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Fabrication and mechanical characterization of glass fiber/Al_2O_3 hybrid-epoxy composite

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Abstract. This paper presents the development and mechanical characterization of hybrid composite consisting of glass fiber and aluminum oxide (Al_2O_3) particles reinforced with epoxy matrix. The hybrid Glass Fiber Reinforced Polymer (GFRP) composite has been fabricated using different weight fractions (20%, 30%, and 40%) and different particles size (20 µm, 40 µm and 60 µm) of Al_2O_3 along with chopped E-glass fiber reinforced with epoxy resin matrix, following the hand lay-up method. Further, the mechanical characterization has been carried out through tensile test, impact test, and bending test. The effect of process parameters on mechanical properties of the composite has been studied using response surface methodology (RSM) and analysis of variance (ANOVA). It has been found that an increase in weight percentage of Al_2O_3 particles improves the mechanical properties. However, the increase in size of Al_2O_3 particles shows an adverse effect on mechanical properties. The results have been optimized using the desirability function approach, and validated through a confirmation test.

Keywords. Glass fiber reinforced polymer (GFRP) composite; glass fiber (GF); aluminium oxide (Al_2O_3) particles; epoxy resin; hand lay-up method; response surface methodology (RSM); ANOVA.

1. Introduction

Development and application of composite materials have been a very old practice. Modern composite materials are lightweight, high strength material, having excellent mechanical, thermal, and electrical properties. Due to their extraordinary properties, these composite materials are widely used in aerospace, aircraft, automotive and military industry. The increase in demand of advanced structural material has created interest among researchers to develop high performance, multi-functional composite materials.

The mechanical behavior of composite materials mainly depends upon the quantity, size, and inter-phase fillers reinforced with the polymer matrix. Epoxy is the most widely used structural polymer, which has excellent adhesion, good chemical resistance, high strength and modulus of elasticity, low shrinkage, and ease of processing. However, its brittleness and deterioration of mechanical properties in contact with moisture are the major issues in wide range of applications. To overcome this, the glass fiber can be reinforced with the epoxy. The glass fiber consists of extremely fine fibers of glass having low density, high stiffness, and high elasticity. Over 95% of the fibers used in polymer matrix are glass fibers because they are easy to manufacture, inexpensive, and have good strength and stiffness [1].

The inorganic particles can also be reinforced with the epoxy resin to overcome its limitations. These inorganic materials have light weight, high strength and corrosion resistance, and thus are suitable for application at elevated temperature. The inorganic particles reinforced composites have good strength, stiffness, wear resistance, high melting point, low density and high corrosion resistance. The particles such as aluminum and amorphous materials, including polymers and carbon black are used as particle reinforcement. The particles reinforcement increases the modulus of elasticity, but decreases the ductility of the composite. Particles are also used for reducing the cost of the composite because their ratio of cost-to-strength is low as compared to that of the fibers.

Fabrication of new composite materials or improvement of existing composite material is the real challenge for most of the material engineers. The epoxy based composite materials have good strength and specific properties. In this study, a set of composite materials has been developed by varying the reinforcement to obtain improved mechanical properties. The chopped E-glass fiber with different weight fractions and different particles size of Al_2O_3 has been reinforced with epoxy matrix. Mechanical characterization has been carried out through tensile test, impact test, and

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bending test. The effect of process parameter on mechanical properties of the composite has been studied using RSM and ANOVA. The optimal results have been obtained using the desirability function approach, and validated through a confirmation test.

2. Literature review

There has been the ancient practice of mixing of different materials together to produce a composite material with improved properties, for example mixing of hay into the mud for making stronger mud walls. Similarly mixing of carbon black in rubber, fiber glass in resin, cement with sand, steel rod in concrete, etc. have been very popular examples of the composites. A lot of work on the development and characterization of polymer composites has been reported in recent decades. A brief review of the research is presented below.

Stanford *et al* [2] studied the mechanism of interfacial shear transfer in discontinuous GF composite. Raman spectroscopy and tensile deformation measurements were used for this investigation. Here epoxy was used as the matrix, and diacetylene-urethane as the coating element above glass fiber. Thermally cross-polymerized diacetylene-urethane was coated over the GF composite. Interface shear stress and strain distributions were determined using classical shear leg theory. The restricted value of interfacial shear stress was evaluated with the help of shear yield stress of the matrix. It was observed that fiber fragmentation comes in a picture when matrix strains achieved a peak value. The fragmentation process showed that the number of fragments attained saturation level at a matrix strain level of 1.1% when the maximum value of interfacial shear achieved the shear yield stress 42 MPa of the epoxy at the end of fiber fragments.

Ellyin and Maser [3] investigated the effect of environmental conditions, such as, moisture absorption and high temperature, on the mechanical properties of GF-epoxy composite. The water absorption rate was observed more in the group of samples dipped into high temperature as compared to the group of samples dipped into room temperature. Furthermore, the moisture absorption rate increases with increase in the distilled water temperature, which causes blistering of matrix and generates residual stress. It was also found that cohesion between fiber and matrix diminishes with soaking of moisture. Also, the weight gain of tubular specimens due to the moisture content for water temperature of 20°C and 30°C was obtained to be 0.23% and 0.29%, respectively. The presence of moisture at the interface of fiber and matrix bottoms out the cohesion force between them.

Avci *et al* [4] fabricated the GFRP composites using GF, sand & polyester resin, and determined their mechanical properties and critical intensity factors. Two types of composite specimens were fabricated – (i) sand reinforced in polyester resin (without use of GF), and (ii) sand reinforced in polyester resin in presence of GF. The second type of composites were fabricated at different weight percentage of polyester resins (13%, 14.75%, 16.50%, 18%, and 19.50%) and at a different weight percentage of GF (1% and 1.5%). In both types of composites, the flexural strength and the flexural modulus of elasticity increase with increase polyester content. In addition, the critical intensity factors were also calculated following three methods – initial notch depth method, J- integral methods, and compliance technique. The critical intensity factors have been found to increase with increased GF ratio. Also, the change in the notch-to-depth ratio reflects no influence in critical intensity factors.

Callaghan *et al* [5] studied the wear properties of dental composite. In the composite samples, GF (1.5 or 3 mm in length) was mixed at different weight fraction (2, 5.1, 5.7 and 7.6% of composite material) with resin. Pin-on-disc method was used for testing of samples. The samples having GF (length 3 mm) at 5.7%, yield excellent results, as compared to all other samples. Also, with increase in the length of fibers, the wear resistance of polymer composites can be improved.

Alexopoulos *et al* [6] investigated the health monitoring of glass fiber reinforced polymers (GFRP) by inserting the carbon nano tubes (CNT) fiber in the GF. The composite was fabricated through hand layup method. The conductive CNT fiber was added to the non-conductive GFRP material to enhance its multi-functional ability. The CNT fiber functions as a sensor for both the tensile and compressive loadings. Addition of CNT fiber to the GFRP produces the same tensile and bending strength. Also, the CNT fiber displays good health monitoring and sensing of damaged parts as compared to other fibers. However, an increase in the applied loading beyond the nominal strain of 1.25% or nominal stress 220 MPa, alters the correlation between the stress induced and electrical resistance.

Asokan *et al* [7] obtained the glass fiber reinforced plastic (GRP) by adding three different weight fractions (0%, 5% and 15%) of the waste powder concrete with 2% superplasticizer (Polycarboxylate: 2% of cement content) to improve the mechanical properties of concrete. Two types of curing processes of the concrete specimens were undertaken – water at 20 $\pm$ 2°C and oven at 50 $\pm$ 2°C. Three types of test specimens were prepared – cubical specimens for compressive test, cylindrical specimens for tensile-splitting test, and prism specimens for shrinkage test. The surface texture of the GRP waste powder concrete was analyzed with the help of scanning electron microscopy (SEM). The study indicates that the compressive strength of concrete-GRP so produced, ramps up about 10% as compared to the concrete without GRP. Also, the properties tensile-splitting strength, total water absorption, shrinkage, density, and initial surface absorption of concrete-(15%) GRP appear to be better than the those of the plain concrete.

Rout and Satapathy [8] fabricated the epoxy-GF/rice husk hybrid composite materials by adding rice husk at four weight fractions – 0, 5, 10 and 15%, following the hand layup method, and investigated their mechanical properties. It was observed that the mechanical properties, such as, modulus of elasticity, impact energy, and hardness of the hybrid composites improve with reinforcing the rice husk. On the other hand, the tensile and flexural strength of composites materials decrease with addition of rice husk. Also, the addition of rice husk enhances the erosion wear performance of the epoxy-GF composites.

Nayak *et al* [9] fabricated the epoxy-GF hybrid composites with addition of three types of fillers - Al_2O_3, SiO_2, and TiO_2 through the hand layup method, and tested for mechanical properties. It was found that mechanical properties such as flexural strength, flexural modulus, and inter laminar shear strength of composites ramp up with addition of Al_2O_3, SiO_2, and TiO_2 powder into epoxy resin. The impact energy is observed maximum for Al_2O_3 powder-based epoxy-GF composites as compared to the composites reinforced with SiO_2, and TiO_2 powder.

Rana *et al* [10] fabricated the epoxy sisal/GF hybrid composite using hand layup technique, and obtained their mechanical properties. The GF was mixed with natural fiber polymer composite to improve the mechanical properties of the composite. Two fixed layers of GF were incorporated with different weight fraction of sisal fiber (0%, 2%, 4%, and 6%) into epoxy matrix composite. The resin and hardener were mixed at 15:1 ratio. It was found that the tensile, impact and flexural strength values of the composite increase up to 4% sisal fiber, followed by a decreasing trend beyond this value. This indicates that increase of weight fraction of the sisal fiber beyond 4% does not contribute towards the interfacial bonding between matrix and reinforcement.

Soni *et al* [11] fabricated epoxy-based hybrid composite with GF and milled carbon as the reinforcement, and studied their effect on mechanical properties. Laminates of the composites were fabricated with different weight fraction of the milled carbon (i.e., 1%, 2% and 3%) into the epoxy matrix, with two layers of woven GF. The impact strength and flexural strength values have been found to improve with addition of milled carbon up to 2%, followed by a decreasing trend, while tensile strength keeps improving throughout.

The review of the research presented above reveals that the development & characterization of the glass fiber reinforced polymer (GFRP) composites has been a very interesting topic for research. This study presents a new class of glass fiber/ epoxy composite reinforced with different weight fractions and different particles size of Al_2O_3. The mechanical characterization has been carried out through tensile test, impact test, and bending test. The variation in mechanical properties has been studied using response surface methodology (RSM) and the effect of process parameters on mechanical properties of the composite has been studied by analysis of variance (ANOVA). The results have been optimized by using the desirability function approach and validated through a confirmation test.

The rest of the paper has been arranged as follows. The next section presents the design of experiments. Section 4 gives a discussion on experimental details. Analysis of the result has been carried out in section 5. Optimization of results and validation through confirmation test have been presented in sections 6 and 7, respectively. Conclusions drawn from the research and direction for future work have been presented in section 8.

3. Design of experiment

The Response Surface Methodology (RSM) is the collection of mathematical and statistical techniques useful for modeling and analysis of problems where the response(s) of interest is influenced by several variables (factors), and the objective is to optimize that response. The RSM is quite useful to obtain the first order or second order mathematical model of responses. The response surface analysis is performed using the fitted surface. These response surface designs are typically used to obtain an optimal setting of the controllable factors. In this study, the development of the response surface models has been carried out with the help of statistical software 'Design Expert (DX-7.0.0)'. The basic terminology used in the model development is explained as below.

Process parameters and levels (x) The particle size and weight fraction of Al_2O_3 powder are the process parameters during fabrication of the hybrid polymer composite. The values 20 µm, 40 µm, 60 µm are the levels of particle size, and 20 g, 30 g and 40 g are the levels of weight fraction (for 100 g epoxy resin) of the alumina powder.

Response parameters (y) It is the quantitative output (performance measures) obtained in the experiments based on the set of input parameters. In this study tensile strength, bending strength and impact energy are the response parameters.

Response surface model The mathematical expression representing the true relationship between the response parameter and process parameters given by Equation (1), is the response surface model. The lower order polynomial for the number of process parameter (k) = 2 (based on Taylor's series expansion) takes the form of Equation (2).

$$y = \emptyset(x_1, x_2, x_3, \ldots, x_k) + e \quad (1)$$

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{11} x_1^2 + \beta_{22} x_2^2 + \beta_{12} x_1 \cdot x_2 + e \quad (2)$$

In this study, the experiments have been designed using, face centered cubic design (FCCD) concept. It gives almost as much information as a three-level factorial design with relatively less number of trials [12]. The design involves a total of 13 experiments

4. Experimental details

4.1 *Raw materials*

Epoxy resin (LY 556 based on Bisphenol-A) has been used as the matrix and hardener (Lapox K-5200) as the curing agent. Chopped E-glass fiber and Al_2O_3 particles have been used as the reinforcements. Mechanical properties of the raw materials are given in table 1 [13, 14].

4.2 *Fabrication of composite*

The fabrication of GFRP based hybrid composites has been done through hand layup technique. Initially, seven-ply of E-glass fiber mat were cut into 25 cm × 8 cm with sharp scissors. The Al_2O_3 powder is mixed with neat epoxy and stirred manually using a glass rod for 10 min. After homogeneous mixing, the hardener is added in a ratio 15:1 to obtain the epoxy adhesive mixture.

Now, the first ply is placed inside the mold box and a thin layer of the epoxy adhesive mixture is applied with the help of the brush until it becomes entirely wet with the adhesive mixture. The additional adhesive mixture is added, and the second ply is placed above the first ply to let it become completely wet. This process is repeated until all the seven plies were superimposed. A mild steel roller is rolled over each layer of the composite surface to remove the excess adhesive mixture and maintain uniform thickness.

In this study, the Al_2O_3 powder has been mixed in different proportions (20 g, 30 g and 40 g) and with different particle sizes (20 μm, 40 μm, and 60 μm). Thus, there are a total of nine distinct combinations of the fabricated composites. The samples of the composites have been prepared as per design matrix (columns 2 and 3 in table 2).

The experiments are designed for total thirteen runs as per the design matrix based on face centered cubic design (FCCD). Here the center point corresponds to a composition (40, 30), i.e., 40 μm particles size at 30 gm alumina powder (for 100 g epoxy resin). As per requirements of FCCD design, the center point needs to be replicated additionally four times. This yields a set of total 13 experiments, one each corresponding to 8-vertices, and five corresponding to the center.

Table 1. Mechanical properties of raw materials.

Properties	Glass fiber	Al_2O_3	Epoxy
Density (mg/mm^3)	2.55	3	1.54
Young's modulus (GPa)	72–85	215–413	3.4–4
Shear modulus (GPa)	30–36	88–165	1.12–1.35
Bulk modulus (GPa)	40–50	137–324	2.25–3
Poisson ratio (μ)	0.21–0.23	0.21–0.33	0.29–0.33

4.3 *Material characterization-mechanical testing*

In general, the strength of a hybrid GFRP composite depends upon the adhesion between matrix and reinforcement. Mechanical tests are conducted for material characterization of the composites. Mechanical tests, such as tensile test, bending test and impact tests have been conducted to determine mechanical properties of the hybrid GFRP composite for all 13 trial runs.

4.3a Tensile test: The tensile test of GFRP specimens is carried out following the ASTM D638 standard. The test has been conducted at a cross head speed of 10 mm/min. The tensile strength (σ_t) is obtained using Equation (3).

$$\sigma_t = \frac{P}{bt} \tag{3}$$

where σ_t = Tensile strength (MPa), P = Breaking load (N), b = Width of specimen (mm), t = Thickness of specimen (mm).

4.3b Bending test: The three-point bending test is conducted to define the material's ability to resist deformation under flexural load. The bending test is carried out following ASTM D790 standard. The bending test is performed at a strain rate of 10 mm/min. The bending strength (σ_b) is calculated by using Equation (4).

$$\sigma_b = \frac{3PL}{2bd^2} \tag{4}$$

where σ_b = Bending strength (MPa), P = Breaking load (N), L = Support span (mm), b = Width of specimen (mm), d = Thickness of specimen (mm).

4.3c Impact test: The impact test is performed to determine the energy absorbed by the material before failure under sudden loading. This indicates the ability of material to resist deformation/ failure under high speed collision. Impact strength has been determined using Charpy method, i.e. taking the specimen as the simply supported beam. The impact test specimens are prepared as per ASTM D6110 standard.

5. Results and discussions

A set of specimens were prepared, and mechanical tests have been conducted in accordance with the design matrix represented in table 2. The experimental observations – tensile strength, bending strength and impact energy have been presented in columns 4, 5, 6 in table 2.

Table 2. Design of experiments and experimental results (weight of Al_2O_3 powder corresponds to 100 g of epoxy resin).

	Input parameters		Response parameters		
Sl. no.	Particles size of Al_2O_3 (μm)	Weight of Al_2O_3 powder (g)	Tensile strength (MPa)	Bending strength (MPa)	Impact energy (J)
1	20.00	20.00	222.54	288.75	16.00
2	60.00	20.00	209.625	262.25	14.50
3	20.00	40.00	259.54	333.75	20.00
4	60.00	40.00	239.75	311.25	18.00
5	20.00	30.00	243.70	312.75	18.50
6	60.00	30.00	228.21	297.75	16.00
7	40.00	20.00	216.12	275.25	15.00
8	40.00	40.00	248.71	321.75	19.00
9	40.00	30.00	232.29	303.75	17.50
10	40.00	30.00	232.78	302.00	17.00
11	40.00	30.00	231.22	305.25	17.25
12	40.00	30.00	231.55	304.75	17.50
13	40.00	30.00	232.78	305.50	17.00

5.1 *Effect of process parameters on tensile strength*

The empirical relationship between response parameter (tensile strength) and input parameters (weight fraction and particle size of Al_2O_3 powder), i.e., regression equation for tensile strength has been obtained using RSM. The insignificant terms have been removed using ANOVA for 95% confidence level. The regression equation in coded form is given as Equation (5), and that in terms of actual factors is given as Equation (6).

$$\sigma_t = 233.05 - 8.03 \times A + 16.62 \times B \tag{5}$$

$$\sigma_t = 199.25897 - 0.40167 \times \text{Particles size} + 1.66200 \times \text{Weight of particles} \tag{6}$$

Fit summary for tensile test, after manual elimination process, has been presented as analysis of variance (ANOVA) in table 3. The insignificant terms (p-value > 0.05) have been eliminated to obtain the reduced quadratic model.

Following points may be noted.

a. The Model p-value less than 0.0001 implies the model is significant. Also, the coefficients A and B appear to be significant model terms. The p-values greater than 0.05 indicate the model terms are not significant, and have been eliminated.
b. The "Lack of Fit p-value = 0.0563" implies that the Lack of Fit is not significant relative to the pure error. The non-significant Lack of Fit is considered good.
c. The R^2 value, which is the measure of proportion of total variability explained by the model, is equal to 0.9841 ≅ 1, is invariably desirable. Also, the Adj R^2 value (0.9805) ≅ R^2 value (0.9841). The "Adeq Precision" (a measurement of the signal-to-noise ratio) = 56.486, a ratio greater than 4 is desirable. Thus, the resulting ratio indicates an adequate signal. This model can be used to navigate the design space.

The normal probability plot indicates whether the residual terms follow a normal distribution or not. Figure 1 shows that the residuals are normally distributed about a straight line which means that errors are normally distributed.

The surface plot for tensile strength corresponding to process parameters – particles size and weight of Al_2O_3 powder, is shown in Figure 2. The figure shows that with increase in weight of Al_2O_3 particles from lower level to higher level, tensile strength increases, while on increasing particles size of Al_2O_3 particles, the tensile strength decreases.

5.2 *Effect of process parameters on bending strength*

The regression equation for bending strength in coded form is shown in Equation (7), and that in terms of actual factors is shown in Equation (8).

$$\sigma_b = 303.96 - 7.04 \times A + 19.79 \times B + 6.44 \times A \times B - 8.76 \times B^2 \tag{7}$$

Table 3. ANOVA for tensile strength.

Source	Sum of squares	df	Mean square	F-value	p-value prob > F	Remarks
Model	2044.55	2	1022.28	309.61	<0.0001	Significant
A-Particles size	387.21	1	387.21	117.27	<0.0001	
B-Weight of particles	1657.35	1	1657.35	501.95	<0.0001	
Residual	33.02	10	3.30			
Lack of fit	33.02	6	5.50	7.840	0.0563	Not significant
Pure error	2.800E−004	4	7.000E−005			
Cor total	2077.57	12				
SD	1.82		R^2			0.9841
Mean	233.05		Adj R^2			0.9805
C.V. %	0.78		Pred R^2			0.9664
PRESS	69.75		Adeq precision			56.4860

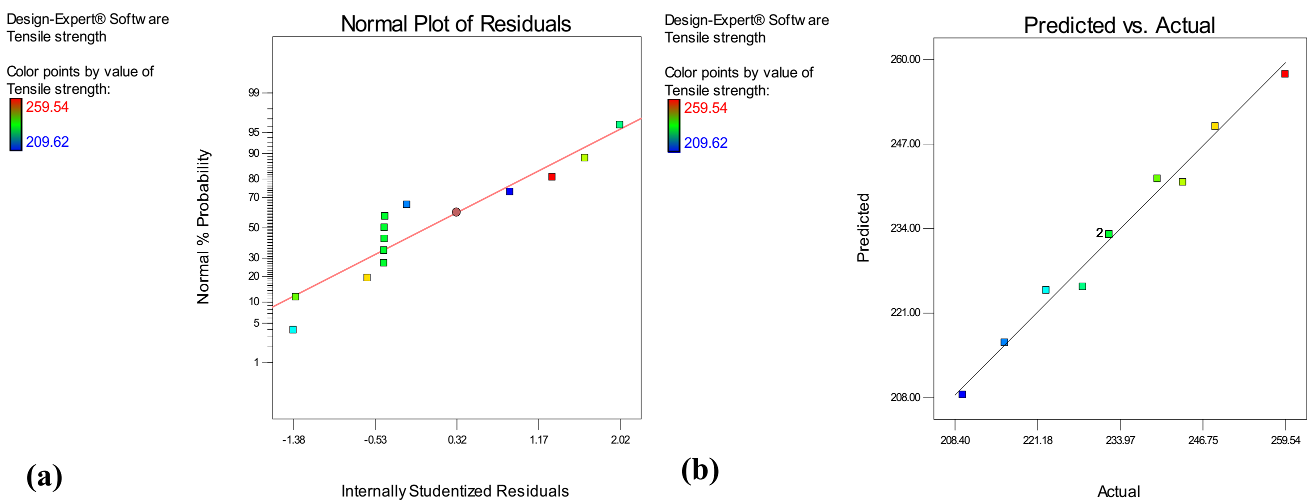

Figure 1. **(a)** Normal plot of residuals. **(b)** Predicted versus actual graph.

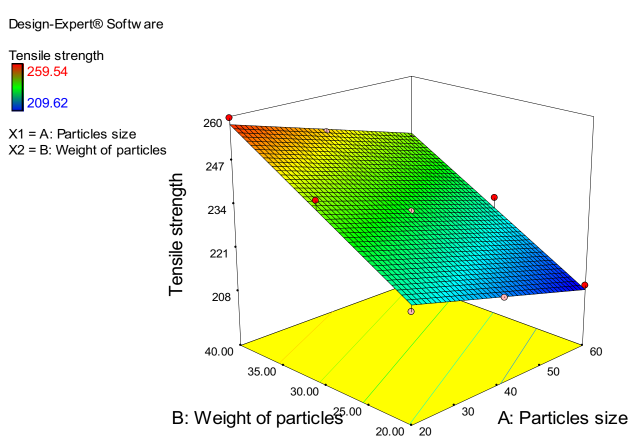

Figure 2. Surface plot for tensile strength corresponding to weight of particles versus particles size.

$$\sigma_b = 218.49405 - 1.31771 \times \text{Particles size} + 5.94524 \times \text{Weight of particles} + 0.032188 \times \text{Particles size} \times \text{Weight of particles} - 0.087560 \times \text{Weight of particles}^2 \quad (8)$$

Fit summary for bending test, after manual elimination process, has been presented as analysis of variance (ANOVA) in table 4. Using manual elimination process, insignificant terms (p-value > 0.05) have been eliminated to obtain the reduced quadratic model.

Following points may be noted.

a. The Model p-value less than 0.0001 indicates the model is significant. Also, the coefficients A, B, AB and B^2 are significant model terms. The p-values greater than 0.05

Table 4. ANOVA for bending strength.

Source	Sum of squares	df	Mean square	F value	p-value prob > F	Remarks
Model	3061.23	4	765.31	82.66	<0.0001	Significant
A-Particles size	297.51	1	297.51	32.13	0.0005	
B-Weight of particles	2350.26	1	2350.26	253.84	<0.0001	
AB	165.77	1	165.77	17.90	0.0029	
B^2	247.69	1	247.69	26.75	0.0009	
Residual	74.07	8	9.26			
Lack of fit	73.64	4	18.41	173.28	0.0678	Not significant
Pure error	0.43	4	0.11			
Cor total	3135.30	12				
SD	3.04		R^2			0.9764
Mean	299.92		Adj R^2			0.9646
C.V. %	1.01		Pred R^2			0.8466
PRESS	480.86		Adeq precision			28.439

indicate the model terms are not significant, and have been eliminated.

b. The "Lack of Fit p-value = 0.0678" implies that the Lack of Fit is not significant relative to the pure error. The non-significant Lack of Fit is always desirable.

c. The R^2 value (=0.9764) $\cong$ 1, is invariably desirable. Also, the Adj R^2 value (0.9646) $\cong R^2$ value (0.9764). The "Adeq Precision" (a measurement of the signal-to-noise ratio) = 28.439, a ratio greater than 4 is desirable. Thus, the resulting ratio indicates an adequate signal. This model can be used to navigate the design space.

The normal probability plot of residuals is shown in Figure 3. The figure shows that residuals are normally distributed about a straight line, which means that errors are normally distributed.

The surface plot for bending strength corresponding to process parameters – particles size and weight of Al_2O_3 powder, is shown in Figure 4. The figure shows that with increase in weight of Al_2O_3 particles from lower level to higher level, bending strength increases, while on increasing particles size of Al_2O_3 particles, the bending strength decreases.

5.3 *Effect of process parameter on impact energy*

The regression equation for impact energy in coded form is shown in Equation (9), and that in terms of actual factors is shown in Equation (10).

$$E_{\mathrm{Imp}} = 17.17 - 1.00 \times \mathrm{A} + 1.92 \times \mathrm{B} \tag{9}$$

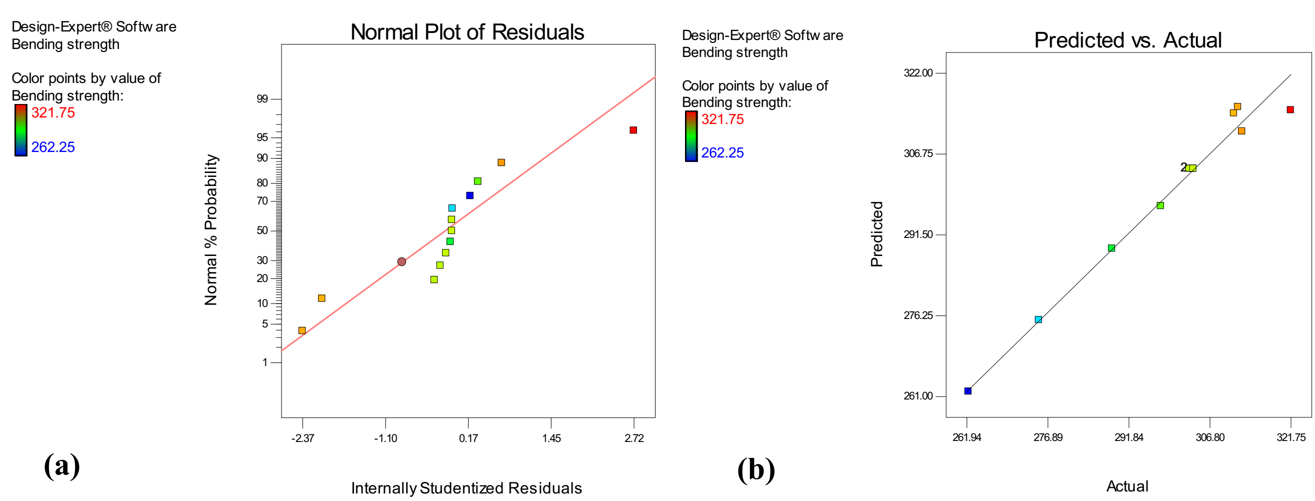

Figure 3. **(a)** Normal plot of residuals. **(b)** Predicted versus actual graph.

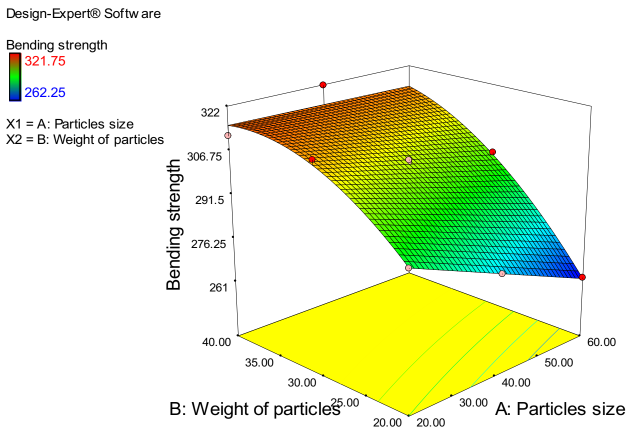

Figure 4. Surface plot for bending strength corresponding to weight of particles versus particles size.

$$E_{\text{Imp}} = 13.42308 - 0.050000 \times \text{Particles size} + 0.19167 \times \text{Weight of particles} \tag{10}$$

Fit summary for impact test, after manual elimination process, has been presented as analysis of variance (ANOVA) in table 5. Using manual elimination process, insignificant terms (p-value > 0.05) have been eliminated to obtain the reduced quadratic model.

Following points may be noted.

a. The Model p-value less than 0.0001 indicates the model to be significant. Also, the coefficients A and B were significant model terms. The p-values greater than 0.05 indicate the model terms are not significant, and have been eliminated.
b. The "Lack of Fit p-value = 0.5178" implies that the Lack of Fit is not significant relative to the pure error. The non-significant Lack of Fit is always desirable.
c. The R^2 value (=0.9780) $\cong$ 1, is invariably desirable. Also, the Adj R^2 value (0.9736) $\cong$ R^2 value (0.9780). The "Adeq Precision" (a measurement of the signal-to-noise ratio) = 48.325, a ratio greater than 4 is desirable. Thus, the resulting ratio indicates an adequate signal. This model can be used to navigate the design space.

The normal probability plot of residuals is shown in Figure 5. The figure shows that residuals are normally distributed about a straight line, which means that errors are normally distributed.

The surface plots for impact energy corresponding to the process parameters – particles size of and weight of Al_2O_3 powder is shown in Figure 6. The figure shows that with increase in weight of Al_2O_3 particles from lower level to higher level, impact energy increases, while on increase in particles size of Al_2O_3 particles, impact energy decreases.

5.4 *General observation*

Mechanical tests have been conducted on specimens of the GFRP hybrid composites to assess the tensile strength, bending strength, and impact strength. In general, similar trends have been observed for all three mechanical properties, as presented below.

1. The mechanical properties – tensile strength, bending strength and impact energy of the hybrid GFRP composite increase with increase in the weight percentage of Al_2O_3 particles. This may be primarily due to improvement of the interfacial bonding between glass fiber and epoxy matrix, resulting from the addition of Al_2O_3 particles. This helps in increasing the load bearing capacity i.e., transfer the load from matrix to glass fiber.
2. The mechanical properties of the hybrid GFRP composite decrease with increase in the particles size of Al_2O_3 particles, possibly because of decrease in adhesion force between GF and epoxy resin.

Table 5. ANOVA for impact energy.

Source	Sum of squares	df	Mean square	F value	p-value prob > F	Remarks
Model	28.04	2	14.02	222.06	<0.0001	Significant
A-Particles size	6.00	1	6.00	95.03	<0.0001	
B-Weight of particles	22.04	1	22.04	349.09	<0.0001	
Residual	0.63	10	0.063			
Lack of fit	0.38	6	0.064	1.02	0.5178	Not significant
Pure error	0.25	4	0.063			
Cor total	28.67	12				
SD	0.25		R^2			0.9780
Mean	17.17		Adj R^2			0.9736
C.V. %	1.46		Pred R^2			0.9616
PRESS	1.10		Adeq precision			48.325

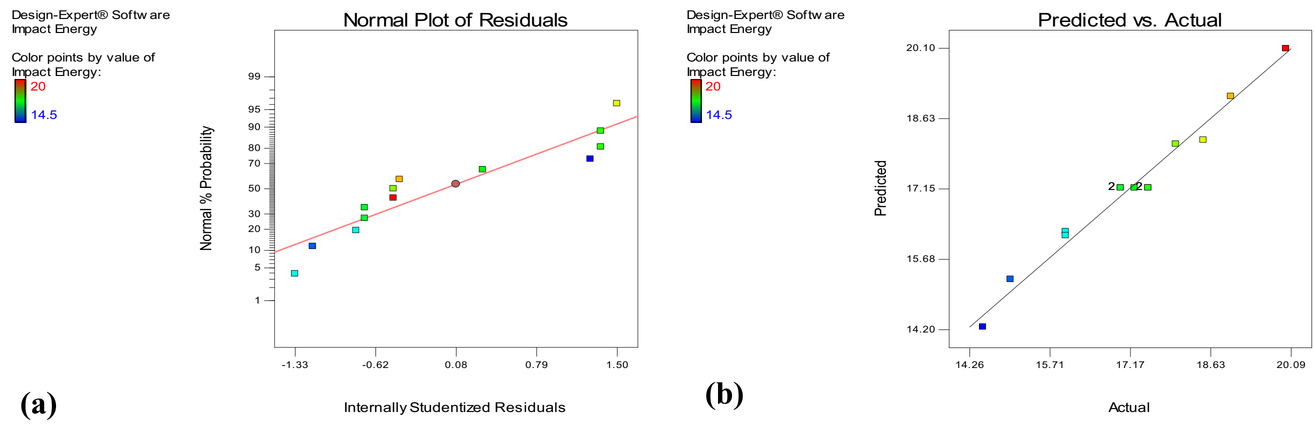

Figure 5. **(a)** Normal plot of residuals. **(b)** Predicted versus actual graph.

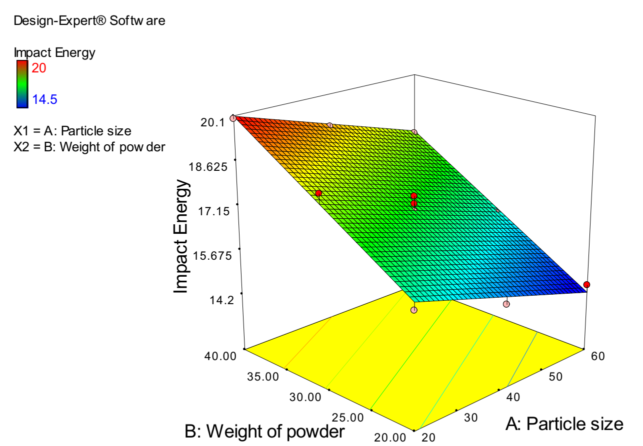

Figure 6. Surface plot for impact energy corresponding to weight of particles versus particles size.

6. Optimization

The optimization of multiple responses can be attempted making use of desirability functions [15]. This is a two-step procedure given below.

- Conversion of each response y_i into an individual desirability function d_i such that $0 \leq d_i \leq 1$. Here, "$d_i = 0$" corresponds to the response being outside the acceptable region, and "$d_i = 1$" corresponds to the response y_i at its target
- The design variables are chosen to maximize the overall desirability, defined by Equation (11).

$$D = (d_1 d_2 \cdots d_m)^{1/m} \tag{11}$$

where, 'm' is the number of responses.

The objective is to obtain an optimal parameter setting that maximizes the overall desirability function for maximum tensile strength, maximum bending strength, and maximum impact energy. Table 6 shows the possible

Table 6. Optimal solutions – possible combination of particles size and weight of Al_2O_3 particles to yield the maximum of all three mechanical properties.

Number	Particles size (μm)	Weight of particles (gm)	Tensile strength (MPa)	Bending strength (MPa)	Impact energy (J)	Desirability	Remarks
1	20.00	40.00	257.706	320.442	20.0897	0.952	Selected
2	20.00	39.76	257.300	319.625	20.0430	0.950	–
3	20.00	39.49	256.854	318.994	19.9916	0.947	–

Table 7. Confirmation test.

Response	Predicted value	Experimental value	Error (%)
Tensile strength (σ_t, MPa)	257.706	259.54	0.7066
Bending strength (σ_b, MPa)	320.442	333.75	3.985
Impact energy (E_{Imp}, J)	20.0897	20.00	0.4485

combination of particles size of Al_2O_3 particles and weight of Al_2O_3 particles to yield the maximum of all three mechanical properties.

7. Confirmation test

The tabulated data in table 6 indicates the highest value of the desirability function corresponding to the trial run already conducted at Sl. No. 3 in table 2. Thus, the experimentally obtained values of the mechanical properties can directly be compared with predicted values (table 7). The tabulated data shows that the predicted and experimental values of all three mechanical properties are in close agreement, and the error is nominal.

8. Conclusion

In this study, GF and Al_2O_3 particles reinforced hybrid epoxy composite has been fabricated by hand lay-up method. The mechanical testing of the composite material indicates following characteristics.

- The mechanical properties – tensile strength, bending strength and impact strength of hybrid GFRP composite increase with increase in the weight fraction of Al_2O_3 powder. This may be due to increase in the interfacial bonding between GF and epoxy resin caused by addition of the Al_2O_3 powder.
- The mechanical properties – tensile strength, bending strength and impact strength of hybrid GFRP composite show a decreasing trend with increase Al_2O_3 particle size. This reflects the decrease in the adhesive force between GF and epoxy with increase Al_2O_3 particle size.
- The confirmation test shows that the error between predicted and experimental values of tensile strength, bending strength and impact energy is 0.7066%, 3.985% and 0.4485%, respectively which are in an acceptable range.

Following issues may be addressed in future course of research.

- Fabrication of symmetric and asymmetric hybrid GFRP composite can also be attempted by changing the orientation angle of glass fiber. Testing of mechanical properties of symmetric and asymmetric hybrid GFRP laminate shall be a good contribution.
- Additional mechanical properties of hybrid composite such as hardness, notch fracture characteristics, interlaminar shear strength, and wear properties, etc. can also be investigated.
- The physical properties such as thermal conductivity and coefficient of thermal expansion of hybrid GFRP laminate can also be explored.

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