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Experimental and Polynomial Regression Modelling of Tensile Characteristics of Hybrid Jute/Hemp Fiber Composites

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Abstract

The present study aims to develop hybrid jute-hemp fiber/epoxy composites by the hand lay-up process with 60% of fiber reinforcement and 40 % of matrix ratio. To measure the change of tensile properties, prepared hybrid composites were tested for normal tensile strength and edge notch tensile (ENT) test as per the ASTM standards. Findings show that, developed composites with reported tensile strength followed by comparing it with fracture toughness. Experimentally, tensile strength of the developed composite was measured around 31MPa and fracture performance measured using ENT test value approximated as 4MPa which showed its application in moderate structural and semi-structural functionalities. Tensile test data were used to train a polynomial regression model used to predict load-displacement behaviour and the results were good as demonstrated by residual error analysis and actual over predicted plot. The tensile behavior was well predicted using the polynomial regression model as evidenced by the convergence of the training loss curve and distribution of the prediction errors evident in the plots. The study also plays a part in the design of environmentally friendly material combinations as it proves that natural fiber hybrids can also help reduce the over dependency of utilization of synthetic reinforcements and reduction in the cost.

Keywords: ENT test, tensile test, polynomial regression, hemp-jute composite, tensile properties

INTRODUCTION

Composite materials have become an inevitable part of the modern engineering because of the possibility to unite two or more separate materials to obtain the high-quality properties that cannot be achieved without their combination [1–2]. The materials, which are a mixture of a matrix and a reinforcement phase, are stronger, stiffer, resist corrosion and less heavy, thus applicable in the aerospace, automobile, marine and civil engineering industries [3–5]. The recent decades have seen an increasing interest in the environmental issues, leading the research to focus on natural fiber-reinforced composites as they offer the benefits of biodegradability, low density, renewability, and cost-effectiveness [6–11]. Jute, hemp, sisal, flax, and bamboo are some of the natural fibers which are being utilized in automotive interiors, construction materials, and consumer products because they have acceptable mechanical properties and have lower environmental impact than synthetic fibers [12–13], [14]. These include jute and hemp which have shown promise as reinforcement materials because

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of the favorable mechanical performance and availability [12]. Sustainable and enhanced mechanical and environmental characteristics are offered by natural fiber–reinforced composites. Hybrid composites like kenaf/banana and palmyra-coconut, with agro-waste fillers, boost strength, stiffness and wear properties, while areca fiber composites with ceramic fillers also offer enhanced properties.

Moreover, incorporation of recycled waste materials in thermoplastics supports circular economy and maintains performance. So, these are lightweight, economical, and environmentally friendly solutions for engineering [15–19]. Factors that affect the mechanical behavior of hybrid composites include the type of fibre, the orientation, volume fraction, interfacial bonding, and the processing methods [19–20]. Some of the important properties include flexural strength and fracture behavior which are important in the determination of performance when bending loads are applied and to crack propagation resistance. Despite experimental investigations that have shown an increase in the mechanical properties, fabrication variability and material variability are still problematic [14, 21]. Here, the data-driven modelling methods are becoming more popular in predicting composite behaviour. Regression techniques allow the creation of relationships between input parameters and output responses and the use of a polynomial regressor is an effective approach to nonlinear material behaviour and the need to conduct extensive experimental testing.

Although the field of natural fiber-reinforced and hybrid composite has achieved significant advances, there are still a number of research gaps. The majority of research done so far has mainly dealt with the hybridization of natural and synthetic fibres, where relatively little research has been done on natural-natural fiber hybrids like jute-hemp reinforced epoxy composites, especially in terms of structural performance. Despite the extensive study of mechanical properties including tensile and flexural strength, there has been minimal consideration of fracture behaviour and crack propagation under bending conditions that are of great significance in determination of reliability in real life situations. Moreover, natural fibers variability and impact of fabrication methods usually give rise to discrepancies in reported outcomes and require a more systematic experimental analysis. Moreover, although experimental characterization is the main strategy in the majority of the studies, one may observe a deficit of combining it with predictive modelling methods that will allow to generalize material behaviour and decrease the reliance on large-scale tests. Specifically, the use of the deformation and mechanical response prediction of hybrid natural fiber composites by the utilization of the model of the linear regression with the help of the polymers remains limited in the literature. Against this backdrop, the current paper seeks to fill these gaps by producing and profiling of hybrid jute and hemp fiber reinforced epoxy composite using a mixed methodology, consisting of experiments and analysis. It is concerned with the assessment of major mechanical characteristics like flexural strength, modulus, and deformation behaviour and exploration of fracture behaviour under bending conditions. Furthermore, a polynomial regression model is then constructed to create a relationship between input parameters and the mechanical response obtained, which is used to predict deformation behaviour. The results of this research are likely to serve the purpose of a deeper insight into hybrid natural fiber composites and offer a solid structure of combining experimental analysis with data-driven modelling to design materials sustainably.

MATERIALS AND METHODOLOGY

The experiments are conducted for Hybrid composite material. The information of material selection, specimen preparation, and the experimentation have been discussed briefly in this section [22].

Materials

- Reinforcements: Jute and Hemp fibers as shown in Figure 1(a) and (b) respectively
- Matrix material: Epoxy resin as shown in Figure 1(c)(L-12 and K-6 as Hardener)

Jute is a multicellular fiber characterized by a substantial cellulose proportion and a minimal alignment angle of microfibrils (~8.0°) are the desirable properties render it for application as a reinforcing phase in polymer composite systems [23]. Mechanical properties are detailed in Table 1.

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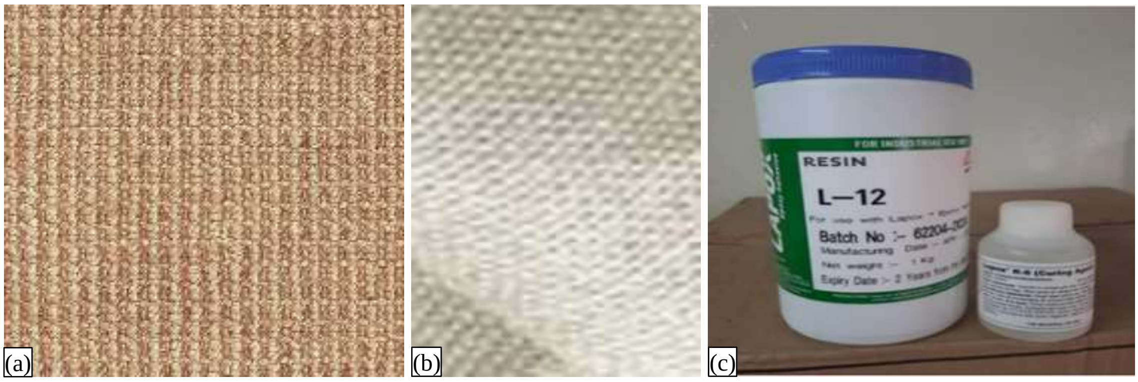

Figure 1.(a) Jute fiber, (b) Hemp fiber and (c) Epoxy and hardener.

Table 1. Mechanical properties of jute fibers [24].

Density (g/cm^3)	Elongation %	Tensile strength (MPa)	Young's modulus
1.3	1.5–1.8	393–773	26.5

Table 2. Mechanical properties of hemp fiber [19].

Density (g/cm^3)	Elongation (%)	Tensile strength (MPa)	Young's modulus(E)
1.4–1.5	2–4	250–900	30–70

Hemp fibers are known for their strength, durability, and versatility. They are among the longest natural fibres, which contributes to their superior tensile strength. Hemp fibers are also resistant to mold, mildew, and UV light, making them suitable for outdoor and marine applications [25]. Mechanical properties are detailed in Table 2.

Epoxy Resin

Epoxy resin Lapox-12 and a hardener K-6 were chosen as the matrix material. At room temperature, epoxy exists in non-crystalline form and is both a strong adhesive (and) excellent in alkali resistance with density of 1.3g/cc and UTS of 50-60MPa [26–28]. The hardener is a curing agent; a mixture of the epoxy is done in a ratio of 10:1.

Methodology

Preparation of Boards

Preparation of hybrid composite plates from calculated number of jute/hemp hybrid fibers been done prior to sample sizing through conventional layup method. Hemp & Jute fibers are made into the form of mat and can be cut according to required dimensions. Sample preparation was carried out by spraying the mould surface with the layer of mould release agent. Overlay the prepared mould with a layer of Hemp fibers, making sure that fibers are evenly distributed and in place. Adding layers increases thickness of the composite. Wet the Hemp fibers by wetting them with brush/roller with resin mixture, making sure that the fibers are completely saturated. Continue the steps of applying fibers and resin until the composite is desired to be thick. Make sure that all layers are adequately impregnated with resin [29].

The cross section of board is 250mm x 250mm for normal tensile test and one more for edge r notch tensile test. Ready composite plate having tensile and ENT test specimen as per Figure 2(a), (b) and (c) respectively

Tests conducted

Tensile Test

Tensile tests were conducted to measure peak load, elastic modulus and ultimate tensile strength of samples as per ASTM D638 standards and three replicates were tested to achieve the statistical reliability [30]. Sample subjected to tensile loading as shown in Figure 3.

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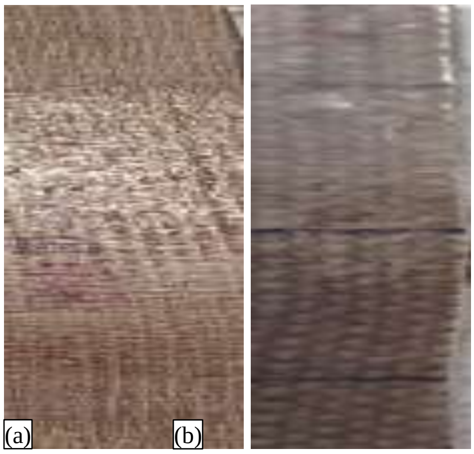

Figure 2. (a) Prepared composite plate, (b) tensile

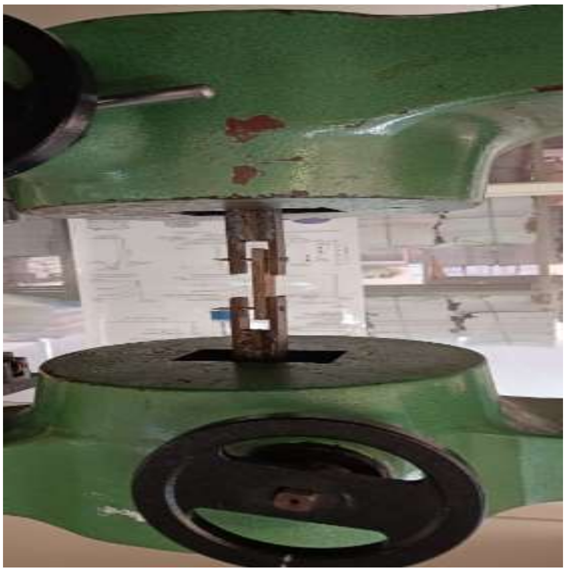
Figure 3. Sample subjected to tensile loading.

Edge Notch Tensile (ENT) Testing

Edge Notch tensile (ENT) test was carried out as per ASTM E1922 standards. Specimens with edge notches were tensile gripped. The test assesses the tensile stress resistance of the material to crack propagation which complements other tests. To explain the fracture behaviour and determine the respective fracture parameters, load-displacement curve was monitored [31].

Predictive Modelling Using Artificial Neural Network

Besides the experimental tensile and edge notch tensile tests, Artificial Neural Network (ANN)-model was used to estimate the prediction of the deformation behaviour of the hemp fiber-reinforced epoxy composites. This predictive approach is based on the mechanical characterization in that it enables prediction of deformation under various loads and geometries which enable optimization of sustainable design, and reduce large physical prototyping. The ANN was set as a deep learning architecture that consisting of multi-layer perceptron architecture. The tensile test data were recorded to give training data where the inputs were in the form of load, size of the specimen (length, width, thickness), fiber volume fraction (60%), and the measured strain and the output in the form of deformation (in mm). Optimizing the model involved the loss measure of Mean Squared Error (MSE) where 200 epochs and training and validation ratio of 80/20 was utilized to ensure that the model under generalization remains.

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RESULTS AND DISCUSSION

Tensile & ENT Test

Variation of deformation under applied load for 2 different samples under tensile and ENT has been reported and detailed in the Table 3 and sample plots are shown in Figure 4.

The given bar plots in Figure 5 compare the performance of the hybrid jute/hemp/epoxy composite under normal tensile testing and ENT (Edge Notch Tension) testing conditions. The peak load plot demonstrates that the specimen of normal testing is able to support a much larger load (approximately 2400 N), than the ENT specimen (approximately 500 N), a clear indication of the decrease to carry load with the presence of a notch that is a concentration of stress and initiates cracks at a very early stage.

Table 3. Tensile test results.

Parameter	Normal Test	ENT Test
Peak Load (N)	2400±84	500±17.5
Tensile Strength (MPa)	31±1.08	4±0.14
Young's Modulus (GPa)	2.1±0.07	2.5±0.08
Elongation at Break (%)	1.4±0.04	0.5±0.01

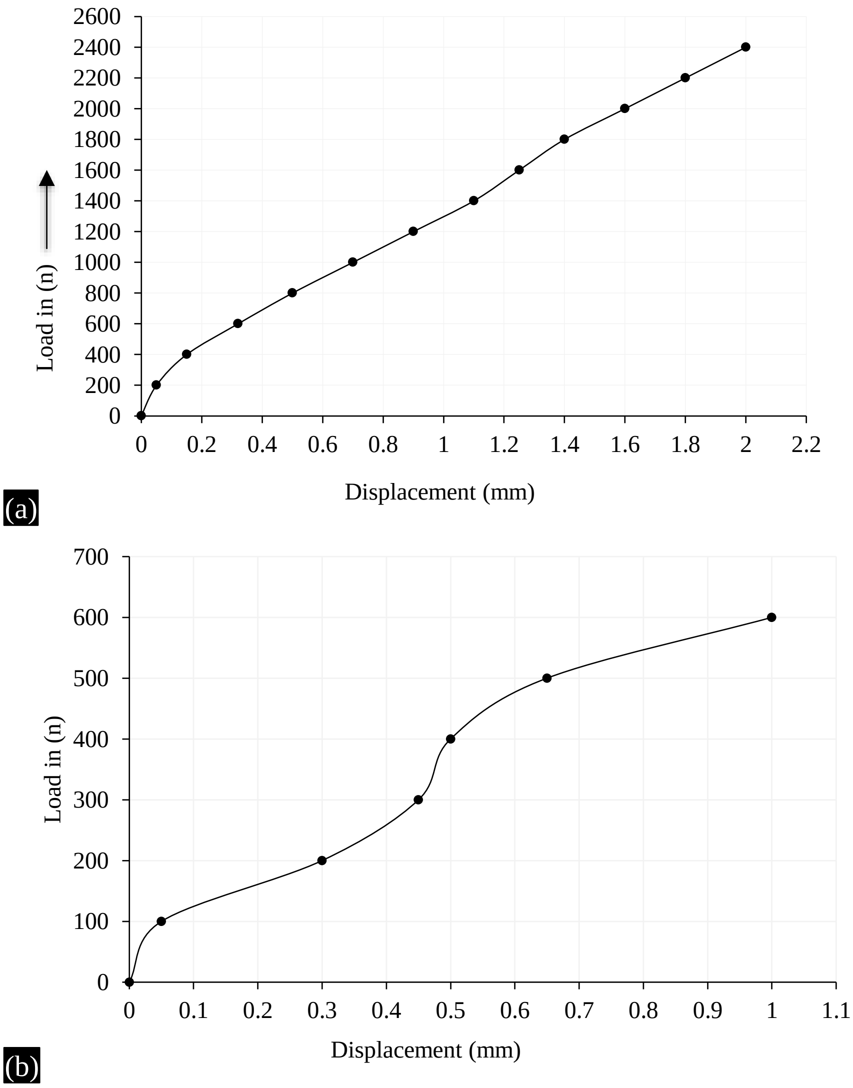

Figure4. (a, b) Load versus deformation plot for tensile and ENT test sample.

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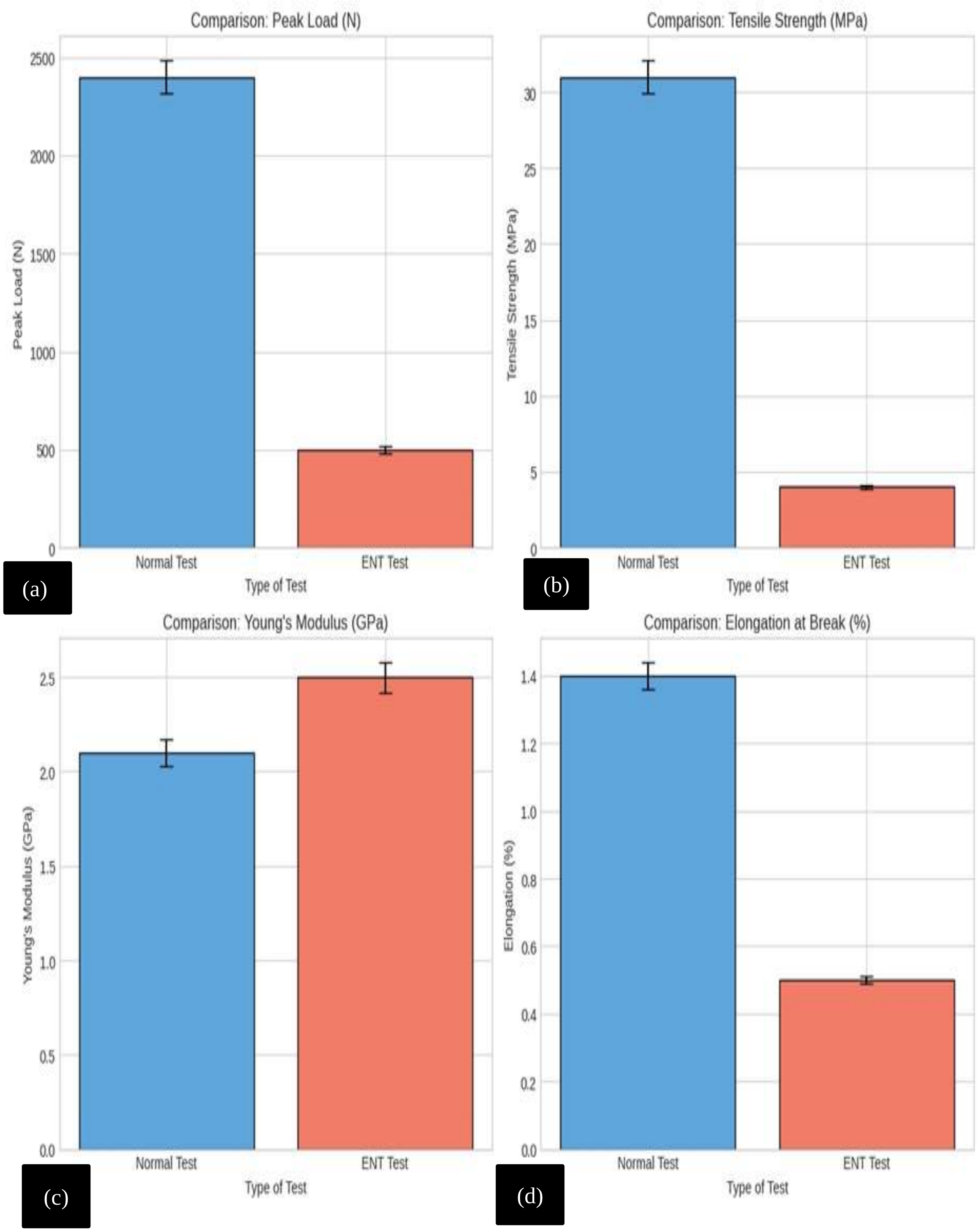

Figure 5. Details of the test results(a) Peak load (b)UTS, (c)Young's Modulus (d) Elongation at break.

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Equally, in the tensile strength plot, we observe a significant reduction in tensile strength of about 31 MPa during normal test to 4 MPa during ENT test and this supports the fact that fracture mechanics had greater impact on the materials performance. Contrastingly, the Young's modulus indicates that there is a minor change in the ENT condition (~2.5 GPa) relative to the normal specimen (~2.1 GPa) that can be explained by the localized stiffness effect around the notch area and decreased plastic deformation prior to failure. The elongation at break plot shows a significant decrease of approximately 1.4 percent to 0.5 percent showing a more brittle behaviour in the notched specimen since it cannot deform as much and the crack propagation is fast. All in all, these plots indicate that though the hybrid composite is good in strength and ductility in normal situations, defects or notches in it severely limit its load bearing and deformation properties, which underscores the need to have fracture resistance and structural integrity in the design implementation.

Discussion of Tensile Properties using Polynomial Regression

The training loss curve in Figure 6 indicates how the model of training the polynomial regression model behaves in convergence. First, the mean squared error (MSE) is large, which means that there is a significant dispersion between the predicted and actual values of tensile loads. The loss declines exponentially with the number of epochs, indicating a fast-learning process in the initial stages. After around 100 epochs, the curve slopes off quite slowly, meaning that the model is converging and any further gains are insignificant. The gradual and steady decrease in MSE, without oscillations indicates effective gradient descent optimization, and lack of instability throughout training. The last low loss value proves that the model has been able to capture the nonlinear relationship between displacement and load.

The histogram of error (Figure 7) indicates how the prediction error (difference between experimental and predicted tensile load values) is distributed. The distribution seems to be fairly symmetrical about zero, which means that the model does not have a high level of systematic bias. Nonetheless, the occurrence of both positive and negative errors points to the slight overprediction and underprediction of various samples. Some bigger deviations (outliers) can also be noticed, which can be explained by experimental variability, heterogeneity of the material, or data noise. In general, the relatively symmetric distribution validates that the model prediction is stable and reasonably accurate anywhere but a few points.

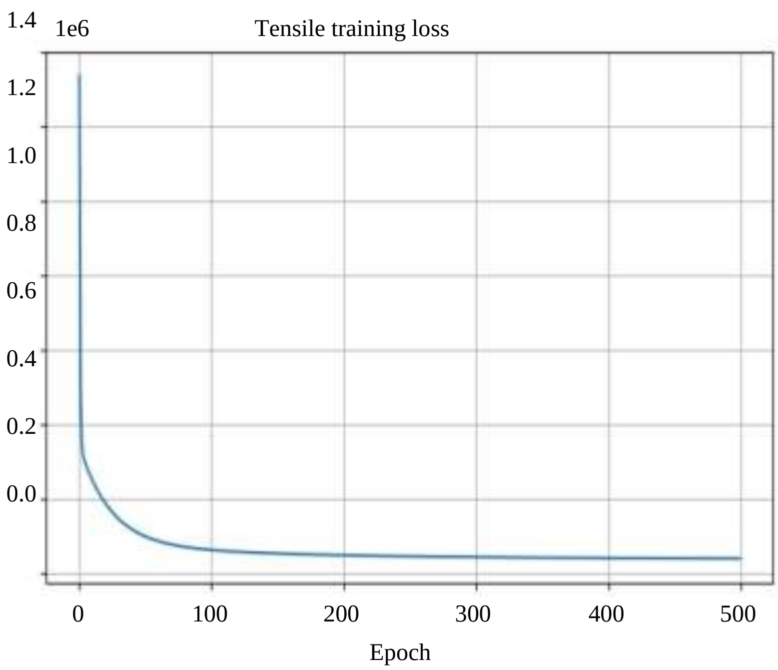

Figure 6. Tensile training loss curve here.

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The error distribution histogram indicates most prediction errors are centered around zero, with a slight positive skew.

The absolute error heatmap visualizes errors across sample indices, highlighting areas of higher deviation. The absolute error heatmap (Figure 8) offers a sample-by-sample visualization of prediction accuracy. The cells are the magnitude of error of a particular test sample. The majority of the samples have moderate values of error, which implies that there is a reasonable predictive performance in the dataset. Nevertheless, some of the samples have very large error values (e.g., of the order of 500 N), indicating local irregularities in which the model is not able to perfectly describe the behaviour.

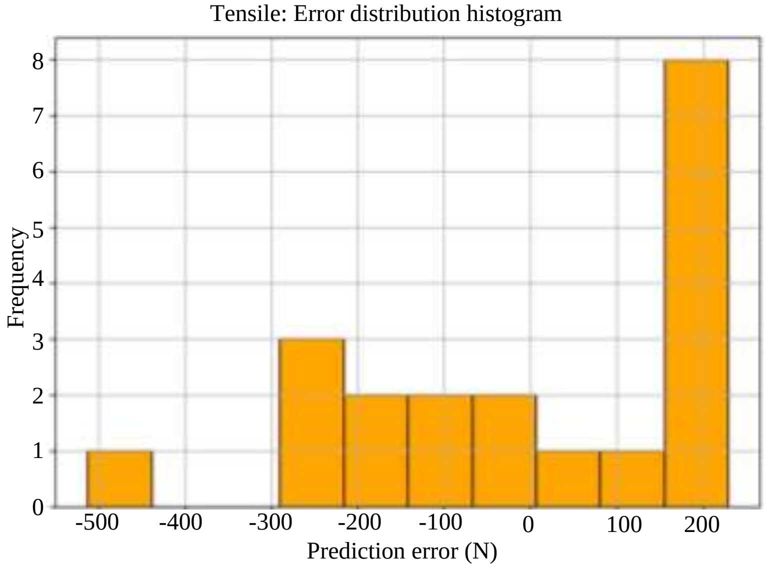

Figure 7. Error distribution histogram.

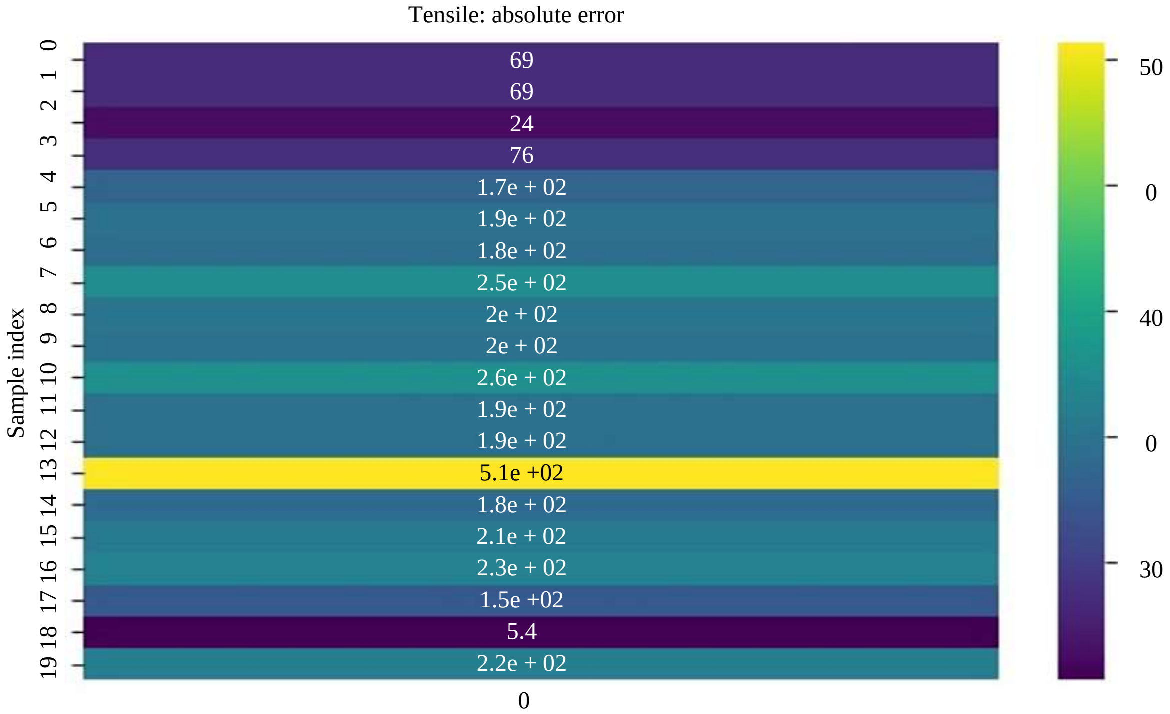

Figure 8. Absolute error heatmap.

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These deviations can be because nonlinearities are not fully represented by the polynomial model or differences in experimental measurements. These localized errors notwithstanding, the general trend shows model is efficient to predict the samples with a constant level of performance. Residual errors plotted against deformation show random scatter around zero, confirming model adequacy without systematic bias [32].

The actual vs predicted load plot shows that it is very close to the 45-degree line with R^2 values above 0.95 [33]. The plot of residual error as presented in Figure 9 indicates the discrepancy between experimental and predicted tensile loads values with deformation. The residuals are spread symmetrically on either side of the zero line, which means that the model is usually not biased with a systematic over- or underestimation. Their largely random distribution implies that the overall direction of the data can be covered by the polynomial regression model. The existence of a few large deviations however points to the localized prediction errors, which could be attributed to the variability of materials or nonlinear behaviour that is not well modelled. In general, the plot shows a good predictive performance with a potential to do better.

The Actual vs Predicted plot (Figure 10) compares the experimental tensile load values with the predicted values of the tensile load using the model of the ten-point regression. The dotted diagonal line is the perfect scenario in which the predictions are perfect matches to the experimental data. The majority of the data points are near this line, which means that there is a good agreement and that the model is generally very accurate in prediction. Nevertheless, there are some points off the line, particularly in the mid-load region, indicating some localized prediction error probably caused by material variability and nonlinear behaviour of the hybrid composite.

The Load vs Deformation plot (Figure 11) is a plot of applied load against deformation which shows the points where the experiment was carried out and the model of the regression of the polygraph. The scatter points (experimental data) show a nonlinear trend and the smooth curve (polynomial) efficiently describes the trend. The fact that the fitted curve closely matches the experimental points shows that developed model is capable to capture the deformation behaviour of the hybrid jute-hemp composite. Some small fluctuations at some deformation levels suggest the natural complexity of material behaviour, but generally, the model gives a good approximation of the load-displacement behaviour. Finally, the load vs deformation curve with model fit overlays the experimental data points with the polynomial curve, validating the model's predictive capability for hybrid composite tensile response.

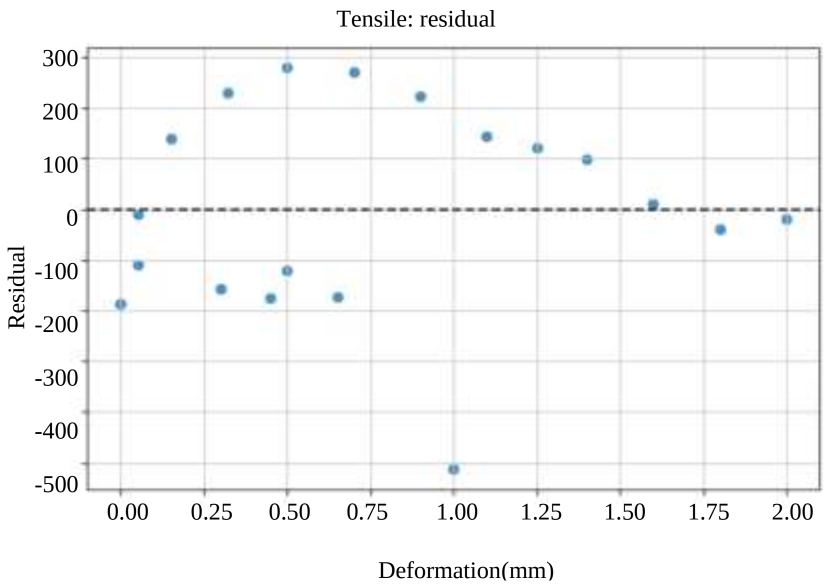

Figure 9. Tensile residual error.

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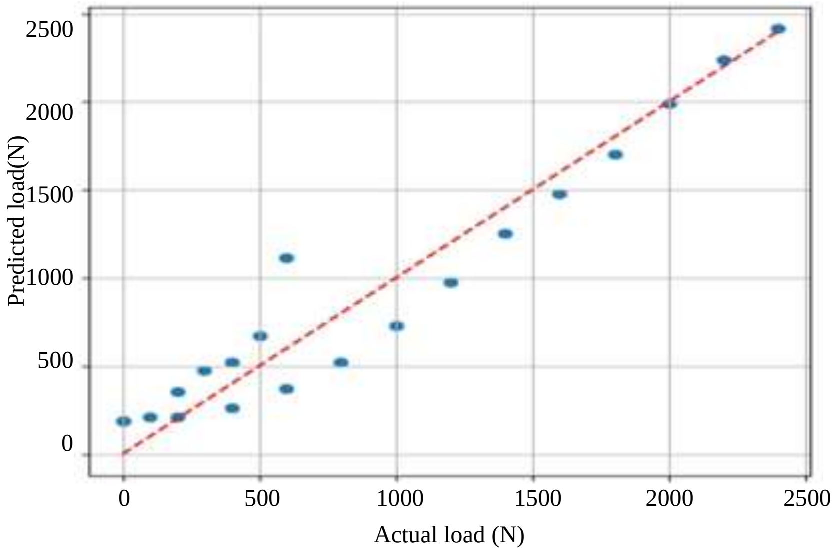

Figure 10. Actual vs predicted value.

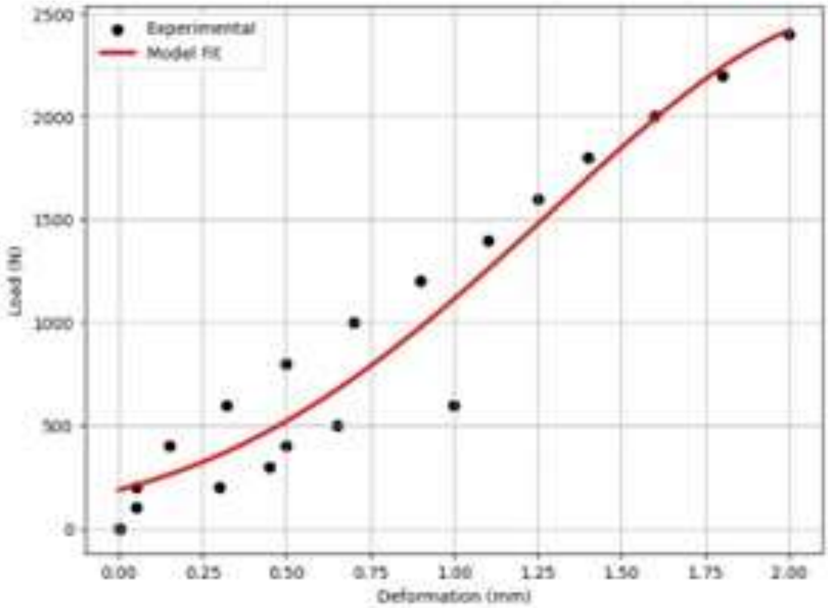

Figure 11. Load vs deformation plot.

CONCLUSION

The hybrid fiber systems have a better energy absorption and dissipation process that gives bio-composite materials better fracture toughness than conventional composite materials. In the current work, hybrid jute-hemp fiber reinforced epoxy composite showed enhanced mechanical performance in relation to compared single natural fiber composites, which demonstrates the usefulness of hybridization.

Experimentally, tensile strength of the developed composite was measured as 31±1.08 MPa and fracture performance measured using ENT test gave a value of 4±0.14 MPa which showed its application in moderate structural and semi-structural. The tensile behaviour was well predicted using the polynomial regression model as evidenced by the convergence of the training loss curve and distribution of the prediction errors evident in the plots which show the ability of the model as a predictive tool in predicting performances as well as optimizing the design.

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