Investigating and Optimizing the Process Variables Related to the Tensile Properties of Short Jute Fiber Reinforced with Polypropylene Composite Board

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ABSTRACT

The effect of temperature, pressure, and time on the tensile strength of jute fiber composite has been studied. The process of preparing the composite specimens is discussed. The best tensile properties were observed if the composite board is manufactured using high pressure and moderate temperature. For tensile strength, the time does not play a significant role. The study identifies the principal experimental pressure variables, which have the greatest effect on the tensile strength of the composite. The composite boards were subjected to tensile tests and the fractured surfaces were observed under SEM. The SEM photomicrographs of the fractured surfaces of the composite board show diverse extents of fiber pull-outs under tensile failure. The tensile strength values are in good concurrence with predicted values and were found have a correlation coefficient of 96%.

INTRODUCTION

The increased interest in using natural fibers, particularly lignocellulosics, as reinforcements in composite manufacturing as a substitute conventional synthetic fibers in some structural applications has become a subject of study [1–5]. Applications of lignocellulosic fiber composites add to the diversity of modern technological uses for these fibers, such as automobile components [6] and result in economic advantages for the producers of such fibers. In recent years, a variety of lignocellulosic fibers including jute, sisal, coir, flax, hemp and even wood have been used as substitute reinforcements for synthetic fibers in polymer matrices with relevant contribution to the world economy [7]. In addition, the integration of these natural fibers significantly improves some mechanical properties of polymeric composites [8–12].

In the light of this, researchers have focused their attention on natural fiber composites or bio-composites composed of natural or synthetic resins reinforced with natural fibers.

Natural fibers have already achieved a record of success as reinforcing material in automotive parts. Natural fibers like jute, flax, hemp coir, and sisal have all proven to be good reinforcement media for thermoset and thermoplastic matrices and are being used in automotive applications, construction, and packaging industries with few drawbacks [13-17].

A composite containing at least one constituent such as a matrix or reinforcement that is derived from readily renewable resources may be considered a bio-composite [18].

The most prominent natural fibers used in structural composites are plant fibers, primarily because of their high stiffness, strength, and availability.

Jute is a suitable natural fiber for use as reinforcement in composite because of its low cost, renewable nature, and much lower energy requirement for processing. Jute is a strong, coarse and rigid fiber with very low extensibility which makes it suitable to act as reinforcing material in a composite. Jute is relatively inexpensive and process friendly [19].

Accordingly, manufacturing of high-performance engineering materials from renewable resources has been pursued by researchers across the world owning to the facts that they are renewable raw materials, are environmentally sound, and do not cause health problem. The prominent advantages of natural fibers include acceptable specific strength properties, low cost, low density, high toughness, and good thermal properties.

Thermoplastic resins that can be processed below 200^0C, should be selected for processing of composites. The most commonly used thermoplastic resins are PE, PP and PVC. PP is one of the cheapest and has excellent toughness and impact strength, but the lowest in service temperature [20]. The mechanical properties of lignocellulosic/PP composites depend not only on the strength of adhesion, but also on the conditions of processing [21].

EXPERIMENTAL DESIGN

Response surface methodology is an experimental modelling technique dedicated to the evaluation of the connection of a set of controlled experimental factors and observed results. Prior knowledge of the process is required in order to achieve a satisfactory statistical model. A detailed account of this technique has been outlined [22-27].

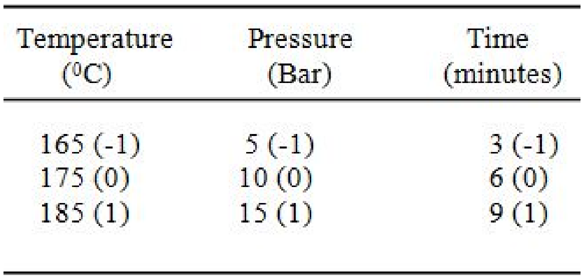
Basically this optimization process involves three major steps: performing the statistically designed experiments, estimating the coefficients in a mathematical model, and predicting the response and checking the competence of the model. The significant variables of temperature, pressure, and time were chosen as the critical variables and designated as X_1, X_2 and X_3 respectively. The low, middle, and high levels of each variable were designated as -1, 0, and +1 respectively, and are given in *Table I*. The actual design of experiments is given in *Table II*. Computation was carried out via multiple regression analysis using the least squares method.

In a system involving three significant independent variables X_1, X_2, X_3 the mathematical relationship of the reaction on these variables can be approximated by the quadratic (second degree) polynomial equation shown in Eq. (1):

$$Y = C_0 + C_1X_1 + C_2X_2 + C_3X_3 + C_{12}X_1X_2 + C_{13}X_1X_3 + C_{23}X_2X_3 + C_{11}X_1^2 + C_{22}X_2^2 + C_{33}X_3^2 \quad (1)$$

Where
Y = predicted yield,
C_0 = Constant,
C_1, C_2 and C_3 = linear Coefficients,
C_{12}, C_{13} and C_{23} = cross product Coefficients
C_{11}, C_{22} and C_{33} = quadratic Coefficients

TABLE I. The levels of variables chosen for the trials.

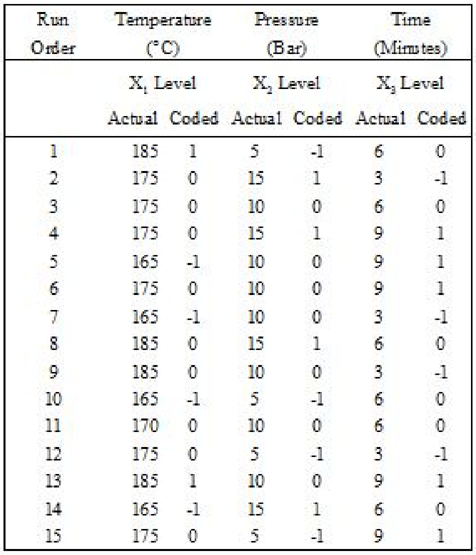


Temperature (^{0}C)	Pressure (Bar)	Time (minutes)
165 (-1)	5 (-1)	3 (-1)
175 (0)	10 (0)	6 (0)
185 (1)	15 (1)	9 (1)

The levels of variables like temperature, pressure, and time are chosen based on the melting point of the resin used, final thickness (minimum of 5 mm) expected in the composite board, and the effect of thermal exposure period respectively. A multiple regression analysis is done to obtain the coefficients and the equation can be used to predict the response. The degree of experiments chosen for this study was Box-Behnken [22-26], a fractional factorial design for three independent variables. It is applicable once the critical variables have been identified [22-27].

In the model given in Eq. (1), interactions higher than first order have been neglected. This design is preferred because relatively few experimental combinations of the variables are adequate to estimate potentially complex response functions [27]. A total of 15 experiments were necessary to estimate the 10 coefficients of the model. Using multiple linear regression analysis, the set of coefficients for its mechanical properties was calculated.

TABLE II. The Box-Behnken design for the three independent variables.



Run Order	Temperature (°C)		Pressure (Bar)		Time (Minutes)	
	X_1 Level		X_2 Level		X_3 Level	
	Actual	Coded	Actual	Coded	Actual	Coded
1	185	1	5	-1	6	0
2	175	0	15	1	3	-1
3	175	0	10	0	6	0
4	175	0	15	1	9	1
5	165	-1	10	0	9	1
6	175	0	10	0	9	1
7	165	-1	10	0	3	-1
8	185	0	15	1	6	0
9	185	0	10	0	3	-1
10	165	-1	5	-1	6	0
11	170	0	10	0	6	0
12	175	0	5	-1	3	-1
13	185	1	10	0	9	1
14	165	-1	15	1	6	0
15	175	0	5	-1	9	1

MATERIALS AND METHODS

The long staple jute fiber was purchased from Jothi Jute Textiles industry, Tamilnadu, India and cut into a fiber length of 30mm. The jute fiber strength is 4 gm/denier, moisture regain 13.5%, breaking extension 1.6% and specific gravity 1.48. The polypropylene staple fiber was purchased from Zenith Fibres Ltd., Baroda, India. The polypropylene fiber length is 51mm, denier 2.5, tenacity 6 gm/denier, melting temperature 163^0C and specific gravity 0.91. In the composite board the fiber reinforcement material is jute fiber and the resin is polypropylene.

Manufacturing of Composite Boards

Mixing of Jute fiber with polypropylene (ratio 1:1) was done homogenously by manual blending. After the mixing the fibers, they were passed through a miniature carding machine four times to ensure homogenous blending prior to web formation. The webs were conditioned at 115^0C for 24 hours to remove any moisture present. Composite boards were produced from the carded web by using the compression molding technique. Fibrous webs were cut into pieces and placed on the mold. Webs were stacked to get the required weight/unit area of 1000 gsm. The platens were pressed to desired specific pressure and temperature for a pre-defined time to get molded product. After completion of the compression cycle, the platens were cooled to optimum temperature and then the pressure was released. To boards, several of such fiber webs were compression molded by varying the process parameters such as temperature, pressure, and time. A sample of composite board so manufactured is shown in *Figure 1*.

FIGURE 1. Jute reinforced polypropylene Composite Board

Tensile Test

All tensile testing specimens were cut into dog-bone shape. The tensile tests were conducted according to ASTM 1882L using an Instron tensile tester (Model 4301) with 1 Kilo Newton load cell at a crosshead speed of 50 mm/min. Tests were performed until tensile failure occurred. Seven specimens were tested and at least five specimens were averaged.

Scanning Electron Microscope (SEM) Analysis

The morphology and microscopy of the composite samples were studied on gold coated tensile strength fracture surfaces by using a JEOL JSM 5400 high resolution electron microscope.

ANOVA Analysis

The analysis of variance (ANOVA) technique was used to check the effects of pressure, temperature, and time on tensile strength. and F-ratios were calculated atthe 95% level of confidence by using MS Excel software 2007. Details are given in *Table III*.

TABLE III. ANOVA: Two-Factor without Replication.

Source of Variation	SS	df	MS	F	P-value
ANOVA: Two-Factor Without Replication (Tensile Strength) Between Samples					
For Temperature vs Pressure					
Rows (Temperature)	0.2160	2	0.1080	0.4161	0.6852
Columns (Pressure)	7.0520	2	3.5260	13.581	0.0164
Error	1.0384	4	0.2596		
Total	8.3066	8			
For Time vs Pressure					
Rows (Time)	0.2102	2	0.1051	0.4691	0.6560
Columns (Pressure)	3.2456	2	1.6228	16.608	0.0115
Error	0.3908	4	0.0977		
Total	9.6482	8			

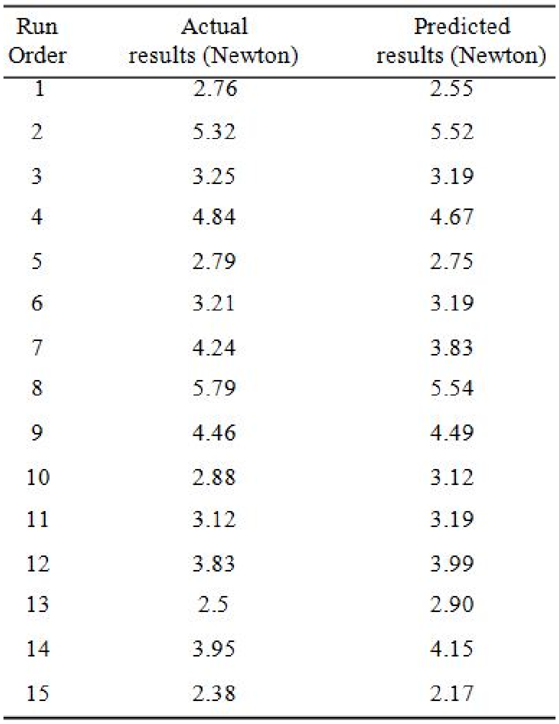
RESULTS AND DISCUSSION

The tensile strength of the composite material was obtained and the results used obtain the regression shown in Eq. (2).

$$Y = 3.19333+0.206*(X_1) + 1.006*(X_2) - 0.667*(X_3) + 0.028*(X_1^2) + 0.623*(X_2^2) + 0.275*(X_3^2) + 0.49*(X_1X_2) - 0.127*(X_1X_3) + 0.242*(X_2X_3) \quad (2)$$

Where‘Y’ is the predicted response, square regression was significant at the level of 95.60%. The tensile strength from each run order is summarized in (*Table IV*) along with actual and predicted values.

TABLE IV. Run Order, Actual and predicted results for Tensile strength.



Run Order	Actual results (Newton)	Predicted results (Newton)
1	2.76	2.55
2	5.32	5.52
3	3.25	3.19
4	4.84	4.67
5	2.79	2.75
6	3.21	3.19
7	4.24	3.83
8	5.79	5.54
9	4.46	4.49
10	2.88	3.12
11	3.12	3.19
12	3.83	3.99
13	2.5	2.90
14	3.95	4.15
15	2.38	2.17

The effects of variables on mechanical properties can effectively be interpreted and explained by a surface plot. The information available from the surface plot diagram regarding the interactions of parameters on mechanical properties is a most useful aid for the manufacture jute composite for various applications.

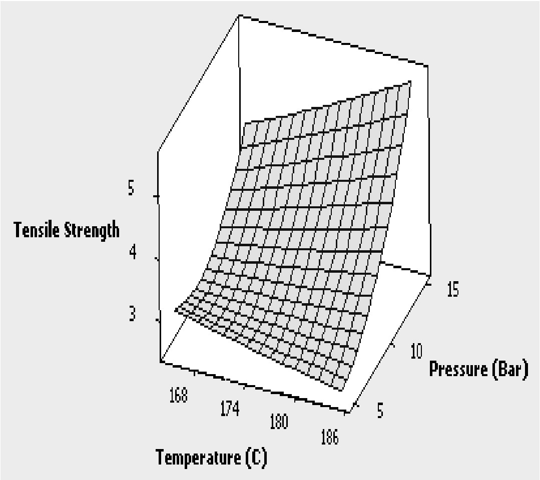


FIGURE 2. Surface Plot of Tensile Strength vs. Pressure (Bar), Temperature (^{0}C)

Figure 2 shows the relationship between temperature and pressure with respect to tensile strength by keeping the middle value of time constant. From the figure, it is clear that as the pressure and temperature increases the tensile strength also increased. This is due to the fact that at high temperature and pressure, the polypropylene melts well and the interface between the fiber surface and resin will be strong because of the homogeneous mixing of jute fiber and polypropylene in fiber stage during the carding process.

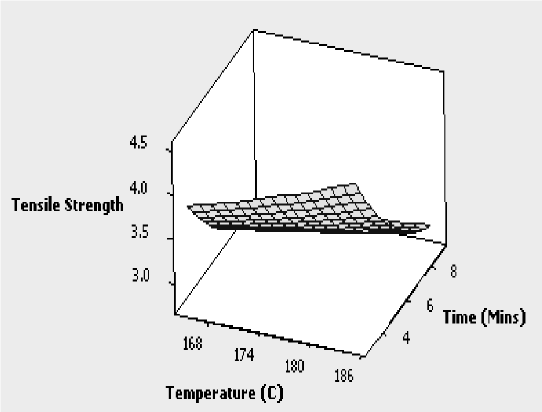


FIGURE 3. Surface Plot of Tensile Strength vs. Time (Mins.), Temperature (^{0}C)

Figure 3 shows the relationship between temperature and time with respect to tensile strength while keeping the middle value of pressure constant. From the figure it is clear that an increase in time will not make a significant difference in tensile strength. Hence temperature only plays an important role. If the temperature increases the tensile strength is also increased. Melting happens when the polymer chains fall out of their crystal structures, and become a disordered liquid. Because of this, good binding results between the reinforcement fibers which in turn increase the tensile strength.

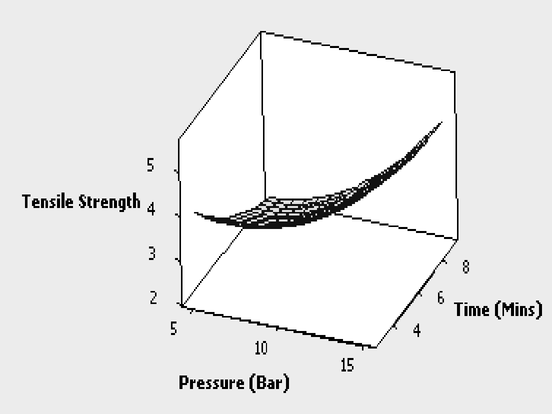


FIGURE 4. Surface Plot of Tensile Strength vs. Time (Mins.), Pressure (Bar).

Figure 4 shows the relationship between time and pressure with respect to tensile strength while keeping the middle value of temperature constant. From the figure it is clear that when the pressure is increased, the tensile strength is also increased with minimum exposure of time. This is due to the fact that the increase in pressure makes the fiber and resin very well compressed. The interactions were good and the R^2 value obtained is 96 %.

SEM Analysis

Interfacial properties of jute fabric reinforced polypropylene resin based composites were investigated by SEM. *Figure 5 (a & b)* show the SEM pictures of tensile fracture surface of composite board with highest and lowest tensile strength obtained in run order 8 and 15 respectively . SEM observations indicate that based on the processing variables, there is a considerable difference in the fiber-matrix interaction between the composites. Fiber pull-out occurrence was observed for all samples. Some gaps between jute fiber and matrix were clearly found for composite board manufactured with low pressure and temperature samples and are attributable to the low tensile strength properties.

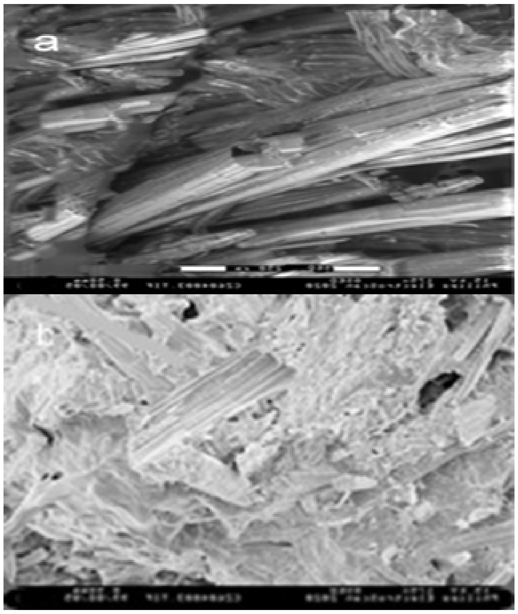


FIGURE 5. SEM images of tensile fracture surface of composite boards (a) run order 8 and (b) run order 15 respectively.

ANOVA Analysis

The mechanical properties of all of the jute fiber composites were analyzed using multivariable ANOVA analysis and their values and are given in *Table III*. From these results, it can be seen that there is significant difference between the samples at the 95% confidence level with Factual > F critical (13.58169 > 6.944272) for temperature vs. pressure and (16.60826 > 6.944272) for time vs. pressure. This is due to the change in parameters of temperature, pressure, and time. It is evident from the ANOVA analysis that pressure plays a significant role, followed by temperature. The time parameter did not have significant influence.

Response Optimization

With the help of Minitab 15 software response optimization values were determined, and from Figure *6* the increase in pressure contributing to the increase in tensile strength followed by the compression temperature can be noted. There was no contribution made by time. Based on this study, to achieve the maximum tensile strength, the global solution would be a temperature of 185^0C, pressure of 15 bars, and time of three minutes.

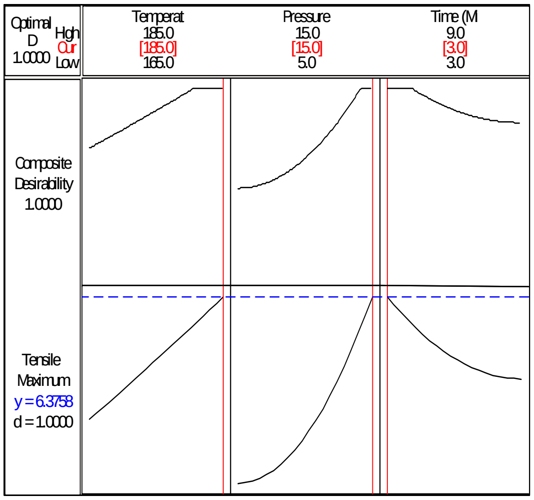


FIGURE 6. Response surface optimization graph.

CONCLUSIONS

Jute fiber reinforced polypropylene resin based composite boards were prepared by using a compression moulding machine.

The tensile strength of jute fiber composite produced by varying the parameters has been analyzed and the following conclusions were made:

The parameter pressure plays a significant role followed by temperature to obtain high tensile strength because of the good interface between fiber and resin.

Exposure of a minimum time of three minutes is sufficient to obtain high tensile strength.

The SEM study supports the finding that processing variables will alter the fiber - matrix interaction between the composite components.

This research work may be useful for researchers and scientists working in the field of technical textiles.

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