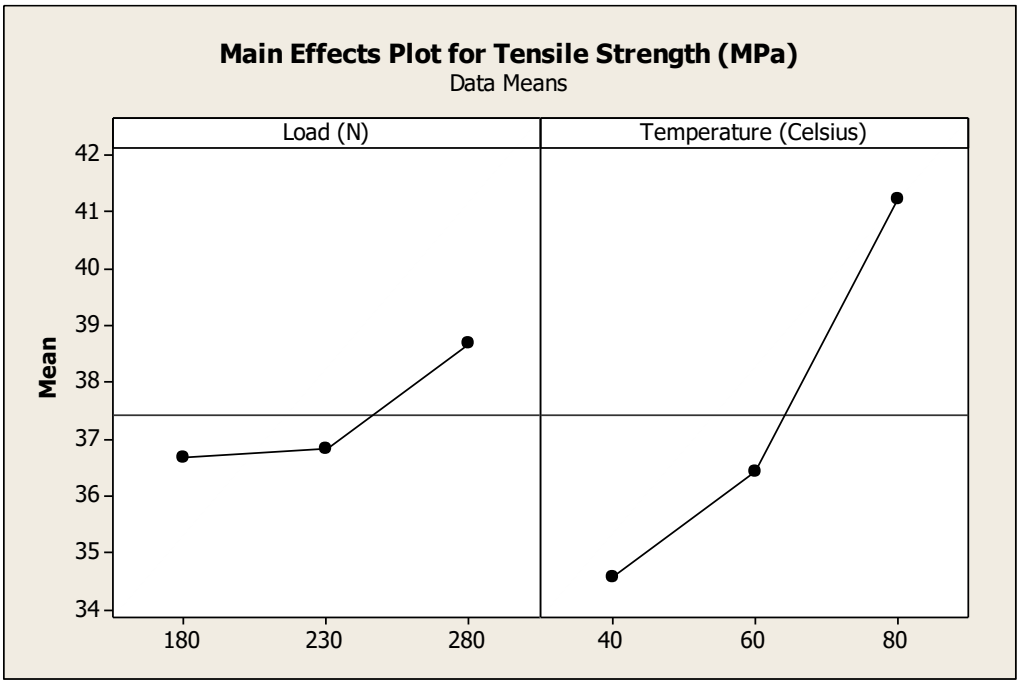

Figure 5.7 Main effects plot for Tensile strength of Jute -vinyl ester composites (IPC)

ANOVA was carried out for the tensile strength of jute-vinyl ester composites. Table 5.7 shows the ANOVA results for the tensile strength. The p-value from the ANOVA results represents that the temperature has the most significant effect on tensile strength while load has no significant effects on the tensile strength of jute-vinyl ester composites. The adjusted R^2 value for the tensile strength of jute-vinyl ester composites (78.13%) suggests an acceptable fitting of the model.

Table5.7 ANOVA table for tensile strength of jute-vinyl ester composites (IPC)

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Load (N)	2	7.542	7.542	3.771	1.56	0.315
Temperature (Celsius)	2	71.162	71.162	35.581	14.73	0.014
Error	4	9.663	9.663	2.416		
Total	8	88.367				
S = 1.55429		**R-Sq = 89.06%**			**R-Sq(adj) = 78.13%**	

5.8 Flexural strength of Jute-vinyl ester Composites (IPC)

The main effect plot of flexural strength for Jute is shown in Fig. 5.8 It was observed that as the load and temperature increase the flexural strength is increased.

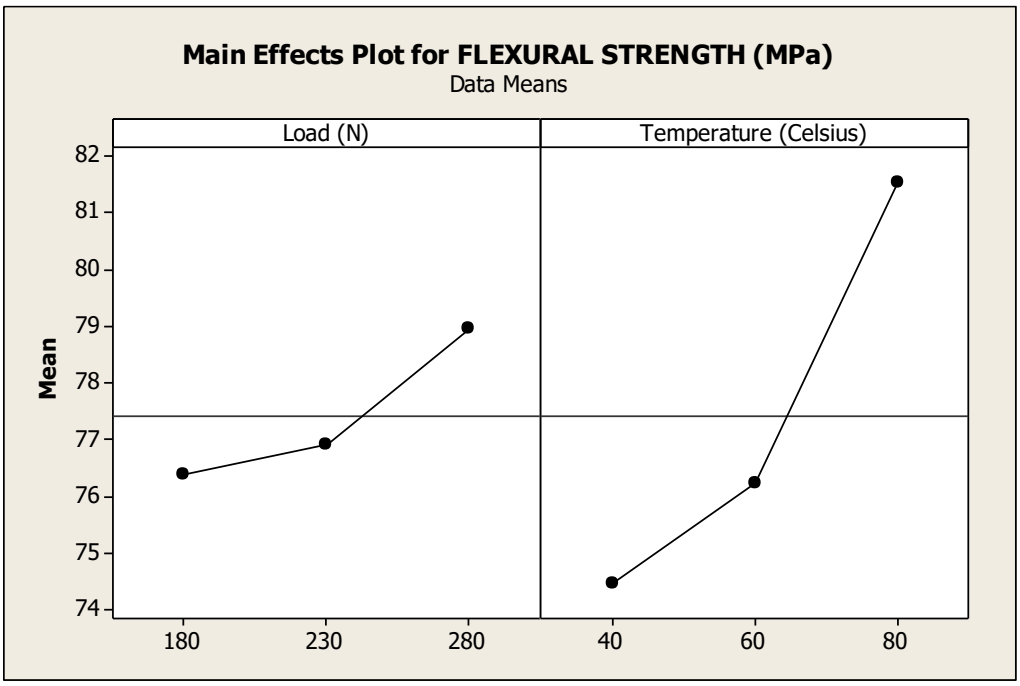

Figure 5.8 Main effects plot for Flexural strength of Jute –vinyl ester composites(IPC)

ANOVA was carried out for flexural strength of jute-vinyl ester composites. Table 5.8 shows the ANOVA results for the flexural strength. The p-value from the ANOVA results represents that the temperature has most significant effect on flexural strength while load has no significant effects on the flexural strength of jute-vinyl ester composites. The adjusted R^2 value for flexural strength of jute-vinyl ester composites (63.08%) suggests an acceptable fitting of the model.

Table 5.8 ANOVA table for flexural strength of jute-vinyl ester composites

Source	**DF**	**Seq SS**	**Adj SS**	**Adj MS**	**F**	**P**
Load (N)	2	11.216	11.216	5.608	1.08	0.423
Temperature (Celsius)	2	80.943	80.943	40.471	7.76	0.042
Error	4	20.866	20.866	5.217		
Total	8	113.025				
S = 2.28397	**R-Sq = 81.54%**			**R-Sq(adj) = 63.08%**		

5.9 Regression Analysis (POST PROCESS CURING - PPC)

The regression analysis helps to approximate the value of one variable from the given value of another. Regression modelling was done to propose empirical models for tensile strength and flexural strength. The empirical models as determined by regression analysis to predict are tensile strength and flexural strength for jute-vinyl ester, basalt-vinyl ester and carbon vinyl ester are as follow,

TENSILE STRENGTH:

$$\sigma_{t\_Jute\_PPC=} 13.1906 + 0.084944 * L + 0.0694444 * T + 0.0124074 * t$$

$$\sigma_{t\_Basalt\_PPC=} 102.114 + 0.674778 * L + 0.541667 * T + 0.00944444 * t$$

$$\sigma_{t\_Carbon\_PPC=} 68.8454 + 0.436944 * L + 1.69444 * T + 0.133333 * t$$

FLEXURAL STRENGTH:

$$\sigma_{f\_Jute\_PPC=} 7.04296 + 0.22125 * L + 0.239875 * T + 0.014338 * t$$

$$\sigma_{f\_Basalt\_PPC=} 37.7867 + 1.08183 * L + 1.04042 * T + 0.110417 * t$$

$$\sigma_{f\_Carbon\_PPC=} - 61.9996 + 1.08678 * L + 1.41111 * T + 0.149306 * t$$

Where,

L= A load applied in Newton
T= Process Temperature in Centigrade (^oC)
t = Time duration in minutes

5.10 Regression Analysis (IN-PROCESS CURING - IPC)

The empirical models as determined by regression analysis to predict are tensile strength and flexural strength for jute-vinyl ester are as follow,

$$\sigma_{t\_Jute\_IPC=} 22.7498 + 0.0202222 * L + 0.166806 * T$$

$$\sigma_{f\_Jute\_IPC=} 60.8896 + 0.0258944 * L + 0.176403 * T$$

From table no 5.11 below, it is clear the value of thermal conductivity increases on increasing the glass fiber content. The effect of bamboo fiber is to reduce thermal conductivity.

Table 5.11 Thermal conductivity of composite plates made from Bamboo fibers, Glass fibers and Bamboo-Glass hybrid fibers with vinyl ester of various composition,

Sr. No.	Specimen	Thermal Conductivity value derived based on			
		Experimental Methods		Theoretical value based on Series Model	Relative error
		Fourier Equation	Comparative Cut Bar Technique		
1	Composite B30	0.155	0.155	0.1687	8.12%
2	Composite B10G20	0.265	0.267	0.2729	2.89%
3	Composite B10G30	0.289	0.291	0.3086	6.35%
4	Composite G40	0.362	0.367	0.3673	1.44%

The following table no 5.12, shows the effect of conductive filler (Cu,Al and Sic) on the thermal conductivity of Jute-polyester composite. Blending the powder of filler in the matrix, the thermal conductivity of the composite considerably increases.

Table 5.12- Thermal conductivity of jute - polyester composite plate (with and without filler)

Sr No.	Specimen	K1 (w/mk)	K2(w/mk)	K3(w/mk)	Average(w/mk)
1	Jute-polyester without filler	0.194	0.198	0.204	0.198
2	Jute-polyester with Cu filler	0.475	0.478	0.480	0.477
% rise due to Cu		144.84	141.41	135.29	140.90
3	Jute-Polyester with Al filler	0.449	0.451	0.453	0.451
% rise due to Al		131.44	127.77	122.05	127.77
4	Jute-Polyester with SiC filler	0.391	0.393	0.397	0.393
% rise due to SiC		101.54	98.48	94.61	98.48

CONCLUSION

The current research work describes mechanical and thermal behaviour of fiber enforced polymer composite. The influence of post processed curing (PPC), considering effects of load, temperature and time were investigated for tensile, flexural properties using ANOVA and Regression Analysis. Similarly, investigations were carried out considering effects of load and temperature during in- processed curing (IPC) using same ANNOVA and Regression Analysis. The indigenous experimental set up was developed to measure thermal conductivity for various natural fibers based composites and composites with different filler materials.

The principal findings of investigations carried out based on above concepts are depicted below:

- It is identified that natural and synthetic fibers reinforced polymer composites can be employed to various mechanical and thermal related applications eg aerospace structures, marine parts, auto motive parts, sports etc.
- To obtain higher tensile strength for jute vinyl ester composite, load during the development of composite must be kept high in post processed curing (PPC) and temperature is also to be kept in the order of above 60^{o}C as very high temperature may damage fibers of jute being a family of natural fiber category. The effect of post curing time is not observed significant after duration of 120 minutes.
- In case of Basalt vinyl ester composite for post processed curing (PPC), load and temperature come out as significant parameter as load and temperature increases, tensile strength also increases.
- For carbon vinyl ester composite, the trend observed is same as Basalt vinyl ester composite as both Basalt and Carbon are of the high strength fiber category.
- The experimental results for flexural strength of Jute vinyl ester, Basalt Vinyl ester and Carbon vinyl ester reveals that in most of the cases, all the three parameters viz. load, temperature and time are observed significant but load comes out to be the most significant. Almost in all the combinations the load, temperature and time increases, flexural strength also increases.
- For the case of in-process curing (IPC) of Jute Vinyl ester composite, temperature has the most significant effect on tensile and flexural effect. The tensile strength and flexural strength significantly improves after 60^{o}C temperature for in- process curing (IPC) conditions.
- The following statistical models of flexural and tensile strength are proposed based on experimental data and through regression analysis carried out for post processed curing and in- process curing.

TENSILE STRENGTH: POST PROCESS CURING (PPC)

$$\sigma_{t\_Jute\_PPC=} 13.1906 + 0.084944 * L + 0.0694444 * T + 0.0124074 * t$$

$$\sigma_{t\_Basalt\_PPC=} 102.114 + 0.674778 * L + 0.541667 * T + 0.00944444 * t$$

$$\sigma_{t\_Carbon\_PPC=} 68.8454 + 0.436944 * L + 1.69444 * T + 0.133333 * t$$

FLEXURAL STRENGTH: POST PROCESS CURING (PPC)

$$\sigma_{f\_Jute\_PPC=} 7.04296 + 0.22125 * L + 0.239875 * T + 0.014338 * t$$

$$\sigma_{f\_Basalt\_PPC=} 37.7867 + 1.08183 * L + 1.04042 * T + 0.110417 * t$$

$$\sigma_{f\_Carbon\_PPC=} - 61.9996 + 1.08678 * L + 1.41111 * T + 0.149306 * t$$

TENSILE STRENGTH AND FLEXURAL STRENGTH : IN-PROCESS CURING (IPC)

$$\sigma_{t\_Jute\_IPC=} 22.7498 + 0.0202222 * L + 0.166806 * T$$

$$\sigma_{f\_Jute\_IPC=} 60.8896 + 0.0258944 * L + 0.176403 * T$$

- The indigenously developed experimental setup was used to determine thermal conductivity of composites made from Bamboo Fibers, Glass fibers and Bamboo- Glass hybrid fibers with Vinyl ester by measuring total heat supplied and using this value in Fourier equation and in Cut bar method to finally evaluate thermal conductivity which is there after compared it with Theoretical value based series model. In most of the cases difference between experimental and theoretical values observed below 10 % which proves the capability of experimental setup developed to determine thermal conductivity values.

- Fibers reinforced polymer composite in general are having very less value of thermal conductivity. In some of the applications minimum to moderate thermal conductivity is essential along with light weight and anticorrosive nature of material. Keeping this is in mind Jute polymer composite with conductive fillers like, Cu, Al and SiC were successfully developed. The thermal conductivity of this composite was determined through developed experimental setup. The developed Jute Vinyl ester composite were prepared by adding Cu, Al and SiC approximately 5%. The result of thermal

conductivity revels that 5% addition of Cu, Al, SiC as filler improves thermal conductivity by 140%, 127% and 98% respectively.

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