Design and development of false ceiling board composite material using pineapple leaf fibre reinforcement in unsaturated polyester matrix

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ABSTRACT

In this research work, the design and development of false ceiling board composite from unsaturated polyester with pineapple leaf fibre reinforcement are discussed. The composite material was developed by the hand lay-up method according to the proportion of the fibre and the resin. The reinforced material is used at the fabric stage, and the structure of the fabric is plain mat weave. Hence, the optimum proportion of the raw materials was identified by using central composite design and the best results were 30% reinforcement and 70% resin with respect to the better value of physio-mechanical properties of the composite material characterised such as tensile strength, compressive strength, bending strength, water absorption and void fraction. The result showed that the maximum tensile strength is 43.13 N/mm², the compressive strength is 39.78 N/mm², the bending strength is 38.65 N/mm², the minimum water absorptivity is 2.52% and the void fraction is 1.1%.

1. Introduction

Composite material can be defined as a combination of two or more materials that results in better properties than when the individual components are used alone. The two constituents are reinforcement and a matrix. The main advantages of composite materials are their high strength and stiffness, combined with low density, when compared with bulk materials, allowing for a weight reduction in the finished par (Roylance et al. 2019).

The two main components of the composite materials are the matrix phase and reinforcement phase. The matrix holds the reinforcements and helps to transfer load. The matrix combines the individual particles of reinforcement, protecting them against external influences, and prevents their damage. The reinforcing phase provides the strength and stiffness. In most cases, the reinforcement is harder, stronger and stiffer than the matrix. The role of the reinforcement in a composite material is the fundamental one for increasing the mechanical properties (Roylance and engineering 2000).

Nowadays, there are so many fibres which are extracted naturally and used as a reinforcement of composite material, due to lightweight, biodegradability, low cost, eco-friendly nature and superior mechanical properties (Azman et al. 2021; de Azevedo et al. 2021; Khalid et al. 2021). Hence, natural fibres such as jute, coir, sisal, pineapple, ramie, bamboo and banana have been the focus in the development of natural fibre composites, primarily in value-added applications. The versatile material system so developed has potential for wood substitute applications like door shutters, flooring tiles, roofing sheets, partitions, etc. and is envisaged to significantly contribute towards forest conservation and environmental protection (Das and Kalita 2014).

The common fibres used for composite material are extracted from plant sources such as steam, leaf, root and seeds. Pineapple leaf fibre is a type of natural fibre that is extracted from leaf of pineapple plants. Pineapple leaf fibre, which is rich in cellulose, relatively inexpensive and abundantly available, has the potential for use as a polymer-reinforced composite. Compared to other natural fibres, pineapple leaf fibres (PALF) exhibit superior mechanical properties due to their high cellulose content (around 70–82%) and low microfibrillar angle (14°). PALF are obtained from the leaves of pineapple plant Ananas comosus, which is a perennial herbaceous plant and widely cultivated. Recently, PALF have been studied by several authors as a reinforcement in thermoplastic materials such as low-density polyethylene (LDPE), polypropylene (PP) and starch/poly (lactic acid) (PLA) (Taj, Munawar, and Khan 2007; Arib et al. 2006; Hoyos Arango, Jaramillo Quiceno, and Santa Marín 2016).

Therefore, in this research work, composite material with pineapple fibre reinforcement and unsaturated polyester matrix is developed. In addition, to determine the physio-mechanical properties of the composite material such as void fraction, water absorption and mechanical strengths (tensile, bending and compressive).

2. Materials and methods

2.1 Materials

Pineapple leaf fibre was utilised as reinforcement and the primary source of strength in this work, while the matrix holds all the fibres together in shape and transfers stresses between the reinforcing fibres. Unsaturated polyester is used as a matrix in order to hold together the reinforcement and to distribute the applied load on the composite material. Also, caustic soda or sodium hydroxide (NaOH) is used to treat the pineapple leaf fibre, which is used to remove unwanted elements of fibre such as lignin, wax and hemicellulose, and polyamide chemical is used for curing purposes of composite development.
Table 1. Physical and mechanical properties of pineapple leaf fibre (Gebino, Muhammed, and Engineering 2018).

| Properties of pineapple fibre | Result obtained |
|------------------------------|-----------------|
| Linear density (g/cm²)       | 1.35            |
| Length (mm)                  | 250–900         |
| Diameter (mm)                | 61.75           |
| Moisture content (%)         | 12              |
| Tensile strength (Map)       | 228.3           |
| Elongation at break (%)      | 2.45            |

Indeed, based on the result shown in Table 1: physical and mechanical properties of pineapple leaf fibre is good result for natural fibre reinforcement of composite materials are moisture content, length and tensile strength.

2.2. Methods

In this work, the pineapple leaf fibre is extracted by using the scrapping method, because this method is relatively used to obtain the better result of fibre strength than the other materials such as chemical and retting. For this reason, the fibre was treated for 30 minutes with 5 percent sodium hydroxide (NaOH) at a material liquor ratio (MLR) of 1:10 to remove lignin, hemicelulose, wax and oils from the pineapple fibre's external surface. Increasing the compatibility of the reinforcement material with the matrix and improving the mechanical properties of the composite material are two benefits of this process (Benyahia et al. 2013; Li et al. 2007; Naveen et al. 2015; Mohd Nazarudin et al. 2013; Rajeshkumar, Hariharan, and Scalici 2016; Bachchan, Das, and Chaudhary 2021; Girimurugan et al. 2021). After treating and drying the fibre develop plain mat weaves, and the characterised results of plain mat weave are presented in Table 2.

Here, the composites were developed by the lay-up method and the physio-mechanical properties of the composite material were tested according to their standard (Nanda and Satapathy 2017; Gopinath, Kumar, and Elayaperumal 2014; Reddy, Reddy, and Reddy 2018).

2.2.1. Tensile strength

The ASTM E 1309 standard specifies basic tension or flat-sandwich tension testing to ascertain this. A cross-head speed of 10 mm/s was used in the universal testing machine Instron 1195, and the tensile strength was calculated as follows:

$$\delta_t = \frac{W_t}{bt},$$

where $W_t$ is the tensile load at failure (N), $b$ is the specimen width (mm) and $t$ is the specimen thickness (mm).

2.2.2. Flexural strength

Testing was conducted using a universal testing machine (Vardhan et al. 2021). The specimens were produced in accordance with ASTM D790. Flexural strength was calculated as follows:

$$T_b = \frac{3WL}{2bt^2},$$

where $W$ is the load at failure (N) and $L$, $b$ and $t$ are the length, width and thickness of the samples (mm).

2.2.3. Compressive strength

The compressive strength of composite materials is tested using a thin, flat rectangular test specimen such as laminate panels, following ASTM D695. The calculation method is shown as follows:

$$T_c = \frac{W_c}{bt},$$

where $W_c$ is the failure load in N, while $b$ and $t$ are the sample’s width and thickness in mm.

2.2.4. Density and void fraction

Weight ratio techniques were used to calculate the composite’s theoretical density. Archimedes’ principle was used to determine the composites’ densities. This concept states that when an item is submerged in a liquid, the apparent weight loss is equal to the liquid’s displacement. Based on ASTM standard D792, distilled water was used to conduct the test. Composite density is computed as follows:

$$\rho_a = \frac{\rho_w W_a}{W_a - W_w},$$

where $W_w$ is the sample weight in air, $W_a$ is the sample weight in water and $\rho_a$ is the actual composite density.

Volume fraction calculation is shown as follows:

$$V = \frac{(\rho_a - \rho_w)}{\rho_t}.$$  \hspace{1cm} (5)

The theoretical and actual densities of the composite material are denoted by $t$ and $a$, respectively.

2.2.5. Water absorption

The tests were performed in compliance with ASTM D570 guidelines.

Afterwards, the samples were put in distilled water that was kept at a constant temperature of 25°C (77°F) for 24 hours. The following is the water absorption amount:

$$\% W = \frac{W_t - W_o}{W_o} \times 100.$$  \hspace{1cm} (6)

When the composite has been submerged in water, its weight is $W_t$, and when it has dried, its weight is $W_o$.

3. Experimental results and discussion

After produce the product test the physio-mechanical property by cutting the sample size according to the specimen size standard of testing machine result shown as follows in Table 3.

Table 2. Plain mat weave thread density tested result.

| Thread type          | EPI | PPI |
|----------------------|-----|-----|
| Warp thread density  | 10  |     |
| Weft thread density  |     | 8   |
Table 3. Tested results of physio-mechanical properties.

| Run No. | Factor 1 | Factor 2 | Response 1 | Response 2 | Response 3 | Response 4 | Response 5 |
|---------|----------|----------|------------|------------|------------|------------|------------|
|         | A: Fibre (%) | B: Resin (%) | Tensile Strength (N/mm²) | Compressive Strength (N/mm²) | Bending Strength (N/mm²) | Water Absorption (%) | Void Fraction (%) |
| 1       | 20       | 80       | 42.65      | 38.43      | 37.32      | 2.91       | 1.1        |
| 2       | 27       | 73       | 42.84      | 38.96      | 37.89      | 2.73       | 1.2        |
| 3       | 25       | 75       | 42.81      | 38.68      | 37.72      | 2.64       | 1.1        |
| 4       | 30       | 70       | 43.13      | 39.76      | 38.65      | 2.52       | 1.1        |
| 5       | 24       | 76       | 42.73      | 38.63      | 37.56      | 2.59       | 1.2        |
| 6       | 25       | 75       | 43.03      | 39.24      | 38.04      | 2.72       | 1.4        |
| 7       | 40       | 60       | 42.84      | 38.73      | 38.02      | 3.81       | 1.9        |
| 8       | 37       | 63       | 42.93      | 39.08      | 38.17      | 3.57       | 1.9        |
| 9       | 22       | 78       | 42.66      | 38.42      | 37.44      | 2.61       | 1.3        |
| 10      | 25       | 75       | 43.11      | 39.73      | 38.63      | 2.54       | 1.2        |
| 11      | 25       | 75       | 42.87      | 39.23      | 38.28      | 3.04       | 1.3        |
| 12      | 25       | 75       | 43.09      | 39.69      | 38.61      | 2.57       | 1.3        |
| 13      | 38       | 62       | 42.97      | 38.94      | 38.09      | 3.48       | 1.5        |

According to the response surface method (central composite design), the solution found the best value at fibre 30 % and resin 70 % from experimental results. Hence, the mechanical properties such as a tensile strength of 43.13 N/mm², a compressive strength of 39.76 N/mm² and a bending strength of 38.65 N/mm² and the physical properties such as a water absorption of 2.52 % and a void fraction of 1.1 % fit the model.

3.1. Tensile strength

The tensile strength of the composite material analysed is shown in Table 4. Regarding the analysis, the F-value is 5.07, and it is suggested that the linear regression model is significant and also the p-value of the model was 0.00201 or less than 0.05, which indicates that the model terms were significant. This means that the factors (fibre and resin) affect the tensile strength of the composite materials.

The lack of fit is not significant, and the p-value of 0.0565 indicates that the model terms are not significant, which means that the result of centre point (fibre 25 % and resin 75 %) is different due to internal and external uncontrolled factors such as void and applied load.

Figure 1 shows the effect of one factor (fibre) loading on tensile strength, and it indicates the fibre percent increases the tensile strength up to the optimum position of the factors. However, the fibre percentage increases above the optimum level and the tensile strength decreases.

Figure 2 shows the 3D surface and helps to identify the optimum position of the factors over the response surface. It also indicates that the fibre and resin increase the tensile strength up to the optimum point.

3.2. Compressive strength

Table 5 shows analysis of the factors (fibre and resin) and its significance on the compressive strength of the composite. The P-value of the model was 0.00416 or less than 0.05, which indicates that the model terms (fibre and resin) were significant. Therefore, the factors have an effect on the compressive strength of composite material.

The lack of fit is not significant, and the p-value of 0.0573 indicates that the model terms are not significant, which means that the result of centre point is different due to internal and external uncontrolled factors.

Figure 3 shows the effect of single factor (fibre) on compressive strength, when fibre percentage increases the compressive strength up to the optimum position.

Figure 4 shows the 3D surface and helps to identify the focal position of the factors (fibre and resin) over the response surface and the best compressive strength. When the fibre and resin increase, the compressive strength also increases up to the optimum point.

3.3. Bending strength

According to 3-point, bending strength of the composite analysis is shown in Table 6. The F-value of the model is 31.88, which suggested that the model is significant, and the P-value is 0.0041 or less than 0.05, which indicates that model terms are significant. The significant model terms are fibre and resin. Therefore, the factors have an effect on the compressive strength of composite material.

The lack of fit is not significant, and the p-value of 0.0584 indicates that the model terms are not significant, which means that the result of centre point is different due to internal and external uncontrolled factors.

Figure 5 shows the effect of fibre on bending strength, when the fibre percentage increases the bending strength up to the optimum position.

Figure 6 shows the 3D surface of the composite and helps to identify the focal position of the factors (fibre and resin) over the bending strength. It also shows that the fibre and resin increase the bending strength up to the optimum point.

Table 4. Analysis of variance for tensile strength.

| Source        | Sum of Squares | Degree of freedom | Mean Square | F-Value | p-value |
|---------------|----------------|-------------------|-------------|---------|---------|
| Model         | 21.11          | 2                 | 10.55       | 5.07    | 0.0020  | Significant |
| A-Fibre       | 13.12          | 1                 | 13.11       | 5.60    | 0.0013  |
| B-Resin       | 7.99           | 1                 | 7.99        | 1.53    | 0.0421  |
| Lack of fit   | 10.22          | 9                 | 1.13        | 0.95    | 0.0565  | Not significant |
Figure 1. Effect of fibre on tensile strength.

Figure 2. The effect of fibre and resin on tensile strength of the composite.

Table 5. Analysis of variance for compressive strength.

| Source    | Sum of Squares | Degree of freedom | Mean Square | F-Value | p-value | Significant |
|-----------|----------------|-------------------|-------------|---------|---------|-------------|
| Model     | 33.24          | 2                 | 16.62       | 10.08   | 0.00416 | Significant |
| A-Fibre   | 23.33          | 1                 | 23.33       | 11.73   | 0.00246 |             |
| B-Resin   | 9.91           | 1                 | 9.91        | 8.42    | 0.00312 |             |
| Lack of fit | 2.33      | 9                 | 0.26        | 2.24    | 0.0573  | Not significant |
Figure 3. The effect of fibre on compressive strength.

Figure 4. The effect of fibre and resin on compressive strength of the composite.

| Source     | Sum of Squares | Degree of freedom | Mean Square | F-Value | p-value | p-value |
|------------|----------------|-------------------|-------------|---------|---------|---------|
| Model      | 32.43          | 2                 | 16.22       | 31.88   | 0.0041  | Significant |
| A-Fibre    | 17.62          | 1                 | 17.62       | 25.82   | 0.0037  |          |
| B-Resin    | 14.81          | 1                 | 14.81       | 37.94   | 0.0043  |          |
| Lack of fit| 1.58           | 9                 | 0.18        | 2.79    | 0.0584  | Not significant |
Figure 5. The effect of fibre on bending strength of the composite.

Figure 6. The effect of fibre and resin on bending strength of the composite.

Table 7. Analysis of variance for water absorption.

| Source    | Sum of Squares | Degree of freedom | Mean Square | F-Value | p-value   |
|-----------|----------------|-------------------|-------------|---------|-----------|
| Model     | 41.35          | 2                 | 20.675      | 19.43   | 0.0035    | Significant |
| A-Fibre   | 25.72          | 1                 | 25.72       | 24.51   | 0.0025    |             |
| B-Resin   | 15.63          | 1                 | 15.63       | 14.34   | 0.0041    |             |
| Lack of fit | 4.98         | 9                 | 0.55        | 1.63    | 0.0583    | Not significant |
3.4. Water absorption

The water absorption samples of each composite type were conditioned before its weight was recorded as the initial weight of the composites. The samples were then placed in distilled water maintained at room temperature (25°C) for 24 hours. The amount of water absorbed by the composites was calculated by using the weight difference of the sample according to the ASTM D570 standard, and the analysis is shown in Table 7.

The F-value of the model is 19.43, which suggested that the model is significant, and the P-value is 0.0035 or less than 0.05, which indicates that the model terms (fibre and resin) are significant. Therefore, the factors have an effect on the water absorption of the composite. In addition, the lack of fit is not significant and the p-value is 0.0583 or greater than 0.05: this means that the result of centre point is different due to internal and external uncontrolled factors. According to Fickian diffusion theory, the presence of the hydroxyl group increases water uptake up to the saturation point (Reddy, Reddy, and Reddy 2018). The relation between fibre loading and water absorption is presented in Figure 7, and it shows that the percentage of fibre loading increases the water absorption.
3.5. Void fraction

The void fraction was calculated based on the result of theoretical and actual densities of the composite ASTM standard D792. The analysis of the void fraction is shown in Table 8. The F-value of the model is 16.41, which suggested that the model is significant, and the P-value is 0.0382 or less than 0.05, which indicates that the model terms (fibre and resin) are significant. Therefore, the factors (fibre and resin) have an effect on the void fraction of composite. However, the lack of fit is not significant and the p-value of 0.0577 indicates that the model terms are not significant, which means that the result of centre point is different due to internal and external uncontrolled factors.

Figure 9 shows that the fibre percentage increases the void fraction up to the optimum level according to statistics results. But at an optimum percentage of fibre and resin, the void fraction was minimum.

Figure 10 shows the 3D view, and the focal position of the factors (fibre and resin) over the response surface and the best (minimum) void fraction are determined.
4. Conclusion

Based on the obtained result, pineapple fibre and unsaturated polyester false ceiling board composite by using the hand lay-up method were used to fill the prepared mould with an appropriate amount of resin mixture and layers of fibres. The optimum proportion result of the factors (fibre and resin) was determined using design of expert (central composite design) software, and the best proportion was 30% fibre and 70% resin. The mechanical properties of the developed product are as follows: a tensile strength of 43.13 N/mm² as per ASTM E 1309, a compressive strength of 39.78 N/mm² as per ASTM D 695 and a bending/flexural strength of 38.65 N/mm² as per ASTM D 790, and the physical properties such as water absorption (2.52 %) and void fraction (1.1 %) are as per ASTM D 570 test standard and ASTM test standard D 792, respectively. Hence, the developed composite material has better physio-mechanical properties than the existing wood-based ceiling board and natural fibre-reinforced composite. Therefore, pineapple leaf fibre reinforced with an unsaturated polyester matrix can possibly be used as false ceiling board materials.

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Disclosure statement

No potential conflict of interest was reported by the author(s).

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Data Availability

In this work, all the relevant data have been included; if you want additional data, you can communicate with the corresponding author.

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