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Prediction and Optimization of Compressive Load of a Green Composite Material from Natural Fiber Using Statistical Approach

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Abstract: In the area of technological advancement, environmental awareness is always drawing the attention of the scientists for eco-friendly and recyclable products. Different kinds of composite materials are available in the world fabricated from different materials. Natural composite fabricated from natural fiber are attracted the researchers because of their unique characteristics like bio-degradable, availability, non-toxic nature etc. In this study, a new composite materials of epoxy matrix reinforced with three different fillers (banana fiber, jute fiber and jute fabricate bio-degradable polythene) have been prepared by die molding process. Different cylindrical block has been made using different types of fiber size with equal weight ratio and different weight ratio of fiber and epoxy resin. The center composite design protocol along with the response surface method has been adopted for compression testing of composite materials. A quadratic model has been proposed to predict the compressive load of the molded green composite materials within five levels of the two process parameters. Statistical tools are used for best fitting of the developed quadratic model and desirability analysis is coupled with it in order to find out the optimum process condition for which maximum compressive load is achieved. It has been observed that grain size more than 1 mm and the weight ratio between fiber and resin close to 50% shows the better compressive strength for this particular composite material within this experimental limit.

Keywords: Natural fiber, die molding process, quadratic model, compressive strength

1. Introduction

Natural fibers are eco-friendly, inexpensive and renewable resource which is readily available in nature and fiber has unique characteristics like low density, high specific properties and good mechanical properties. The applicability of natural fiber reinforcement composite is going to increase because those inherent properties of natural fibers that meet the expectations of the global market especially for those industries who are concerned in weight reduction or light weight products, i.e. automotive, aerospace and heavy machineries manufacturing [1–2]. K. Kannan et. al [3] used in their study banana and jute fiber reinforced vinyl ester composite in treated and untreated conditions and found that untreated composite natural fiber has good mechanical properties compared to treated one. K. Bakkal et. al [4] investigated the mechanical properties for different forms glass fibers composite laminates reinforcement and found that glass fiber has positive hybridization effect and increased tensile strengths, elastic modules and impact strengths in laminar hybrid composites. R.H. Hu et al. [5] made a review study on Natural fiber reinforced composites materials that are used in many industries specially on automotive industry considering the superiority of natural fiber reinforced

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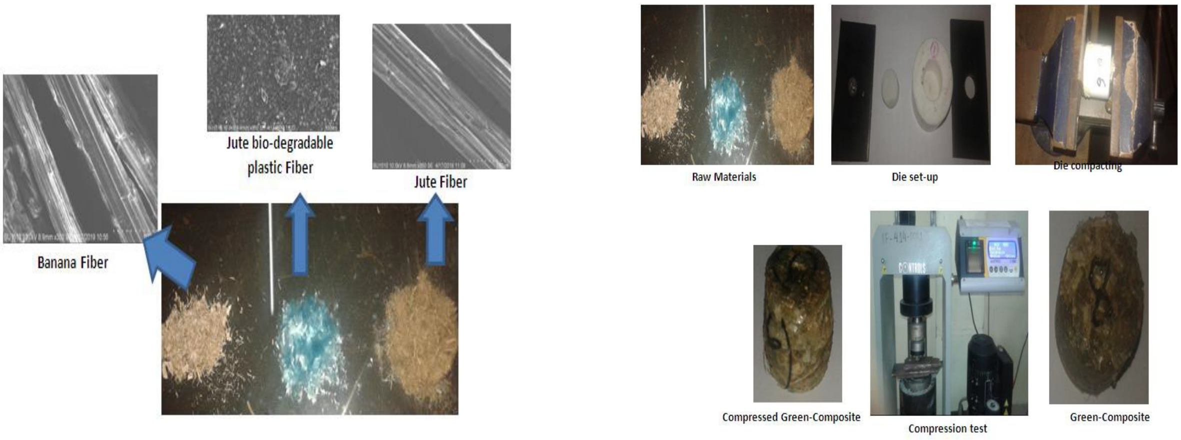
composite materials to glass fiber reinforced composite material, and its recent developments. R. R. Firly et al [6] in their study evaluated the flexural properties of Bambu Tali (Gigantochloa Apus) composite for its applicability in industries. C. Umachitra et al. [7] studied the applicability of different surface treatments techniques (NaOH, SLS, KMnO4) for the improvement of mechanical properties of the Banana/Cotton Woven Fabric Vinyl Ester Composite. P. P. Gohil et.al.[8] made an experimental investigation for the evaluation of mechanical property of unidirectional banana reinforced polyester composites. It is becoming increasingly difficult to ignore the important role of natural fiber composites in advanced technology. Mohd Radzuan et. al. [9] made a numerical simulation on uni-directional Kenf reinforcement PLA composite by Thermo-forming process. Ismail, A. E. et. al [10-11] made an intensive study on kenaf fiber for assess the properties of the composite. In this present study, three different types of fiber materials like jute fiber, banana fiber and jute fabricated bio-degradable plastic of different loading have been used for the fabrication of a new composite materials with epoxy resin and a mathematical model has been utilized as reinforcement in epoxy resin composite to optimize the composite strength from analytical results by experiment and mathematical model using CCD and RSM. The developed model has been coupled with desirability analysis to find the maximum compressive load.

2. Selection of the raw materials and process sequence

Three different types of raw materials like banana fiber, jute fiber and bio-degradable jute plastic fiber has been used as filler having different fiber size with same weight ratio. Sample picture of the raw materials and SEM view are shown in Figure 1 (a). Epoxy resin with hardener has been used with 10:1. The process sequence for the resin molding process of the green composite with die-set-up, die compacting and compression test are shown in figure 1(b). In this study, Teflon die with 25 mm diameter has been used with lubricant for easy removal of molded composite. For the compression test, compression machine, model C13A02 with maximum load capacity of 1500 kN has been used to measure the compressive strength of the casted green composite. For die compacting, bench-vise tool has been used.



(a) (b)

Fig. 1 - (a) Different types of Raw materials used in this study with SEM view (b) Process sequence for the resin casting of the green composite materials4

Table 1 - Upper limit and lower limit of the process parameters

Process Variable	Lower Limit	Upper Limit
A, Fiber Size (mm)	0.28	3.47
B, Ratio of grain (A)and resin (B)	A: B	A: B
wt in gm	20.86	49.14

Table 2 - Coding Identification for individual variable for epoxy resin casting of Green composite

Levels Coding	Lowest $-\sqrt{2}$	Lo -	Centr 0	Hig +	Highes $+\sqrt{2}$
A, Fiber Size (mm)	0.28	0.75	1.88	3	3.47
B, Ratio of grain and resin wt	20.86	25	35	45	49.14

2.1 Independent variables and coding levels

For this experiment the upper limit and lower limit of the process parameters as shown in Table 1 are considered as follows: Fiber size has been take within the limit of 0.28 mm to 3.47 mm for all the different fillers of banana, jute, bio-degradable plastics and weight ratio has been varied between grain and resin from the limit of 20.86 to 49.16. The range of the independent variables was coded from initial experimentation and the raw materials size and weight ratio considerations. Levels of independent and coding identification are presented in Table 2 for experiment which shows the five level variations of process variables.

3. Experimental design and Discussion

In the current research central composite design (CCD) concept of RSM was adopted to design the experiments. It is frequently used together with response models of the second order. A Central Composite Design (CCD) contains an imbedded factorial or fractional factorial design with center points which are augmented with a group of “star points" that allow estimation of curvature. Experimental design has been made based on central composite design for two variables with five level factorials having 3 central points with 8 non-center point. 11 Experiment has been designed with the different combinations of fiber size and ratio of the grain wt and resin wt. Experimental conditions in coded factors and the measured compressive load are presented in Table 3.

Table 3 - Compressive load results and process conditions in coded factors

Std Order	Coding of Level		Compressive load (kN)
	A, Fiber Size (mm)	*B*, Ratio of grain and resin (wt)	
1	-1	-1	24
2	1	-1	28
3	-1	1	38
4	1	1	24
5	-1.414	0	19
6	1.414	0	18
7	0	-1.414	20
8	0	1.414	30
9	0	0	14
10	0	0	12
11	0	0	11

Mathematical model has been developed based on the experimental findings of compressive load for different fabricated cylinder made from the three different filler materials. The analysis of mathematical models was carried out using sum of squares and Lack of fit tests. The tests results are shown in Table 4. From the sequential model of sum of squares as shown in Table 4 (a), indicate that the quadratic CCD models was more significant and suggested compare to other models and it has also proved that quadratic model has a significant lack of fit (LOF) as shown in Table 4(b). Therefore, based on the analysis made by fit summary, the quadratic model was chosen in order to develop the CCD model. The second order compressive load model is given as:

$$\boxed{\text{Compressive load} = +89.40663 - 1.40405*A - 4.56281*B + 3.76955*A^2 + 0.080208*B^2 - 0.40*A*B}$$

The analysis of variance (ANOVA) as shown in Table 5 was used to check the adequacy of the developed model. As per the ANOVA test the calculated “F value” of the second-order model is 5.31 which indicates that there is only a 4.53% chance that a “Model F-value” this large could occur due to noise. The corresponding “Prob > F” for 95% confidence is less than 0.00500 as obtained from statistical tables. Lack of fit of the developed model shows not significant having the F-Value 14.64. Figure 2 shows the contours of actual results and the predicted values of quadratic CCD model. The graphs indicate that the quadratic model leads to closer results to the actual values. All the 11 experimental results have been compared with the developed model prediction values.

Table 4- Selection of the model based on (a) sequential model of sum of squares and (b) Lack of fits tests

(a) Sequential Model Sum of Squares

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Mean	5149.45	1	5149.45		Suggested	
Linear	89.14	2	44.57	0.61	0.5683	
2FI	81.00	1	81.00	1.12	0.3251	
Quadratic	399.25	2	199.63	9.32	0.0206	Suggested
Cubic	11.36	2	5.68	0.18	0.8453	Aliased
Residual	95.79	3	31.93			
Total	5826.00	11	529.64			

(b) Lack of Fit Tests

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Linear	582.74	6	97.12	41.62	0.0236	
2FI	501.74	5	100.35	43.01	0.0229	
Quadratic	102.	3	34.1	14.64	0.0646	Suggested
Cubic	1	91.1	39.0	0.0247	Aliased	
Pure Error	4.67	2	2.33			

Table 5 - Analysis of variance (ANOVA) of quadratic CCD model

ANOVA for Response Surface Quadratic Model
Analysis of variance table [Partial sum of squares]

Source	Sum of Squares	DF	Mean Square	F Value	Prob > F	
Model	569.39	5	113.88	5.31	0.0453	Significant
A	16.29	1	16.29	0.76	0.4232	
B	72.86	1	72.86	3.40	0.1245	
A^2	128.53	1	128.53	6.00	0.0580	
B^2	363.30	1	363.30	16.95	0.0092	
AB	81.00	1	81.00	3.78	0.1095	
Residual	107.15	5	21.43			
Lack of Fit	102.48	3	34.16	14.64	0.0646	not significant
Pure Error	4.67	2	2.33			
Cor Total	676.55	10				

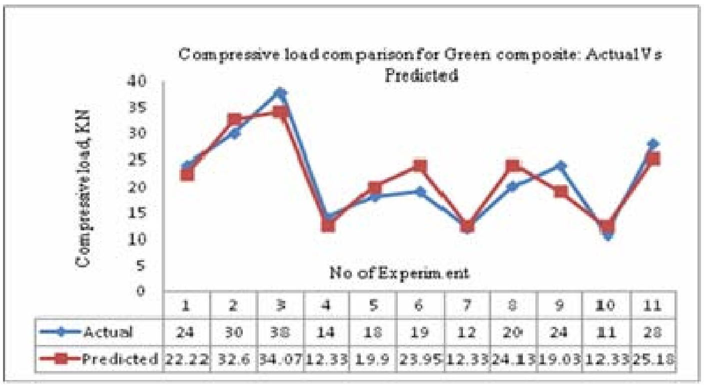
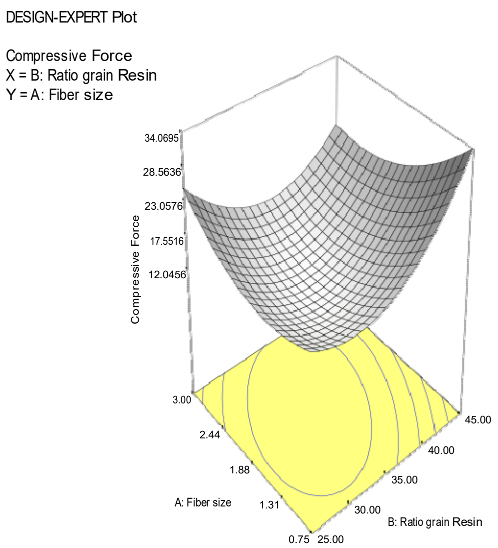
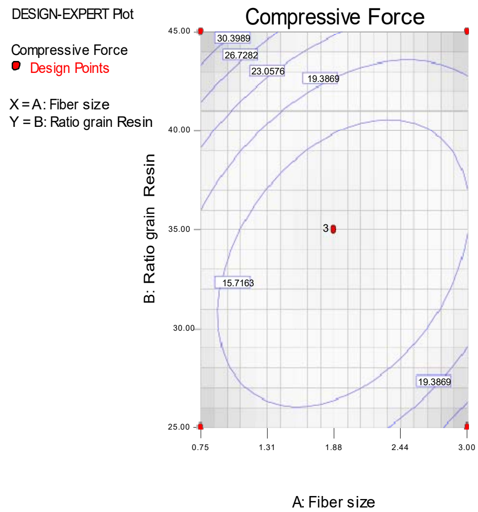


Fig. 2 - Compressive load comparison of experimental and quadratic CCD predicted values

Figure 3 (a) shows the 3D-response surface of quadratic CCD model, Figure 3 (b) shows the 2D compressive load contour profile based on the effect of Fiber size and weight ratio of the fiber and resin with hardener on fabricated green composite compressive load and Figure 3(c) shows the fracture patter of the compressed green composite. Most of the fracture pattern it appears that buckling occurs in the middle part of the composite cylinder.



(a)



(b)

(c)

Fig. 3 - (a) 3D Response surface of the quadratic CCD model for green composite fabrication (b) 2D contour profile of compressive load with the variation of Fiber size and weight ratio of the fiber and resin with hardener. (c) Fracture behavior of the compressed green composite

The contour affirms that compressive load is affected by the Fiber size and followed by weight ratio of the fibre and resin with hardener. It has been observed from the developed model that with the increase of fibre size compressive load decreases up-to a certain limit and then it increases for a constant ratio of fiber wt and resin wt. For the analysis of the developed quadratic model for compressive load prediction of green composite made from jute, banana and jute-bio-degradable plastic-a perturbation analysis has been done to assess the process parameter effects on compressive load. Figure 4 shows the trace or perturbation plot with in the design space at different process values. The intersection of the lines is at the reference point and the actual conditions for the factors at the said point are as indicated in the Figure 4. It has been appeared that proceed parameter A & B has the similar trend that it move from left to right with a decreasing tendency up to a certain limit and then it started to increase.

3.1 Result of desirability test

Desirability function approach has been adopted to find out the maximum compressive load with the combination of the process parameters within the designed space limit considering the developed quadratic model as fitness function. If the desirability value is greater than 0.9 the values of process parameters was considered to be the optimum for giving maximum compressive load. Following table 6 shows the parameters and results of desirability function.

Table 6- Desirability test for optimum process parameters

Name	Goal	Lower Limit	Upper Limit	Lower Weight	Upper Weight	Importance
A	is in	-1.414	1.414	1	1	3
B	is in	-1.414	1.414	1	1	3

Optimum process parameters derived from desirability test

Fiber size (A)	Ratio grain Resin+hardner	Compressive Force (kN)	Desirability
1.10	48.	39.41	1.0

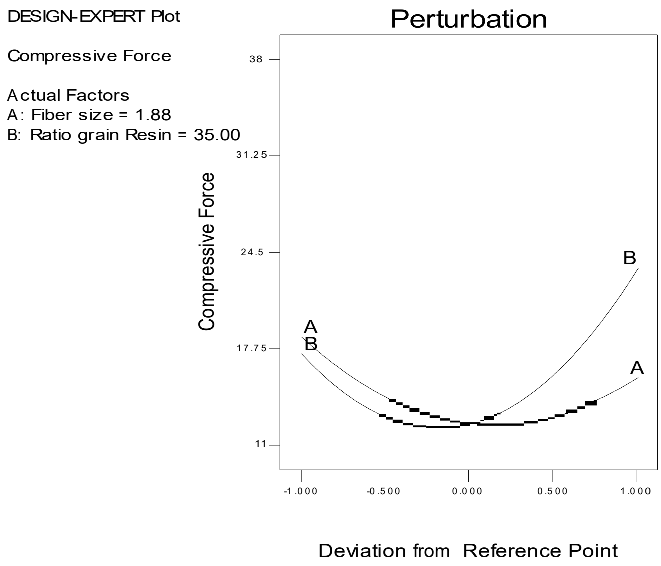


Fig. 4 - Effect of process parameters on compressive load by perturbation analysis for green composite fabrication

4. Conclusions

A mathematical model has been developed for prediction and optimization of compressive load of newly fabricated composite materials from natural fibre in terms of fibre size and weight ratio in between fiber and resin and hardener combination. The developed model was considered as fitness function and coupled it together with desirability function approach to predict the optimum process parameters within the mentioned range. From the optimized data predicted from desirability analysis, it has been observed fiber size of 1.10 mm of equal length and weight for three different materials having the resin and fiber wt ratio 48 results the maximum compressive load of 39 KN. It has been observed that both the process parameters have signification effects on compressive load. For constant weight ratio of resin and fiber at 35, it has been found that with the increase of fiber size from 0.28 mm to 1.88 mm the compressive load varied with a decreasing tendency from 19 KN to 14 KN but after that limit with the increase of fiber size from 1.88 mm to 3.47mm the compressive load reaches from 14 KN to 18 KN load with an increasing tendency. For constant fiber size at 1.88, it has also been found that with the increase of weight ratio from 20 to 35 compressive load varied with a decreasing tendency from 20 KN to 14 KN but after that limit with the increase of weight ratio from 35 to 49 the compressive load reaches from 14 KN to 30KN load with an increasing tendency. The general tendency of the developed model shows that up-to a certain limit with the combination of process parameters the compressive load goes down but at a certain point the compressive load is going to increase.

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