Investigation of the Mechanical Properties of Bagasse Fiber-Reinforced Epoxy Composite using Taguchi and Response Surface Methodology

Kanthavel Karuppusamy,[a,]* Palanisamy Ramanaicker,[b] and Vivek Somasundaram [a]

Fiber-reinforced polymer composites are widely used in various applications because of their mechanical properties and ease of manufacture. Fiber-reinforced plastics are being developed using synthetic fiber and natural fibers of bagasse, palm biomass, *etc*. In this study, the mechanical strength of bagasse fiber-reinforced epoxy composite was investigated using a Design of Experiment technique. The parameters of fiber volume percentage, alkali concentration, and treatment time with three levels were considered, and an L27 design matrix was developed using the Taguchi orthogonal array. The bagasse was first treated with sodium hydroxide solution (NaOH); subsequently, 27 specimens were developed for experimental investigation. The mechanical strength of newly developed bagasse fiber-reinforced epoxy composite was investigated using a three-point bending testing machine. The flexural strength was calculated using three-point bending strength for length *versus* load combination. The analysis and optimization was done using the Taguchi method, and a second-order mathematical model was developed using response surface methodology (RSM). A significant performance improvement in the flexural strength of the newly developed composite was found.

Keywords: Bagasse fiber; Epoxy composite; Flexural strength; Taguchi; Response surface methodology

Contact information: a: Department of Mechanical Engineering, Anna University Regional Centre Coimbatore, India; b: Department of Mechanical Engineering, JKKM College of Technology, India;
** Corresponding author: kandavelkk@gmail.com*

INTRODUCTION

Natural fiber-reinforced composite materials are becoming dominant emerging materials and are a prospective replacement for glass fiber-reinforced composites because of their distinctive properties of strength, heat resistance, and lightness in weight. Bagasse is a byproduct of sugarcane that is abundantly available in India. Bagasse is the lignocellulosic fibrous residual remains of crushed sugarcane (Samariha and Khakifirooz 2011). The cellulose content in dry bagasse is more or less the same as in wood, and so it is also used as a fibrous raw material in pulp, paper, and particle board manufacturing (Yadav *et al.* 2006). When binding with resin, bagasse fiber shows excellent mechanical properties and can be used to produce particle boards for making furniture (Sousa *et al*. 2004). Sousa *et al.* (2004) further investigated the effect of the three process parameters, the size of the chopped material, the pretreatment derived from the previous processing of the bagasse material on mills for the extraction of sugar and alcohol or liquor, and molding pressure over flexural strength. Their work showed that composites fabricated with bagasse with a size of under a 20-mesh sieve that were pre-processed for sugar and alcohol extraction showed the best mechanical performance.

Recently, bagasse fiber composites have been developed (Acharya *et al.* 2011) by treatment with alkali on the fiber surface to increase adhesion between the fiber and the resin matrix. The existing work used volume fractional analysis, fiber surface treatment with varying concentrations of alkali, and treatment time for different fiber washing conditions. As a continuation, in this newly proposed bagasse composite work, an experimental design combining the Taguchi method and response surface methodology was applied. Three major factors of bagasse composites, *i.e.*, fiber volume, alkali concentration, and treatment time, were considered with three levels for investigation. The experimental plan was developed by selecting an L27 orthogonal array. Experiments were conducted based on the experimental design matrix, with 27 trials with different combinations to measure the flexural strength using a three-point bending test. Statistical analysis was carried out using analysis of variance and response surface methodology to optimize parameters. The significant improvements in flexural strength with the selected parameters are presented in the discussion.

EXPERIMENTAL

Materials

Bagasse fiber collected from sugarcane has a high moisture content and needs to dry for two weeks in the shade to minimize its moisture level. In this experiment, the long fibers were trimmed to a uniform dimension with a length of 10 mm, a breadth of 1 mm, and a width of 1 mm. The fibers were then washed with pressurized water for one hour to remove fine bagasse particles, sugar residues, and organic materials, and finally dried using dry compressed air.

Alkali treatment is one of the most commonly used chemical treatments for natural fibers used to reinforce thermoplastics and thermosets. The bagasse fibers were soaked at three concentration levels, *i.e.*, 4%, 5%, and 6% NaOH solution, at room temperature for three varying treatment durations of 3, 4, and 5 h. Three fiber-resin volume percentages of 40% fiber with resin, 50% fiber with resin, and 60% fiber with resin were considered for our experiment. For the combination of three factors with three levels, 27 trials were determined based on the Taguchi L27 orthogonal array. The fibers were then washed several times with fresh water to remove any NaOH sticking to the fiber surface, neutralized with dilute acetic acid, and finally washed again with distilled water.

A compression moulding technique was used for preparation of the samples. Epoxy resin (AW554) and HY 951 hardener at a 10:1 weight ratio were mixed with gentle stirring to minimize air inclusions. The bagasse fibers were then distributed uniformly over resin in the mould with hand pressure, and specimens were further processed in 800 N compression mouling machine. Specimens were then allowed to cure at room temperature for 48 h. The ratio of fiber and resin used in this study was as follows: 40% fiber with resin, 50% fiber with resin, and 60% fiber with resin. In this work, further efforts were made to fabricate a composite material from bagasse fiber and to check their flexural properties for comparison with another material. The rough specimens of 3-mm thickness were trimmed to test specimen dimensions based on ASTM D790-10, with a length of 127 mm and a width of 13 mm.

Design of Experiment

The Taguchi method has been described (Asiltürk and Süleyman 2012) as an efficient design of experiment (DoE) technique for a systematic approach and for optimizing parameters with a minimum number of experiments. Some of these losses are caused by the variation of the products' actual functional characteristics, and these uncontrollable characteristics are called noise factors. The response values are transformed into a signal-to-noise ratio to measure the quality characteristics deviating from the desired value; a larger S/N ratio has higher-quality characteristics. The optimum process parameter is determined based on the S/N ratio, given in Eq. 1, having a greater value, and in the available three types, larger ratios are preferred:

$$S/N = -\log \frac{1}{n}\sum \frac{1}{y^2}. \tag{1}$$

Response surface methodology

Response surface methodology (RSM) is a collection of mathematical and statistical techniques that is useful for modeling and analyzing problems in which a response of interest is influenced by several variables (Montgomery 2001). The second-order quadratic polynomial model used to establish the function is expressed in Eq. 2,

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} x_i^2 + \sum_{i<j}\sum \beta_{ij} x_i x_j + \in \tag{2}$$

where y is the response, β_0 and β_i are the regression coefficients to be determined, k represents the number of factors x_i, and $\in$ is the statistical error. Response surface methodology can be used to estimate the mean flexural strength with optimal performance conditions.

RESULTS

The test specimen was experimentally tested to study its flexural strength through a three-point bending test to determine the maximum strength of the composite fiber and the optimum combination of levels of the parameters (Fig. 1). Flexural strength is the ability of the material to resist deformation under load. It was determined by the failure due to inter-laminar shear of composite materials in a three-point bending test using a Universal Testing Machine (UTM-FN500, Forcome, China) in accordance with ASTM D790-10 (2010).

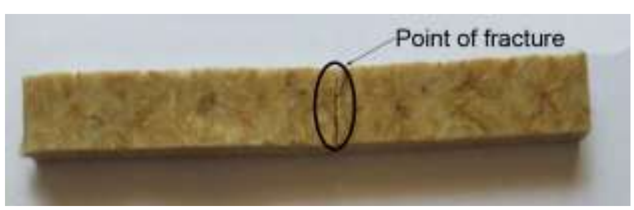

Fig. 1. Tested specimen

The specimen was measured by loading the desired shape with a span length at least three times its depth. Flexural MR is about 10 to 20% of compressive strength depending on the type, size, and volume of the coarse aggregate used. However, the best correlation for specific materials is obtained by laboratory tests for given materials and mix design. The modulus of rupture (MR) determined by three-point loading was lower than the MR determined by centre-point loading, sometimes by as much as 15%. The signal-to-noise ratio has been computed for the flexural strength of the 27 trials in the Taguchi orthogonal array design matrix, shown in Table 1.

Table 1. Experimental Results with Calculated S/N Ratio

Trial	Fiber Volume (%)	Alkali Concentration (%)	Treatment Time (h)	Flexural Strength	S/N Ratio
1.	40	4	3	37.70	31.5268
2.	40	4	4	36.45	31.2340
3.	40	4	5	36.30	31.1981
4.	40	5	3	37.45	31.4690
5.	40	5	4	37.10	31.3875
6.	40	5	5	36.55	31.2577
7.	40	6	3	32.45	30.2243
8.	40	6	4	31.55	29.9800
9.	40	6	5	31.10	29.8552
10.	50	4	3	29.05	29.2629
11.	50	4	4	27.60	28.8182
12.	50	4	5	27.30	28.7233
13.	50	5	3	28.10	28.9741
14.	50	5	4	28.45	29.0816
15.	50	5	5	27.95	28.9276
16.	50	6	3	25.77	28.2223
17.	50	6	4	24.95	27.9414
18.	50	6	5	25.10	27.9935
19.	60	4	3	24.80	27.8890
20.	60	4	4	24.30	27.7121
21.	60	4	5	23.90	27.5680
22.	60	5	3	24.80	27.8890
23.	60	5	4	24.60	27.8187
24.	60	5	5	23.60	27.4582
25.	60	6	3	22.10	26.8878
26.	60	6	4	21.70	26.7292
27.	60	6	5	21.45	26.6285

In this investigation, Eq. 1 was applied to calculate the S/N ratio, as flexural strength should be at a maximum for composite materials. The mean of the S/N ratio was calculated for fiber volume, alkali treatment, and treatment time at each level, as shown in Table 2.

Table 2. Response Table for Signal to Noise Ratios; Larger is Better

Level	Fiber Volume (%)	Alkali Concentration (%)	Treatment Time (h)
1	30.89	29.33	29.15
2	28.66	29.36	28.97
3	27.40	28.27	28.85
Delta	3.51	1.09	0.30
Rank	1	2	3

The difference between the minimum and maximum mean value of each factor was calculated as delta, and these values were ranked from largest to smallest. In Table 2 the fiber volume percentage had a delta value of 3.51, which was ranked 1, and subsequently ranks 2 and 3 were awarded to alkali concentrations with a delta value of 1.09 and treatment time with a delta value of 0.3, respectively.

Figure 2 shows the main effect plot of the S/N ratio of the flexural strength, which reveals that the flexural strength reached its maximum fiber volume percentage at level 1, its maximum alkali concentration at level 2, and its maximum treatment time at level 1.

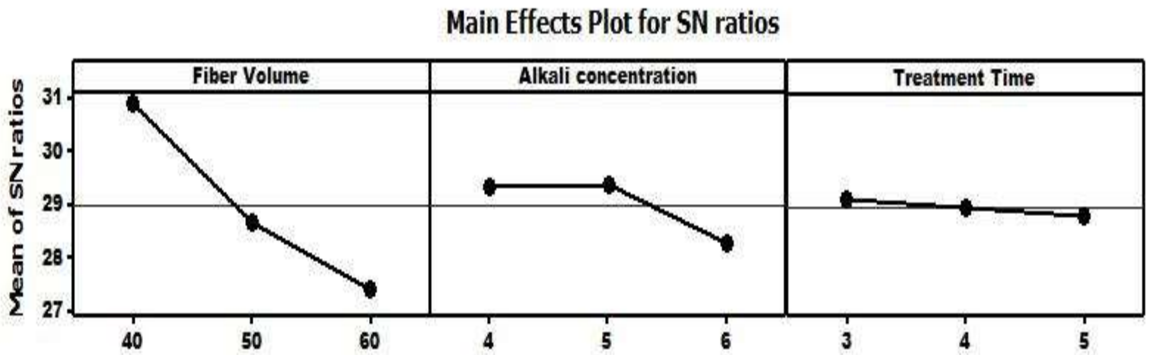

Fig. 2. Taguchi main effects plot for S/N ratio

The statistical analysis was done through analysis of variance (ANOVA) to determine the significance among the factors at a 95% confidence level. The ANOVA reveals that the factors of fiber volume percentage, alkali concentration, and treatment time had a significant effect on the response flexural strength with p values of less than 0.05. The value for R^2 was 99.45%, and the adjusted R^2 was 99.28%. The test specimen fractured surface SEM image with the magnification of 100 µm and 200 µm is presented in Figure 3.

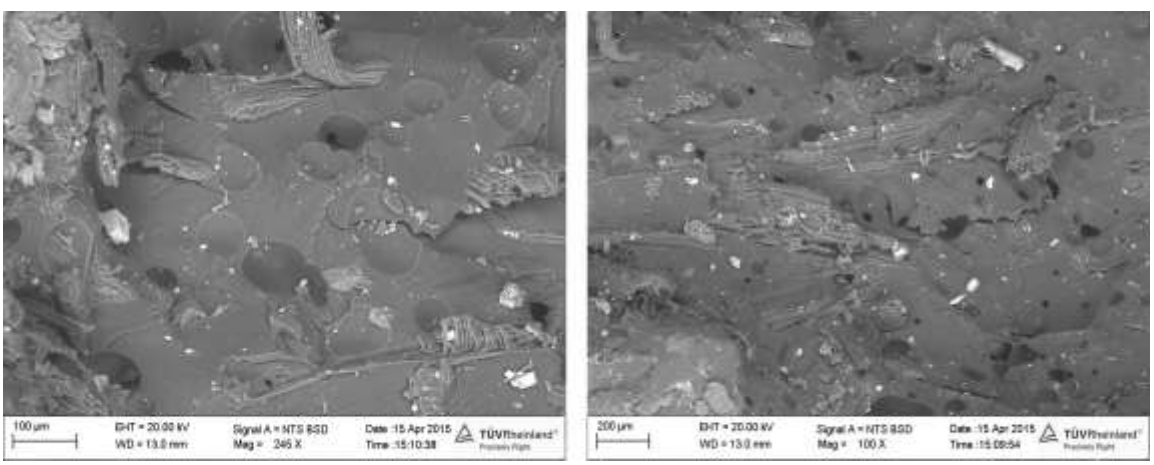

Fig. 3. SEM micrograph of fracture surface

DISCUSSION

Response surface methodology is used to optimize process parameters by quantifying the correlation between the input factors and responses (Murthy *et al.* 2012). The quadratic model for flexural strength was developed using Minitab 16 (USA) and is shown in Eq. 3:

$$\sigma_f = 97.68778 - 3.11889A + 13.32167B - 2.36833C + 0.021867A^2 - 1.86833B^2 + 0.115C^2 + 0.063333AB + 0.0075AC + 0.115BC \quad (3)$$

The quadratic model was used to predict flexural strength for different combinations of process parameters. Figure 4 shows the normal probability plot of the residuals' flexural strength, as well as the differences of the predicted and observed response values. The second-order quadratic model was further analyzed to determine the significance of the process parameters using ANOVA, as shown in Table 3.

Table 3. ANOVA for Response Surface Quadratic Model

Source	Sum of Squares	DoF	Mean Square	F	p-value
A	617.18	1	617.18	1978.78	0.0001
B	54.18	1	54.18	173.72	0.0001
C	4.47	1	4.47	14.33	0.0015
A^2	28.69	1	28.69	91.98	0.0001
B^2	20.94	1	20.94	67.15	0.0001
C^2	0.079	1	0.079	0.25	0.6205
AB	4.81	1	4.81	15.43	0.0011
AC	0.068	1	0.068	0.22	0.6477
BC	0.16	1	0.16	0.51	0.4853
Residual Error	5.30	17	0.31		
Total	735.88	26			

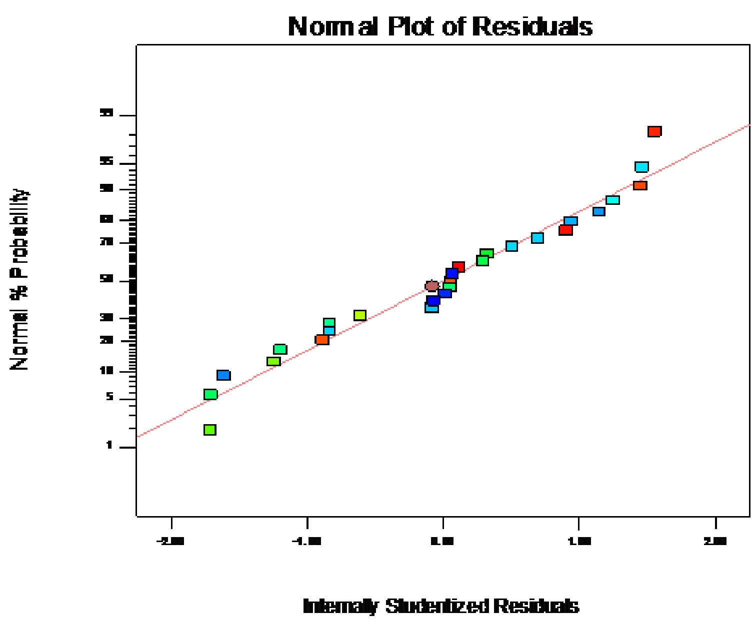

Fig. 4. Normal probability plot

The ANOVA results reveal that the quadratic model fiber volume, alkali concentration, treatment duration, pair-wise interaction of fiber volume *versus* alkali concentration, parameter squares fiber volume percentage, and alkali concentration all had a significant effect on flexural strength. Treatment time and pair-wise interactions had no significant effect on the response.

The determination coefficient R^2 of 0.9928 indicates the goodness of fit of the model. The predicted R^2 value of 0.9825 indicated a good agreement with the adjusted R^2 0.9890. A precision value of 47.599 implies that the model is satisfactory for prediction. The value of standard deviation is 0.56, and a mean value of 28.60, a C.V value of 1.95, and a PRESS value of 12.91 were calculated for the model using ANOVA.

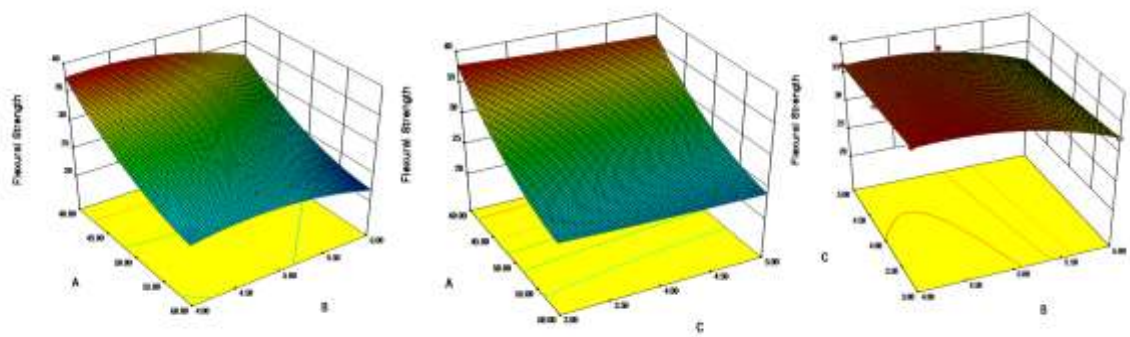

Fig. 5. Response surface graphs showing the effect of two variables on flexural strength: a) fiber volume *versus* alkali concentration, b) fiber volume *versus* treatment time, c) alkali concentration *versus* treatment time

The three-dimensional response surface plots were plotted based on the response surface model equation. Because three parameters were considered for this study, a total of three surface plots were plotted, as shown in Fig. 5(a–c) by keeping the flexural strength in the Z axis common for all three plots and interactions AB, AC, and BC of the three factors “A,” fiber volume percentage, “B,” alkali concentration, and “C,” treatment time, in the X and Y axis. The maximum flexural strength estimated from the response surface plot was 37.86 MPa for the best combination of fiber volume of 40%, an alkali concentration of 4.34, and a treatment time of 3 h.

CONCLUSIONS

1. In this investigation, a robust bagasse composite experimental design was developed by combining the Taguchi method and response surface methodology.
2. An experimental plan with an L27 orthogonal array for the three factors at each level and flexural strength was measured using a three-point bending test.
3. This investigation revealed that fiber volume, alkali concentration, and treatment time are major factors in reaching maximum flexural strength. Statistical analysis indicates that fiber volume and alkali treatment have a significant effect on flexural strength.
4. This investigation optimized the possible flexural strength of 37.86 MPa with the best combination of parameters.

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Article submitted: November 14, 2014; Peer review completed: February 23, 2015; Revisions received and accepted: April 29, 2015; Published: May 1, 2015.
DOI: 10.15376/biores.10.2.