Optimisation of Mechanical Properties of Wood Dust-reinforced Epoxy Composite Using Grey Relational Analysis

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Abstract In the present era of product development, composites are being used because of the ease in manufacturing and low weight to volume ratio. The increasing awareness towards environmental issues and requirement of more versatile polymer-based materials has led to higher interest in natural fibre/filler composites. In this paper, epoxy composite with six different filler contents (wt%) of sundi wood dust are tested at three different speeds. Tensile and flexural tests are performed according to ASTM standard. Different design parameters i.e., filler content (wt%) and speed for load, tensile stress and flexural stress values are optimised using grey relational analysis (GRA). Entropy method determines the corresponding weights to each criterion. A grey relational grade (GRG) has shown the improved performance parameter, and the best performance is observed at 10 % filler content with speed of 1 mm/min.

Keywords Wood dust · Reinforced epoxy composite · Mechanical properties · Entropy method · Grey relational analysis

Nomenclature

$X_i'(k)$	Comparability sequence
$X_0'(k)$	Reference sequence
$X_i^*(k)$	Comparability sequence after normalising

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K.N. Das et al. (eds.), *Proceedings of Fourth International Conference on Soft Computing for Problem Solving*, Advances in Intelligent Systems and Computing 336,
DOI 10.1007/978-81-322-2220-0_2

m	Number of experimental data items
n	Number of parameters
Δ'_0	Deviation sequence of the reference sequence and comparability sequence
ξ	Identification coefficient
γ	Grey relational coefficient
ζ	Grey relational grade
D_j	Degree of divergence
Z_j	Weight of entropy

1 Introduction

The rising concern towards environmental problem and the need for more multifarious polymer-based materials have led to increasing interest about polymer composites filled with natural organic fillers, i.e., fillers coming from recyclable sources. The natural fibre composites, also known as green composites, have shown a growth of interest because of their recyclability, biodegradability and abundant availability. In past few decades, natural fibre composite has got immense exposure. Natural fibres are hair-like materials primarily composed of cellulose, hemicelluloses and lignin [1]. These natural fibres provide a substitute for glass fibres and other constituent synthetic fibres (e.g., nylon, polyester, acrylic and polyolefin). Natural fibres are superior to glass fibres as they are less polluting, light in weight resulting improved fuel efficiency than that of glass fibres [2]. The most important advantage of natural fibre is that they are renewable and bio degradable. Not only from nature's point of view but also they are profitable for providing high strength, low weight, corrosion resistance and low processing cost. The major disadvantages of natural fibres are including moisture absorption, thermal degradation, fire and UV (ultraviolet). But this can be deal by maintaining proper blend ratio of chemical additives, using UV stabilizer and fire retardants. [3]. Various properties and application of many natural fibres including bamboo, sugarcane, curaua, date palm, jute, sisal, hemp and wood are studied by different researchers.

Bamboo fibre-reinforced composites have shown better mechanical properties (tensile and flexural strength) than the glass fibre-based composites [4, 5]. Curaua fibres have also shows higher mechanical property [6]. The study of Arundo Donax fillers-epoxy composites shows that the size and content of Arundo Donax fillers yields higher tensile moduli, flexural moduli and lower strength properties of the matrix [7]. The date palm wood flour/glass fibre-reinforced hybrid composites of recycled polypropylene show improved mechanical properties as well as thermal properties [8, 9]. The flexural modulus of coconut fibre polypropylene matrix composite can be improved by using adequate fibre granulometry and extruder screw speed and that of agave fibre-reinforced epoxy composite were significantly high due to alkali treatment of the fibre [10, 11]. The flexural strength and tensile strength of date wood palm flour-based polyethylene composite were decreased by increasing the filler content, while the flexural modulus was increased [12]. The tensile behaviour of jute epoxy laminated composite shows that the tensile strength of jute fibre influences the property of composite [13].

Almost all of the commonly available natural plant fibres that are cheap and abundant in nature are being used for reinforcement in combination with non-biodegradable matrix materials such as unsaturated polyester, epoxy resin, polyethylene and polypropylene [14]. Among these, epoxy resins are very versatile in nature. They are one of the most important classes of thermosetting polymers which are widely used as matrices for fibre-reinforced composite materials and as structural adhesives. They are amorphous, highly cross-linked polymers and this structure results in these materials possessing various desirable properties such as greater tensile strength and modulus, uncomplicated processing, fine thermal and chemical resistance, and dimensional stability [15].

For the natural fibre composite, most of the researches were focusing on experimental test of mechanical properties of natural composites. The correlation between the mechanical properties and the characteristic parameters, e.g., the composition of the composite and the operating conditions, is of prime importance for designing proper composites in order to satisfy various functional requirements. Optimisation of various influencing parameter is very much important. In this study, an attempt is made to analyse the effect of characteristic parameters on mechanical properties of wood dust-reinforced epoxy composites and to find out the optimal combination of parameters. For optimisation process, the various techniques such as genetic algorithm [16], artificial neural network [17], Taguchi method [18] and Multi-attribute decision making (MADM) [19] are available. In the present work, MADM method is used due to its ability to find the best and worst alternative from the given set of data.

MADM is applied for decision-making in multi-criteria problems. MADM has many methods including analytic hierarchy process (AHP), entropy, technique of order preference by similarity to ideal solution (TOPSIS) and grey relational analysis (GRA) [19, 20]. It is very difficult to optimise all the criteria individually. In this respect, grey relational grade (GRG) provides best optimal criteria for multi-decision problem. GRA is used to arrest the correlations among various factors and parameters of a system. Grey stands for uncertain, incomplete or improper. One of the advantages of GRA is that from several factors with inadequate data, quantitative and qualitative relationship can be obtained. This leads to the study of decision analysis field-GRA [20]. Also, the weight of each evaluation criteria is assigned using entropy method. Weights are given by entropy approach. GRA solves MADM problems by combining the entire range of performance attribute values being considered for every alternative into one, single value. This reduces the original problem to a single-attribute decision-making problem. Therefore, alternatives with multiple attributes can be compared easily after the GRA process [20]. The optimisation of machinability of polyester/modified jute fabric composite was done using GRA. Factorial design-based experiments were conducted at different levels of speed and feed rate. Analysis of variance has been used to study the influence of chemical treatment on delamination. GRA is employed to find the optimum drilling condition [21]. The end milling parameter for glass fibre-reinforced plastic using GRA gives a GRG to evaluate the multiple performance characteristics [22]. As a result, optimisation of the complicated multiple performance characteristics can be converted into optimisation of a single GRG.

In this paper, the tensile and flexural properties at different filler contents (wt%) and speed are determined for wood dust-reinforced epoxy composite. Filler content and speed are considered as process parameter in order to determine how it behaves for load, tensile stress and flexural stress. GRA is used to optimise the mechanical properties of wood dust filled epoxy composite.

2 Entropy Integrated Grey Approach

Grey analysis is extensively used to combine multiple decision criteria into one. Grey analysis is done in several steps including data pre-processing and calculation of GRG followed by calculation of grey relational coefficient. Steps for using GRA approach are as follows [20].

A preference sequence is set by $X'_o(k)$, $k = 1, 2, 3 \ldots n$.

In GRA, data pre-processing is done to transfer the original sequence to a comparable sequence. All the criteria are normalised by considering their values within the range of 0–1.

Normalised data with the aim of maximisation can be obtained by

$$X_i^*(k) = \frac{X'_i(k) - \min X'_i(k)}{\max X'_i(k) - \min X'_i(k)} \tag{1}$$

where, $i = 1, 2, 3 \ldots m$ and $k = 1, 2, 3 \ldots n$.

Normalised data with the aim of minimisation can be obtained by

$$X_i^*(k) = \frac{\max X'_i(k) - X'_i(k)}{\max X'_i(k) - \min X'_i(k)} \tag{2}$$

Normalised data with the aim to obtain certain optimum value can be obtained by

$$X_i^*(k) = 1 - \frac{|X'_i(k) - Y'_i|}{\max|X'_i(k) - Y'_i|} \tag{3}$$

Difference between data are obtained by

$$\Delta_0' = X_0'(k) - X_i^*(k) \tag{4}$$

Then $\Delta_{\max}$ and $\Delta_{\min}$ are also calculated.

Grey relational coefficient of 'q' in difference set 'i' is

$$\gamma(q) = \frac{\Delta_{\min}' - \xi\Delta_{\max}'}{\Delta_i'(q) + \xi\Delta_{\max}'} \tag{5}$$

$\Delta_i'(q),\ \Delta_i'$ is the q value. The value of coefficient ξ is between 0 and 1. Generally, the value of ξ is taken as 0.5 in most cases.

Finally, GRG is calculated by

$$\zeta(X_0', X_i') = \sum_{k=1}^{n} \gamma_i\big(X_0'(k), X_i'(k)\big) * w\big((k), X_i'(k)\big) \tag{6}$$

where w is the weight calculates by the entropy approach.

Entropy approach is used to provide weightage to parameters. The algorithm for entropy approach is given below.

- Decision matrix is selected.
  say X_{ij}' $(i = 1, 2, \ldots, m;\ j = 1, 2, \ldots, n)$ is the value of ith alternative to the jth criteria.
- Then the decision matrix is normalised.

$$W_{ij} = \frac{X_{ij}'}{\sqrt{\sum_{i=1}^{m} X'^2}} \tag{7}$$

- Value of F_j of jth criteria is obtained from

$$F_j = -k \sum_{i=1}^{m} W_{ij} \ln\big(W_{ij}\big) \tag{8}$$

  where k = 1/ln c so that 0 ≤ F_j ≤ 1 and c is the number of alternatives.
- Degree of divergence can be obtained by

$$D_j = |1 - F_j| \tag{9}$$

- For jth criteria, weight of entropy is obtained by

$$Z_j = \frac{D_j}{\sum_{j=1}^{n} D_j} \tag{10}$$

3 Materials and Experimental Details

3.1 Materials Used and Preparation of Composites

In this paper, sundi wood dust with particle size 2 μm and density 0.779 g/cc is used. Low temperature curing epoxy resin (Araldite LY 556) which is chemically belongs to 'epoxide' family is mixed with hardener (HY 951) in a ratio of 10:8 by weight. The sundi wood dust particle after proper cleaning and drying is reinforced in epoxy resin (density 1.26 g/cc) for preparing the composite. Then, it is stirred mechanically and gradually poured into the vacuum chamber which is coated with glasspaper of dimension of 125 mm × 25 mm × 5 mm. The system is then cured for 24–48 h at room temperature. Then the fibre-reinforced composite is used for various testing.

3.2 Tensile Test and Flexural Test

Tensile and flexural tests are carried out on the prepared fibre-reinforced composite samples. Testing is done for three different speeds and six different types of filler content. Speeds considered are 1, 2 and 3 mm/min with filler content (wt%) of 0, 2.5, 5, 7.5, 10 and 12.5 %. The tensile test is carried out according to ASTM D 638-03 using universal testing machine with grip capacity of 100 kN. The three-point flexural tests of composites are carried out using universal testing machine as per ASTM D 790-03. The testing is performed at ambient temperature of 24 °C and relative humidity of 53 %. For each filler content (wt%), six specimens are tested to achieve the repeatability in the result. The control factors for the experiment are listed in the Table 1.

Table 1 Control factors used in experiment

	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6	
Control factors	0	1	2	3	4	5	Units
Filler content	0	2.5	5	7.5	10	12.5	wt%
Speed	1	1	1	1	1	1	mm/min
	2	2	2	2	2	2	
	3	3	3	3	3	3	

4 Results and Discussions

4.1 Tensile and Flexural Test Results

The tensile and flexural tests are carried out using six different filler content samples at three different speeds. The variations of load versus filler content, tensile stress versus filler content and flexural stress versus filler content are shown in Fig. 1a–c, respectively. From figure, it is observed that as the filler wt% increases load, tensile stress and flexural stress values and becomes maximum at 10 % filler content by weight, and then these properties decreases and becomes minimum at 12.5 % filler weight. The experimental values of load, tensile stress and flexural stress with filler content and speed are shown in Table 2. The maximum and minimum values of load at 1 mm/min are 3,550.36 and 1,482.08 N, respectively. The maximum and

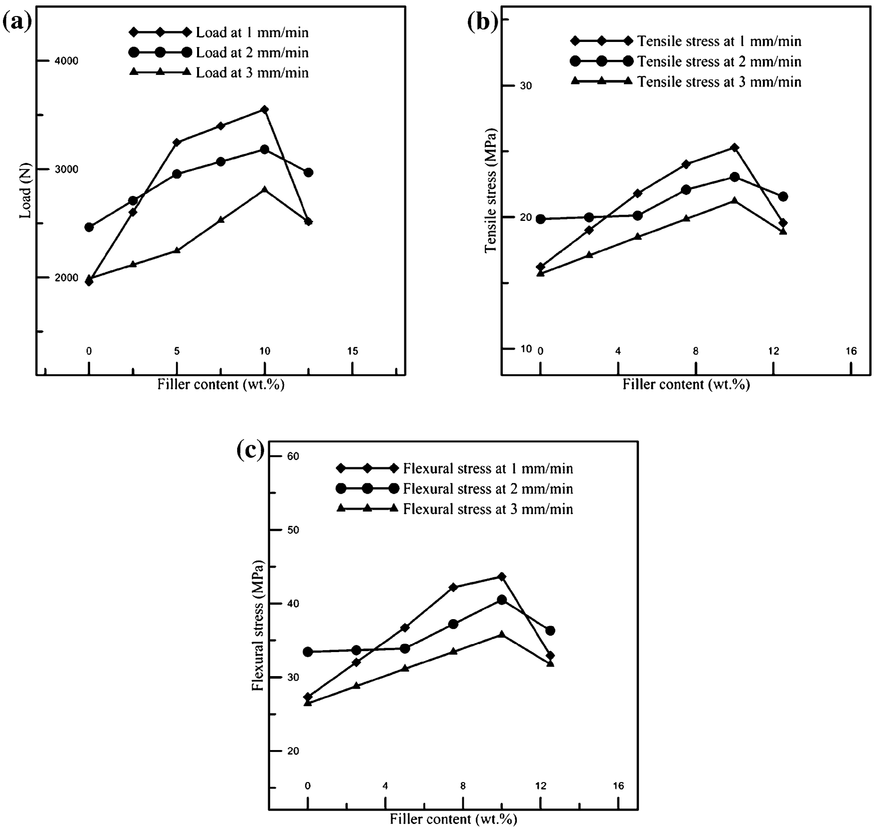

Fig. 1 **a** Load versus filler content (wt%) at various speeds. **b** Tensile stress versus filler content (wt%) at various speeds and **c** Flexural stress versus filler content (wt%) at various speeds

Table 2 Experimental results

Test run	Speed (mm/min)	Filler content (wt%)	Load (N)	Tensile stress (MPa)	Flexural stress (MPa)
1	1	0	1958.54	16.220	27.32
2	2	0	2464.27	19.850	33.43
3	3	0	1989.46	15.690	26.43
4	1	2.5	2602.22	19.010	32.02
5	2	2.5	2709.59	19.985	33.66
6	3	2.5	2117.72	17.085	28.78
7	1	5	3245.91	21.800	36.72
8	2	5	2954.92	20.120	33.89
9	3	5	2245.97	18.480	31.13
10	1	7.5	3398.14	24.015	42.19
11	2	7.5	3068.36	22.085	37.20
12	3	7.5	2527.52	19.855	33.43
13	1	10	3550.36	25.290	43.65
14	2	10	3181.80	23.050	40.51
15	3	10	2809.07	21.230	35.76
16	1	12.5	2516.22	19.560	32.94
17	2	12.5	2969.15	21.560	36.32
18	3	12.5	2512.24	18.860	31.77

minimum values of tensile stresses at the speed of 1 mm/min are 28.29 and 10.83 MPa, respectively. Similarly, the maximum and minimum values of flexural stresses are 47.65 and 18.24 MPa, respectively.

4.2 Entropy Integrated Grey Approach Results

In GRA, experimental data are normalised in the range of 0–1. The main purpose of normalisation is transferring the original data into comparability sequences. Then from normalised data, grey relational coefficient is calculated. The GRG is then computed by averaging the grey relational coefficient and assigning weights using entropy approach to each response, considering equal importance for all the parameters.

The final results obtained by GRA analysis. Normalised sets of data obtained by Eqs. (1)–(3) are presented in Table 3 calculated for as per requirement considering normalised data with the aim of maximisation, minimisation or to obtain certain optimum value. It gives the comparative sequence $(X_i^*(k))$ after pre-processing. The calculation of difference (Δ_0') values for load and stress using Eq. 4 is given in Table 4. From Table 5, Δ_{max} and Δ_{min} values for experimental parameters are 1 and 0, respectively. After calculating Δ_{max} and Δ_{min}, grey relational coefficient can be

Table 3 Normalised data for experimental values

	Load	Tensile stress	Flexural stress
X'_O	1	1	1
1	0	0.055	0.051
2	0.318	0.433	0.406
3	0.019	0	0
4	0.404	0.345	0.325
5	0.472	0.447	0.420
6	0.099	0.145	0.136
7	0.809	0.636	0.597
8	0.625	0.461	0.433
9	0.180	0.291	0.273
10	0.904	0.867	0.915
11	0.697	0.666	0.625
12	0.357	0.434	0.406
13	1	1	1
14	0.768	0.767	0.819
15	0.534	0.577	0.542
16	0.350	0.403	0.378
17	0.635	0.611	0.574
18	0.348	0.330	0.310

Table 4 Deviation of normalised values

	Load	Tensile stress	Flexural stress
1	1	0.945	0.949
2	0.682	0.567	0.593
3	0.981	1	1
4	0.596	0.655	0.675
5	0.528	0.553	0.580
6	0.901	0.855	0.864
7	0.191	0.364	0.402
8	0.375	0.539	0.567
9	0.819	0.709	0.727
10	0.096	0.133	0.085
11	0.303	0.333	0.375
12	0.643	0.566	0.593
13	0	0	0
14	0.232	0.234	0.182
15	0.466	0.422	0.458
16	0.65	0.597	0.622
17	0.635	0.389	0.426
18	0.652	0.67	0.690
Δmin	0	0	0
Δmax	1	1	1

Table 5 Weightage value by entropy method

Load	Tensile stress	Flexural stress
0.333	0.333	0.333

Table 6 Calculation of grey relational coefficient and grey relational grade

Test run	Load	Tensile stress	Flexural stress	Grey relational grade	Rank
1	0.333	0.346	0.3450	0.341	17
2	0.423	0.469	0.472	0.450	11
3	0.337	0.333	0.333	0.335	18
4	0.456	0.433	0.425	0.438	13
5	0.486	0.475	0.460	0.474	9
6	0.356	0.369	0.367	0.364	16
7	0.723	0.579	0.554	0.619	4
8	0.571	0.481	0.469	0.507	8
9	0.379	0.413	0.407	0.400	15
10	0.839	0.790	0.854	0.828	2
11	0.622	0.599	0.572	0.598	5
12	0.437	0.469	0.457	0.455	10
13	1	1	1	1.000	1
14	0.683	0.681	0.733	0.699	3
15	0.518	0.542	0.522	0.527	7
16	0.434	0.456	0.446	0.445	12
17	0.440	0.563	0.540	0.560	6
18	0.434	0.427	0.420	0.427	14

calculated using Eq. 5. Assuming equal importance for all the parameters, GRG is calculated using Eq. 6. Weightage calculation required for GRG formula is done by entropy method using Eqs. 7–10 given in Table 5. The grey relational coefficient and GRG are given in Table 6. Highest GRG indicates the best preferred option. GRG results show that test run number 13 provides optimum process capability. From the Grey analysis, it is found that load value of 3,550.36 N, tensile stress value of 25.29 MPa and flexural stress value of 43.65 MPa show the best option. Corresponding to this, the speed of 1 mm/min and filler content of 10 % provides the optimised value of output.

5 Conclusion

The mechanical properties of sundi wood dust-reinforced epoxy composite were studied under the variation of filler content and speed. The experimental results supported the successful fabrication of sundi wood dust-reinforced epoxy composites based on its tensile stress, flexural stress and load corresponding to different fillers %wt and also confirmed the fact that sundi wood dust possesses can be used as filler with 10 %wt as it improved the tensile and flexural properties of the composite when compared to the polymeric resin. Load, tensile stress and flexural test values are optimised using GRA. Optimisation through GRA has the advantage of selecting best and worst options. GRG shows that test run number 13 is the best suited and test run number 3 is the least important. Epoxy composite with 10 filler contents (wt%) at corresponding speed of 1 mm/min shows best performance and on the other hand with 0 filler content (wt%) at the speed of 3 mm/min shows the worst performance.

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http://www.springer.com/978-81-322-2219-4

Proceedings of Fourth International Conference on Soft Computing for Problem Solving
SocProS 2014, Volume 2
Das, K.N.; Deep, K.; Pant, M.; Bansal, J.C.; Nagar, A.K. (Eds.)
2015, XIII, 668 p. 230 illus., Softcover
ISBN: 978-81-322-2219-4