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Optimization of Bamboo Fibre Reinforcement in Green Composites using Response Surface Methodology

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ABSTRACT

At present, materials obtained from nature are adopted with high priority due to exploitation of natural resources of the materials. This work is focused on the use of natural fibre with nano-silica as reinforcement in epoxy resin as a matrix. The polymer composites were developed by mixing an appropriate amount of nano SiO_2 with bamboo fibres. After composite fabrication, specimens of standard size were prepared, and tests related to mechanical properties were performed. 32H composites performed best in the tensile test. The flexural test value for 32G composite was the highest. We found that the 32H composite had better energy absorption capacity. Response surface methodology (RSM) was used to find the optimum composition of composites, and the effects of fibre and nano-SiO_2 on their mechanical properties were investigated. A central composite design was employed to analyse the composite properties. A second order polynomial model was used for predicting strength of the composites. It has been found that the composite was best fit by a quadratic regression model with an excessive co-efficient to determine the R^2 value. Effects of bamboo fibre and nano-SiO_2 were examined using analysis of variance (ANOVA).Experiment found that two-layer natural bamboo fibre with 2 wt.% of silica is of high quality. Nano composites of fabricated natural fibre reinforced polymer has numerous uses in automotive, aircraft, aerospace, sporting, structural, and home appliance industries.

Keywords: Bamboo fibers · Bidirectional woven mat · Nano SiO_2 · Response surface methodology (RSM) · ANOVA · Mechanical properties

I. Introduction

Materials are regarded as the foundation of the manufacturing sector which uses a wide range of composites, alloys, and pure metals. As pure metals are unable to meet the demands of contemporary products, attention is being shifted to the usage of composites. The promising qualities of composites such as significant strength, excellent damping capacity, and high specific modulus render them as one of the most widely used materials in today's manufacturing sector, gradually replacing their traditional counterparts. Composite materials first emerged in the 1920s, initially created by reinforcing them with fiber. Multiphase materials made up of two components or more with unique properties are called composite materials [1]. Epoxy resins have been extensively used over the past century due to their key functional properties, including excellent adhesion, flame resistance, and chemical stability. In the last two decades, significant advancements have been made in epoxy resin technology, making them more versatile and essential in various applications, including paints and coatings, wind energy, construction, composites, and electrical systems. A hardener, typically a viscous liquid, is commonly mixed with epoxy resins to initiate the curing process, which solidifies the wet composite. Once a curing agent is added, the epoxy resin transforms into a stable liquid with a long shelf life [2]. Recent research has focused on further developing epoxy resin composites, building on their already strong performance by modifying and using them as composite matrices [1]. Natural fiber is considered as a feasible substitute because of its advantages over synthetic fiber, namely its excellent strength and elasticity modulus, abundant availability, low cost, low energy requirements, renewability, and biodegradability [3]. Kenaf, jute, flax, sisal, coir, and bamboo fiber are among the plant fibers that are frequently researched [4]. Our endeavor seeks to address the

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paucity of studies on bamboo fiber composites. Due to its low density, high stiffness, excellent strength, and rapid growth leading to its abundance, bamboo fiber has emerged as the most prominent among all natural fibers [5]. For instance [6], explored the mechanical properties of bamboo fiber (BF) composites filled with epoxy resin at varying fiber weight percentages (9, 13, and 18 %) and curing temperatures (26, 38, and 50 ◦C). The impact of fiber loading on the mechanical qualities of bamboo mesoparticle/nylon 6 composites at an average size of 0.25 lm and fiber loadings of 9, 13, and 18 wt. % was examined by [7]. The fiber loading of 13 wt. % was found to have the best tensile strength and modulus. Flexural strength and modulus increased slightly with the gradual increase of fiber loading from 9 wt. % to 13 wt. %. Proving that the partial addition of bamboo fiber powder has a significant impact on epoxy composite behavior is one of the research's challenges because the even dispersion of the powder can promote a strong bond and enhance the mechanical qualities of epoxy composites. Bamboo is an inexpensive, lightweight, flexible, robust, and high-tensile material usable in the furniture and construction industries, particularly for home usage, packing, and shipping. Natural fibers (NFs) have been recently demonstrated as viable substitutes for synthetic fibers, offering advantages such as low abrasiveness, minimal health risks, excellent sound absorption properties, affordability, and biodegradability. NFs are particularly abundant in emerging nations such as Malaysia, Indonesia, Thailand, and other Asian countries [8]. Among the natural fibers commonly used are kenaf [3,4], rice husk [5], and bamboo [7,9–11,12]. Bamboo, a fast-growing and cost-effective plant, stands out as an excellent raw material for various industries, including polymer composites [13]. Bamboo fiber is especially attractive due to its affordability and wide availability. However, its low thermal stability, similar to other NFs, presents a major challenge, as BF degrades at around 200 ◦C. As a result, bamboo fiber is primarily used as reinforcing filler for resins that cure below this temperature, such as polypropylene (PP), polyethylene (PE), polyvinyl chloride (PVC), polyester (PS) and epoxy resin [14]. Several studies have focused on improving the compatibility of bamboo fibers with polymer matrices through treatment methods. Huynh et al. [15], developed bio composites using Bambusa tulda and cashew nut shell oil-based bio-epoxy resin, using varying NaOH concentrations (2, 4, 6, 8, and 10 %) to determine the optimal treatment for bamboo fibers. Composites were produced with fiber weight fractions ranging from 10 % to 40 %. Similarly, [16] investigated the mechanical properties of BF/epoxy composites produced using compression molding and manual lay-up techniques, treating bamboo strips with NaOH solutions (5, 8, 12, and 15 %) for 12 h. Their findings showed that BF strips treated with NaOH at 8, 12, and 15 % were more compatible with the resin, and that compression molding produced composites with superior mechanical properties compared to the hand lay-up method. Barman et al. [17], studied the mechanical properties of BF derived from Gigantochloa scortechinii and reinforced with epoxy, polyester, and vinyl ester. They treated bamboo splints with NaOH at varying concentrations (0 % to 15 %) and soaking times (0, 24, 48, and 72 h). Their results indicated that BF-reinforced epoxy composites with a 40 % fiber volume fraction achieved the highest tensile and flexural strengths compared to polyester and

vinyl ester composites. This study has used three weight loading (9 %,13 %,18 %)wt % . The weight loading has an effect on the results of all the mechanical tests and the stronger loading of 13 % and particle size 0.52 μm with an optimum tensile strength of 41.6 MPa. An increase in weight loading will increase the tensile modulus of epoxy composite. Previous studies have shown that removing the lignin and cellulose coating of bamboo fibers will weaken their properties [17]. Therefore, it was used with epoxy these ratios in this study for bamboo yielded superior mechanical properties. However, recommendations for future studies include increasing the ratio of bamboo powder to epoxy specifically to achieve optimal results. A powerful statistical approach for optimizing the experimental properties of natural fiber composites is the response surface methodology (RSM). Common RSM techniques include 3-level factorial designs, central composite design (CCD), Doehlert Design (DD), and Box Behnken Design (BBD) [8]. For instance, RSM was used in a previous study [18] to optimize the mechanical strength of bamboo mesoparticle/polyamide 6 (PA6) composites, using particle size, loading, and alkali concentration as variables to achieve the best tensile, flexural, and impact strengths. CCD is widely used in the membrane separation optimization process to determine the ideal state of the experimental parameters. CCD is a preferable method compared to other methods like Box–Behnken design etc., because the CCD methodology gives better information within or beyond the limits of the spinning process, while the BBD method does not give information about the spinning process limitations and cannot be built in two steps from the 2k design (N. Szpisjak-Gulyas et al.2023). (Similarly, [2] explored how the physic-mechanical properties of epoxy/Deleb palm fiber composites were affected by fiber parameters such as reinforcement weight composition and fiber length, optimizing these parameters using RSM to produce the best possible epoxy-Deleb fiber composite. The main novelty of this article is to optimize the mechanical strength of bamboo fiber/epoxy composites through simultaneous parameter optimization. Previous literature is referred to and cited in this article, but using different materials the bamboo fiber and composite materials have been varied in this article. The novelty of this research work was the study of the influence of epoxy resin-reinforced fiber and the optimization mechanical properties of bamboo fibers, . Used central composite design (CCD), we focus on two key parameters namely particle loading and particle powder size to identify the optimal combination. Design-Expert software 12.1.0 was used to ensure the precision of the parametric optimization and statistical analysis, while the mechanical behavior of several composites was investigated under optimal conditions. Thus determining their potential for specific engineering applications.

II. literature survey

2. Materials and methods

2.1. Natural fibers

The main reinforcing component used for the epoxy composite is Gigantochlea Scortechini BF powder, aging three to four years. BF exhibits considerable potential as a replacement for conventional fibers in composite materials such as carbon fiber (CF) and glass fiber (GF) due to its superior mechanical properties [6,19–23]. 2.2. Resin and hardener In order to create the matrix, Epoxy resin was utilized to form the matrix, offering superior binding properties between the fiber layers. The resin used in the current experiment is room-temperature liquid epoxy E-182. As epoxy resins are being widely used for many advanced composites due to their many advantages such as excellent adhesion to wide variety of fibers, good performance at elevated temperatures and superior mechanical and electrical properties. To improve interfacial adhesion and reinforce the composite, a hardener (H-192) was used. This improved hardener was selected due to its high viscosity and rapid pace of cure. The ideal matrix composition was achieved by using a ratio [6].

2.3. Fabrication of bamboo fiber-reinforced epoxy composite (BFRC)

A 3.2 mm thick stainless-steel mold was used to construct the BFRC prototype, and the composite material was mixed by hand as shown in Fig. 1. The BFs were first powdered and then dried in the sun to remove any remaining moisture. In order to avoid the composites from sticking to the mold surface after removal, the mold surface was cleaned and then treated with a silicone release agent spray mold. A total of 100 g of epoxy resin (E-182) and 50 g of hardener (H-192) were added to the BF over the course of 24 h for the BFRC production process. After adding the hardener, the BF powder and epoxy were combined in a container

Fig. 1. Photo of (a) bamboo fibers powder (b) epoxy resin and hardener (c) stirring (bamboo fiber), and (d) molding parts of the tensile specimens.

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and stirred well for 10 min. To achieve a homogenous mixture, the mixture's predicted amount of fibers (ratio 2:1) were stirred again at room temperature for 5 min entailing fibers with particle sizes of 0.25, 0.52, and 1.5 µm. To ensure that the volume of the polymer compound in each sample was the same, we filled the mold with a mixture of BF and epoxy and repeated the operation. Finely, pressed to on top of the mold to remove the trapped air. After that, the liquid was poured into the mold and allowed to cool at room temperature for 24 h to dry and solidify. Fig. 1. Show the method used to convert BF into different size of particles. The BFRC specimens were cured for an entire day at ambient temperature in order to promote cross-linking between the fibers and thermosetting resin [6,20]. After the composite solidified, it was removed from the mold. Three different loadings from BF were used (9, 13, and 18 wt. %). In this study the reason for selecting 9 %, 13 %, and 18 % fiber content, these percentages represent a gradual increase in fiber content, allowing researchers to observe how the material properties change with increasing amounts of bamboo fiber. This step-wise approach helps identify the optimal fiber content that provides the best balance between strength, durability, and workability. Bamboo is a natural and sustainable material, but increasing its content also means higher material usage and possible processing issues. Also, by selecting 9 %, 13 %, and 18 %, in this study can evaluate not just the performance gains but also the cost-effectiveness and practicality of each level. These levels may come from prior studies or standards where optimal mechanical or physical properties (like tensile strength or fracture toughness) were observed within this range. The goal is often to find a sweet spot: maximum performance without negative trade-offs (e.g., processing difficulty, cost, or brittleness).

2.4. BF parameter effect optimization utilizing response surface methodology In this study, the weight fiber 9 to 18 wt. % and particle size 0.25 to 1.5 µm of the BF were formulated to provide the best mechanical strength. RSM was used to examine how the independent variables of particle size (A) and particle loading (B) affected the BF/epoxy composite's tensile strength, flexural strength, and impact strength. In order to acquire models and other parameters that corresponds to the optimization process, these variables for input factors (A and B) and output composite's tensile strength, flexural strength, and impact strength

III. Result and discussion

Model fitting and anova analysis for mechanical properties The experimental results and predicted responses after tensile, flexible

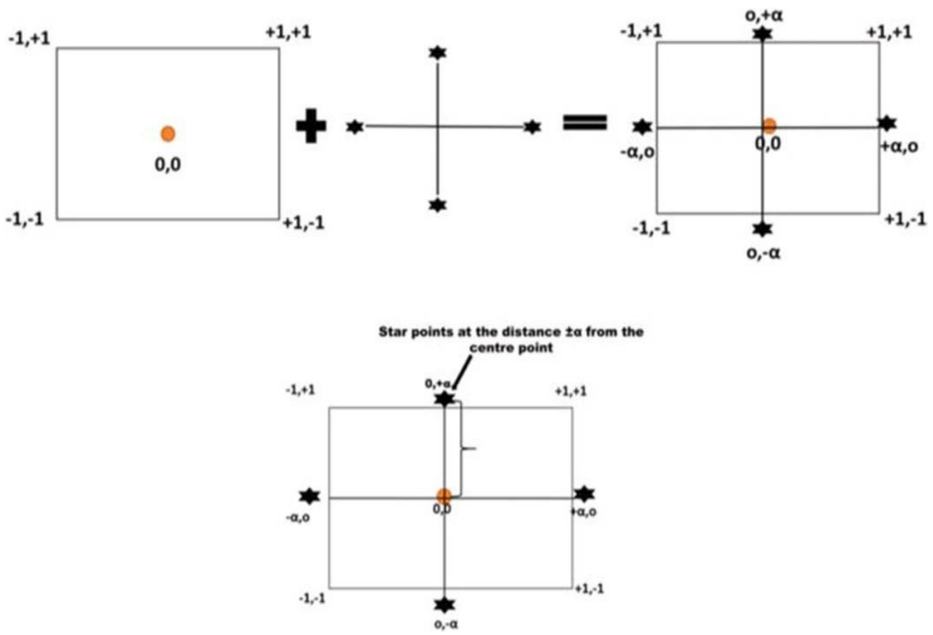


Fig. 2. Dimensions image of specimens, (a) tensile test, (b) flexural test, and (c) impact test.

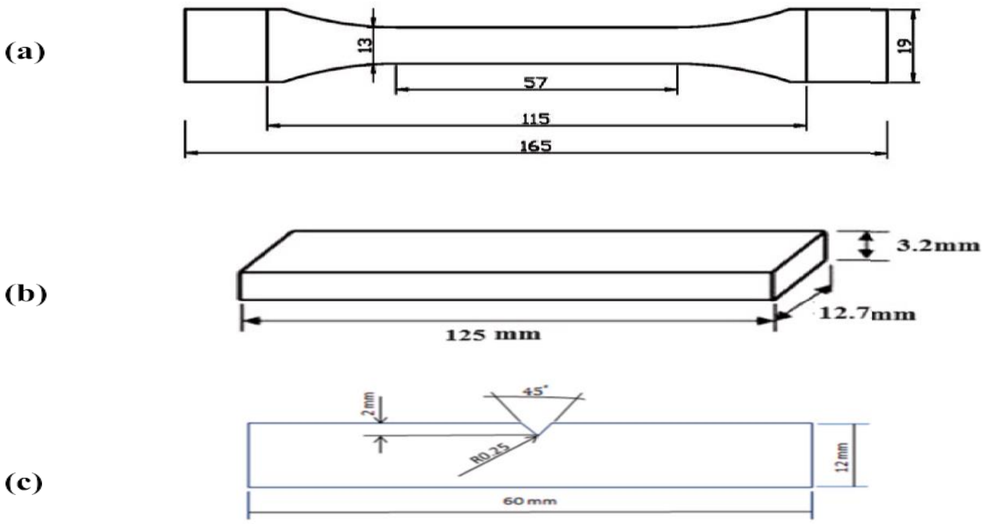


Fig. 3. Dimensions image of specimens, (a) tensile test, (b) flexural test, and (c) impact test.

Table 1 Mechanical properties of bamboo fiber/epoxy composites.

Materials	Strength (MPa)	Strength(MPa)	(J/m^2)
(Epoxy+hardener)+ bamboofiber9%	38.7	89	4640
(Epoxy+hardener)+ bamboofiber13%	41.6	105	4322
(Epoxy+hardener)+ bamboofiber18%	36.1	88	5593

Tensile strength $= - - 3.17447 + 41.84656 \times A + 3.49171 \times B + 0.318222 \times A \times B - - 21.82927 \times A2 - - 0.144546 \times B2$ (1)

Flexural strength

$= +34.07 + 14.2164 \times (A) + 7.5178 \times (B) + 0.8 \times (A) \times (B) - - 8.80941(A)\ 2 - - 0.318(B)\ 2$ (2) Impact strength $= - 3.17447 + 41.84656 \times A + 3.49171 \times B + 0.318222 \times A \times B - - 21.82927 \times A2 - - 0.144546 \times B2$

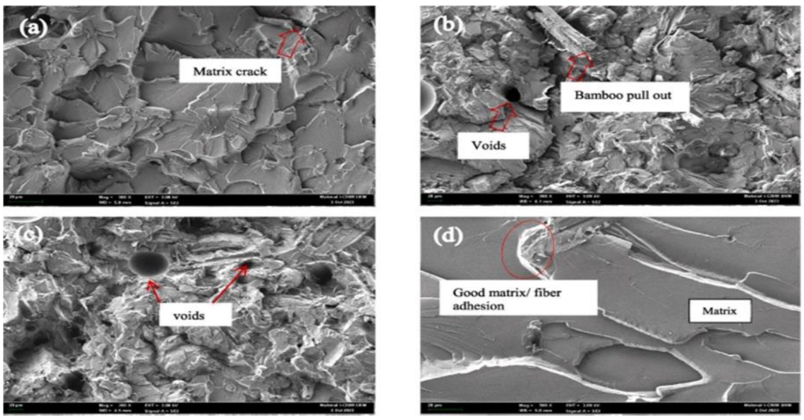
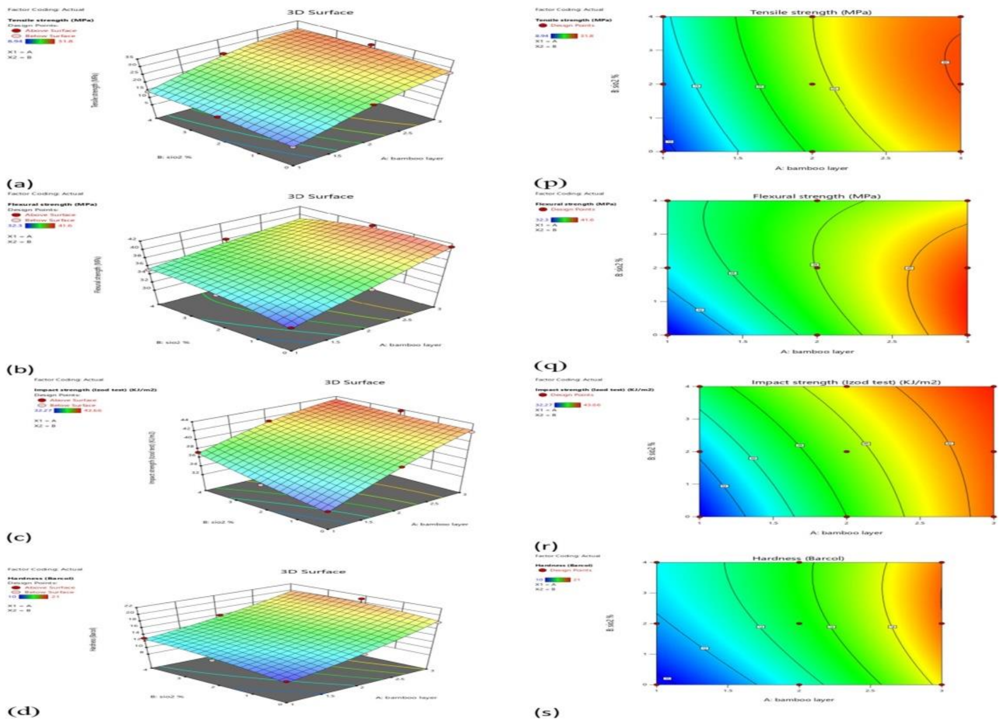


Fig. 4. SEM micrograph of tensile section failure for bamboo fiber/epoxy composites at 500x magnification.

Fig. 5. Typical 3D plots of particle loading (wt. %) versus particle size (μm) on (a) tensile strength, (b) flexural, and (c) impact strength for bamboo/epoxy composite.



IV. Conclusion

In this study, central composite design (CCD) was used to analyze the effects of particle loading and particle size on the mechanical properties of bamboo fiber (BF)/epoxy composites. The two independent variables were fitted with a two-factor interaction model, resulting in a strong relationship between the predicted and experimental values for tensile, flexural, and impact strength, with high agreement between R^2, predicted R^2, and adjusted R^2 values. The optimal parameters for achieving the highest tensile strength were determined to be 13.5 wt. % particle loading and a particle size of 0.875 μm, with a predicted tensile strength of 41.28 MPa, closely matching the experimental value of 41.6 MPa. For flexural strength, the optimal conditions were 13.6 wt. % particle loading and 1.425 μm particle size, yielding an experimental value of 105 MPa, approximating the predicted 95.35 MPa value. The highest impact strength was achieved at 18 wt. % particle loading and a particle size of 1.5 μm, with a predicted impact strength of 5389 J, closely aligning with the experimental value of 5593 J. This study demonstrates that the CCD approach is an efficient and cost-effective method for optimizing the mechanical properties of natural fiber composites within a short time frame. Future research could focus on optimizing matrix modifications, particularly investigating the influence of particle size on the mechanical strength of natural fiber/polymer composites using CCD techniques.

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