OPTIMIZATION OF MECHANICAL BEHAVIORS OF BIO PARTICULATES FILLED COIR-POLYESTER COMPOSITES USING SIMULATED ANNEALING

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ABSTRACT

The mechanical behaviors of Coir-Polyester composites are greatly improved by the impregnation of bio particulates. The present investigation is focused on the evaluation and optimization of mechanical behaviors of Coir-Polyester composites filled with bio particulates such as red mud and termite mound soil. The composite fabrications were planned as per Design of Experiments with fabrication parameters like fiber length (mm) and particulate content (%). The tensile, flexural and impact strength of fabricated composites were evaluated as per ASTM standards. The effect of fiber length and particulate content on the mechanical behaviors of Coir-Polyester composites was studied using ANOVA and Response Surface plots. The nonlinear regression models were developed for the prediction of mechanical behaviors over the specified range of conditions. The fabrication parameters for the optimum value of mechanical behaviors were determined using the single solution metaheuristic algorithm called Simulated Annealing.

Keywords: coir fiber, mechanical behaviors, red mud, termite mound soil, simulated annealing.

1. INTRODUCTION

The interest in natural fiber-reinforced polymer composite materials is rapidly growing both in terms of their industrial applications and customer needs because of its inherent property like relatively high stiffness, low density and biodegradable [1]. The mechanical behaviors of coir-polyester composites are greatly improved by the addition of particulate materials [2]. Fillers are added to a polymer matrix to reduce cost (since most filler are much less expensive than the matrix resin), increase modulus, reduce mold shrinkage, control viscosity and produce smoother surface. The major constituents of particulate (filler added) composites are particles of mica, silica, glass spheres, alumina, calcium carbonate, or others. The inorganic fillers are used in the fiber reinforced composites for producing the desired mould shape; reduce the manufacturing cost of composites and also to enhance the mechanical behaviors [3]. The effect of alumina and calcium carbonate on the mechanical behaviors of coir-polyester composites were studied in recent years [4, 5]. The effective utilization of bio waste particles has been emphasized in society for environmental and economic concerns. Industrial by-product red mud and naturally available termite mound soil has been used in composite applications due to their potential. The previous attempts by various researchers to incorporate red mud and termite mound soil particulates in polymer composites [6-8] initiated a new building for the development of bio particulate reinforced material. The present work investigated the influence of hybrid bio particulates on the mechanical properties of coir-polyester composites.

2. EXPERIMENTAL PROCEDURE

2.1. Materials

Red mud was collected from Madras Aluminium Company (MALCO) at Salem, India and Termite mound Soil was collected from southern region of Tamilnadu which is enriched with red soil. The collected particles were sieved finely to obtain particle size in the range of 75-100 μm. The compositions of bio particulate are given in Table-1.

Table-1. Composition of red mud and termite mound soil.

S. No.	Constituent materials	Composition (%)	
		Red Mud	Termite mound soil
1	SiO_2	15.21	94.17
2	Al_2O_3	16.8	0.02
3	Fe_2O_3	33.8	0.20
4	Na_2O_3	11.87	0.04
5	CaO	2.45	-

The natural green husk coir fiber was selected as reinforcement material in this investigation. The bio particulates were mixed (50: 50) with resin system for different percentage of weight content and blended by using simple mechanical stirring at 20 rpm for 10 mins in the room temperature [25^0C]. The resin system consists of unsaturated orthophthalic polyester resin, Methyl Ethyl Ketone Peroxide (MEKP) as a catalyst and Cobalt Octoate as accelerator were mixed in the ratio of 1:0.015:0.015 [9, 10].

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2.2. Composite fabrication

A stainless steel mould having size of 300 × 300 × 3 mm^3 was used for composite fabrication in compression molding process. The operating pressure of 3 MPa and temperature of 60°C was maintained for 3 hrs for uniform curing of composite sheets. The fabrication parameters and their levels are given in Table-2. The resin content of 60% and fiber content of 40-x%, where x is the particulate content in weight % was maintained for the different combinations process parameters. The photographic images of fabricated composite sheets are given in Figure-1.

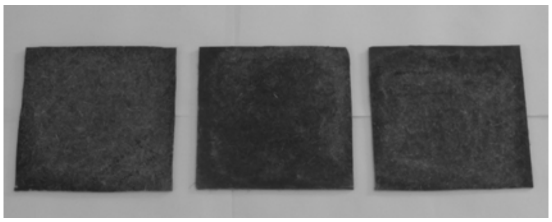

Figure-1. Photographic image of fabricated composite sheets.

Table-2. Selection of parameters and levels.

S. No.	Parameter Levels	Fiber length (mm)	Particulate content (%)
1	Very Low	10	5
2	Low	20	10
3	Medium	30	15
4	High	40	20
5	Very High	50	25

2.3. Mechanical testing

Specimens for mechanical testing were cut from the prepared composite sheets and finished to the accurate size using emery paper. Tensile and three point bending test were conducted using Computerized Universal Testing Machine as per ASTM D638 and ASTM D790 standards. The length, width and thickness of tensile test specimens are approximately 165 mm, 25 mm and 3 mm respectively. The rectangular test pieces of 12.7 × 12.7 × 3 mm dimension are used for flexural test from the prepared composites [11, 12]. The impact test was carried out using Tinius Olsen Impact Tester with a specimen size of 60 × 15 × 3 mm as per ASTM D256 standard. Five specimens with identical dimensions for each composition were tested and average result is derived. Testing conditions of 23±2 ^{0}C temperature and relative humidity of 50 ±5% were followed.

2.4. Simulated annealing

Simulated Annealing is inspired by annealing in metallurgy which is a technique of controlled cooling of material to reduce defects [13-14]. The simulated annealing algorithm starts with a random solution. If this solution is a better solution, it will replace the current solution. If it is a worse solution, previous iteration value may be chosen to replace the current solution with a probability that depends on the temperature parameter. The following steps are adopted in simulated annealing [15].

Step-1: Choose an initial point $x^{(0)}$, a termination criterion €.Set T a sufficiently high value, number of iterations to be performed at a particular temperature n, and set t = 0.

Step-2: Calculate a neighboring point $x^{(t+1)} = N(x^{(t)})$. Usually, a random point in the neighborhood is created.

Step-3: If $\Delta E=E(x^{(t+1)}) - E(x^{(t)}) < 0$, set t = t+1:
Else create a random number (r) in the range (0, 1).If $r \le \exp(-\Delta E/T)$ set t = t+1
else go to step-2.

Step-4: If $\left| x^{(t+1)} - x^{(t)} \right| <$ € and T is small, Terminate;
Else if (t mod n) = 0 then lower T according to a cooling schedule.
Go to step 2; else go to step-2.

The simulated annealing algorithm is used in this investigation to optimize the mechanical behaviors of red mud and termite mound soil particulate impregnated coir-polyester composites.

3. RESULTS AND DISCUSSIONS

3.1. Effect of process parameters on mechanical behaviors

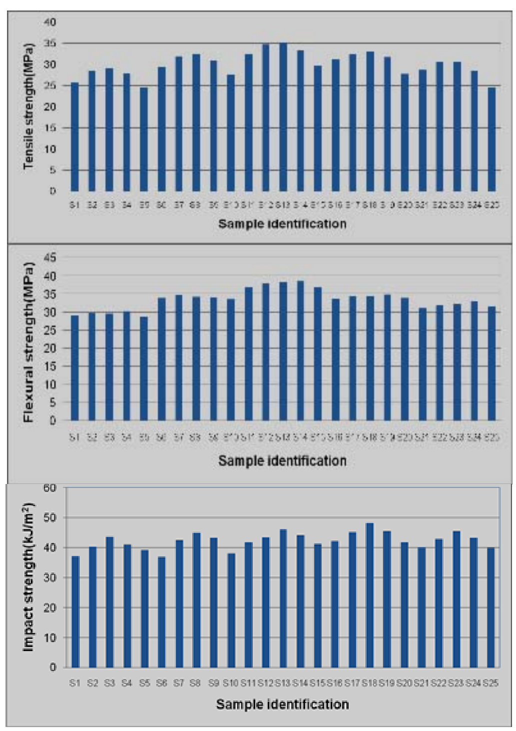

Figure-2. Effect of process parameters on mechanical behaviors.

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The effect of fiber length and particulate content (red mud and termite mound soil) on the mechanical properties of coir fiber reinforced polyester composites are shown in the Figure-2. From the plot, it can be inferred that the fiber length and particulate content play a prominent role in increasing the tensile, flexural and impact strength of the fabricated composites. The composite with 15% particulate content formed by equal composition of red mud and termite mound soil exhibited better tensile and flexural properties and at the same the tensile and flexural properties of the composites were found to dwindle when the particulate content was increased beyond 15%. The tensile and impact strength was found to be better for the fiber length of 30 mm and found to decrease with the increase in fiber length beyond 30 mm. The flexural and impact strength was found to better at 30 mm fiber length and 20% (10% red mud and 10% termite mound soil) particulate content, respectively.

3.2. Non linear regression analysis

The fiber length and particulate content are given as input values and the mechanical properties such as tensile, flexural and impact strength are assigned as output values and the non linear equations were modeled using statistical software. The terms f_l represents fiber length whereas p_c represents particulate content in weight percentage. Equations (1), (2) and (3) are the developed nonlinear regression models of tensile strength *(ts)*, flexural strength *(fs)* and impact strength *(is)* respectively. The quadratic model was selected based on fit summary. The coefficient of correlation, R^2 values of tensile, flexural and impact models were 0.97, 0.90 and 0.89, respectively.

$$ts = 14.24100+0.5769f_l+1.58169p_c-0.0035f_lp_c-0.009f_l^{\,2}-0.046743p_c^{\,2} \quad (1)$$

$$fs= 20.10200+0.13849f_l+1.84171p_c+0.0013 f_l\, p_c-0.0025f_l^2 -0.059257p_c^2 \quad (2)$$

$$is= 25.60500+0.83436f_l+0.84929p_c -0.0025f_lp_c - 0.013014f_l^2-0.020743p_c^2 \quad (3)$$

3.3. Analysis of variance

The interaction effects of fabrication parameters are validated using the ANOVA Tables for mechanical behaviors. Degrees of freedom (df) are number of levels for the term minus one whereas mean square is sum of squares divided by degrees of freedom.

The null hypothesis H_0 and an alternative hypothesis H_1 were set to perform a test of hypothesis. The two-tailed ANOVA test was performed in this investigation to analyze the effect of process parameters on tensile, flexural and impact behaviors. The test is performed at 5% confidence level which means there is a 5% chance of wrongly rejecting H_0. The decision to reject the null hypothesis is set by saying "there is significant evidence at the 5% level to suggest the hypothesis is false"[2].

3.3.1. ANOVA for tensile strength model

The ANOVA for tensile strength model was listed in Table-3. The Model F-value of 149.63 and the values of "Probability > F" less than 0.0500 indicated that the model terms were significant.In this case f_l, p_c, f_l.p_c, f_l^2 *and* p_c^2 were significant model terms.

Table-3. ANOVA for tensile strength model.

Source	Sum of squares	df	Mean square	F-value	p-value Prob > F
Model	193.50	5	38.70	149.63	<0.0001
f_l	21.00	1	21.00	81.18	<0.0001
p_c	6.48	1	6.48	25.06	<0.0001
f_l- p_c	3.20	1	3.20	12.39	0.0023
f_l^2	67.23	1	67.23	259.94	<0.0001
p_c^2	95.59	1	95.59	369.60	<0.0001
Residual	4.91	19	0.26		
Corrected total	198.41	24			

3.3.2. ANOVA for flexural strength model

The ANOVA for flexural strength model was listed in Table-4. The Model F-value of 34.73 implied that the model was significant. In this case p_c, f_l^2 and p_c^2 were significant model terms. Values greater than 0.0500 indicated that the model terms were not significant .

Table-4. ANOVA for Flexural Strength.

Source	Sum of squares	df	Mean square	F-value	p-value Prob > F
Model	172.18	5	34.44	34.73	<0.0001
f_l	0.080	1	0.080	0.081	0.7794
p_c	13.42	1	13.42	13.53	0.0016
f_l- p_c	0.44	1	0.44	0.44	0.5154
f_l^2	4.63	1	4.63	4.67	0.0437
p_c^2	153.62	1	153.62	154.95	<0.0001
Residual	18.84	19	0.99		
Corrected total	191.02	24			

3.3.3. ANOVA for impact strength model

The ANOVA for impact strength model was listed in Table-5. The Model F-value of 26.09 implied that the model was significant. In this case p_c, f_l^2 and p_c^2 were significant model terms.

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Table-5. ANOVA for Impact Strength.

Source	Sum of squares	df	Mean square	F-value	p-value Prob > F
Model	168.61	5	33.72	26.09	<0.0001
f_l	1.19	1	1.19	0.92	0.3502
p_c	28.43	1	28.43	21.99	0.0002
$f_l \cdot p_c$	1.61	1	1.61	1.25	0.2779
f_l^2	118.56	1	118.56	91.73	<0.0001
p_c^2	18.82	1	18.82	14.56	0.0012
Residual	24.56	19	1.29		
Corrected total	193.17	24			

3.4. Response surface plots

The model was displayed in three dimensions and provided a clearer view of the surface. The distribution of response surfaces with respect to two different parameters were illustrated using 3D surface plot. Contour line displayed the connections of all points that had the same responses to produce constant lines. The 3D Response surface and contour plot for tensile, flexural and impact strength models are shown in Figures 3, 4 and 5, respectively.

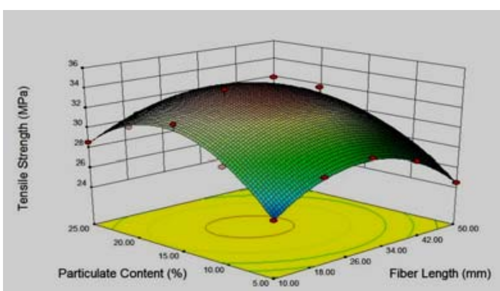

Figure-3. 3D Response and contour plot for tensile strength.

In the response surface design, all the terms were included in the mathematical model of responses, for getting the minimum standard error. The Figure-3 shows the curvatures obtained in all the interactions, and the maximum value of the tensile strength for various combinations of fiber parameters were studied using the 3D surface plots.

The 3D surface plots for flexural model shown in the Figure-4 indicates the interactions between the variables on the flexural strength of the composites. As the particulate content and fiber length increase, the tensile and flexural strength increases continuously, after reaching the maximum it decreases slowly. The same pattern was also observed for impact strength of the fabricated composites as shows in the Figure-5. The curvature of the fiber length and particulate content indicates their mechanical behavior of the composites relies on the interaction between the fabrication parameters.

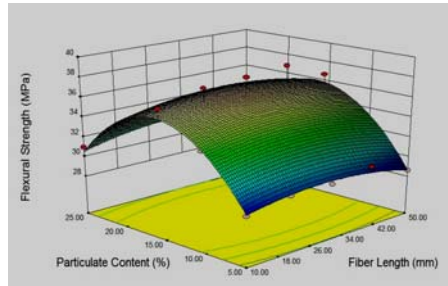

Figure-4. 3D Response and contour plot for flexural strength.

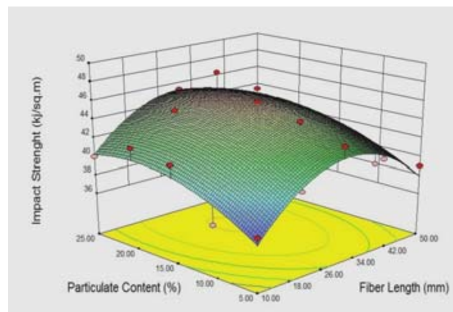

Figure-5. 3D Response and contour plot for impact strength.

3.5. Optimization using simulated annealing

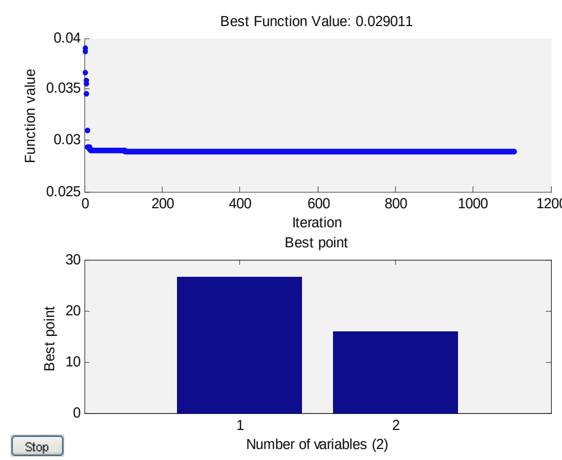

Figure-6. Best point and current function value plots for tensile strength.

The nonlinear regression equations are optimized using simulated annealing procedure by setting the following parameters.

Lower Bounds : [10 5]
Upper Bounds : [50 25]
Starting Point : [10 5]

Annealing function : Boltzmann annealing
Temperature update : Exponential

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The SA algorithm was developed in GUI of MAT LAB R2010a for minimization function. The maximization function in M-file is represented as 1/f(x) where f(x) is the minimization function. The optimum mechanical behaviors and the corresponding fabrication parameter values are shown in Figures 6 to 8.

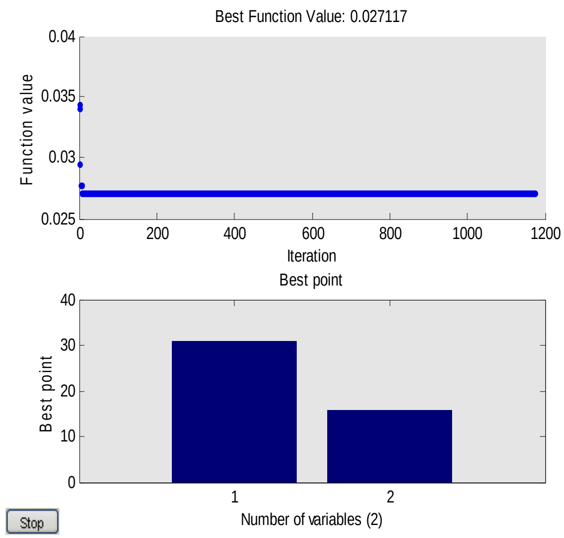

Figure-7. Best point and current function value plots for flexural strength.

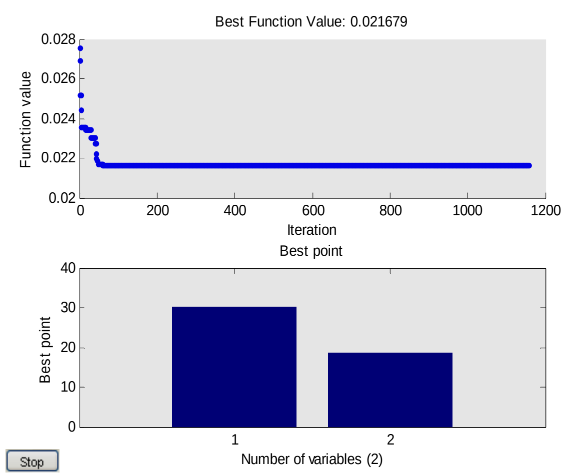

Figure-8. Best point and current function value plots for impact strength.

The optimum value of tensile, flexural and impact behaviors are obtained for the iteration of 1175, 1156 and 1104 respectively. The optimum conditions and the corresponding mechanical behaviors are obtained using single solution metaheuristic simulated annealing algorithm and are given in Table-6.

Table-6. Optimum mechanical behaviors.

S. No	f_l	p_c	*ts*	*fs*	*is*
1	26.6	15.9	34.5	-	-
2	30.7	15.8	-	36.9	-
3	30.2	18.6	-	-	46.1

3.6. Validation of regression models

Confirmation experiments were conducted for seven set of conditions for intermediate values of experimental design and optimum conditions obtained. The experimental values and the values predicted from regression models were compared. The absolute percent error was calculated using the following formula (4) for validating the quadratic models.

Absolute % error =|estimate - actual|/actual ×100 (4)

Table -7. Validation of Regression models

Run	Fiber length (mm)	Particulate content (%)	Experimental values			Predicted values using regression models			Percent error		
			ts	fs	is	ts	fs	is	ts	fs	is
1	15.0	7.5	30.2	33.0	40.2	29.7	32.2	40.4	1.6	2.3	0.5
2	25.0	12.5	33.8	35.5	44.5	34.4	36.2	45.7	1.8	1.9	2.8
3	35.0	17.5	34.0	37.2	45.6	34.6	36.8	47.5	1.8	1.2	4.1
4	45.0	22.5	31.8	33.1	45.8	30.4	34.0	45.6	4.5	2.8	0.5
5	26.6	15.9	35.0	35.4	45.2	35.1	36.9	46.0	0.2	4.2	1.7
6	30.7	15.8	33.0	37.0	44.5	35.1	36.9	47.1	6.3	0.2	5.7
7	30.2	18.6	34.0	36.2	46.3	34.7	36.5	46.2	2.2	0.8	0.1
Average Absolute Error Percentage									2.6	1.9	2.2

From the Table-7 it was observed that the average absolute percent error for tensile strength = 2.6 %, flexural strength = 1.9 % and impact strength = 2.2 % and better accuracy was obtained using the developed non linear regression models. It is also observed that the optimum values obtained through simulated annealing algorithm are very closer to the experimental values.

4. CONCLUSIONS

The bio particulates such as red mud and termite mound soil were used to fabricate Polymer Matrix Composites (PMC) successfully. The optimum value of tensile strength of 34.5 MPa, flexural strength of 36.9 MPa and impact strength of 46.1 kJ/m^2 were determined by simulated annealing algorithm by optimizing non linear regression models. The mechanical performance of coir - polyester composite has been greatly improved by incorporating bio particulates. Hybrid particulates in coir-polyester composites may open up new applications for low load bearing needs. This specific investigation on bio particulate impregnated coir-polyester composites provides an initiative for the development of new variety of coir-polyester composites in engineering applications.

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