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Effect of red mud on the mechanical properties of banana/polyester composites using design of experiments

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Abstract

This study reveals the potential use of red mud, the industrial waste, as a filler material for making banana fiber reinforced polymer matrix composites. Composites are prepared through hand lay-up and subjected to mechanical testing to find impact, flexural, and tensile strengths. Taguchi design of experiments with L_9 orthogonal array is used to optimize the parameter with respect to length, treatment, and weight fraction of fiber and red mud weight percentage. Fiber of different lengths (5, 10, and 15 mm) with different treatments (NaOH and silane), different weight fractions (15, 20, and 25 wt%), and red mud of different weight compositions (5, 10, and 15 wt%) are taken for this study. Scanning electron microscopy study is carried out to observe inference about the fracture behavior of composites and the optimized results are reported.

Keywords

Banana fiber, red mud, polyester, mechanical properties, Taguchi method

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Introduction

Red mud (RM) emerges as the major waste material during production of alumina from bauxite by the Bayer's process. The RM which is derived from the bauxite by different methods is potentially applicable to use in building materials due to its strength.[1–3] The use of RM is justified as a potential filler in composite material, using polypropylene as a matrix material. X-ray diffraction and differential scanning calorimeter analysis are carried out and the results indicate that the crystallization effect of the polymer increases with the increase in RM content.[4]

Tensile and flexural properties studies are carried out using epoxy as a matrix along with banana fiber and for different test conditions the mechanical behavior is analyzed using analysis of variance (ANOVA). Pothan and Thomas[5] and Pothan et al.[6] carried out investigations on the effect of chemical modification on mechanical, electric properties, and moisture absorption behavior of banana fiber–polyester composites.[7] In the case of short fiber, the mechanical properties of the composites depend on factors such as fiber length, fiber weight percentage, and fiber orientation. The surface modification of fiber carried out by the treatment of fibers with alkali solution and different types of silanes, also enhances the properties to a marginal extent which has been proved through earlier investigations.[8,9] Venkateshwaran et al.[10] dealt with the tensile, flexural, and water absorption studies of banana–epoxy composite materials which show a poor result and it can be improved in a better way by the addition of sisal fiber along with banana fiber in different weight percentages.

The comparative study carried out on bamboo fiber and glass fiber reinforced epoxy matrix composites filled with different weight proportions of RM shows improvement in mechanical properties. Erosion tests carried out on the prepared specimen and witnessed RM as a potential filler along with polymer matrix composites.[11] The addition of ceramic fillers along with polyester matrix composites shows better results; however, the drawback is in the costs involved. In order to avoid this issue, composites are developed using waste materials as reinforcement.[12] Study on erosion wear behavior with air jet type erosion rig through design of experiments (DOE) for glass fiber reinforced polyester composites carried

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out by Mahapatra et al.[12] From the optimal parameter obtained, the material loss due to erosion is reduced. Further work on erosion studies are carried out using ceramic particulates along with glass fiber polyester composites.[13,14] Glass fiber reinforced polyester composites along with alumina particle property studies were carried out by Satapathy and Patnaik[15] through Taguchi approach, the erosive performance of these composites were studied and concluded that the addition of filler improves the property. Glass fiber filled with RM-reinforced epoxy composites studies are carried out by Patnaik et al. They also constructed mathematical model for finding the damage caused due to erosion. Using Taguchi method with the interaction of the various control factors, they carried out the studies to find out the factors which affect the wear rate.[16]

Optimization of flexural properties and tensile properties of epoxy and polypropylene-reinforced nanoclay composites are carried out using Taguchi method and the results are reported.[17,18] The effect of various process parameter on the mechanical and wear properties of nanoclay composites have been done in the earlier investigations using the DOE approach and Taguchi method.[19,20] Tensile, flexural, and impact properties of coir fiber reinforced polyester composites along with calcium carbonate as a filler reinforcement has been studied by Sathiyamurthy et al.[21] and the results are compared with mathematical models using statistical package. The usage of silica as filler along with banana fiber reinforced epoxy composite and their mechanical properties have been studied. It has been noticed that the impact strength of composites is increased by the epoxy materials and silica filler. Water absorption studies were also done and results indicate that the silica-filled banana composites are suitable for moisture applications.[22] The utilization of particle reinforcement along with natural fiber improves the thermal conductivity has been reported by Nandi et al.[23]

In this study, banana fiber with different fiber lengths and different weight proportions are taken randomly to prepare composites by mixing different weight percentages of RM with pure polyester. Mechanical properties of the composites are found and results are compared. In addition to this, Taguchi DOE with L_9 orthogonal array is used to get an optimal value for mechanical properties of the composites.

Experiment details

Materials used

Banana fiber is obtained from the local market. The resin used is unsaturated polyester (GP, general purpose) resin; it is obtained from GVR enterprises, Madurai. Catalyst and accelerator used are methyl-ethyl-ketone-peroxide (MEKP) and cobalt naphthenate also purchased from GVR enterprises, Madurai. RM (industrial waste) obtained from Madras Aluminum Company at Salem, Tamilnadu. The composition of RM is presented in Table 1. For treatment purposes, NaOH (high medium) and tricholorovinyl silane are used.

Fabrication of composites

Unsaturated general purpose polyester resin filled with RM is reinforced with banana fibers treated with NaOH, silane, and untreated to prepare the composites. The composite slabs are made by conventional hand lay-up technique; 2% cobalt naphthenate (as accelerator) is mixed thoroughly in GP polyester resin and then 3% MEKP as hardener is mixed in the resin prior to reinforcement. RM collected is sieved to obtain particle size in the range 75–100 μm. At first, polyester mixed (manual mixing) with different weight percentages of RM (5, 10, and 15 wt%) and fiber loading of different weight compositions (15, 20, and 25 wt%) for different fiber lengths (5, 10, and 15 mm) as per requirement.

The specimens are subjected to load for about 5–6 h in order to achieve proper curing at room temperature. Similar procedure is adopted for the preparation of banana-reinforced polymer composites. The specimen is shown in Figure 1. The banana fibers are treated in NaOH to remove the cellulose

Table 1. Composition of RM.

SiO_2	Al_2O_3	Fe_2O_3	Na_2O_3	CaO
15.21	16.8	33.8	11.87	2.45

RM: red mud.

Figure 1. Banana fiber filled RM specimen.
RM: red mud.

content in the fiber; to achieve this, 60 g of sodium hydroxide is mixed with 1 L of distilled water and the banana fibers are immersed in the NaOH solution for 1 h. After 1 h, the fiber is taken and cleaned with distilled water and dried at 65 °C for 24 h in oven. The NaOH-treated fibers are immersed in silane-treated water for 1 h and dried in the room temperature for 24 h.

Experimental design using Taguchi's technique

The following are the steps involved in the experimental design using Taguchi technique.

Step 1: Identification of parameters. The following four parameters which mostly influence the output response namely, impact, flexural, and tensile strengths are identified as follows:

(a) RM;
(b) fiber treatment;
(c) length of fiber; and
(d) weight fraction of fiber.

Step 2: Selection of orthogonal array. Selection of suitable orthogonal array is an important step in conducting this experiment. There are four parameters and each has three levels with the exception of valve type. The maximum number of levels is three and hence L_9 orthogonal array is followed.

Step 3: Level settings. In this investigation, three levels for all factors are considered. Table 2 presents the control factors and levels. The corresponding layout of L_9 orthogonal array is presented in Table 3. Therefore, L_9 orthogonal array is selected in this study to conduct the experiments.

Results and discussion

Impact strength

Impact tests are done as per ASTM D 256 with specimen size of $65 \times 13 \times 3\,mm^3$. The value of impact strength increases with the addition of RM. It is also proved in the L_9 experiment which shows increase in impact strength, as indicated in Figure 2. In experiment number 5, the impact strength value decreases due to the treatment of fiber with NaOH, whereas in the case of experiment number 4 and 7, impact strength is maximum in both the cases for untreated fiber with RM content of 10 and 15 wt%, respectively.

Table 2. Control factors and levels.

		Levels		
Parameters		L1	L2	L3
A	RM (wt%)	5	10	15
B	Fiber treatment	Untreated fiber	Fiber treated with NaOH	Fiber treated with silane
C	Length of fiber (mm)	5	10	15
D	Weight fraction of fiber (%)	15	20	25

RM: red mud.

Table 3. Layout of L_9 orthogonal array.

					S/N ratio		
Experiment	RM (wt%)	Fiber treatment	Length of fiber (mm)	Weight fraction of fiber (%)	Impact strength (kJ/m^2)	Flexural strength (MPa)	Tensile strength (MPa)
1	1	1	1	1	42.69	30.02	26.00
2	1	2	2	2	30.06	34.49	31.00
3	1	3	3	3	33.29	35.28	31.80
4	2	1	2	3	46.96	31.60	29.00
5	2	2	3	1	28.09	31.69	29.61
6	2	3	1	2	33.12	34.49	29.11
7	3	1	3	2	48.03	32.28	29.23
8	3	2	1	3	41.70	31.40	28.13
9	3	3	2	1	30.47	32.04	28.94

RM: red mud; S/N ratio: signal-to-noise ratio.

To find the optimum value of response, the average signal-to-noise (S/N) ratio is calculated for all experiments in Table 3. The computation of variation using L_9 orthogonal array for impact strength is presented in Table 4.

The scheme for ANOVA for impact strength is presented in Table 5. Effect of RM percentage of different treatments of fiber is shown in Figure 3. RM (15 wt%) filled with untreated banana fiber combination enhances the impact strength. Average S/N ratio for control factors is shown in Figure 4. The maximum values of average S/N ratio are the optimum values for the parameters and hence it is noted. The contribution of each parameter on impact strength is given in Table 6. The percentage contribution ratio of parameters on impact strength is shown in Figure 5.

The significant factors are chosen from the left-hand side in the chart, which is a cumulative contribution of about 90%. From this figure, fiber treatment, weight fraction of fiber, RM percentage, and length of fiber are identified as significant factors affecting impact strength. The optimum control factors for the impact strength is found to be the 15 wt% RM, untreated fiber with 5 mm fiber length, and 15 wt% weight fraction of fiber. The comparison of impact strength of unfilled banana fiber reinforced polyester composites with optimum condition is presented in Table 7, which clearly indicates that the

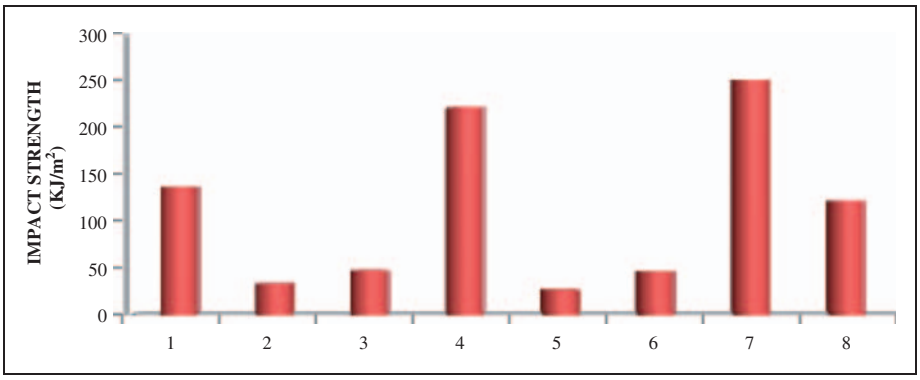

Figure 2. Average impact strength for L_9 experiment.

Table 4. Computation of variation using L_9 orthogonal array for impact strength.

		RM (wt%)	Fiber treatment	Length of fiber (mm)	Weight fraction of fiber (%)	
Factors		A	B	C	D	Total
Sum at factor level	L1	106.04	137.68	117.51	101.25	334.41
	L2	108.17	99.85	107.49	111.21	
	L3	120.20	96.88	109.24	121.95	
Sum of square of differences (s)		349.76	3104.6	171.86	643.48	4269.7
Contribution ratio (%)		8.19	72.72	4.02	15.07	100

RM: red mud.

Table 5. Scheme for ANOVA for impact strength.

Source of variations		Sum of squares	Degree of freedom (ψ)	Mean sum of square (s/ψ)	Variance (f_o)
RM (%)	A	349.76	2	174.88	2.035
Fiber treatment	B	3104.6	2	1552.3	18.064
Length of fiber (mm)	C	171.86	2	85.93	–
Weight fraction of fiber (%)	D	643.48	2	321.74	3.744

RM: red mud.

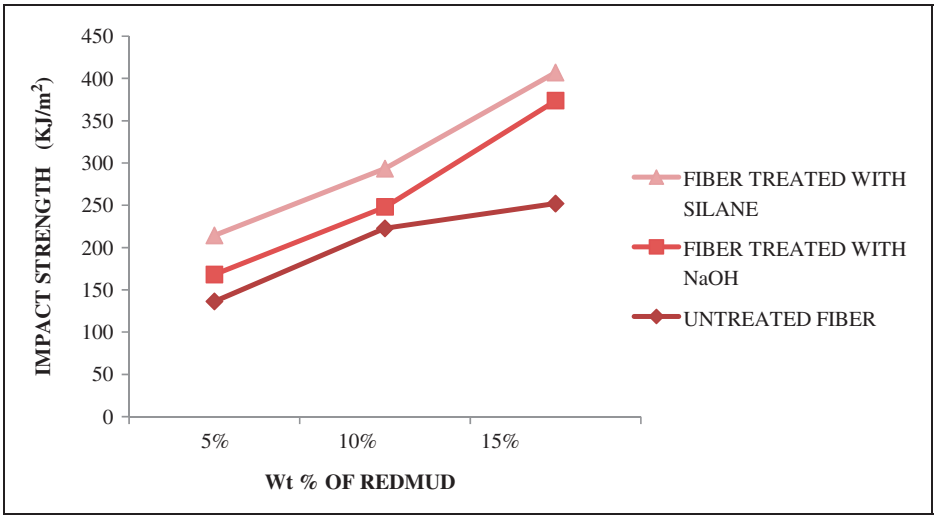

Figure 3. Effect on RM wt% of different treatments.
RM: red mud.

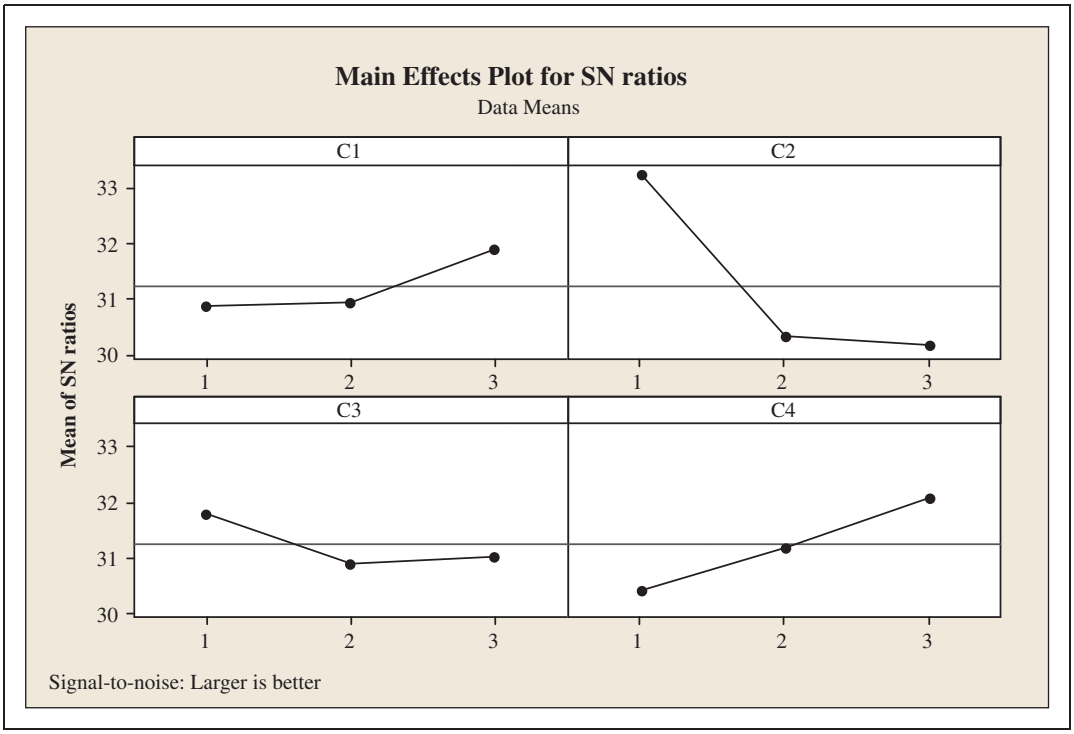

Figure 4. Average S/N ratio for control factors.
S/N ratio: signal-to-noise ratio.

Table 6. Contribution ratio for impact strength.

	Fiber treatment	Weight fraction of fiber (%)	RM (wt%)	Length of fiber (mm)
Factors	B	D	A	C
Contribution ratio (%)	72.72	15.07	8.19	4.02
Cumulative contribution ratio (%)	72.72	87.79	95.98	100

RM: red mud.

addition of RM filler along with banana fiber reinforced polyester enhances the impact strength.

Flexural strength

The flexural test is performed in UTM through three-point bend test. A span of 50 mm is taken and cross-head speed was maintained at 2 mm/min. Flexural test is performed on all samples of dimension $127 \times 13 \times 3\,mm^3$ as per ASTM D 790 test standards. The value of flexural strength increases with the addition of RM. It is also proved in the L_9 experiment which shows increase in flexural strength as indicated in Figure 6. In experiment number 1, flexural value decreases in the case of untreated fiber. From experiment numbers 3 and 2, it is noted that the

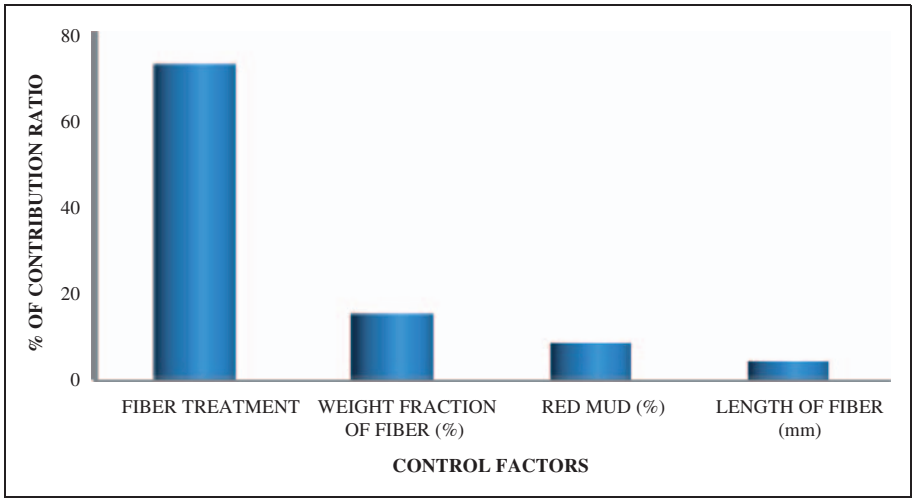

Figure 5. Chart for contribution ratio (%) of control factors.

Table 7. Comparison of impact strength of unfilled banana fiber reinforced polyester composites and optimum condition.

Condition	Fiber	Impact strength (kJ/m^2)
Unfilled composites	Untreated	103
	Treated with NaOH	68
	Treated with silane	81
Optimum	Untreated	201

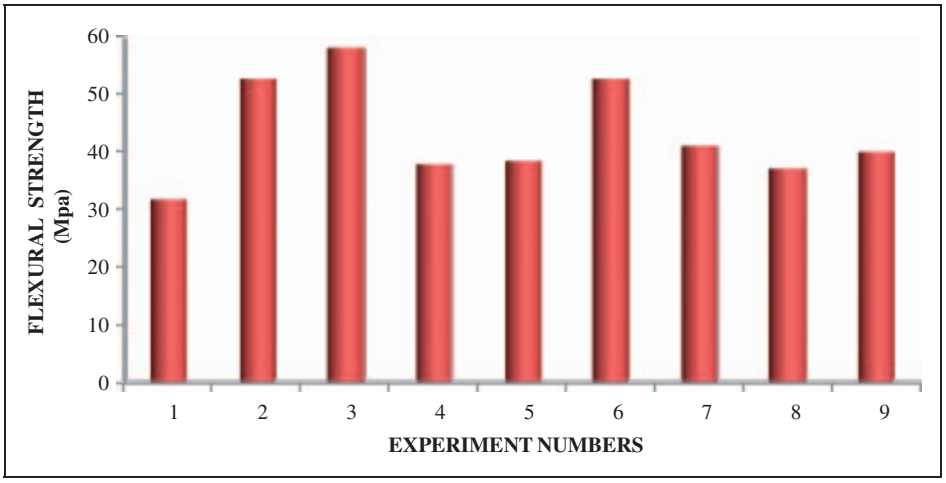

Figure 6. Average flexural strength for L_9 experiment.

flexural strength is maximum in both the cases of treated fiber with NaOH and silane, respectively, where silane treatment has maximum value. To find the optimum value of response, the average S/N ratio is calculated for all experiments. The computation of variation using L_9 orthogonal array for flexural strength is presented in Table 8.

The scheme for ANOVA for flexural strength is presented in Table 9. Average S/N ratio for control factors is shown in Figure 7. The maximum values of

Table 8. Computation of variation using L_9 orthogonal array for flexural strength.

		RM (wt%)	Fiber treatment	Length of fiber (mm)	Weight fraction of fiber (%)	
Factors		A	B	C	D	Total
Sum at factor level	L 1	99.79	93.90	95.91	93.75	293.29
	L2	97.78	97.58	93.13	101.26	
	L3	95.72	101.81	99.25	98.28	
Sum of square of differences (s)		24.85	94.00	17.34	85.80	221.99
Contribution ratio (%)		11.20	42.34	7.81	38.7	100%

RM: red mud.

Table 9. Scheme for ANOVA for flexural strength.

Source of variations		Sum of squares	Degree of freedom (ψ)	Mean sum of square (s/ψ)	Variance (f_o)
RM (wt%)	A	24.85	2	12.425	1.433
Fiber treatment	B	94.00	2	47	5.420
Length of fiber (mm)	C	17.34	2	8.67	–
Weight fraction of fiber (%)	D	85.80	2	42.9	4.94

RM: red mud.

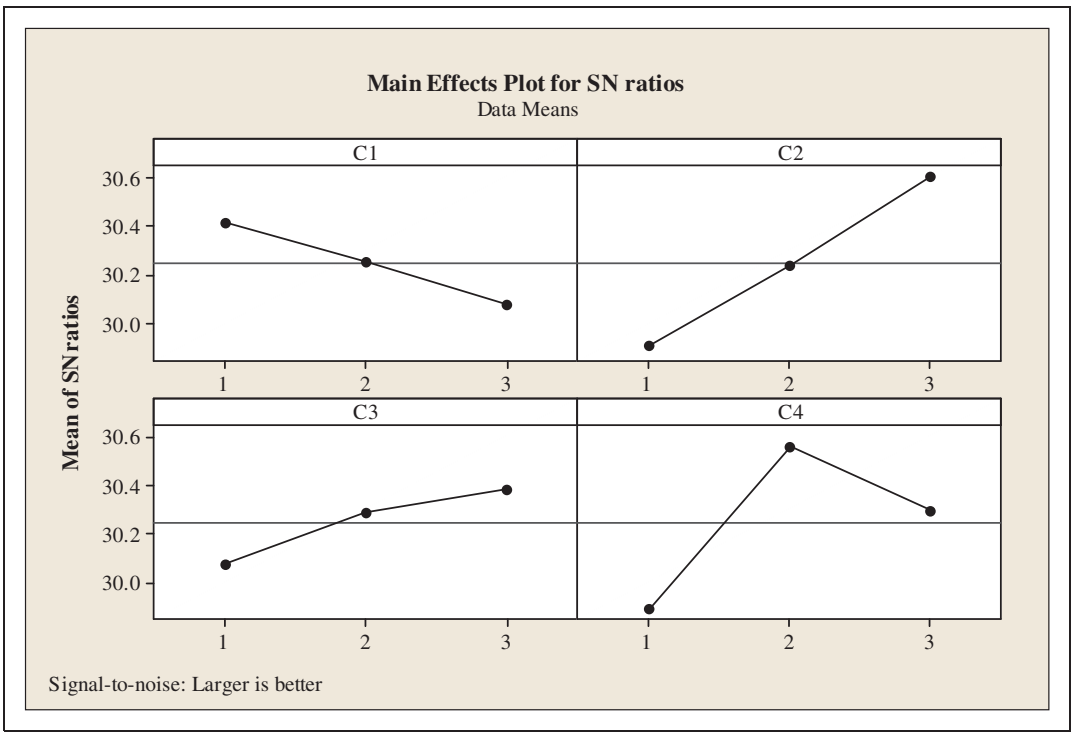

Figure 7. Average S/N ratio for control factors.
S/N ratio: signal-to-noise ratio.

average S/N ratio are the optimum values for the parameters. The optimum parameters are identified to get enhanced flexural strength. The contribution of each parameter on flexural strength is given in Table 10. The percentage contribution ratio of parameters on flexural strength is shown in Figure 8.

The significant factors are chosen from the left-hand side in the chart which is a cumulative contribution of about 90%. From this figure, fiber treatment, weight fraction of fiber, RM percentage, and length of fiber are identified as significant factors affecting flexural strength. The optimum control factors for the

Table 10. Contribution ratio for flexural strength.

	Fiber treatment	Weight fraction of fiber (%)	RM (wt%)	Length of fiber (mm)
Factors	C	B	D	A
Contribution ratio (%)	42.29	38.7	11.2	7.81
Cumulative contribution ratio (%)	42.29	80.99	92.19	100

RM: red mud.

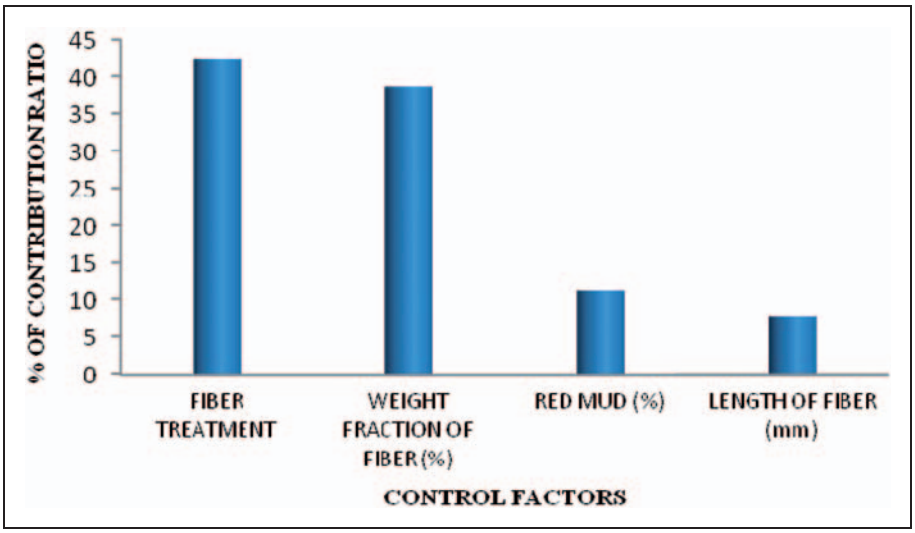

Figure 8. Chart for contribution ratio (%) of control factors.

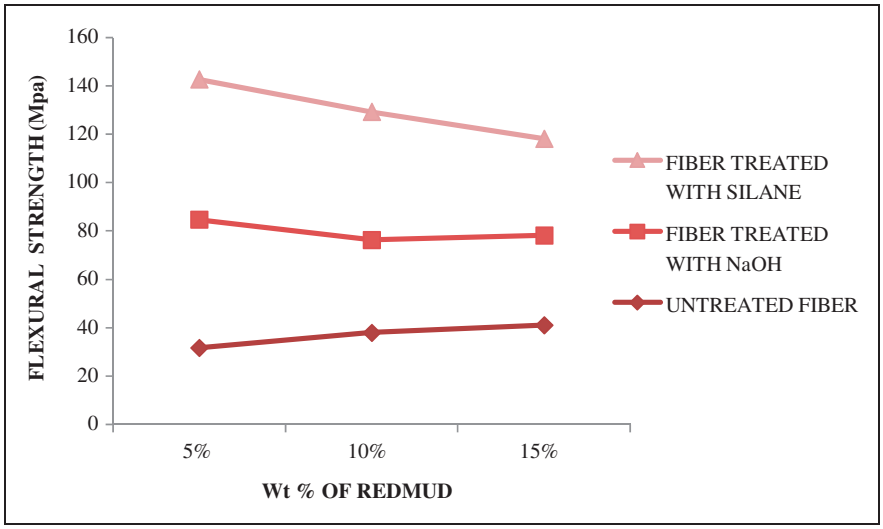

Figure 9. Effect on RM wt% of different treatments.
RM: red mud.

impact strength are found to be the 15 wt% RM, fiber treated with silane with 10 mm fiber length, and 15 wt% weight fraction of fiber. Effect of RM percentage of different treatments of fibers is shown in Figure 9. RM (5 wt%) filled with banana fiber treated with silane combination enhances the flexural strength. The comparison of flexural strength of unfilled banana fiber reinforced polyester composites with optimum condition is presented in Table 11.

Table 11. Comparison of flexural strength of unfilled banana fiber reinforced polyester composites and optimum condition.

Condition	Fiber	Flexural strength (MPa)
Unfilled composites	Untreated	35
	Treated with NaOH	41
	Treated with silane	44
Optimum	Treated with silane	51

Tensile strength

The tensile test is performed in UTM with a crosshead of 1 mm/min. The tension test is performed on all samples as per ASTM D638 test standards with specimen size $165 \times 10 \times 3\,mm^3$. A uni-axial load is applied through the ends. The experimental result of tensile strength is shown Figure 10. To find the optimum value of response, the average S/N ratio is calculated for all experiments. The untreated banana fiber filled with RM enhances the tensile strength than other combination. The computation of

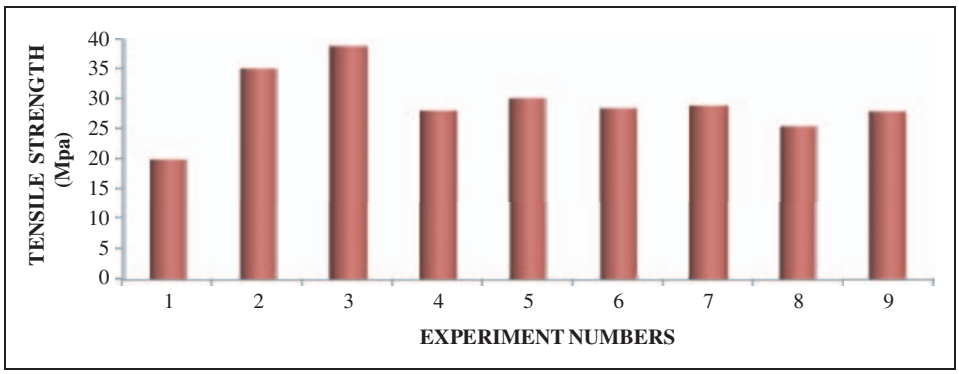

Figure 10. Average tensile strength for L_9 experiment.

Table 12. Computation of variation using L_9 orthogonal array for tensile strength.

		RM (wt%)	Fiber treatment	Length of fiber (mm)	Weight fraction of fiber (%)	
Factors		A	B	C	D	Total
Sum at factor level	L1	88.80	84.23	84.05	84.55	262.82
	L2	87.72	88.74	88.94	89.34	
	L3	86.3	89.85	90.64	88.93	
Sum of square of differences (s)		9.433	53.16	70.23	42.29	175.113
Contribution ratio (%)		5.40	30.36	40.11	24.15	100%

RM: red mud.

Table 13. Scheme for ANOVA for tensile strength.

Source of variations		Sum of squares	Degree of freedom (ψ)	Mean sum of square (s/ψ)	Variance (f_o)
RM (%)	A	9.432	2	4.716	–
Fiber treatment	B	53.16	2	26.58	5.64
Length of fiber (mm)	C	70.23	2	35.12	7.45
Weight fraction of fiber (%)	D	42.29	2	21.15	4.48

RM: red mud.

Table 14. Contribution ratio for tensile strength.

	Fiber treatment	Weight fraction of fiber (%)	RM (wt%)	Length of fiber (mm)
Factors	C	B	D	A
Contribution ratio (%)	40.09	30.36	24.15	5.40
Cumulative contribution ratio (%)	40.09	70.45	94.60	100

RM: red mud.

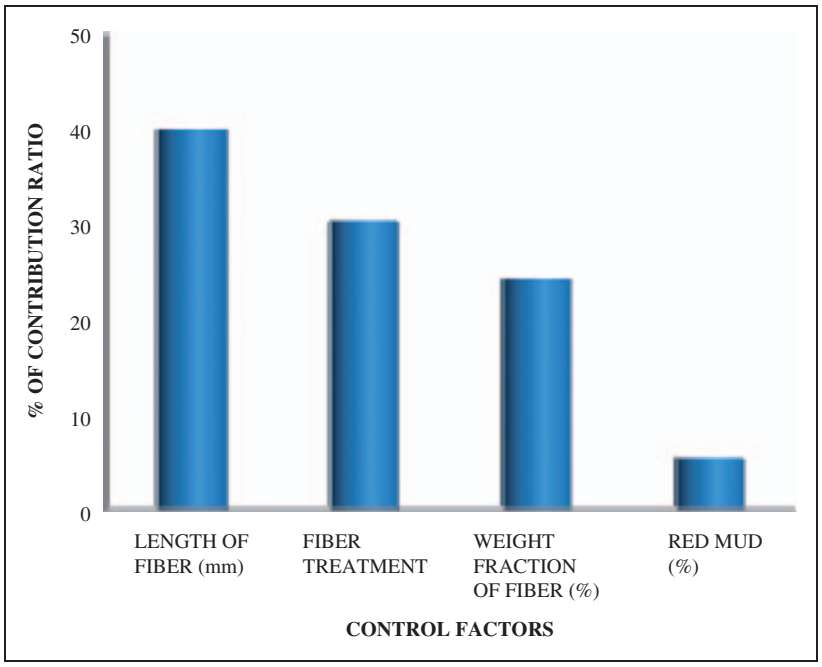

Figure 11. Chart for contribution ratio (%) of control factors.

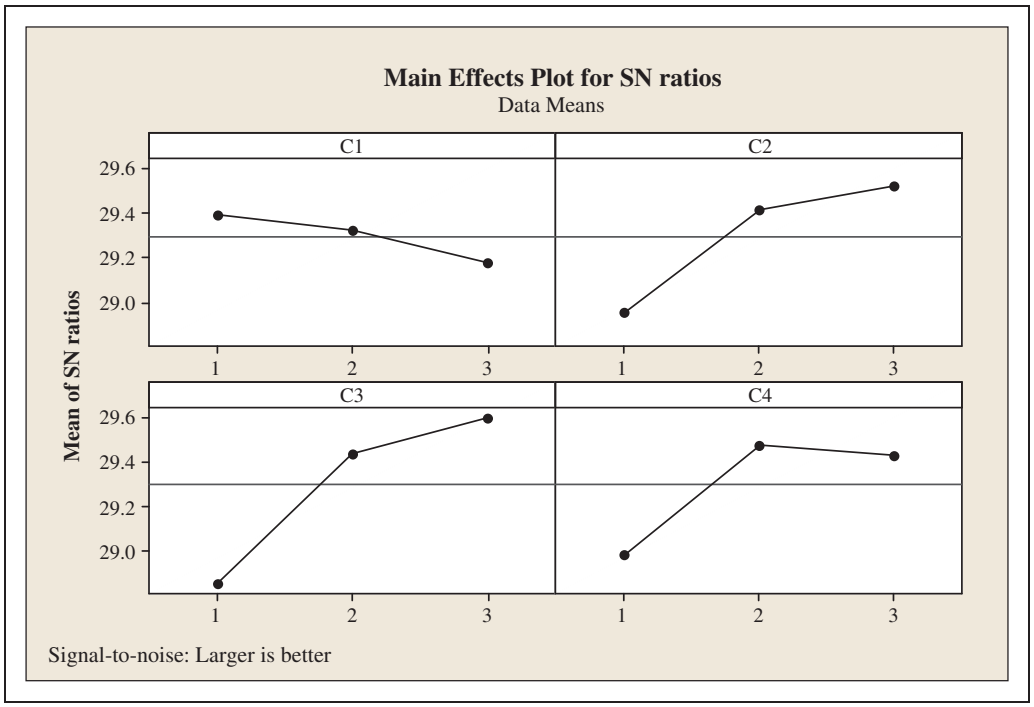

Figure 12. Average S/N ratio for control factors.
S/N ratio: signal-to-noise ratio.

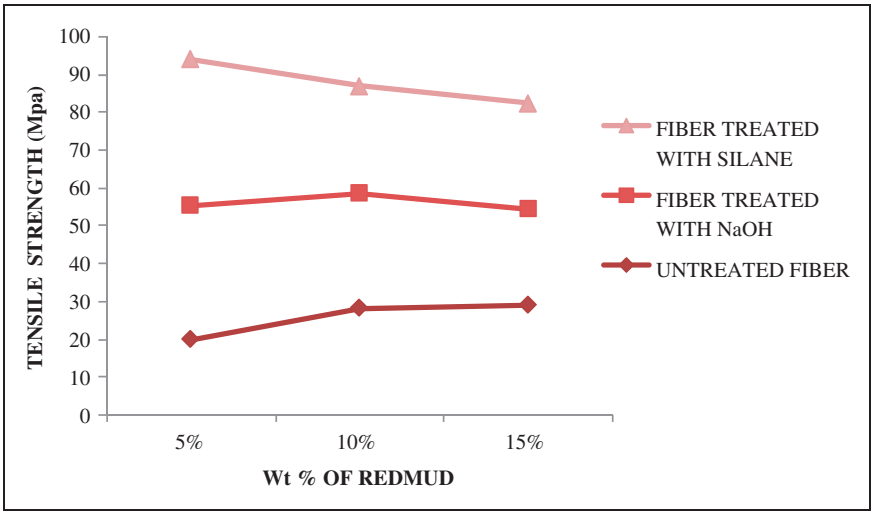

Figure 13. Effect on RM wt% of different treatments.

variation using L_9 orthogonal array for tensile strength is presented in Table 12.

The scheme for ANOVA for tensile strength is presented in Table 13. The contribution of each parameter on tensile strength is given in Table 14. The percentage contribution ratio of parameters on tensile strength is shown in Figure 11. From this, weight fraction of fiber, fiber treatment, RM percentage, and length of fiber are identified as significant factors affecting tensile strength. The optimum control factors for the tensile strength are found to be the 15 wt% RM, fiber treated with silane with 10 mm fiber length, and 15 wt% weight fraction of fiber. The average S/N ratio for control factors is shown in Figure 12. The maximum values of average S/N ratio are the optimum values for the parameters. The optimum parameters are identified to get enhanced tensile strength.

Effect of RM percentage of different treatments of fibers is shown in Figure 13. RM (5 wt%) filled with banana fiber treated with silane combination enhances the tensile strength. The comparison of tensile strength of unfilled banana fiber reinforced polyester composites with optimum condition is presented in Table 15.

The fracture behavior of the specimens is studied under scanning electron microscope (SEM). Figure 14(a) and (b) shows the SEM images for the fractured surface of the impact strength test carried out over the prepared RM-filled banana fiber composites. From Figure 14(a), it is clearly seen that fiber pull out takes place which results in the failure of the material. Figure 14(b) indicates the presence of voids which normally takes place due to the pullout phenomenon. From Figure 14(c) and (d), it is noted that fiber pull out is disturbed by the presence of RM particulates which increase the impact strength. The poor interfacial bonding between the fiber and matrix due to non-uniform distribution of the RM particulates over the surface results in poor mechanical property and also reduce tensile strength.

Table 15. Comparison of tensile strength of unfilled banana fiber reinforced polyester composites and optimum condition.

Condition	Fiber	Tensile strength (MPa)
Unfilled composites	Untreated	15.14
	Treated with NaOH	12.88
	Treated with silane	25.31
Optimum	Treated with silane	27.18

Conclusions

Mechanical properties of short-fiber banana polyester composites change with respect to their weight compositions and fiber length. However, irrespective of all this, the addition of RM improves the properties. It shows the potential applicability of RM for making composites. It is observed that impact and flexural strengths of the composites increase on randomly taking different fiber lengths (10 and 15 mm) and fiber weight percentages (10, 15, and 20 wt%), alternatively tensile strength value decreases due to the distribution of the particulates along with the matrix which results in poor stress interface between matrix and filler. Impact and flexural strengths of RM-filled banana polyester composites are more when compared to banana epoxy composites. Tensile strength also increases when compared to banana epoxy composites. The optimum parameter for impact strength is obtained for the combination of untreated fiber with 5 mm length, 15 wt% of RM and fiber. In the case of flexural and tensile strengths, the optimum parameter is obtained for the combination of fiber treated with silane of 10 mm length,15 wt% of fiber,

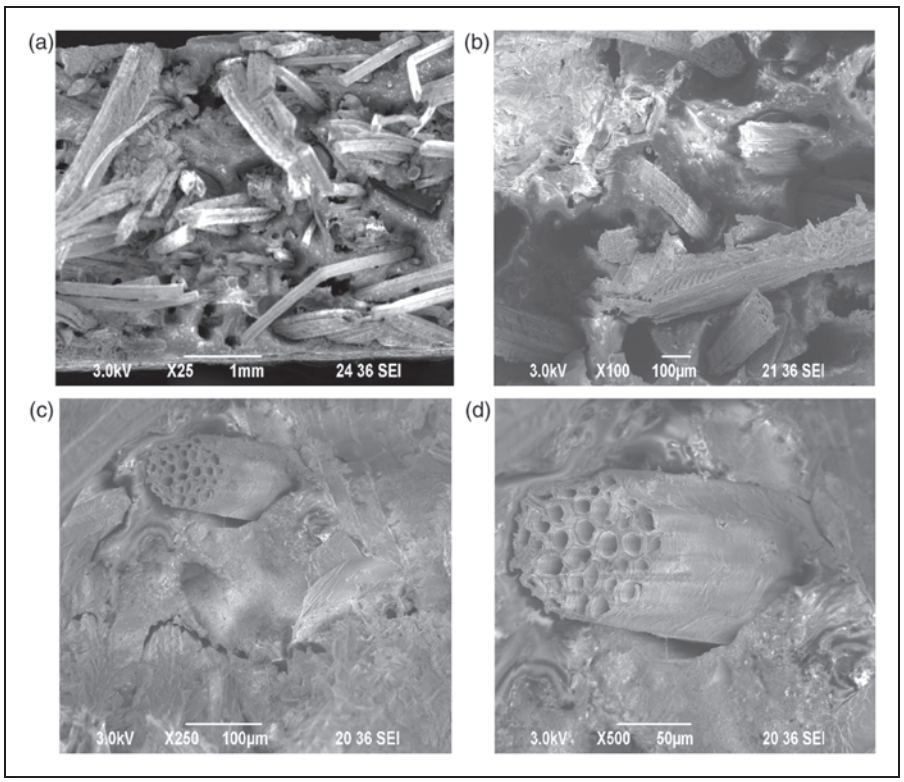

Figure 14. SEM images of the impact and tensile fractured surface of RM-filled banana polyester composites.

and 5 wt% RM. Due to highest impact and flexural strengths, RM-filled banana polyester composites are suitable for withstanding high load and load-bearing applications. Environmental pollution related issues are minimized drastically using the RM, as filler for composite fabrication.

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