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Mechanical Behavior and Predictive Modeling of Phenoplast Composites Reinforced with Abaca, Flax, and Hybrid Fibers

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ABSTRACT

Research on natural fiber-reinforced polymer composites as substitutes for synthetic equivalents has been prompted by the growing need for environmentally friendly engineered materials. The mechanical performance of phenoplast composites reinforced with flax, abaca, and a hybrid abaca–flax structure is examined in this work. Fabricated specimens underwent tensile, flexural, and impact strength testing before being validated using an Artificial Neural Network (ANN) model. The results show that because of synergistic reinforcing, hybrid composites surpass single-fiber composites in terms of tensile modulus (6.3 GPa) and flexural strength (37 MPa). The hybrid composite successfully balanced strength, stiffness, and toughness, but abaca composites showed more impact energy absorption (0.154 J). The ANN model demonstrated a strong capacity to predict mechanical characteristics, as shown by its close agreement with experimental data. In order to optimize natural fiber composites and provide affordable, environmentally friendly solutions for structural and functional applications, this study emphasizes the benefits of hybridization and predictive modeling.

Keywords - *Abaca fiber, Artificial Neural Networks (ANN), Flax fiber, Flexural strength, Hybrid composites, Impact strength ,Mechanical properties, Natural fiber composites, Phenoplast resin, Tensile strength.*

1. INTRODUCTION

Research on polymer-based composites reinforced with natural fibers has intensified recently due to the rising need for high-performance, sustainable engineering materials. Despite their strength and durability, traditional synthetic fibers like glass and carbon have disadvantages including non-biodegradability, high cost, and energy-intensive manufacturing, which is why people are moving toward more environmentally friendly options. [1] The low density, renewability,biodegradability, and affordability of natural fibers like jute, hemp, abaca, flax, coir, and others make them desirable reinforcements for polymer matrices [2,3]. Among matrices, phenoplast (phenolic) resins provide superior dimensional stability, inherent flame resistance, and thermal stability, making them suitable for both structural and functional applications[4,7]. The mechanical, thermal, and morphological behavior of natural fiber/phenoplast systems is documented in a large body of literature. Along with fiber type, orientation, and surface treatment, interfacial adhesion is consistently shown to be a key factor influencing tensile and flexural response [1,3,13]. When structures are well-designed, hybridization—the blending of two or more fibers—can balance stiffness, strength, and toughness and often outperforms single-fiber composites [10,14]. While flax fabrics in phenolic or bio-phenolic matrices achieve competitive tensile/impact properties when fiber content and processing are optimized, abaca and flax have both demonstrated promising tensile and impact behavior in polymer composites; for instance, abaca/PP systems can outperform jute and flax in impact resistance [6,11,12]. Nevertheless, nothing is known about the synergistic impact of mixing flax with abaca, particularly in a phenoplast. As a result, there is still a glaring research gap: thorough side-by-side comparisons of the tensile, flexural, and impact characteristics of abaca-, flax-, and hybrid abaca–flax phenoplast composites are rare, especially when coupled microstructural/interfacial evaluations are required. Furthermore, despite mounting evidence that ANNs can accurately predict composite strength and impact metrics and save experimental time and cost, predictive modeling—particularly Artificial Neural Networks (ANNs)—is underutilized for validating and forecasting mechanical performance in such systems [4,8,9,15–17].

The mechanical behavior of phenoplast composites reinforced with flax, abaca, and their hybrid configurations is examined and contrasted in this work. Fabricated specimens undergo standard tensile, flexural, and impact testing. Following that, an ANN model is developed for predicting these features and its accuracy and predictive ability compared with the experimental results.

2. MATERIALS AND PROCEDURES

Due to its good dimensional stability, flame resistance, and thermal stability, phenolplast resin was selected as the matrix material for structural composite applications. Due to their higher mechanical properties, biodegradability, and natural availability, abaca and flax fibers were selected as reinforcements. Flax fibers deliver higher stiffness and tensile strength, whereas abaca fibers deliver toughness and energy absorption. Abaca and flax fibers were mixed in a predetermined weight ratio to the hybrid composite to leverage their synergetic reinforcing potential. The fibers were washed, dried, and cut to appropriate sizes to facilitate good dispersion in the matrix before fabrication. The composites were formed by hand lay-up followed by compression molding for uniform consolidation. The three specimens prepared were abaca/phenoplast, flax/phenoplast, and hybrid abaca–flax/phenoplast. The specimen for testing were all cut and shaped according to ASTM specification to have uniformity in the evaluation. The tensile, flexural, and impact strength tests were used to evaluate the mechanical performance of the composites. Three-point bending tests were utilized to determine flexural behavior, tensile properties were measured in terms of a Universal Testing Machine, and Charpy/Izod test was utilized to determine impact strength to calculate absorbed energy. Mechanical properties were modeled by an Artificial Neural Network (ANN) model in parallel to experimental testing. Tensile, flexural, and impact strength were the target outputs of artificial neural network (ANN) model, using fiber weight %, specimen geometry, and processing parameters as inputs. Three hidden layers containing 64, 32, and 16 neurons activated by the ReLU function constituted the architecture. The accuracy of the model was verified by comparing the predicted outcomes with experimental values after training was completed using the Adam optimizer with Mean Squared Error (MSE) loss.

3. RESULTS AND DISCUSSION

3.1 Tensile test

The three composites' stress-strain graph (fig. 1) makes it evident how the Flex, Abaca, and hybrid Flex–Abaca phenoplast composites behave mechanically under tensile loading. The first linear section, which represents the elastic deformation zone where the slope matches the elastic modulus, shows that stress rises proportionately with strain. The Abaca composite has the lowest modulus (approximately 3.6 GPa), followed by the Flex composite (about 5.8 GPa) and the hybrid Flex–Abaca composite (about 6.3 GPa), which has the steepest slope of the three. This outcome may be explained by the hybrid composite's synergistic reinforcing, which includes phenolic resin matrix for effective stress transmission, Flex fibers for high tensile strength, and Abaca fibers for toughness. Because Flex fibers are robust, the Flex-only composite has a reasonable amount of stiffness but does not have the hybrid effect. However, since hemicellulose and lignin found in natural lignocellulosic fibers like abaca decrease stiffness, moisture resistance, and interfacial interaction with the matrix, the Abaca composite performs the worst. These results are in line with earlier observations that natural fiber hybridization increases modulus by balancing toughness and strength [18], while single-fiber composites, such Abaca, have stiffness restrictions because of their chemical makeup and worse interfacial adhesion [19].

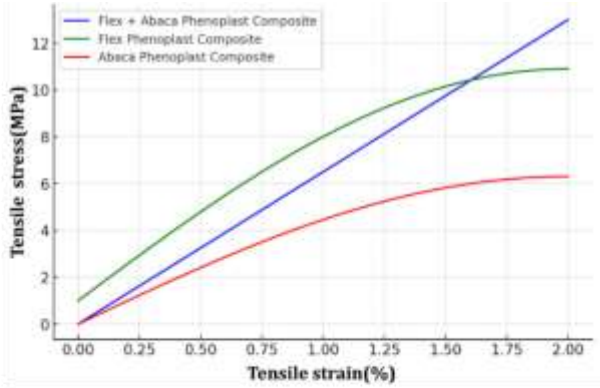

Fig.1 Tensile stress versus strain graph of various graph

3.2 Flexural test

The bending performance of Flex, Abaca, and hybrid Flex–Abaca phenoplast composites is contrasted in the flexural stress–strain graph (fig. 2). Superior flexural strength and stiffness are shown by the hybrid composite's greatest flexural stress, which approaches 37 MPa at 0.8% strain. In comparison to the single-fiber composites, the hybrid curve's first linear part has a steeper slope, indicating a greater flexural modulus. Flex fibers, which provide high tensile stiffness, and Abaca fibers, which contribute ductility and energy absorption, work together to increase stress transfer and resistance to bending loads.

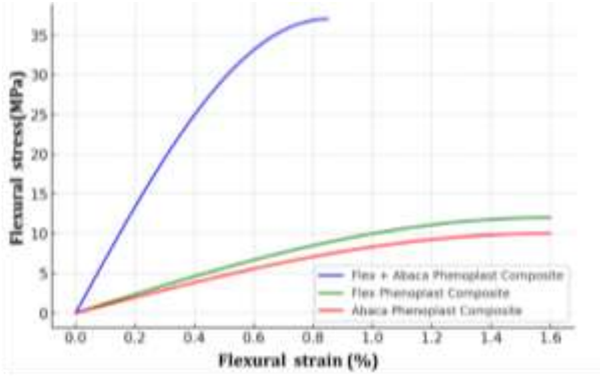

Fig. 2 Flexural stress versus strain graph of various graph

This improvement is known as the synergistic reinforcing effect. The Abaca composite has the lowest flexural strength, at around 10 MPa, whilst the Flex composite demonstrates intermediate flexural performance, with stress peaking at about 12 MPa. Abaca's high hemicellulose and lignin content, which decreases stiffness and bonding with the resin matrix, explains its comparatively poor performance. Strength and toughness are increased by the hybridization effect, which also improves interfacial adhesion and crack-bridging capabilities. Similar results have been documented in the literature, whereby hybrid fiber-reinforced composites exhibit increased strength and flexural modulus as a result of complementing reinforcing methods and better fiber–matrix interaction. [20,5, 8].

3.3 Impact test

The Fig.3 represent the impact strength and absorbed impact energy of Flex, Abaca, and hybrid Flex–Abaca phenoplast composites. From the left chart, it is evident that the Flex–Abaca hybrid composite demonstrates the highest impact strength at approximately 44.4 J/m, compared to Flex (38.9 J/m) and Abaca (36.9 J/m). This improvement indicates that hybridization of Flex and Abaca fibers enhances the material's resistance to crack growth and sudden failure on impact loading. The right graph, which corresponds to absorbed impact energy, shows the same trend. Abaca composite indicates the highest absorbed energy (0.154 J), followed by the Flex–Abaca hybrid (0.139 J) and then Flex (0.137 J). The increased energy absorption of Abaca can be attributed to its increased ductility and elongation of fibers at fracture, while the hybrid has a balance of energy absorption and strength. The enhanced performance of the hybrid composite is the result of the synergy between Flex (stiffness and load-carrying capacity) and Abaca (toughness and energy dissipation), creating enhanced stress distribution and impact resistance. These findings are consistent with previous studies reporting that natural fiber hybridization enhances toughness and resistance to sudden impact failures in polymer composites [15].

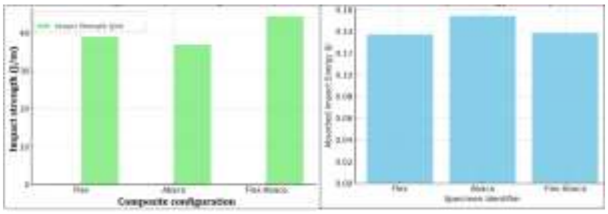

Fig. 3 (a) Impact strength and (b) Absorbed energy

3.4 ANN Prediction

The above graphs (fig.4) show comparisons between experimental and ANN-predicted tensile strength, flexural strength, and impact strength of composites made from phenoplast. The graph 4(a) of tensile strength displays the experimental results in red and predicted results in blue. Both lines are very closely following each other, with a constant increment in strength with respect to the sample index. Only slight deviations at some points (for example, slightly higher value at the lastsample) indicate that while the ANN model slightly underpredicts at higher values, it still captures the overall mechanical behavior with good accuracy. In flexural strength plot 4(b), the simulated values (blue line) are in close agreement with the experimental values (green line). Both plots increase steadily with sample index, and the ANN model shows high precision in recording stiffness and load-carrying capacity of the composites. The negligible deviation indicates that the model performs well to replicate flexural behavior, which is highly dependent on fiber–matrix adhesion. In the graph 4(c) for impact strength, the predicted (blue line) and experimental (magenta line) values are again tracking closely with each other. While minute fluctuations can be seen at the intermediate sample points, the ANN is able to predict the impact strength in all the samples. This shows that the model is capable of explaining energy absorption behavior and toughness, which are typically more scattered due to microstructural flaws or interfacial debonding.

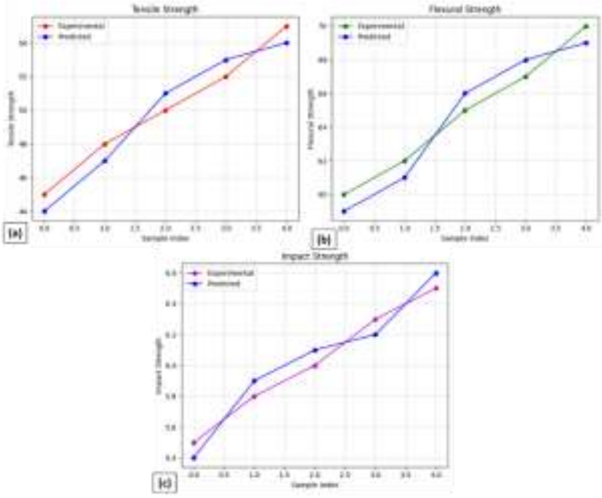

Fig.4 Experimental and ANN-predicted values of (a) Tensile strength,(b) Flexural strength, and (c)Impact strength of phenoplast-based composites.

3. CONCLUSION

This research fully assessed the mechanical properties of abaca, flax, and hybrid composite-reinforced phenoplast composites. The findings distinctly prove that the hybridization increases tensile, flexural, and impact performances over single-fiber systems. In particular, the best stiffness and strength were exhibited by the hybrid composite owing to flax (high tensile stiffness) and abaca (toughness and energy dissipation) complementing roles. While abaca composites had greater impact energy absorption, but with inferior interfacial bonding and stiffness, flax composites exhibited moderate and consistent performance. Importantly, the ANN model successfully predicted tensile, flexural, and impact properties, thus proving its potential as a tool to reduce experimental workload and optimize material design. In short, the findings characterize abaca–flax hybrid phenoplast composites as viable options for sustainable engineering applications that are both environmentally friendly, economical, and mechanistically balanced. Surface fiber treatment and more sophisticated hybridization strategies can be focused on in future work for further enhancements in performance and durability.

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