Summary

of

The Ph.D. Thesis

Entitled

Investigations on Mechanical and Thermal Behaviour of Fiber Reinforced Polymer Composites

By

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(FOTE/901 Dt.07/05/2016)

A thesis submitted to the Maharaja Sayajirao University of Baroda in fulfilment of the Requirement of Degree of

DOCTOR OF PHILOSOPHY

In

MECHANICAL ENGINEERING

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(June 2020)

1. INTRODUCTION

1.1. Composite Materials

Composite materials are engineered or naturally occurred materials prepared from two or more ingredient materials with appreciably different physical and chemical properties that remain detach and distinct within the refined structure. Most of the composites have sturdy and stiff fibers in a matrix which is weaker and less stiff. The purpose is usually to make a component that is physically strong and stiff, with low density. Industrial material commonly has glass or carbon fibers in matrices based on thermo-setting polymers, like epoxy or polyester resins. Sometimes, thermoplastic polymers are preferred, as they are mouldable after initial production. (Martin A.M., 2013)

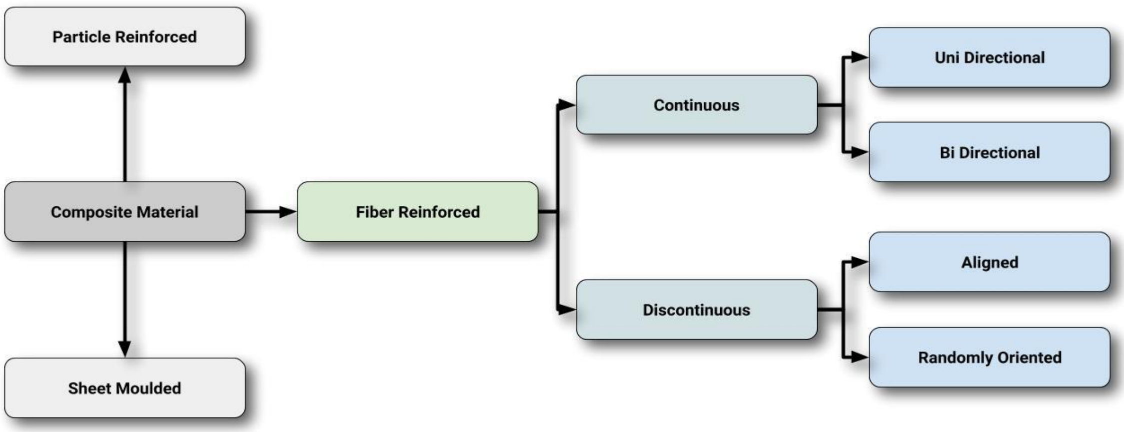


Figure 1.1 Classifications of Composites

1.2 Fiber Reinforced Polymer Composites

Fiber Reinforced Polymer-matrix (FRP) composites consist of a polymer resin as the matrix, with fibers as the reinforcement medium. These materials are used in the variety of applications, as well as in the major quantities, in light of their room-temperature properties, ease of manufacture, and cost. The performance of a fiber-reinforced composite is decided by fibers' length, shape, orientation, and composition of the fibers and the mechanical properties of the polymer matrix. In this section fibers and polymer, resins are discussed according to reinforcement type (i.e. Synthetic and Natural), along with their use and the various polymer resins that are applied.

1.3 Mechanical and Thermal Behaviour of Fiber Reinforced Composites

Composites are heterogeneous material. Therefore, the real performance of composite materials is quite dissimilar from the predictions coming from the conventional material. Because of the increasing structural performance required for inventive composites, the knowledge of the mechanical properties for different loading cases is a basic source of concern. Experimental categorization in different environmental conditions is extremely important to understand the mechanical behaviour of these new materials.

The performance of composite materials is often responsive to changes in temperature. This arises for two main reasons. Firstly, the reaction of the matrix to an applied load is temperature-dependent and, secondly, changes in temperature can affect internal stresses developed due to differential thermal contraction and expansion of the two constituents. In addition, significant stresses are usually present in the material at ambient temperatures, while it has been cooled at the end of the fabrication process. Finally, the thermal conductivity of composite materials is of concern, since many applications and processing engage heat flow of some type. This property can be broadcasted from the conductivities of the constituents, although the situation may be difficult by poor thermal contact across the interfaces.

The purpose of the present research work is to characterize a composite material developed for such applications considering the effect of load, temperature, and time during the development of composites. Test specimens were prepared from jute, basalt, and carbon fibers using vinyl ester as a matrix at different combinations of temperature, load (pressure) and time derived using the Taguchi method by applying in-process and post-process curing. Mechanical tests were conducted and the effects of temperature, load, and time on mechanical properties (tensile strength and flexural strength) were observed. Test specimens from jute using polyester as matrix were also prepared with different fillers (Cu, Al, and SiC) to observe their effects on thermal conductivity, and also mechanical strength was compared to know the effects of fillers.

2. LITERATURE REVIEW

2.1 Curing of Polymer Composites

Ray and Rathore (2014) stated that mechanical properties of Polymer Matrix Composites (PMCs) were considerably affected by heat i.e., variation in temperature. Curing was an irretrievable reaction where chemical covalent cross-links were produced which were thermally and mechanically substantial. The curing process acted a vital role to attain the end mechanical properties and chemical resistance of PMCs. For the fabrication of PMCs, resin, and curing agents (hardener) with correct ratios were used. During cross-linking, the state of the matrix changed from liquid to gel and then transformed into solid. Curing was generally be done at room temperature as well as at elevated temperatures. (Aruniit et al. 2012)

2.2 Effect of Post-Process Curing (PPC) and In-Process Curing (IPC) on Mechanical Properties 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 made by utilizing hand layup vacuum bag moulding of woven carbon and glass fiber fabric plies. At three different temperatures (i.e. 25, 62.5, and 100°C), the post-curing was done for one hour. The impact (Charpy) and tensile tests were conducted along with the statistical analysis to know the impact of post-curing and different types of hybrid plies. The results reflected that post-curing had an encouraging effect on the energy absorption capacity and mechanical properties of FRC. This was because, during post-curing, the epoxy polymer matrix made the composite stronger due to improved formation of cross-linking.

Kumar et al. (2015) emphasized the effects of post-curing parameters on thermal and mechanical properties of the Glass Fiber Reinforced Polymer (GFRP) composite. Post curing was carried out at three different temperatures (80° C, 110° C and 140° C) for changed periods (2h, 4h, 6h, 8h, and 12h). It was revealed that post-curing at 140°C for 6 hrs shows better thermal and mechanical properties compared to post-curing at different temperatures and periods. The curing cycle had a strong influence on the thermal and mechanical behaviour of thermosetting polymers. The amount of cross-linking which was a strong function of curing temperature and time was directly correlated to the glass transition temperature (Tg) of the thermosetting polymer. This transition temperature determined the transformation of the polymer from the glassy phase to the rubbery phase, hence determined the applicability of the material at a certain temperature with a certain degree of safety and reliability.

Chavan et al. (2018) conducted experiments and examined the impact of post-curing on GFRP hybrid composites. The results availed show that the samples only with natural fiber had more challenging results compared with synthetic fiber. The synthetic fibers get crumpled due to post-curing whereas no such visuals in the natural fibers.

Furtos et al. (2012) investigated that mechanical properties were enhanced by post-curing and by increasing the content of glass fiber in the composites. SEM micrographs present strong interfacial interaction amongst glass fibers and polymer matrix.

Bourchak et al. (2013) revealed that preheating epoxy resin for extended duration could decline the material ultimate tensile strength and enhance its stiffness while post-curing the epoxy resin for two hours at 80°C to some extent increased ultimate tensile strength but made the material considerably stiffer due to a large decreased in the material ultimate tensile strain.

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

Cao et al. (2007) investigated that the tensile properties of FRP composites had also been affected by curing temperature applied during the fabrication of composite materials. Usually, the specimens had been cured at room temperature. However, the increase in curing temperature improved the mechanical properties compared to curing at room temperature stated Joshi et al. (2003). Systematic research work based on in-process curing of a polymer-based composite was not observed in the literature.

2.3 Thermal Conductivity Measurement of Fiber Reinforced Polymer Composites (FRPC)

Increasing in the use of composites makes space in engineering systems and emphasizes its importance/significance in various applications through thermal property analysis. The thermal conductivity of a composite can be measured by investigational methods. Analytical equations are necessary to predict the thermal conductivities of a composite material. Knowledge of the thermal properties of composite materials would facilitate the design of an engineering system made from FRPs.

Measurement of thermal conductivity (K) of materials is generally classified into two methods: steady-state methods and non-steady state (transient methods) mainly differ from each other from an equilibrium point of view. In steady-state methods, assessment is done when the temperature of the system becomes constant with time (i.e. equilibrium or steady-state condition). Where as in transient methods assessment is done during the heating process and no need to wait for the system to reach a steady-state. Hence the method is rapid but less accurate compared to the previous.

Table 2.1 Comparison of Some of The Steady-State Methods and Unsteady-State Methods (Transient Method) for Measuring Thermal Conductivity [Czichos et al.(2006), Tong X C (2011), Yüksel (2016), Evitherm (internet)]

Sr.No.	Methods	Temperature Range	Uncertainty	Materials
		Steady-State Methods		
1	Guarded Hot Plate (GHP)	80K–800 K , 80K–1500 K	2% 2–5%	Insulation Materials, Composite Materials and Solid, Opaque, Insulators
2	Cylinder	4K–1000 K	2%	Metals
3	Heat-Flow Meter	Normally −100C–200C 90K–1300K (Axial Heat Flow) 298K–2600K (Radial Heat Flow)	3–10% 0.5–2% (Axial) 3–15% (Radial)	Insulations, Plastics, Glasses, Ceramics Metals and Solids
4	Comparative	20K–1300C	10–20%	Metals, Ceramics, Plastics

5	Direct Heating	400K–3000K	2–10% 2–5% and 10–200 W/(m K)	Tubes of Electrical Conductors ,Metals Wires, Rods,
6	Pipe Method	20K–2500C and 50C–800C	3–20% and 0.02–2 W/(m K)	Solids Calcium Silicates,
Transient Methods				
1	Hot Wire, Hot Strip	20C–2000C , 298K–1800K for hot wire	1–10 % 5–15%	Liquids, Glasses, Refractory Materials
2	Hot Disk (TPS technique)	30K–1200K	--	Liquids, Pastes, Solids and Powders
3	Laser Flash	−100K–3000C and 100K–3300K	3–5% 1.5–5 %	Solids, Liquids, Powders, Liquid Metals, Ceramics
4	Photo-Thermal(PT), Photo-Acoustic(PA)	30K–1500K for PT,200K–800K for PA	1–10 %	Solids, Liquids, Gases, Thin Films, Small Solid Parts

2.3.1 Guarded Hot Plate (GHP) Method

The guarded hot plate, also recognized as the Poensgen apparatus, Itis the most frequently used and most effective method for evaluating the thermal conductivity of insulative materials. The GHP depends on a steady temperature difference against a known thickness of a specimen and its primary function is to control the heat flow through the material. The experimental setup of the guarded hot plate (GHP) applies a steady-state heat transfer between a hot plate and a cold plate. The standardized GHP method is the ideal method for researchers and scientists in the field of thermal testing material and it is considered as a perfect measurement method.

2.4 Effect of Filler Material on Mechanical and Thermal Behaviour of Composites

Polymer matrix composites are prepared as per requirement by adding filler in a matrix material. These fillers enhance the various properties like wear-resistance and hardness, cost reduction, control of thermal expansion, density control, etc. Recently ceramic or metal particles are used as hard fillers while glass is used as the fiber filler to improve the wear resistance up to two to three times stated by Sawyer et al. (2003) In the various industrial applications such as heaters, electrodes, thermal durability at high temperatures, polymer matrix composite with metal particles as filler are used (Kim et al. 2004). Silica particles are used to form a composite to improve thermal, electrical, and mechanical properties of the fabricated composite Nielsen L.E and Landel R.F., (1994), Srivastava et al. (1988), researched the fracture toughness of the epoxy resin and concluded that by adding fly ash particles as filler, enhancement in the toughness of composites was observed. It also affected the tensile properties according to size and interfacial bonding.

2.5. Effect of Fiber Properties on Mechanical and Thermal Behaviour of Composite

The thermal conductivity of composites is anisotropic. The knowledge of the thermal conductivity of composites is needed for accurate design (see table no. 2.2)

Table No. 2.2 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 fibers at different loading rates.	Around 15% in fiber content is better than other compositions for thermal insulation.
2		Gudapati et al. (2018)	Areca Palm fibers extracted from its stalk 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 and thermal conductivity of epoxy. SBF enhanced the mechanical strength but reduced the thermal conductivity of epoxy.
4	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 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.	Thermal behaviour 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 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	Fiber surface treatments improve interfacial adhesion between fiber surface and matrix

9		Adekunle (2015)	Natural Fibers	which enhances good mechanical properties of polymer-based composites.
10	Effect of Agglomerations	Teja et al. (2016)	Fabricated sisal fiber polymer composites by hand lay-up method. Three different samples with 0%, 5%, 10% SiC powder were considered .	Addition of SiC filler powder, thermal conductivity increased, specific heat capacity gradually increased
11		G.U. Raju and S. Kumarappa (2012)	Composite boards were fabricated with the different weight percentages of groundnut shell particles (the combination of smaller particle size of 0.5 mm with a higher weight (%) of filler material 80%)and epoxy resin.	Thermal conductivity of composite specimens ranges from 0.07638 to 0.3487 W/m-K and linear thermal expansion varies from 0.725×10^{-6} to 1.296×10^{-6}/°C.

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 investigations are made on polymer composites based on natural and synthetic fibers. Fibers reinforced polymer composites can be fabricated from thermoplastic or thermoset polymers in different shapes and sizes. The polymer composites are fabricated with very good mechanical strength and stiffness, along with resistance to corrosion.

It is known that polymers are insulators, which restricts their usages in applications where thermal conductivity is necessary for heat to be efficiently dissipated or stored. According to the research and study of conductive composites which 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, there is a need for time to tailor polymer-based fiber composites to be mechanically strong and thermally conductive/non-conductive as per demand by using appropriate matrix and reinforcement materials selecting proper filler material.

FRC has attracted much attention from technologists and scientists for applications in civil, military, industrial, spacecraft, and biomedical sectors. In the past two decades, the growing interest in FRC has resulted in wide research. The driving forces are,

- Cost reduction,
- Weight reduction, and
- Marketing (application of renewable materials).

Technical requirements were of less significance; hence application remained restricted to non-structural parts for a long time. Recent research, however, shows 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 the effect of post-process curing and in-process curing as well as its effect on their thermal behaviour. Mechanical and thermal behaviour of the fiber-reinforced polymer composites are future challenges and attract the researchers to research this new area.

Studies also emphasized the effect of post-curing on the mechanical characterization of fiber-reinforced polymer (FRP) composite. The curing cycle has affected strongly on the mechanical properties of thermosetting polymers. The amount of cross-linking which is a strong function of curing temperature and time is directly correlated 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 for a user-friendly laboratory set up to measure the thermal conductivity of the composite. Research survey reflects that only a 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 influence on the mechanical and thermal behaviour of thermosetting polymers. The scale (amount) of cross-linking which is a strong function of curing temperature and time is directly associated 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 a 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 laboratory set up for measuring the thermal conductivity of the composites material using the guarded hot plate (GHP) 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

- Fig. 3.1 shows the research scheme of the work carried out.

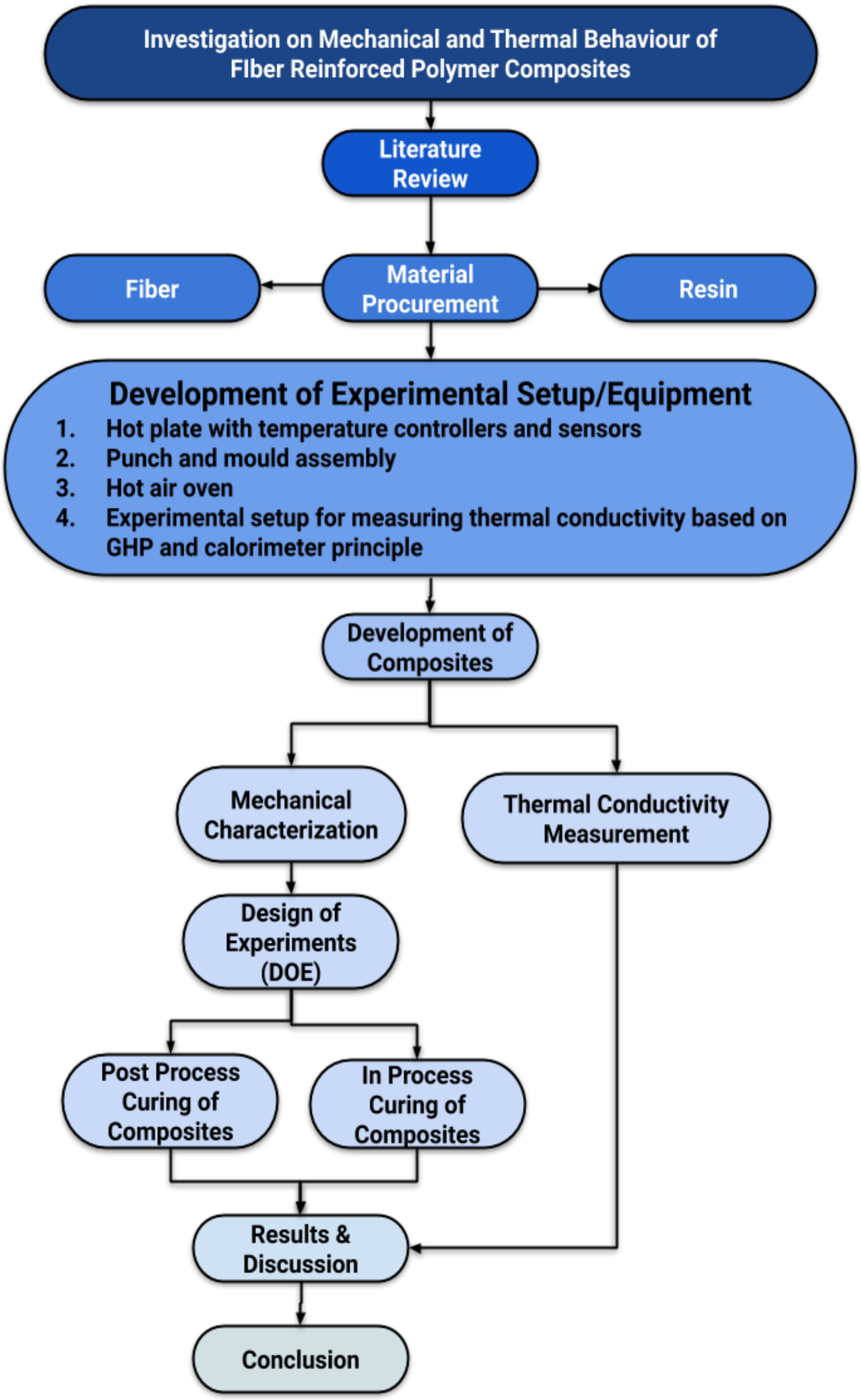


Figure 3.1 Research Scheme

4. EXPERIMENTAL SETUP AND METHODOLOGY

4.1 Post-Process Curing (PPC) of Composite Materials

Polymer matrix-based composites are post cured at an eminent temperature to boost the amount of cross-linking to attain better chemical and thermal resistance and also better mechanical properties. For suitable post-cure parameters, plates were fabricated and post cured with varying time and temperature in a developed hot air oven. The outcome of post-curing on the mechanical properties of composites has been studied. The fig.4.1 shows developed hot air oven used for post-process curing

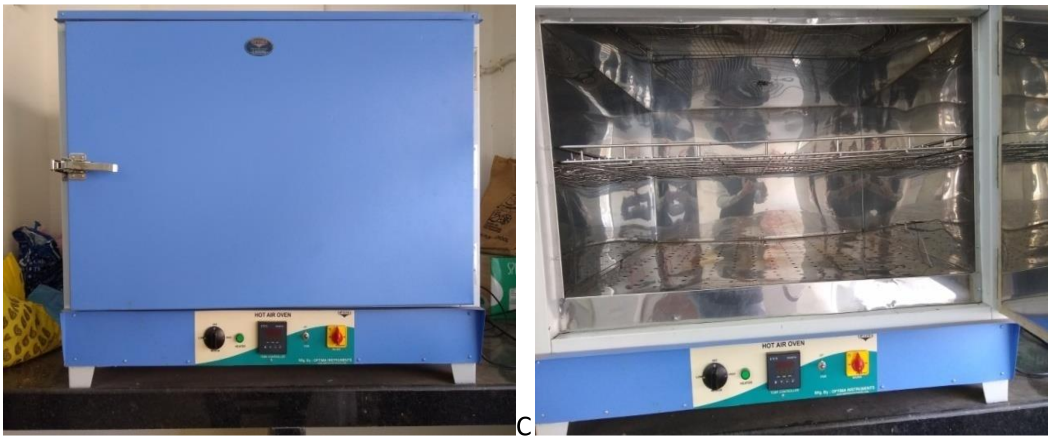


Figure 4.1 Developed Hot Air Oven for Post-Process Curing

4.2 In-Process Curing (IPC) of Composite Materials

An experimental set up of hot plate with temperature controller and sensors with punch and mould (Fig 4.2) was prepared to know the effect of load applied during the fabrication process at controlled temperature (in process curing)

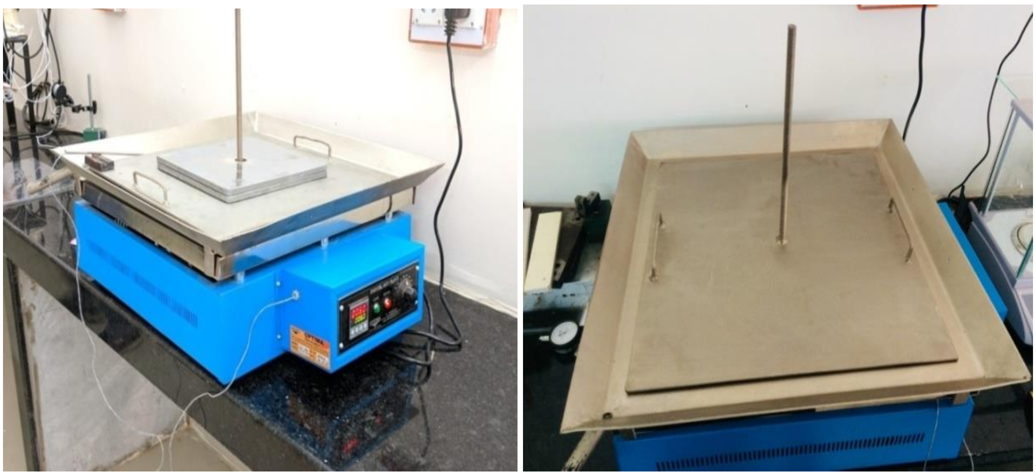


Figure 4.2 Developed Punch and Mould Assembly with Hot Plate for In-Process Curing

The hand layup method was followed in the laboratory for the development of fiber-reinforced polymer composites

4.3 Taguchi Method and Analysis of Variance (ANOVA)

In any investigational research, test procedures are normally expensive and time-intense, the need to gratify the design objectives with the smallest number of tests is an important requirement. In this perspective, the Taguchi method provides the investigator with an organized and ingenious approach for conducting tests to establish near-optimal settings of design parameters for performance and cost.

The most significant stage in the design of experiment (DOE) lies in the selection of the process parameters. Therefore, three factors pressure (load), temperature and time are included as process parameters for the tensile and flexural test which are given in Table 4.1 and Table4.2

Table 4.1 Parameter Setting for The Test

Control process parameters	Fixed parameters
Load (Pressure) (N)	Fiber
Temperature (^oC)	Resin
Time (Minutes)	Accelerator
	Hardner

Table 4.2 Levels for Various Control Factors

Control Process parameters	Levels			Units
	I	II	III	
Load (Pressure)	180	230	280	Newton (N)
Temperature	40	60	80	Centigrade ^0C
Time	60	120	180	Minutes

The tests are conducted as per the experimental design given in Table 4.3 for a different set of pressure, temperature, and time.

Table 4.3 Combination of the Three Parameters Selected for The Experimentation (L_9 Orthogonal Array)

Sr No	**Load (Pressure) (N)**	**Temperature (°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

Analysis of variance (ANOVA) is an analysis tool used in statistics that splits an observed collective variability found within a data set into two parts: systematic factors and random factors. The systematic factors have a statistical influence on the given data set, while the random factors do not

Composite plates were prepared from jute, basalt, and carbon fibers with vinyl ester as a resin. 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, specimens were prepared with a different set of load and temperature. (Refer fig. 4.7)

Figure 4.7 (a) Plate of Carbon-Vinyl Ester Post Cured

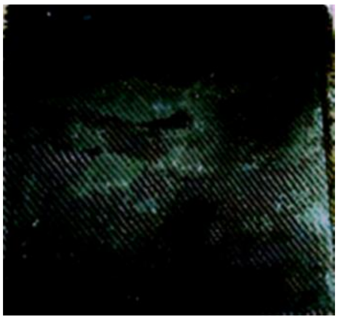


Figure 4.7 (b) Plate of Basalt-Vinyl Ester Post Cured

Figure 4.7 (c) Plate of Jute –Vinyl Ester Post Cured

Hand lay-up process is used to fabricate composite plates in the laboratory as per the details mentioned above in the tables 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

4.4 Experimental Set Up Developed for Measuring Thermal Conductivity

The hot plate and cold plate surface should remain straight during the experimentation process of the apparatus. Also, the surface of the specimen should be such that they are parallel 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 (fig.4.19 and fig 4.20).

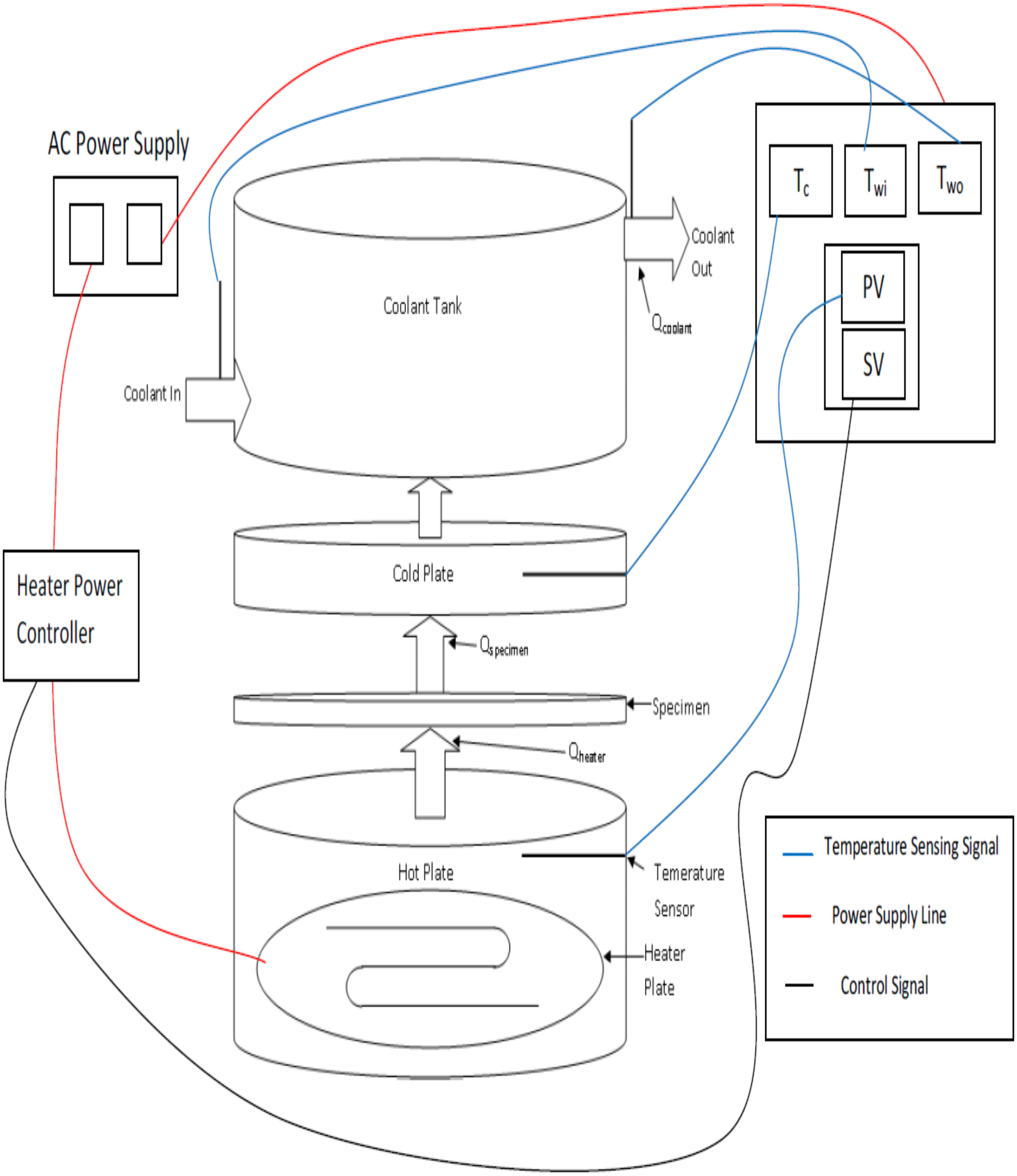


Figure 4.19: Schematic Diagram of the Developed Experimental Setup for Measuring Thermal Conductivity

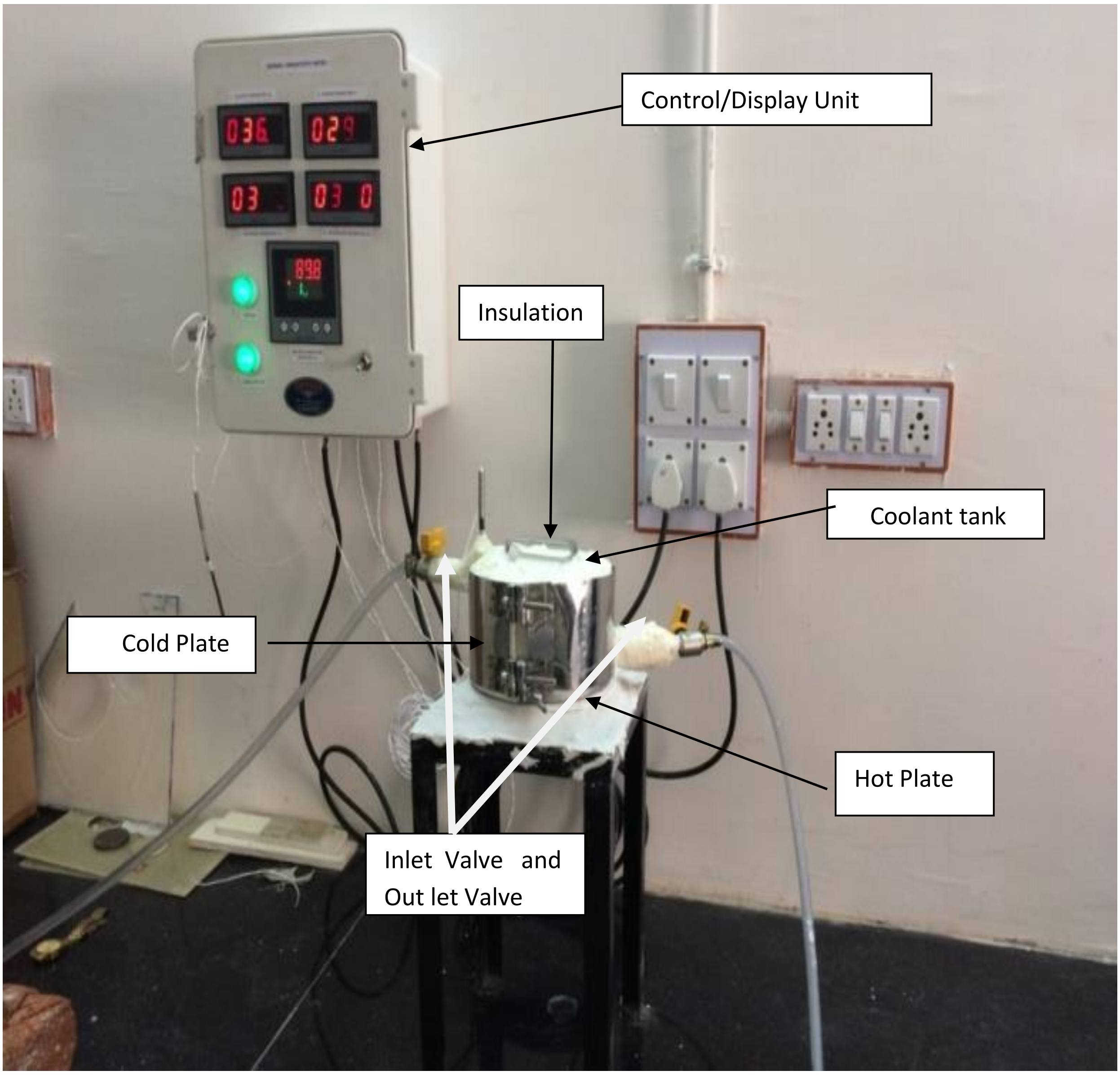


Figure 4.20 Developed Experimental Set Up for Measuring Thermal Conductivity

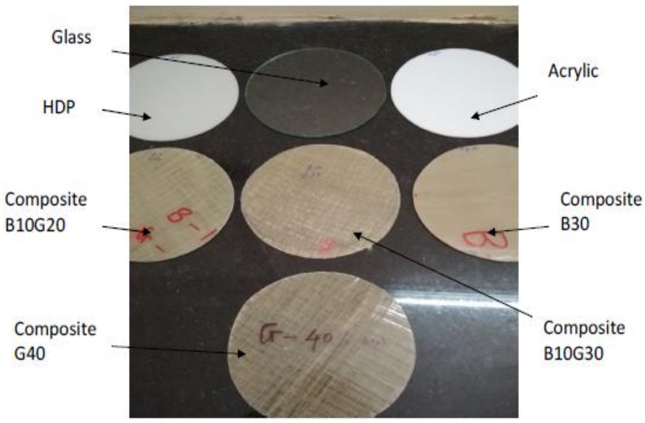


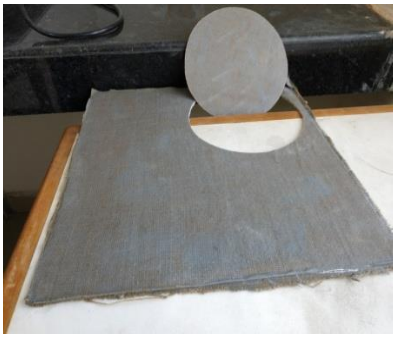
Figure 4.21 Specimens Prepared for Thermal Conductivity Measurement (as per ASTM C1530) of Different Combination of Bamboo and Glass Fibers

The specimen size of 50.8mm diameter and 0.5 to 25.4mm thick can be selected as per ASTM C1530. The composite specimens were prepared by hand layup technique (fig. 4.21 and fig 4.22)

Composite plates with filler are fabricated by hand lay-up process using jute fibers. Filler powder (20gms) is added during the fabrication process. Jute- Polyester composite plates with different fillers are shown in figure 4.22 below.

(a) With Cu Filler

(b) With SiC filler



(c) With Al Filler

Figure 4.22 Specimen for Testing Thermal Conductivity of Jute-Polyester Composite as per ASTM C1530

5. RESULTS AND DISCUSSION

5.1 Tensile Properties of the Composites Prepared with PPC

The depicted tensile strength values in table 5.1 are the average of five specimens’ values.

Table 5.1 Tensile Properties of the Composites Prepared with Post-Process Curing (PPC)

Load (N)	Temperature (^{O}C)	Time (Min)	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

5.2 Flexural Properties of the Composites Prepared with PPC

The depicted flexural strength values in table 5.2 are the average of five specimens’ values.

Table 5.2 Flexural Properties of the Composites Prepared with Post-Curing

Load (N)	Temperature (^{0}C)	Time (Min)	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

5.3 Tensile and Flexural Properties of the Composites Prepared with IPC

The depicted tensile and flexural strength values in table 5.3 are the average of five specimen values.

5.3 Tensile and Flexural Properties of the Composites Prepared with In-Process Curing.

Load (N)	Temperature (°C)	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

5.4 Tensile strength of Jute-Vinyl ester Composite (JVC-PPC)

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

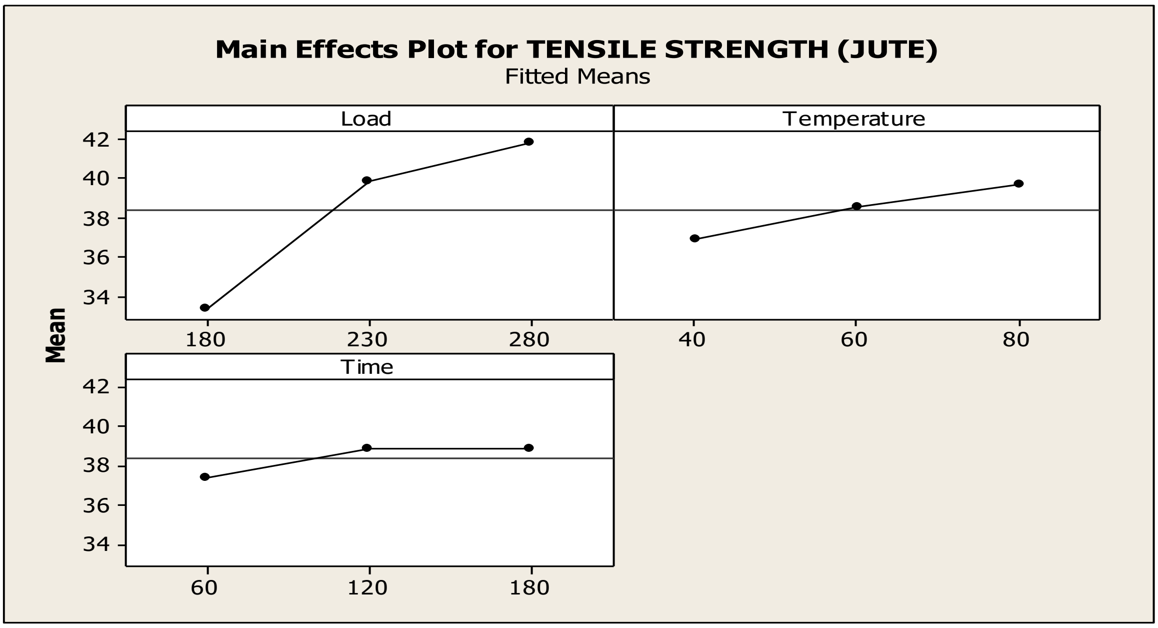


Figure 5.1 Main Effects Plot for Tensile Strength for Jute-Vinyl ester Composite (PPC)

5.5 Tensile strength of Basalt-Vinyl ester Composite (BVC-PPC)

The main effect plot of tensile strength for basalt is shown in fig. 5.2. It is observed that as the load increases the tensile strength is increased. There is 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

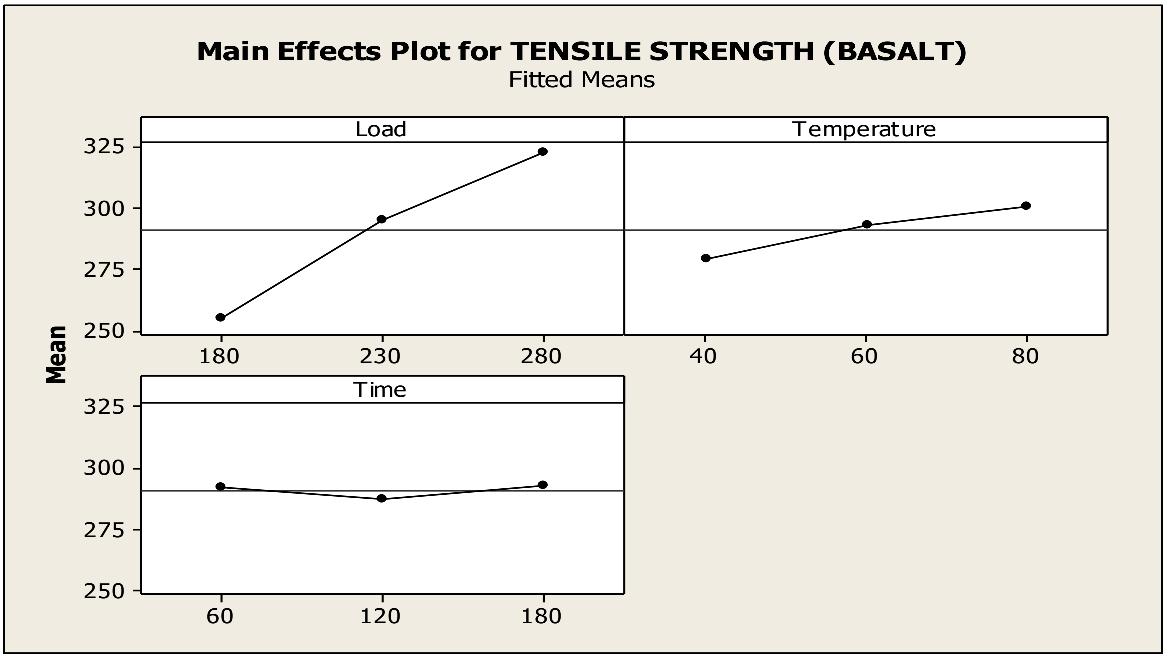


Figure 5.2 Main Effect Plot for Tensile Strength of Basalt-Vinyl ester Composites (PPC)

5.6 Tensile strength of Carbon-Vinyl ester Composite (CVC-PPC)

The main effect plot of tensile strength for carbon-vinyl ester is shown in fig. 5.3.Itis 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.

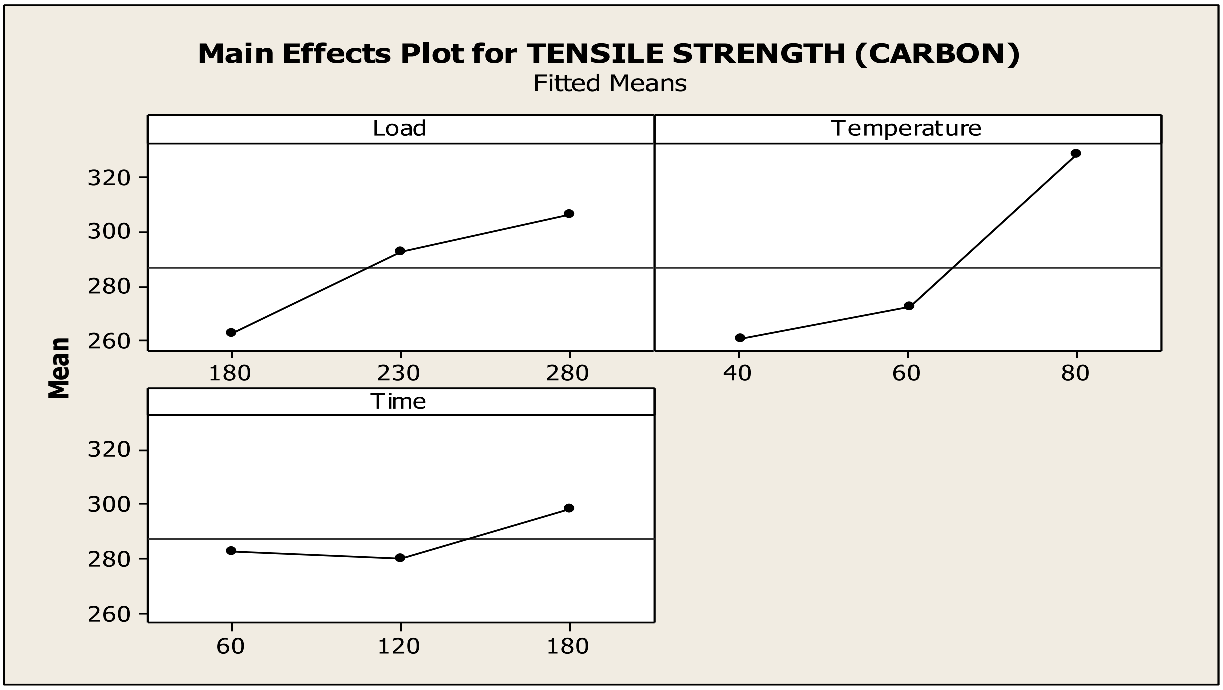


Figure 5.3 Main Effect Plot for Tensile Strength of Carbon-Vinyl ester Composites (PPC)

5.7 Flexural strength of Jute-Vinyl ester Composites (JVC-PPC)

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

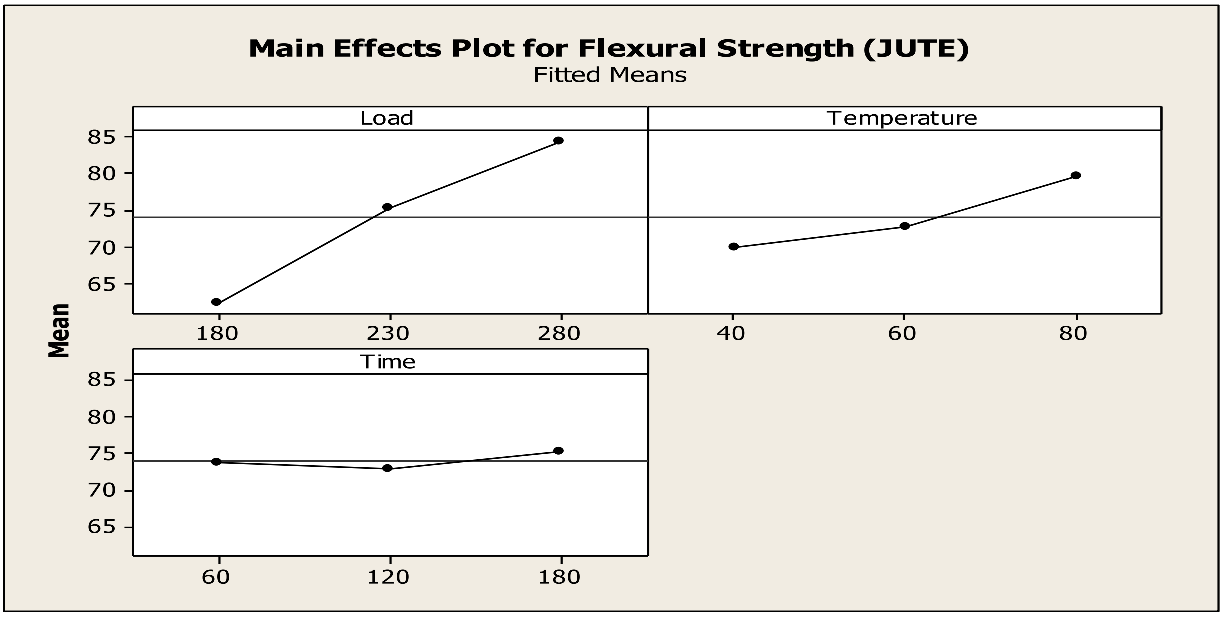


Figure 5.4 Main Effects Plot for Flexural Strength of Jute-Vinyl ester Composites (PPC).

5.8 Flexural strength of Basalt-Vinyl ester Composites (BVC-PPC)

The main effect plot of flexural strength for basalt is shown in fig. 5.5 It is 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.

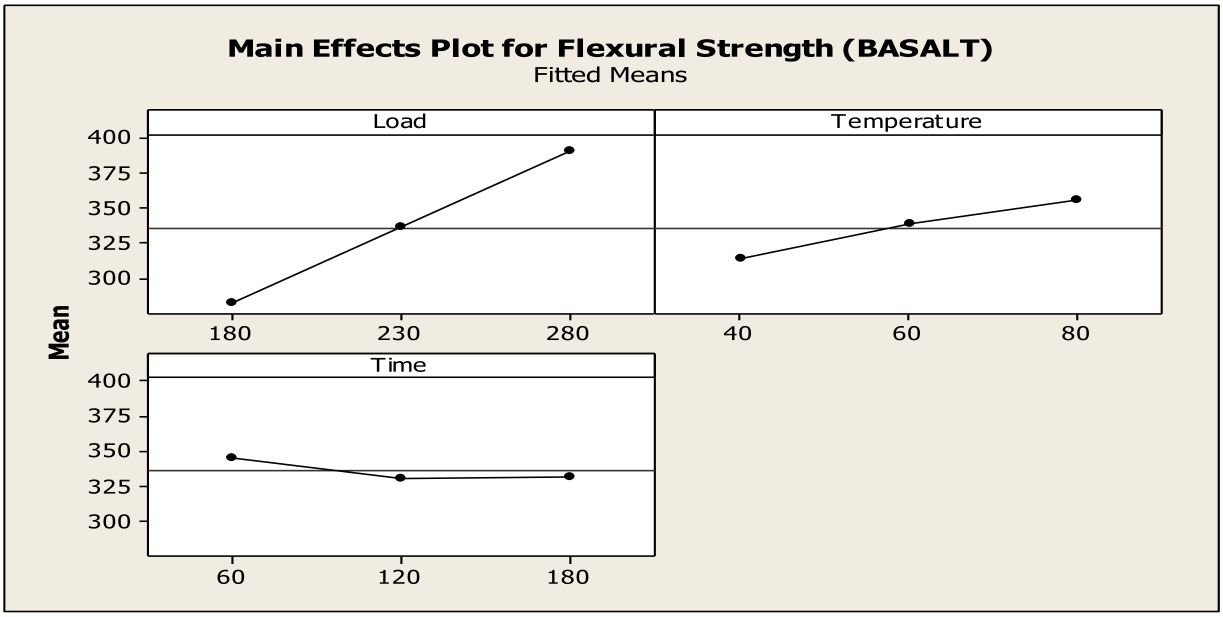


Figure 5.5 Main Effects Plot for Flexural Strength of Basalt-Vinyl ester Composites (PPC)

5.9 Flexural strength of Carbon-Vinyl ester Composites (CVC-PPC)

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

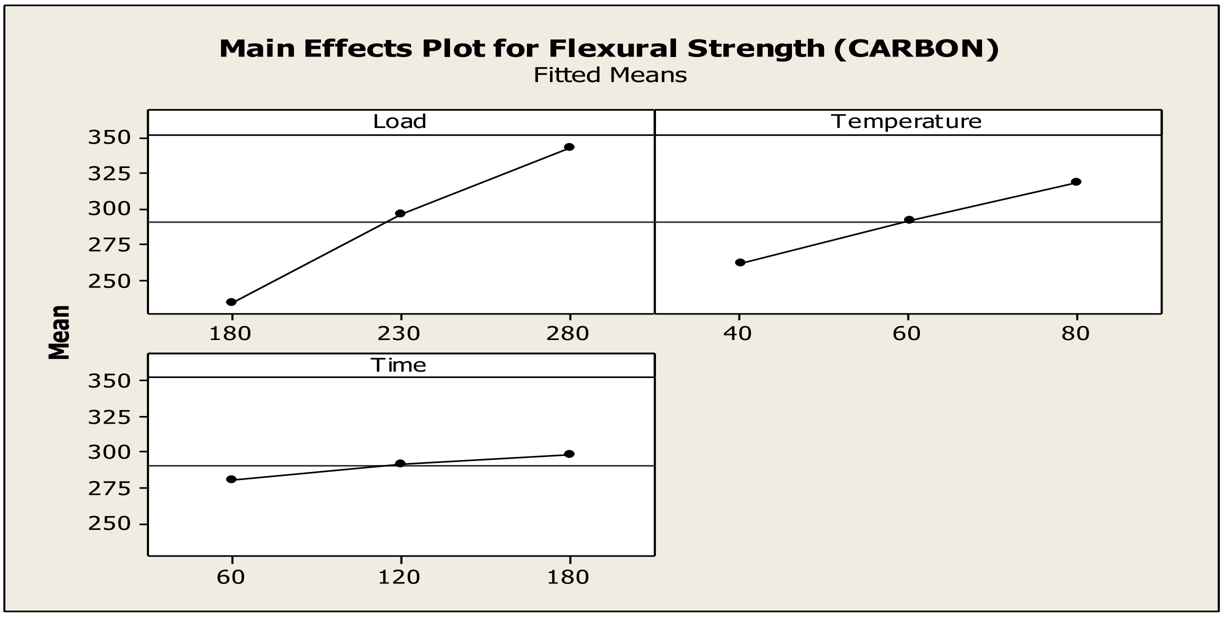


Figure 5.6 Main Effects Plot for Flexural Strength of Carbon-Vinyl ester Composites(PPC)

5.10 Tensile strength of Jute-Vinyl ester Composites (JVC-IPC)

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

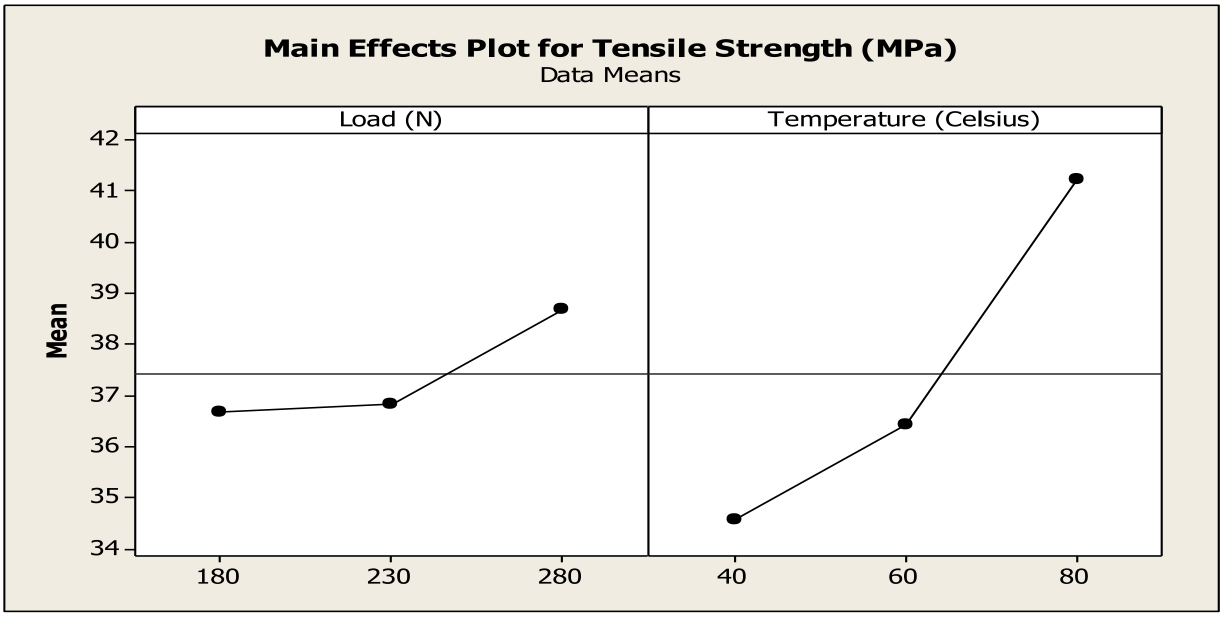


Figure 5.7 Main Effects Plot for Tensile Strength of Jute -Vinyl ester Composites (IPC)

5.11 Flexural strength of Jute-Vinyl ester Composites (JVC-IPC)

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

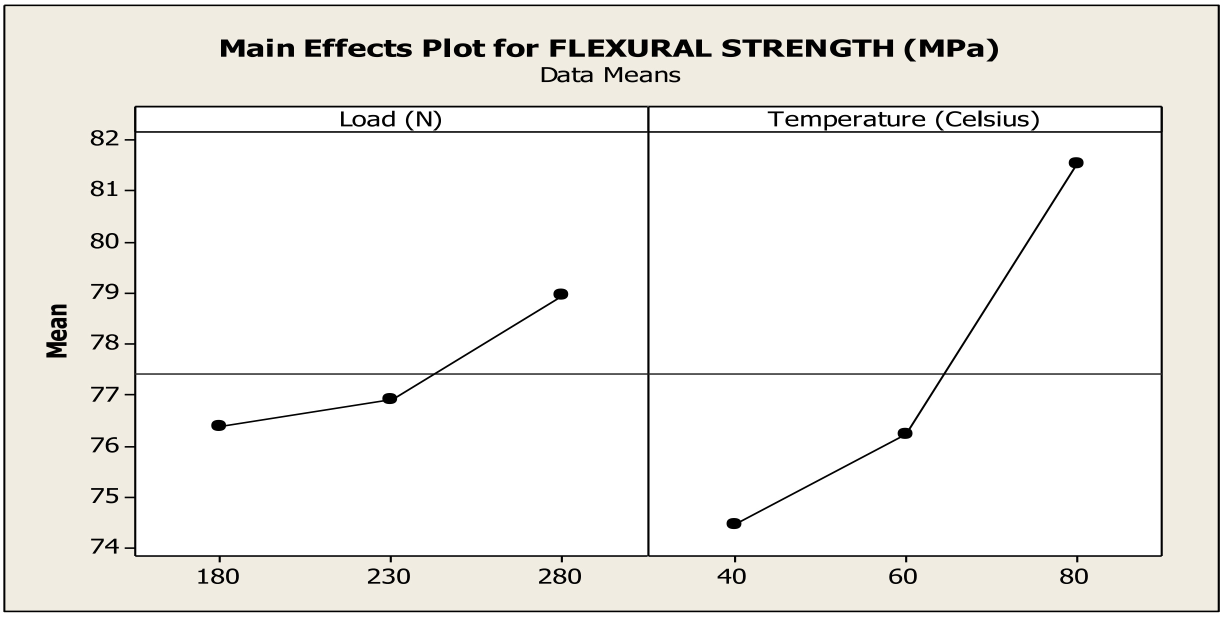


Figure 5.8 Main Effects Plot for Flexural Strength of Jute –Vinyl ester Composites(IPC)

5.12 Regression Analysis (PPC)

The regression analysis helps to approximate the value of one variable from the given value of another. Regression modeling 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 JVC, BVC and CVC are as follow,

TENSILE STRENGTH:

$\sigma_{t\_Jute\_PPC=}13.1906 + 0.084944 * L + 0.0694444 * T + 0.0124074 * t$ (Eqn no 5.1)

$\sigma_{t\_Basalt\_PPC=}102.114 + 0.674778 * L + 0.541667 * T + 0.00944444 * t$ (Eqn no 5.2)

$\sigma_{t\_Carbon\_PPC=}68.8454 + 0.436944 * L + 1.69444 * T + 0.133333 * t$ (Eqn no 5.3)

FLEXURAL STRENGTH:

$\sigma_{f\_Jute\_PPC=} 7.04296 + 0.22125 * L + 0.239875 * T + 0.014338 * t$ (Eqn no 5.4)

$\sigma_{f\_Basalt\_PPC=} 37.7867 + 1.08183 * L + 1.04042 * T + 0.110417 * t$ (Eqn no 5.5)

$\sigma_{f\_Carbon\_PPC=} - 61.9996 + 1.08678 * L + 1.41111 * T + 0.149306 * t$ (Eqn no 5.6)

Where,

L= Load applied in Newton

T= Process Temperature in Centigrade (^{o}C)

t = Time duration in minutes

5.13 Regression Analysis (IPC)

The empirical models as determined by regression analysis to predict are tensile strength and flexural strength for JVC are as follow,

$\sigma_{t\_Jute\_IPC=} 22.7498 + 0.0202222 * L + 0.166806 * T$ (Eqn no 5.7)

$\sigma_{f\_Jute\_IPC=} 60.8896 + 0.0258944 * L + 0.176403 * T$ (Eqn no 5.8)

5.14 Effect of Volume Fraction Of Bamboo (Natural) and Glass Fibers (Synthetic) On Thermal Conductivity

Experiments were conducted to find thermal conductivity of bamboo fibers and glass fibers separately and hybrid composite plates made from both fibers on developed experimental set up for measuring thermal conductivity. The observed values are shown in table 5.12 below,

Table 5.4 Thermal Conductivity of Composite Plates Made from Bamboo Fibers, Glass Fibers and Bamboo-Glass Hybrid Fibers with Vinyl ester of Various Composition

Specimen	Thickness (mm)	Time	T_{hp} (ºC)	T_{cp} (ºC)	T_{wo} (ºC)	T_{wi} (ºC)	Flow Rate	k (W/m.K)	Average
B10G30	3	2.18	50	38	37.5	36.8	9.16	0.291	0.293
		2.25	50	38.1	37.5	36.8	9.16	0.294	
		2.35	50	38.1	37.5	36.8	9.16	0.294	
B10G20	3	2.55	50	35.2	34.6	33.1	4.5	0.248	0.259
		3.00	50	35.2	34.7	33.1	4.5	0.265	
		3.15	50	35.2	34.7	33.1	4.5	0.265	
B30	3	10.01	50	34.3	33.7	32.7	3.937	0.136	0.145
		10.11	50	34.3	33.8	32.7	3.937	0.150	
		10.15	50	34.3	33.8	32.7	3.937	0.150	
G40	2.5	9.55	50	36.2	35.6	34.2	7.5	0.345	0.346
		10.00	50	36.2	35.6	34.2	7.5	0.345	
		10.02	50	36.3	35.6	34.2	7.5	0.348	

In the above composites, resin material used is vinyl ester. B and G stand for bamboo fiber and glass fiber used as reinforcement. The number next to them indicates the proportion of reinforcement material by weight. e.g. B30 indicates 30% of bamboo fiber by weight and remaining is a matrix. The specimens are prepared by hand layup technique

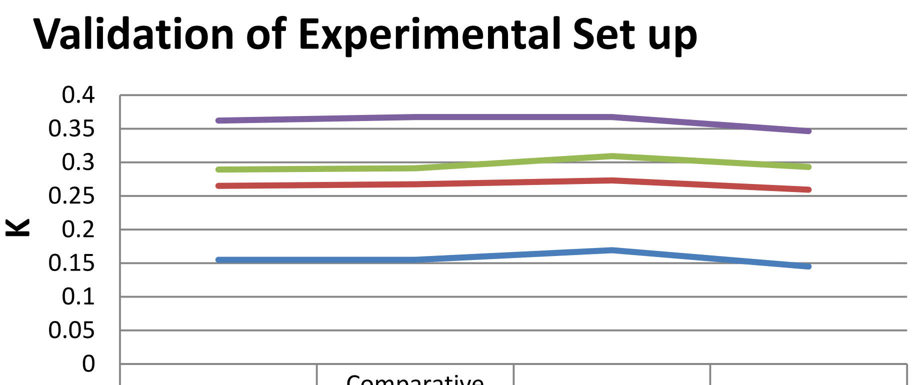
5.15 Validation of Experimental Results

The experimental results obtained from the developed experimental set up developed for measuring the thermal conductivity of the composite material are also compared with other analytical methods existing in the literature for the validity of the results which are as follows,

Table 5.5 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 value of thermal conductivity increases on increasing the glass fiber content. The effect of bamboo fiber is to reduce thermal conductivity (fig5.9). The experimental results obtained from the developed experimental set up for measuring the thermal conductivity of the composite material are compared with other analytical methods existing in the literature for the validity of the results (fig 5.10)



	Fourier Equation	Comparative Cut Bar Technique	Theoratical Series Model	Experimental Value
Composite B30	0.155	0.155	0.169	0.145
Composite B10G20	0.265	0.267	0.273	0.259
Composite B10G30	0.289	0.291	0.309	0.293
Composite G40	0.362	0.367	0.367	0.346

Figure 5.9 Plot of the Effect of Volume Fraction of Fibers on Thermal Conductivity Measured by Different Methods

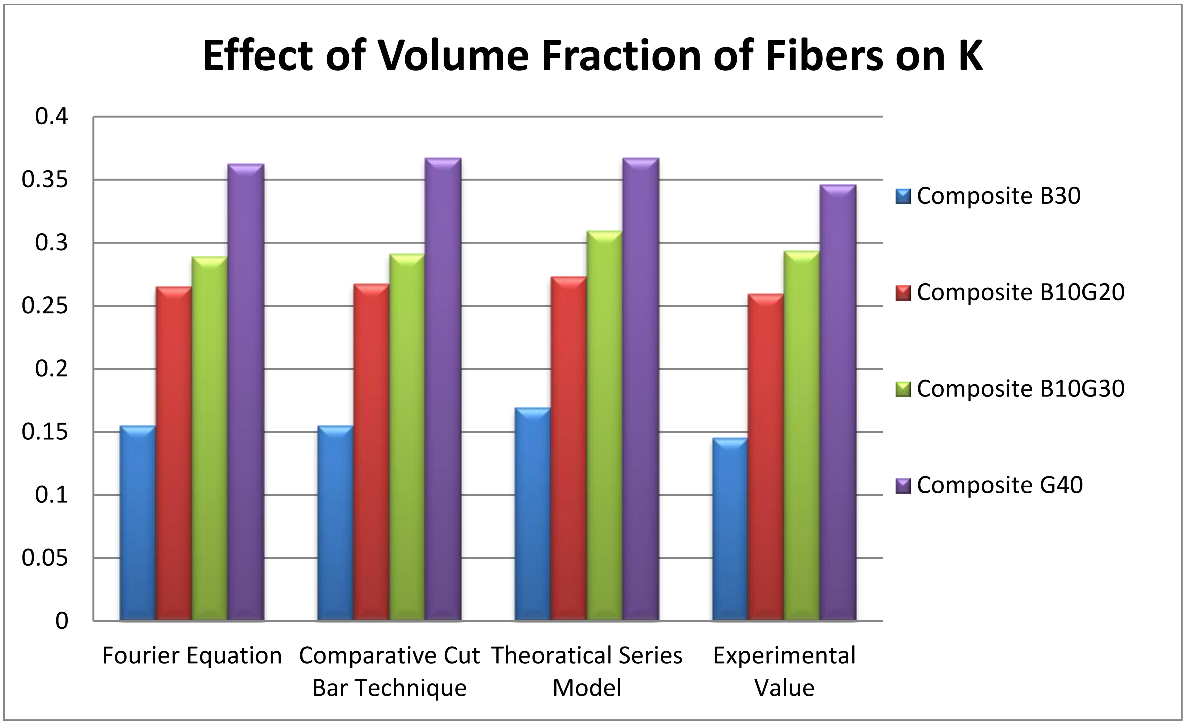


Figure 5.10 Plot of Validation of Experimental Results Compared with Other Methods

5.16 Effect of Filler on Mechanical Strength and Thermal Conductivity of Jute-Polyester Composite (JPC)

The following table no 5.16, shows the effect of conductive filler (Cu, Al, and Sic) on the mechanical strength of Jute-polyester composite and table no. 5.17 shows the effect of conductive filler (Cu, Al and Sic) on Thermal Conductivity (K) of Jute-polyester composite. Mechanical strength and thermal conductivity of the composite increase by adding filler in the resin during the fabrication process.

Table 5.6 Mechanical Strength of Jute - Polyester Composite Plate (with and without Filler)

Mechanical Strength of JUTE -POLYSTER Composites (JPC)								
	Tensile Strength (MPa)				Flexural Strength (MPa)			
Sr.No.	Without filler	SiC Filler	Cu Filler	Al Filler	Without filler	SiC Filler	Cu Filler	Al Filler
1	31.6	39.6	43	38.2	42.1	46.4	51.7	56
2	34.1	34.3	35.7	35.2	45.3	53.3	51.7	47.3
3	33.8	36.2	36.9	35.5	47.6	48.4	45.5	50.5

4	35.2	38.2	40.3	34.9	41.2	47.3	49.1	52.8
5	32.2	28.1	35	34.7	44.4	50	52.5	58.2
Average	33.38	35.28	38.18	35.7	44.12	49.08	50.1	52.96
% increase		5.69	14.3	6.95		11.24	13.55	20.03

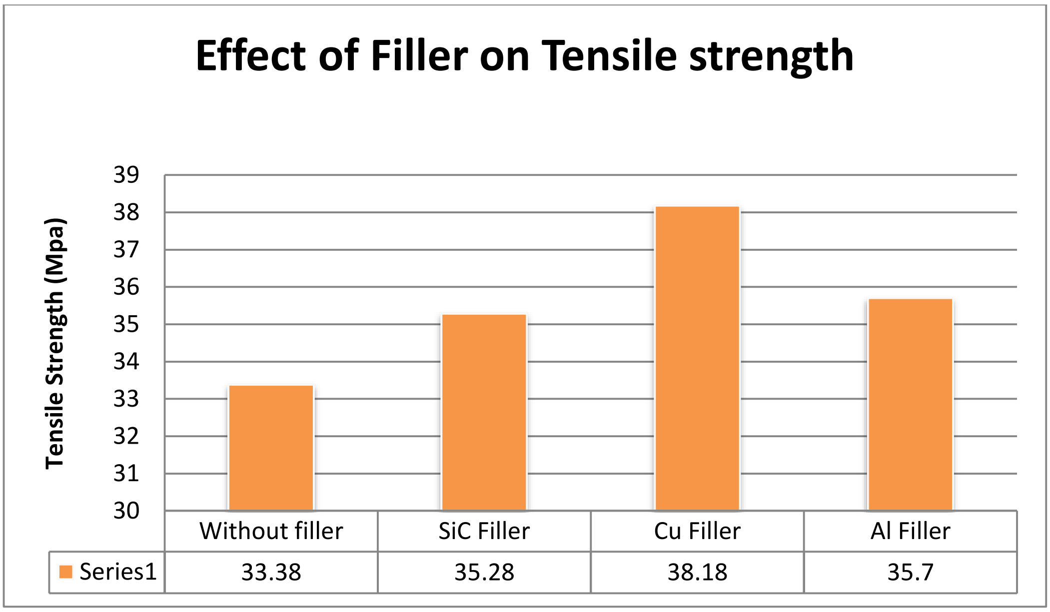


Figure 5.11 Effect of Filler on Tensile Strength

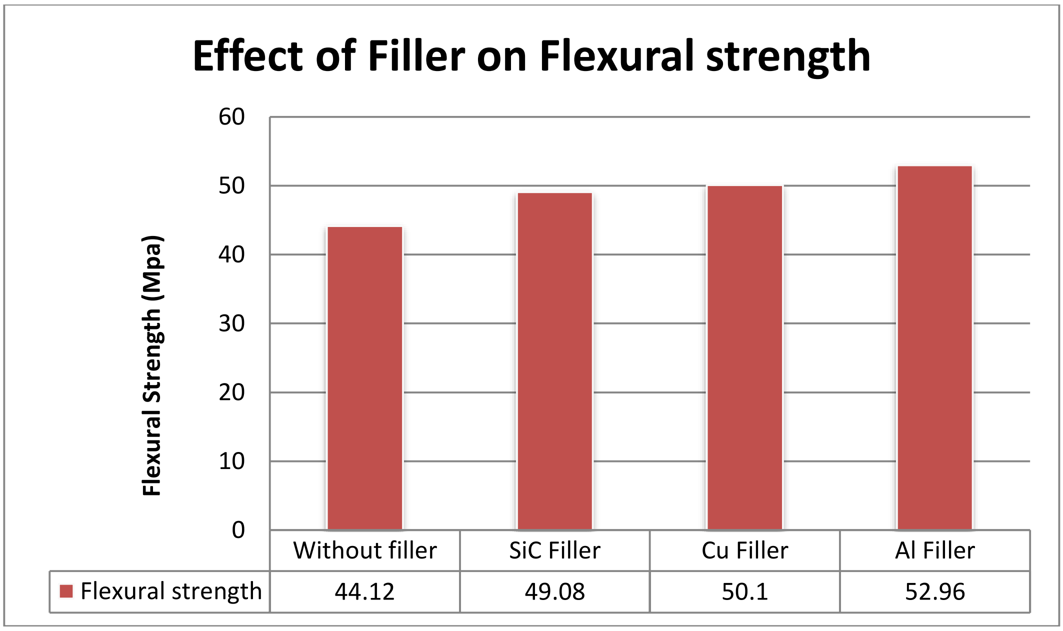


Figure 5.12 Effect of Filler on Flexural Strength

Table 5.7 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

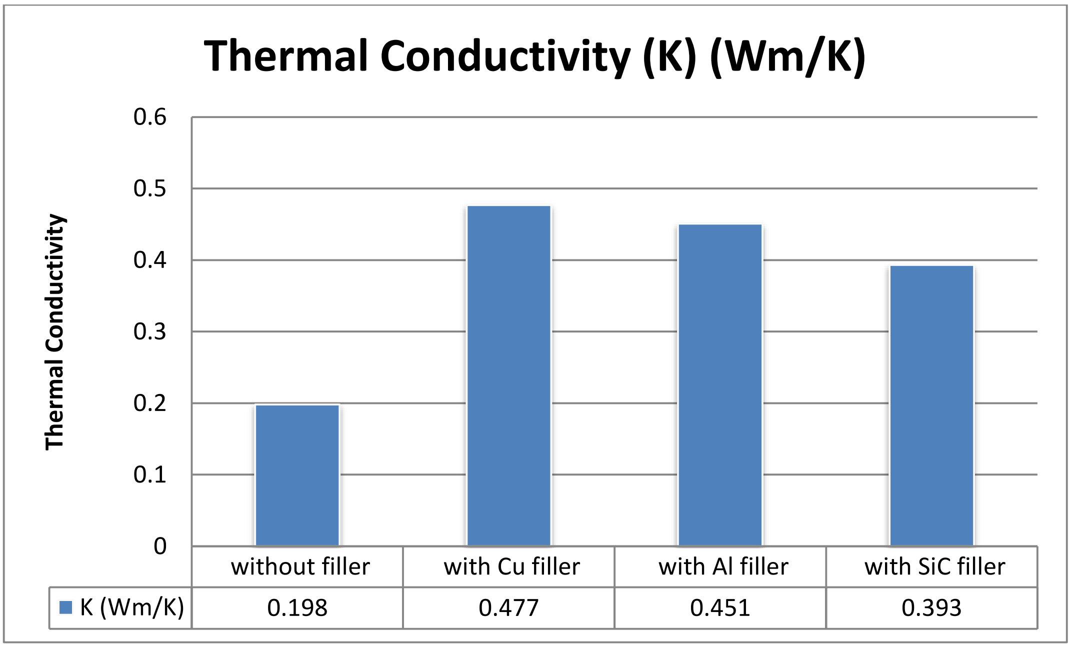


Figure 5.13 Effect of Filler on Thermal Conductivity

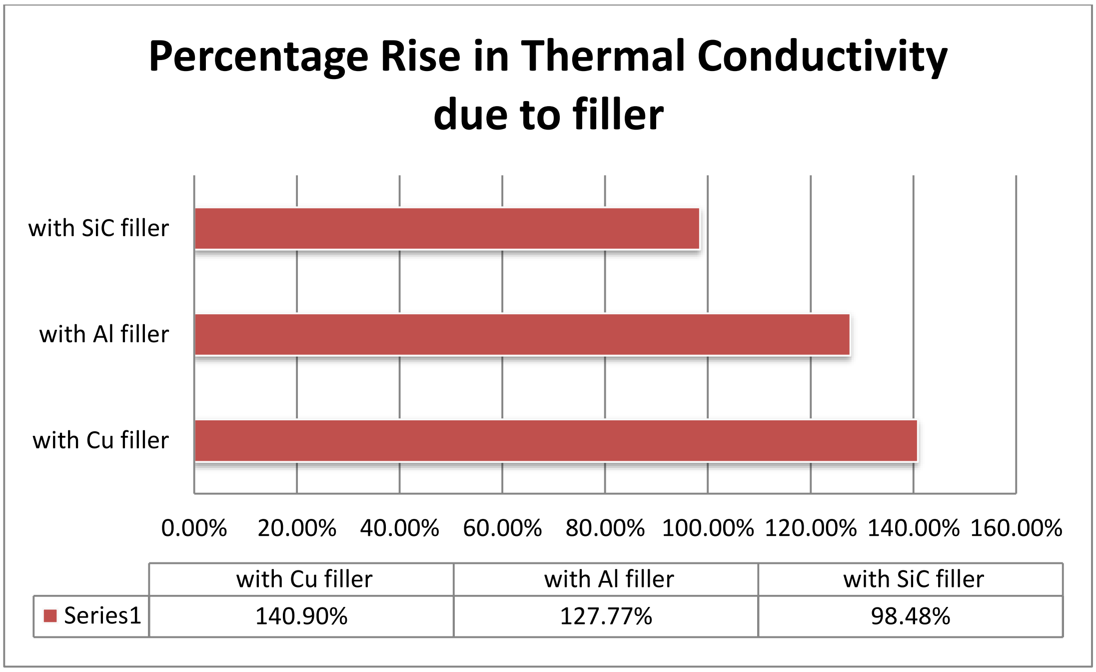


Figure 5.14 Percentage Rise in Thermal Conductivity due to Filler

The effect of the fillers on the JPC is to increase tensile strength and flexural strength (fig 5.11 and 5.12) as well as fillers affect positively on heat transfer i.e. rise in thermal conductivity. Amongst Cu, Al, and Sic fillers, the effects of Cu filler is more competent (fig 5.13 and 5.14)

6. CONCLUSION AND FUTURE SCOPE

6.1 Conclusion

The current research work describes the mechanical and thermal behaviour of fiber-reinforced polymer composite. The influence of post-processed curing (PPC), considering the effects of load, temperature, and time were investigated for tensile and flexural properties using ANOVA and Regression Analysis. Similarly, investigations were carried out considering the effects of load and temperature during in- processed curing (IPC) using the same ANOVA 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 the 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, automotive 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 the 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 120 minutes.
- In the 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 the 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 increase, flexural strength also increases.

- For the case of in-process curing (IPC) of Jute Vinyl ester composite, the temperature has the most significant effect on tensile and flexural effects. 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 the 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 Cut bar method to finally evaluate thermal conductivity which is thereafter compared it with Theoretical value-based series model. In most of the cases, the difference between experimental and theoretical values observed below 10 % which proves the capability of experimental setup developed to determine thermal conductivity values.

- The thermal properties of polymer-based composites are critical parameters for material design in heat transfer applications. The properties of natural fibers depend on their inherent physical and chemical structure. There is a hollow cavity in natural fibers, which is called 'lumen' because of that heat conductivity of natural fibers is lesser than that of solid mineral fibers. From the experimental data of thermal conductivity measured, it was observed that on increasing the glass fiber content, the value of thermal conductivity increases. The significance of bamboo fiber is to reduce thermal conductivity.

- Fibers reinforced polymer composite, in general, are having very little value of thermal conductivity. In some of the applications minimum to moderate thermal conductivity is essential along with lightweight and anticorrosive nature of the 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 a developed experimental setup. Jute Vinyl ester composite was prepared by adding Cu, Al, and SiC approximately 5%. The result of thermal conductivity reveals that 5% addition of Cu, Al, SiC as filler improves thermal conductivity by 140%, 127%, and 98% respectively.

6.2 Future Scope

- Determination of Mechanical Properties at an elevated temperature
- Determination of the thermal conductivity with varying filler contents
- Statistical modelling of the thermal conductivity using DOE technique

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LIST OF PUBLICATION

Research Grant.

Research and Consultancy Cell of The Maharaja Sayajirao University of Baroda, (vide letter no. RCC/Dir/2017/335/29 dated 10-02-2017) to carry out my research entitled **Study and Development of Natural Fiber Based Reinforced Composites**

Patent

Patent filed having title of invention" Determination **of Thermal Conductivity through Heat Flow Measurement using Hybrid Instrument based on GHP and Calorimeter Principle** "on 20th June 2020 Ref File no. **202021026243**

Paper Publications

1. Paper titled "**An Apparatus for Measuring Thermal Conductivity Developed Using Calorimeter Principle: Relation Between Flow Rate and Time to Reach Steady State" PUBLISHED in** i-manager's Journal on Future Engineering & Technology, Vol. 14 · No. 2 · November 2018 - January 2019.pp 18-28

2. "**Bio Composites Material: Review and its applications in various fields" in Nature based and inspired composite materials**" ACCEPTED and ONLINE to the section of the book of "Encyclopaedia of Materials: Composites' with Elsevier.

3. **"Mechanical Properties Review: Part 1- Range of Natural Fibers" SUBMITTED** in the journal of Journal Of Natural Fibers (Taylor & Francis) Ref WJNF-2020-0660 Print ISSN: 1544-0478 Online ISSN: 1544-046X

4. Research Story titled "**घास-फूस से बनी कोम्पोसीट शीट ट्रान्स्पोर्टेसन क्षेत्र एवं हीट इन्स्युलेशन व हीट ट्रान्सफर के लिए उपयोगी होगी – सस्टेनेबल ग्रीन टेक्नोलोजी की तरफ एक महत्वपुर्ण कदम**" **SUBMITTED** to the AWSAR, Department of Science and Technology (DST), India. (AW/2020/3234)

Future Publication

Few more research papers which are planned from the experimental analysis, results and discussion as following

1. Post-process curing of Jute-Vinyl-ester composites
2. Post-process curing of Basalt-Vinyl-ester composites
3. Post-process curing of Carbon-Vinyl-ester composites
4. In- process curing of Jute-Vinyl-ester composites.
5. Comparison of IPC and PPC
6. Effects of fillers on Mechanical and Thermal Characterisation of Jute –Polyester composites