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Optimizing the Parameters of Epoxy Composites Reinforced with Bismarck Palm Fibre and Cashew Friction Dust Particles

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Abstract

Objective: In recent years, researchers have paid more attention to using natural fibres rather than synthetic glass fibres when manufacturing polymer matrix composites. Therefore, the current study focuses on fabricating and optimizing the parameters for maximizing the Flexural Strength (FS) of an epoxy composite reinforced with Bismarck Palm Fibre (BPF) and Cashew Friction Dust (CFD) particles. **Methods:** The water retting technique was used to extract the BPF from leaf stalk of Bismarck palm tree. The composites were fabricated by hand lay-up method. The process parameters for the research were Fibre Length (FL), Volume Fraction (VF), and CFD particle size (CFD). The experiments were developed using the Central Composite Design (CCD) method. The significance of process parameters on output response of the FS was examined using the response surface methodology (RSM). Using a scanning electron microscope (SEM), the fractured surface of the flexural specimen was examined. **Findings:** The results demonstrated that the optimal parameter conditions for flexural strength were a fibre length of 22 mm, a fibre volume fraction of 24%, and CFD particle sizes of 300 μm. The optimal flexural strength of the produced composite is 46.60 MPa. The most important fabrication parameters that affects the flexural strength of epoxy composites reinforced with BPF and CFD particles is known as the fibre volume fraction. The SEM images showed the various failure mechanisms such as fibre breakage, fibre tear, fibre pull out, fibre/matrix bonding, and matrix breakage. **Novelty:** This research is evidence that BPF and CFD reinforced epoxy composites have higher flexural strength compared to other natural fibres reinforced composites such as date palm fibres, sugar palm fibres, and date palm sheath fibres reinforced composites. The optimal parameter conditions obtained for fabricating epoxy composites reinforced with BPF and CFD particles could be used for further research.

Keywords: Bismarck palm fibre; Cashew friction dust particles; Epoxy; Optimization; Flexural strength

1 Introduction

Researchers and academicians can now examine natural fibres and their composites because of sustainability and increased environmental awareness. The disposal of synthetic fibres manufactured by humans, such as carbon, Kevlar, nylon, aramid, glass fibre, etc., causes environmental problems[1]. Synthetic fibres can be replaced with natural fibres, which is an easy solution. Natural fibres are preferred over synthetic fibres because they have a number of advantageous qualities, including low price, less density, biodegradability, non-toxicity, less weight, ease of processing, renewable, and wide availability. In comparison to synthetic fibres, it also has a significant amount of mechanical strength[2]. Natural fibres are being employed in products like small home appliances, the textile industry, applications in aerospace, the construction industry, electronic components, and automotive components, including bumpers, windshields, doors, and brake friction materials[3]. Several properties determine the strength of a natural fibre reinforced composite. First, the portion of the plant from which fibre is obtained. Further, the environment in which the plant is grows, its chemical constituents (cellulose, hemicellulose, lignin, pectin, wax, etc.), and lastly, the matrix and fibre bonding properties[4].

A new natural cellulose Bismarck Palm Fibres (BPF) was extracted from the leaf stalk of the Bismarck palm tree, and their physical, chemical, mechanical, and thermal properties were evaluated. According to the findings, BPF has superior mechanical and thermal properties compared to other natural fibres because of its higher cellulose content of 70%[5]. Natural fibres are hydrophilic by nature compared to synthetic fibres. The hydrophilic behaviour of natural fibre has decreased the compatibility between the fibre and the hydrophobic polymeric resin during the manufacturing of composite materials[6]. Research has shown that chemical treatments like alkalization, acetylation, silane, benzoylation, etc. can improve the compatibility of resin with fibre, physical, chemical, and mechanical characteristics of natural cellulose fibres[7]. The pineapple leaf fibre (PALF) reinforced-epoxy composites were developed using a hand lay-up method and the mechanical properties were evaluated as per ASTM standard. The maximum flexural strength of the composite was increased with increase of PALF length and volume fraction up to 15 mm and 34 % respectively[8].

Fillers are inserted into polymer matrixes to reduce costs, reduce the tool wear, lessen shrinkage caused by moulds, increase modulus, control viscosity, and produce a smooth finish. The primary elements of natural particulate composites are particles of egg shell, peanut shell, walnut shell, coconut shell, almond, cashew nut shell, rice husk, fly ash, nano clay, areca nut, or other materials[9]. The mechanical properties and environmental friendliness of the polymer matrix are improved by adding natural particles as filler[10]. The liquid from cashew nut shells is polymerized with a curing agent to create cashew friction dust. It is a component of materials used in friction. A dynamometer was used to examine the effects of various cashew friction dust concentrations (5, 10, and 15%) on the tribological behaviour of brake friction materials. It was shown that friction materials containing 10% cashew friction dust were more resistant to fading and more durable[11]. The study investigated the utilization of wood charcoal powder as filler in composites made of jute fibre reinforced unsaturated polyester resin. The results indicated that the composite with a filler concentration of 4 wt% exhibited enhanced tensile strength and thermal stability when compared to composites without any filler. However, in this study, it was shown that increasing the loading of wood charcoal filler beyond 4 wt% resulted in a decrease in tensile strength[12].

The epoxy composites reinforced with Bismarck palm fibre and Cashew friction dust particles were fabricated using the conventional hand layup method. The tensile strength of the fabricated composites was determined, and composite fabrication parameters such as fibre length, fibre volume fraction, and particle size were optimized using the Response Surface Methodology[13]. From the current state of the art, it is obvious that natural cellulose fibres and natural particles have a significant impact on polymer matrix composites. A novel material with good mechanical properties that may be used in automotive applications must be created from natural resources like Bismarck palm fibres and cashew friction dust particles. Only a small number of studies have examined the combination effect of natural cellulose fibre and natural particles reinforced polymer composites. Therefore, the goal of this study is to investigate low-cost composite materials with reinforcement that are made from natural resources. The current investigation includes experimental design, fabrication, determining flexural strength, modeling, and optimization of the flexural strength of epoxy composites reinforced with Bismarck palm fibre and cashew friction dust particles.

2 Methodology

2.1 Materials

The current investigation makes use of BPFs, CFD particles (300, 600 and 900 μm), epoxy resin (LY 556), and hardener (HY 951). Chemicals, such as acetic acid, sodium hydroxide, and benzyl chlorides were utilized to chemically treat the fibres for increasing their compatibility with polymer matrix.

2.2 Fibre extraction, preparation and pre-treatments

BPFs were derived from the leaf stalk of the Bismarck palm tree, which was extracted from locally accessible Bismarck palm trees. The extraction of BPFs used a water retting technique. The fibres are exposed to the sun and allowed to dry out in order to remove the moisture that is contained in them. These fibres are then minced into pieces measuring 10, 20, and 30 mm and collected in three distinct trays. For 30 minutes, the fibres are submerged in distilled water and a 5% sodium hydroxide solution to remove pectin, wax, oils, lignin, cellulose, and other organic substances[14]. The mechanical properties of these fibres are then maximized by soaking them in 4% acetic acid mixed with distilled water for 20 minutes[15]. Then, for 10 minutes, the fibres are immersed in a 5% benzyl chloride solution diluted with distilled water to enhance their thermal stability, strength, and contact with the matrix[16]. These fibres are then dried in the sun after being rinsed several times with distilled water.

2.3 Experimental Design

The mechanical properties of discontinuous and randomly oriented natural fibre reinforced composites made of polymer matrix are influenced by factors like fibre length, fibre volume fraction, and the size of the filler particles. In Table 1, the factors, codes, and related levels are listed.

Table 1. Factors, Codes and their Corresponding Levels

Factors	Codes	Levels		
		-1	0	+1
Fibre length (mm)	FL	10	20	30
Fibre volume fraction (%)	VF	21	24	27
CFD Particle size (μm)	CFD	300	600	900

2.4 Response Surface Methodology

The analysis of a problem using an empirical model is done using a set of statistical and mathematical methods called the response surface methodology. The main objectives of the RSM tool are to reduce the number of tests and enhance the flexural strength of composites. RSM developed empirical models for process variable evaluation. In this study, models were created using the Central Composites Design (CCD) method to optimize the flexural strength of the composites produced. As independent variables in this investigation, Bismarck palm fibre length (mm), Bismarck palm fibre content (%), and cashew friction dust particle sizes (μm) were all employed. Software called Minitab (version 18) was used to plan, analyze, and improve the experiment. 20 tests were included in the CCD design. The following expression represents u as a quadratic expression.

$$u = y_0 + \sum_{i=1}^{n} y_i x_i + \sum_{i=1}^{n} y_{ii} x_i^2 + \sum_{j>i}^{n} y_{ij} x_i x_j + \varepsilon \quad (1)$$

Where $y_o$denotes the linear effect of x_i, y_{ii} denotes the quadratic effect of x_i and y_{ij}denotes the linear by linear interaction between x_i and $x_i x_j$. The cross-product terms, squared terms, and linear terms are all included in the response surface u. The purpose of using this quadratic model of u in this study is not only to look at all of the parameters, but also to find the region of the desired target where the responses are best or close to best. Table 2 presents the design matrix with coded and actual values.

Table 2. Central Composite Design Matrix with Flexural Strength Results

Ex. No	Coded Values			Actual Values			FS (MPa)
	A	B	C	FL (mm)	VF (%)	CFD (μm)	
1	0	0	-1	20	24	300	46.49
2	1	1	-1	30	27	300	40.96
3	-1	-1	1	10	21	900	35.57
4	0	-1	0	20	21	600	38.21
5	1	1	1	30	27	900	40.36
6	0	0	0	20	24	600	46.16
7	0	0	0	20	24	600	46.26
8	-1	-1	-1	10	21	300	36.01
9	1	0	0	30	24	600	44.96
10	0	0	1	20	24	900	45.76

Continued on next page

Table 2 continued

11	0	1	0	20	27	600	42.11
12	0	0	0	20	24	600	46.15
13	-1	0	0	10	24	600	43.83
14	-1	1	1	10	27	900	39.60
15	1	-1	1	30	21	900	36.47
16	-1	1	-1	10	27	300	39.87
17	0	0	0	20	24	600	46.22
18	1	-1	-1	30	21	300	37.32
19	0	0	0	20	24	600	46.16
20	0	0	0	20	24	600	46.21

2.5 Composites Fabrication

A steel mould with dimensions of 250 mm x 250 mm x 3 mm was used to create composites. Composites were easily removed from the mould using silicon spray (a mould release agent). The oldest and most popular method for creating fibre reinforced polymer composite materials with good mechanical properties is hand lay-up. The composites were manufactured according to the composite design matrix presented in Table 2. In a 10:1 ratio, the epoxy and curing agent have been blended. A blended epoxy matrix (70 % volume fraction) has been mixed with chopped fibre and CFD particles according to the experimental design. Following that, the mixture was poured into the moulds. To evenly distribute the mixture and remove any air pockets, a roller was softly rolled over the coating. Then it was covered with the plastic sheet. The mould is then sealed using the top mould plate and put under a 50 kg load for 24 hours. Curing takes place at ambient temperatures.

2.6 Flexural TestAccording to the ASTM D790 standard, flexural tests (three-point bending) were carried out using a servo controlled universal testing machine (Make: FIE Pvt. Ltd., India, Model: UNITEK 94100) designed with a load cell of 100 KN. The flexural tests were performed with a crosshead speed of 2.5 mm/min at room temperature. Flexural testing was performed on a specimen with dimensions of 80 mm x 13 mm x 3 mm and a span length of 48 mm. The following formula is used to determine the flexural strength (FS) of the composite specimens:

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

Where P is ultimate failure load (N), L is the span length (mm), b and d are width and thickness of specimen for flexural test respectively. The before and after fracture of a flexural test specimen are shown in Figure 1 (a) and (b).

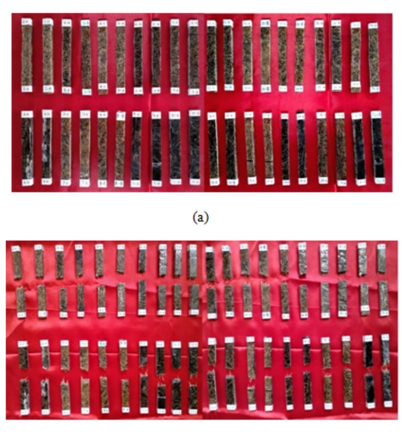

Fig 1. (a) Prepared flexural test specimen and (b) Fractured flexural test specimen

3 Results and Discussions

3.1 Mathematical Modelling

A second order polynomial equation was created using experimental results to determine the FS of fabricated epoxy composites. The significance test for the regression model, individual model coefficients, and for a lack of fit must be performed in order to ensure the quadratic model of FS in the current study is well-fitted. The above tests are summarised using analysis of variance. A typical formula for calculating the F statistic is to divide the mean square for the relevant effect by the mean square error. The probability value decreases with an increasing F statistic value. The terms are significant if this probability is < 0.05, and their inclusion enhances the model. The P value for the regression model can be found in Table 3, and it is shown to be less than 0.05 (which corresponds to a confidence level of 95%). This implies that the model has been thought to have statistical significance. It suggests that the model terms have a substantial influence on the response.

$$FS = -364.18 + 0.8291\,FL + 32.862\,VF - 0.000722\,CFD - 0.018068\,FL*FL - 0.67131\,VF*VF \\ -0.000001\,CFD*CFD - 0.001500\,FL*VF - 0.000031\,FL*CFD + 0.000058\,VF*CFD \tag{3}$$

Table 3. ANOVA Table for Quadratic Model of Flexural Strength

Source	DF	Adj SS	Adj MS	F-Value	P-Value
Model	9	308.948	34.328	11033.94	0.000
Linear	3	40.855	13.618	4377.36	0.000
FL	1	2.694	2.694	865.81	0.001
VF	1	37.326	37.326	11997.80	0.000
CFD	1	0.835	0.835	268.46	0.002
Square	3	267.987	89.329	28713.04	0.000
FL*FL	1	8.978	8.978	2885.68	0.001
VF*VF	1	100.385	100.385	32266.76	0.000
CFD*CFD	1	0.016	0.016	5.22	0.045
2-Way Interaction	3	0.107	0.036	11.43	0.001
FL*VF	1	0.016	0.016	5.21	0.046
FL*CFD	1	0.068	0.068	22.00	0.001
VF*CFD	1	0.022	0.022	7.09	0.024
Error	10	0.031	0.003		
Lack-of-Fit	5	0.022	0.004	2.26	0.195
Pure Error	5	0.010	0.002		
Total	19	308.979			

Table 4 contains the significant parameters and coefficients of all terms. For flexural strength, the important terms are fit to the quadratic model, and the model is found by using Equation (3). As a result of the analysis of variance, the other significant coefficient, R^2, which measures the degree of fit, is described as the explained variation divided by the total variation. The more closely the response matches the real data, the closer the R^2 is to unity. The value of R^2 that was calculated for this model is greater than 0.95, which corresponds to a 99.05% correlation. This value is satisfactory because it is reasonably close to unity. That is, the model explains 95% of the variation in the data. Furthermore, the adjusted R^2 is 98.95%, indicating that the quadratic model is appropriate for representing tensile strength variation as a result of the parameters chosen.

Table 4. ANOVA for Significance of Variables

Term	Coef	SE Coef	T-Value	P-Value
Constant	46.1967	0.0192	2409.24	0.000
FL	0.5190	0.0176	29.42	0.000
VF	1.9320	0.0176	109.53	0.000
CFD	-0.2890	0.0176	-16.38	0.000
FL*FL	-1.8068	0.0336	-53.72	0.000

Continued on next page

Table 4 continued

VF*VF	-6.0418	0.0336	-179.63	0.000
CFD*CFD	-0.0768	0.0336	-2.28	0.045
FL*VF	-0.0450	0.0197	-2.28	0.046
FL*CFD	-0.0925	0.0197	-4.69	0.001
VF*CFD	0.0525	0.0197	2.66	0.024

The normal probability plot reveals if the residuals are normally distributed, in which case all the location points form a line. From Figure 2, there have been some moderate deviations from normality, which are suitable.

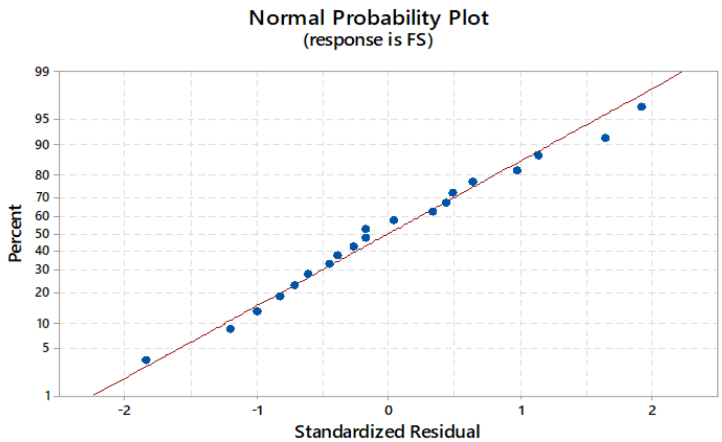

Fig 2. Normal Probability Plot for FS

3.2 Parameters Effects on FS

Figure 3 a to c represent the three-dimensional response surface plots for the combined effect of the composite fabrication parameters on the response of flexural strength of BPF and CFD particle reinforced epoxy composites. The value of flexural strength is very low at the conditions of fibre length (10 mm), fibre volume fraction (21%), and CFD particle size (900 μm). This is caused by inadequate fibre length, a low fibre volume fraction, and a larger particle size. Figure 3 a and c shows that the flexural strength of the composites increased with the increase in fibre length up to 22 mm and decreased with further increase in length. This is due to the fact that the greater fibre length may possess an increased aspect ratio, thereby creating difficulties for the matrix polymer in achieving complete wetting and adhesion to the fibres. Insufficient bonding between the matrix and the fibres might give rise to diminished load transmission, thereby resulting in a decrease in flexural strength[(17)]. According to Figure 3 b and c, the flexural strength of composites increased with an increase in fibre volume fraction up to 24% and then diminished with further increases in fibre volume fraction. This is due to the aggregation of fibres in composites at larger volume fractions, which results in poor resin regions and insufficient bonding between BPF and epoxy. This decreases the transfer of stress from matrix to fibre in composite materials, resulting in low flexural strength[(18)]. From Figure 3 a and b, it is observed that flexural strength of composites increased with decrease in CFD particle size. The greatest flexural strength of the composites was obtained with a CFD particle size of 300 μm. This is due to the fact that the CFD particle size of 300 μm has more surface area interaction with epoxy matrix. As a result, a strong interconnected zone between the CFD particle size of 300 μm and the epoxy matrix is formed[(19)]. It is observed from the results the parameter of volume fraction has the most effect on the flexural strength of the BPF and CFD reinforced epoxy composites, followed by the fibre length and CFD particle size. The composites with a fibre length of 22 mm, a fibre volume fraction of 24%, and a CFD particle size of 300 μm exhibited the highest flexural strength of 46.60 MPa.

3.3 Microstructure Analysis of the Composites

The fracture surfaces of the BPF and CFD reinforced composites after the flexural test have been shown in Figure 4 a to c. From Figure 4 a, the SEM image indicates that there was matrix breakage, the presence of CFD particles, and a hole left after the fibres

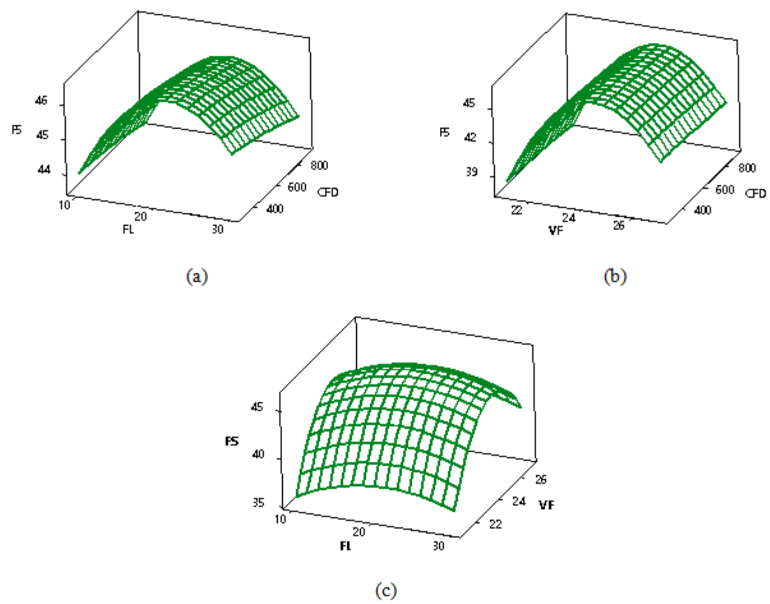

Fig 3. (a) Effect of FL and CFD on FS, (b) Effect of VF and CFD on FS, and (c) Effect of FL and VF on FS

detached from the matrix due to poor interfacial strength between the matrix and the fibres. This interfacial strength can be enhanced by increasing the fibre length to 20mm, the fibre volume fraction to 24%, and decreasing the CFD particle size to 300 μm. The fibre breakage is visible in the Figure 4 b SEM image, and there is no fibre detached from the matrix. This is evidenced by the good interfacial strength between the fibres and matrix. Figure 4 c SEM image shows a large number of holes in the fractured surface specimen after the fibres detached from the matrix. This is due to the accumulation of fibres when increasing the fibre length to 30 mm, the volume fraction to 27 %, and the CFD particle size to 900 μm.

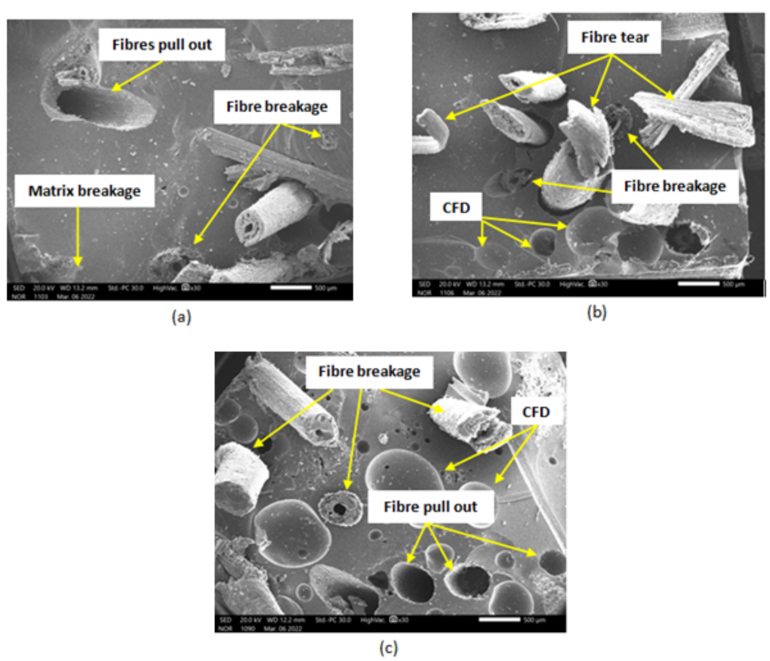

Fig 4. SEM images (a)(10mm/21%/300μm), (b) (20mm/24%/300μm), and (c) (30 mm/27%/900 μm).

3.4 Optimization of FS

The process parameters of the epoxy composites reinforced with BPF and CFD particles were optimized using the Response Surface Methodology. Further, the maximum flexural strength of the composites was determined under optimal parameter conditions. At the parametric conditions of 22 mm FL, 24% VF, and 300 μm CFD particle size with a desirability value of 0.96, the maximum FS of 46.60 MPa was obtained. Figure 5 shows the optimal parameters for flexural strength of the fabricated epoxy composites reinforced with BPF and CFD particles.

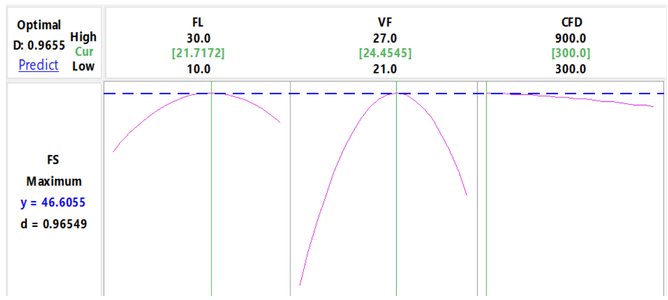

Fig 5. Optimization plot for FS

3.5 Confirmation of Experiments

Confirmation tests are required to verify the validity of the response surface equation. With the optimum parameter settings (FL of 22 mm, VF of 24%, and CFD particle sizes of 300 μm), the experiments were run in triplicate. The results, which are shown in Table 5, show that the RSM technique could be used with mathematical experimental design to successfully optimize process parameters for the FS of fabricated epoxy composites. The outcomes agree more with those of the response surface analysis.

Table 5. Confirmation Experiment Results

Ex. No	FL (mm)	VF (%)	CFD (μm)	Flexural Strength (MPa)		Error (%)
				Predicted	Actual	
1					45.12	2.6
2	22	24	300	46.34	45.73	1.3
3					45.21	2.4

4 Conclusion

In this study, the BPF and CFD particle reinforced epoxy composites were developed by hand layup technique, and the responses of FS were obtained from experimental results. A mathematical model was created for optimizing the composite fabrication parameters employing the Response Surface Methodology. Following are the findings of this investigation:

1. The maximum FS of 46.49 MPa was obtained under the specified parameter conditions of fibre length of 20 mm, fibre volume fraction of 24 %, and CFD particle size of 300 μm.
2. FS value were optimized to be 46.60 MPa under the parameter conditions of 22 mm FL, 24% VF, and 300 μm CFD particle size. For visual optimization, an optimization plot was created to give the manufacturer a rapid visual aid for choosing the proper optimal value for a given set of control parameters in accordance with the requested specifications.
3. The fibre breakage, adherence in between the fibres and the matrix, the existence of CFD particles, and hole left after the fibres detached from the matrix were observed in the fractured surface of the flexural test specimen using SEM.
4. Confirmation experiments were performed to verify the validity of the regression equation for FS. The results are more consistent with those from the RSM.

Based on experimental results, BPF and CFD particle reinforced epoxy matrix composites have higher flexural strength compared to the other natural fibres reinforced composites such as Date palm fibres, Sugar palm fibres, and Date palm sheath fibres reinforced composites. Researchers could use this flexural strength results in comparative studies between Bismarck palm fibres reinforced composites and other natural fibres reinforced composite materials. Such comparisons can highlight the unique advantages and disadvantages of using Bismarck palm fibres, aiding in material selection for specific applications. The utilization of response surface methodology in this work has demonstrated its effectiveness as a tool for analyzing flexural strength.

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