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ORIGINAL PAPER

Flexural and impact response of bamboo and pineapple leaf fiber reinforced composites using experimental and numerical techniques

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Abstract

The flexural and impact response of completely biodegradable natural composites, specifically bamboo and pineapple leaf fiber (PALF) reinforced composites, is investigated using a combination of experimental and simulation techniques. The flexural strength and bending modulus are determined through 3-point bending tests while varying the weight fraction of the selected natural fibers from 5 to 15%. The impact of alkaline treatment at different percentages of 2 to 10% on the same properties such as flexural strength and bending modulus is also investigated. Subsequently, simulation techniques are employed to determine the behavior of the natural composite materials under bending loads. Finite element models are utilized to analyze the normal, and shear stresses in the composite structures. The research findings unveiled that incorporating a 10% weight fraction of bamboo fiber along with an 8% NaOH treatment led to the most significant enhancement in flexural strength, showcasing a notable advancement of 111.02%. Within the PALF fiber reinforced composite, employing 2% NaOH treated PALF fiber at a 15% weight fraction yielded an impressive improvement of 125.6%.

Keywords Bamboo fiber · PALF · Weight fraction · Alkaline treatment · Finite element method

1 Introduction

There is indeed significant potential to replace synthetic fibers with cellulose-based natural fibers in the production of polymer matrix composites [1]. This shift is driven by both the environmental concerns associated with synthetic materials and the desire to explore more sustainable alternatives. Indeed, numerous studies have demonstrated the capabilities of natural fibers in enhancing the properties of resulting composites, including their specific weight, tensile strength, and stiffness [2]. Natural fibers possess inherent mechanical properties that contribute to the overall performance of the composites [3].

Various types of natural fibers, such as jute, flax, hemp, bamboo, sisal, pineapple leaf fiber (PALF), and coir, have gained significant attention from researchers due to their unique properties and potential applications [4]. In particular, these natural fibers are finding their place in the automotive industry, where weight reduction and strength are crucial

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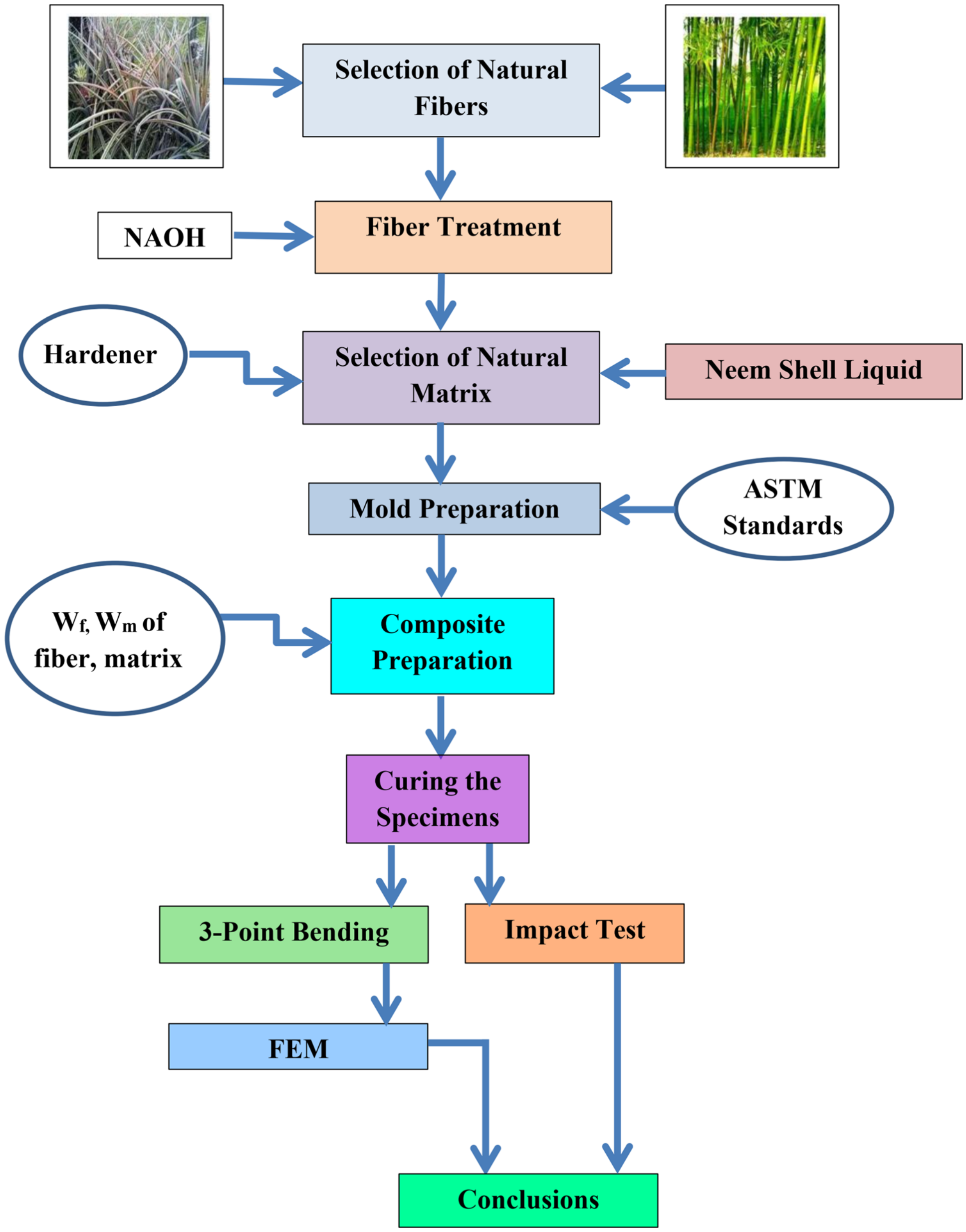


Fig. 1 Flow chart for the process adopted in the preparation of natural composites

factors. While natural composites may exhibit strength in specific loading conditions, their response can vary in different modes of loading such as bending and shear. It is crucial to conduct a thorough mechanical characterization and analysis to understand the material's behavior and determine its suitability for specific applications. [5] In line with the present scope of the work, the behavior of the natural fiber-reinforced composite under bending load is well explored for different composite materials by conducting experimental studies. There are several treatments available for natural fibers to prepare them for use in composite materials. These treatments aim to improve the compatibility between the fibers and the matrix, enhance the fiber properties, and optimize the overall performance of the resulting composites. Alkaline treatment, [6] acetylation [7], silane [8] mercerization [9], benzoylation [10], and maleic anhydride treatment [11] are a few examples of the treatments available for natural fibers.

One common objective of these treatments is to remove impurities like waxes, hemicellulose, and lignin from the surface of the natural fibers. These impurities on the surface of the fiber can hinder the interaction between the fibers and the matrix, resulting in weak interfacial bonding and reduced mechanical properties of the composites. [12, 13] Removing these unwanted particles, through treatments increases the surface roughness and exposes the clean cellulose fibers, promoting better fiber-matrix adhesion. [14].

Table 1 The physical and chemical properties of bamboo fiber, pineapple leaves, and Neem shell liquid resin [42–45]

Fiber	Bamboo	Pineapple leaf	Neem shell liquid resin
Cellulose (wt.%)	48.2–73.8	71.6	
Lignin (wt.%)	30	5–12.7	
Hemicellulose (wt.%)	21–31	4.58	
Microfibril angle (θ)	2–10	14	
Density (g/cm^3)	1.23	1.3	1.1
Tensile strength (MPa)	500–575	150–1627	62

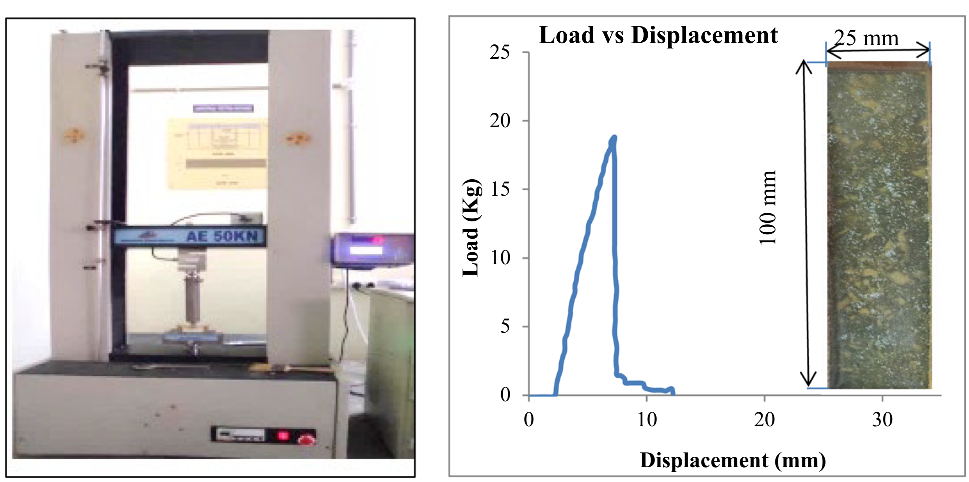
The selection of the fiber treatment depends on the specific type of fiber and its constituent concentration. Different fibers have different characteristics and surface properties, requiring tailored treatment approaches to achieve optimal results. Additionally, the concentration of the fiber in the composite can influence the effectiveness and impact of the treatment. Furthermore, it is observed that the identical fiber exhibits distinct responses under tensile and bending loads when combined with the same filling material. Specifically, the incorporation of 4% aluminum particles results in a significant increase in tensile strength. On the other hand, a lesser amount of the same aluminum particles, only 2%, is sufficient to enhance the bending strength significantly. This discrepancy highlights the different mechanical behaviors of the composite material under different loading conditions. [15]

Numerous researchers have embraced the finite element method as a means to characterize natural fiber-reinforced composites. This approach has been employed for various purposes, including harmonic analysis and modeling [16], investigating the impact of waviness in natural fiber on elastic and buckling strength [17, 18], exploring the influence of hierarchical fiber structures [19], studying the impact behavior of natural fibers [20, 21], and predicting tensile behavior under ambient temperature conditions [22]. The application of the finite element method enables a successful understanding of these complex mechanical phenomena in natural fiber-reinforced composites. Furthermore, significant efforts have been dedicated to the study of conventional metals, smart materials, porous materials, nanomaterials, and their alloying variants [23–30]. Moreover, the synthesis of nanomaterials has expanded opportunities for their characterization and practical applications including composite materials. [31–41]. However, considerable work needs to perform on the natural fiber-reinforced composite.

In this work, by considering the specific features of bamboo fiber and PALF, the flexural strength, flexural modulus, and impact strength of the resulting composite are estimated by varying the weight fraction of these fibers by following an alkaline treatment. Further, the parameters considered for the testing are transmitted to the simulation studies to analyze the prepared composite for normal, shear, von Mises, and principal stresses under a similar type of loading.

2 Materials and methods

The biodegradable hosting medium used for the present work is neem shell liquid resin. This resin and compatible Hardener are procured from Vruksha Composites and Services, 14-63-4, Morriespet, Tenali, Andhra Pradesh, 522,202, India. To prepare the natural fiber-reinforced composites two different types of natural fibers are selected one is bamboo fiber and another one is pineapple leaf fiber (PALF). Neem Shell Liquid (NSL) resin is a natural and biodegradable resin. This resin is secreted from special ports or cavities present behind



(a) (b)

Fig. 2 **a** Setup for Flexural test **b** load versus displacement curve of bamboo fiber reinforced composite at 6% NaOH solution

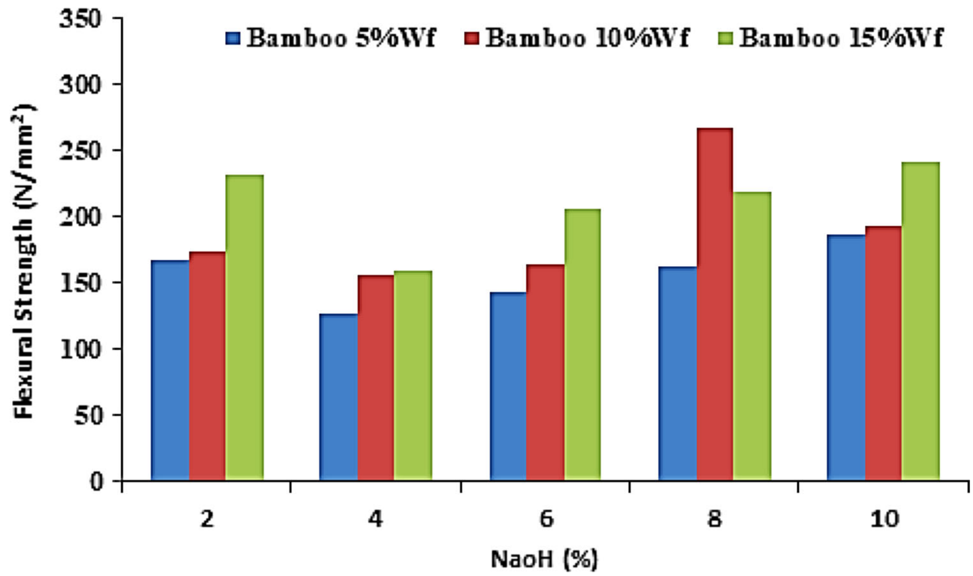


Fig. 3 Flexural strength of the bamboo fiber reinforced neem shell resin composite w.r.t NaoH treatment

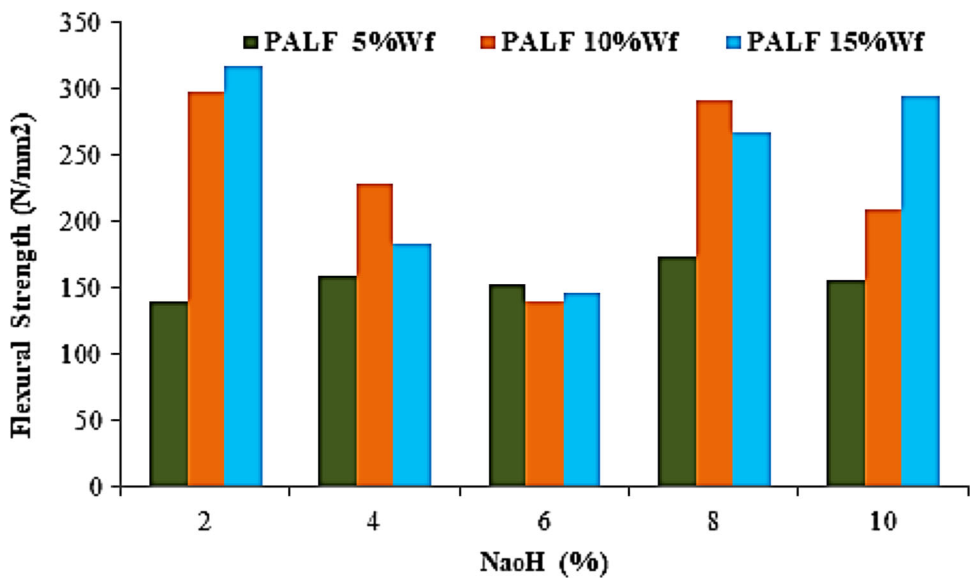


Fig. 4 Flexural strength of the palf fiber reinforced neem shell resin composite w.r.t NaoH treatment

the bark of the Neem tree. When the bark is removed a liquid is secreted from the tree which is collected and treated with a few chemicals and finally, the resin is obtained. It is mixed with hardeners and made use of. It is an eco-friendly resin and doesn't cause any environmental pollution. NaOH solution is prepared using Sodium Hydroxide pellets, MERCK make are purchased from the local market to prepare NaOH solution. A schematic representation of composite preparations has been illustrated in Fig. 1. The physical and mechanical properties of the neem shell liquid resin, bamboo fiber, and PALF used in this work are summarized in Table 1.

Prior to the preparation of composite specimens, the Bamboo and PALF fibers are treated with different concentrations of NaOH solution. Initially, the fibers are washed with hot water to eliminate any contaminants that have adhered during the extraction process. Subsequently, the fibers are rinsed with distilled water and allowed to dry thoroughly at room temperature. Once dried, the Bamboo fibers and PALF are cut into 250 mm lengths and subjected to alkaline treatment as part of the composite preparation. The NaOH solution is prepared by adjusting the percentage of NaOH from 2 to 10%, with intervals of 2%, mixed with a known amount of water.

The bamboo and PALF fibers are immersed in this NaOH solution for 4 h. After 4 h of alkaline treatment, the fibers are taken out of the solution and washed with distilled water to remove the NaOH residue from the fiber surface. Subsequently, the natural fibers are dried at room temperature and utilized in the preparation of natural composites using the

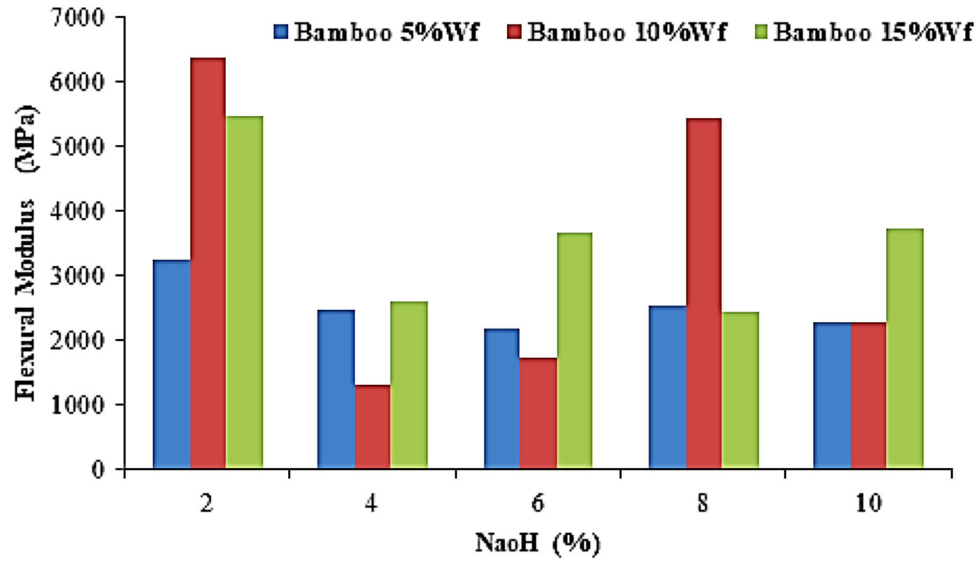


Fig. 5 Flexural modulus of the bamboo fiber reinforced neem shell resin composite w.r.t NaoH treatment

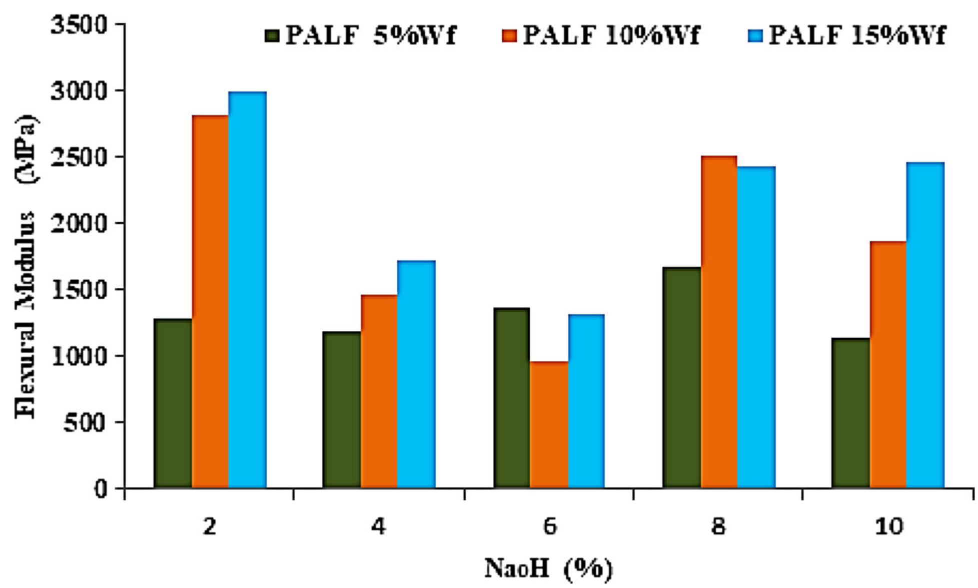


Fig. 6 Flexural modulus of the palf fiber reinforced neem shell resin composite w.r.t NaoH treatment

hand lay-up technique. The specimens are prepared by following the ASTM D790. The study is conducted by testing four specimens at a given weight fraction and NaOH concentration.

3 Mechanical testing

The samples are tested on a digital universal testing machine with a capacity of 20 kN (Fig. 2a) and the flexural test is conducted at a testing speed of 5 mm/min following the ASTM D790 standard. (Fig. 2b) The bending load is increased until the failure of the specimen occurs, and the load versus deformation curve is generated.

For the impact test, the specimens were prepared as per the ASTM D256 standard. A motorized notch cutter was used to create a notch on the specimen. The testing setup and the load versus deformation curve at 6% NaoH treatment at 10% weight fraction of bamboo fiber reinforced neem shell resin composite is presented in Fig. 2b. The three-point bending and impact test are carried out using the universal tensile testing machine and digital impact testing machine at a renowned engineering institution in Andhra Pradesh. All the tests were conducted at room temperature. The specimen prepared for the bending test is also depicted in Fig. 2b.

4 Results and discussion

In this study, it is observed that increasing the weight fraction of bamboo fiber from 5 to 15% resulted in an increase in flexural strength. However, it is important to note that the

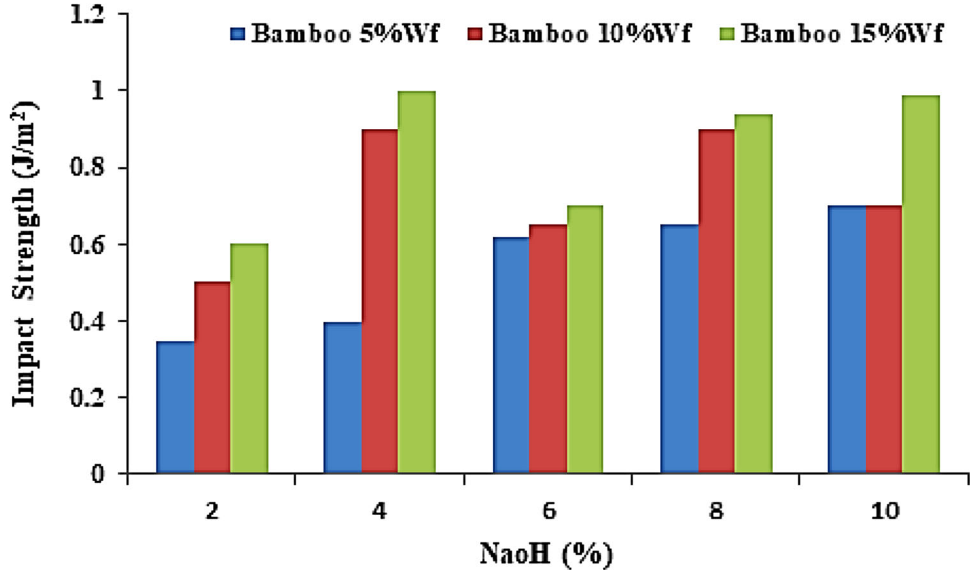


Fig. 7 Impact strength of the bamboo fiber reinforced neem shell resin composite w.r.t NaoH treatment

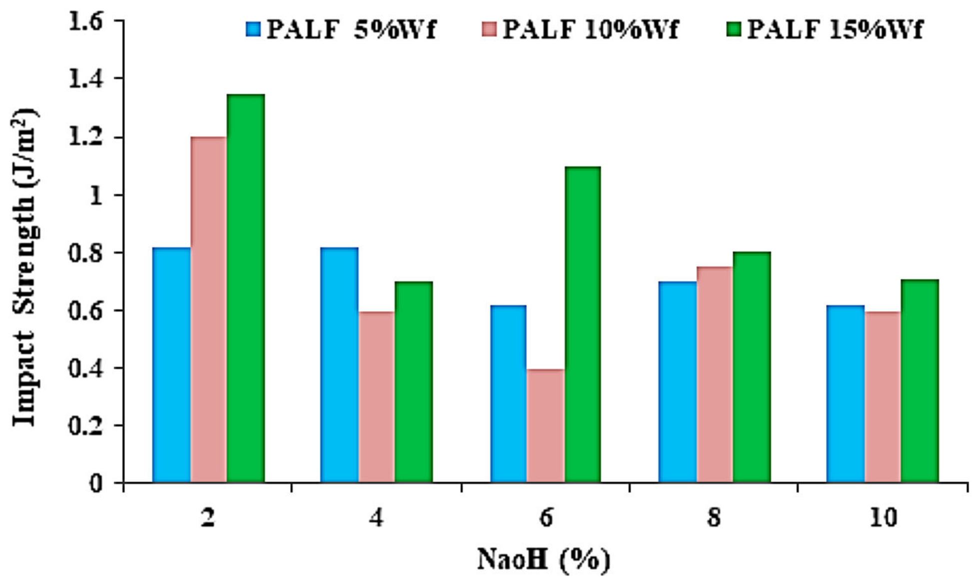


Fig. 8 Impact strength of the palf fiber reinforced neem shell resin composite w.r.t NaoH treatment

effectiveness of natural fiber in enhancing flexural strength depends on the fiber treatment method employed. The effect of fiber treatment is also studied by varying the NaOH concentration from 2 to 10%.

The results demonstrated that the maximum improvement in flexural strength, amounting to 111.02%, is achieved at a weight fraction of 10% for the fiber and an 8% NaOH treatment. This suggests that the combination of a 10% weight fraction of fiber and an 8% NaOH treatment significantly enhanced the material under bending loading. Alkali treatment enhances the adhesive nature of the bamboo fiber surface by removing impurities hence there is an improvement in flexural strength of the composite [46]. With a further increase in the weight fraction of the fiber, there is a decrease in flexural strength due to poor bonding between the fiber and the resin. Therefore 8% of NaOH and 10% of weight fraction is the optimum alkali concentration that provides better interface adhesion between the bamboo fiber and the neem shell resin matrix as shown in Fig. 3.

Similar studies are performed on PALF-reinforced composites. Compared to bamboo fiber-reinforced composites, PALF-reinforced composites showed higher flexural strength. It is observed that 2% NaOH-treated PALF with a 15% weight fraction exhibited better flexural strength (Fig. 4).

The flexural modulus is another crucial property to consider while evaluating the behavior of materials when subjected to bending load. In the case of bamboo fiber-reinforced composites, it is observed that at weight fractions of 10 and 2% NaOH treatment composite material has exhibited the

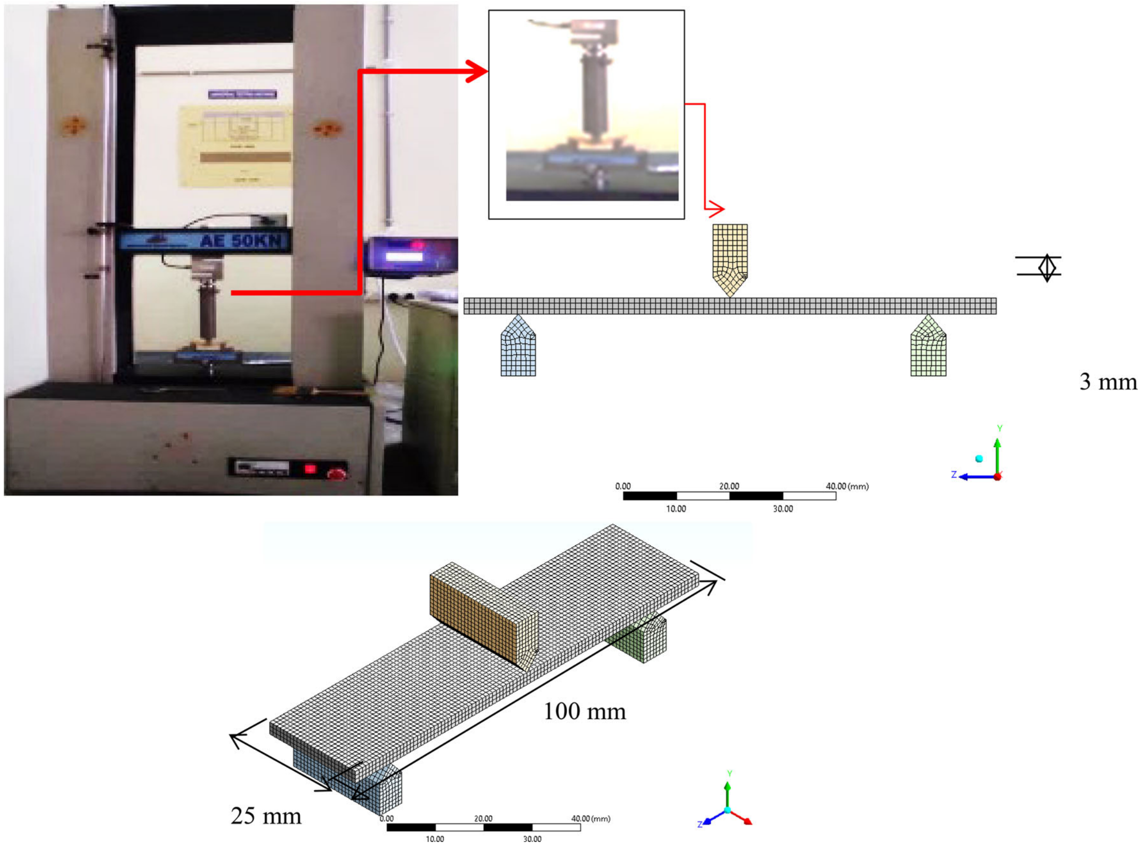


Fig. 9 Testing setup and Finite element modeling

highest flexural modulus as shown in Fig. 5. The observed trend can be attributed to the stiffness exhibited by the bamboo fibers at this particular weight fraction. This increased resistance to bending results in a higher flexural modulus, indicating a stiffer material response.

Figure 6 illustrates the flexural strength of PALF-reinforced composites. It is clear that the PALF exhibits the highest modulus when treated with 2% NaOH and at a weight fraction of 15%. This particular combination of fiber weight fraction and NaOH treatment has contributed to a strong bond between the PALF and the NSL resin. Further, an increase in fiber treatment can indeed suppress the flexural modulus of the composite, and one of the reasons is the removal of lignin, which is a natural polymer that provides structural support, and rigidity of plant fibers which leads to a reduction in flexural modulus and excess alkaline percentage may damage the surface of the natural fiber [47, 48].

5 Impact strength

The impact strength of the bamboo and PALF reinforced composite is performed by varying the weight fraction of the fiber and % NaOH treatment. Increasing the weight fraction of bamboo or PALF-reinforced composite improved the shock resistance of the resulting composite. Increasing the NaOH percentage influenced the impact strength of the composite. In the case of bamboo fiber reinforced composite, the highest improvement is observed when treated with 4% NaOH solution (as depicted in Fig. 7) and in the case of PALF reinforced composite, treatment with 2% NaOH has given a good response to the impact strength (as shown in Fig. 8).

The treatment provided to the bamboo and PALF fibers increases the surface roughness this roughness promotes better mechanical locking as a result the impact strength is improved. Another reason is with the NaOH solution treatment, the amount of cellulose in the concerned fiber will be activated by removing the unwanted dust particles, and by the NaoH treatment hydrophilic nature of the natural fiber will be suppressed. From these studies, it is found that impact strength not only improves with the fiber weight fraction but also depends on fiber treatment. [49–51].

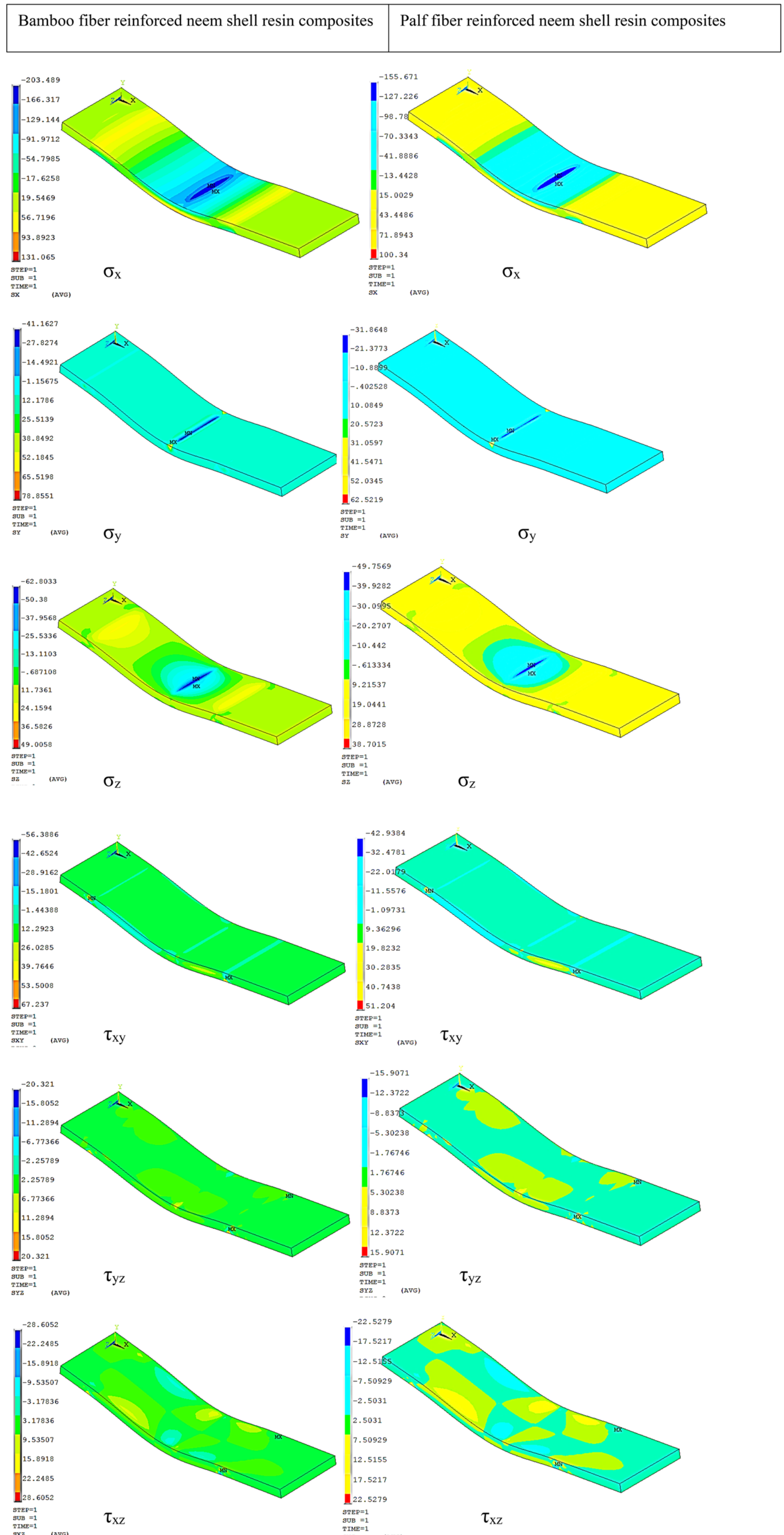


Fig.10 Comparison of normal and shear stresses results of bamboo and palf fiber reinforced neem shell resin composites

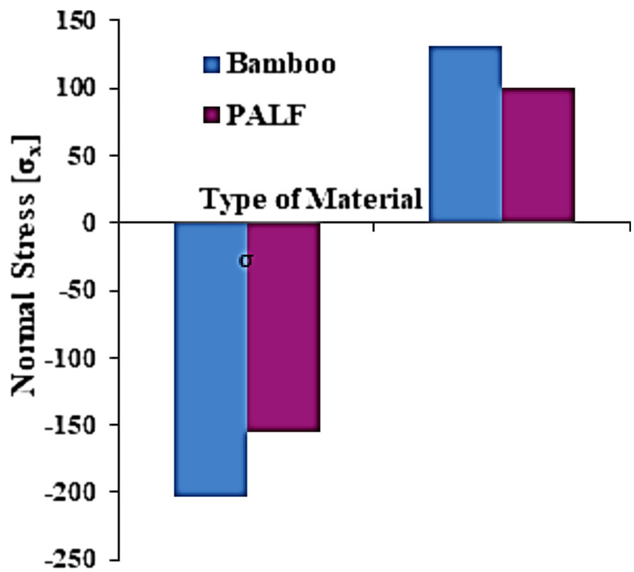


Fig. 11 Variation of σ_x

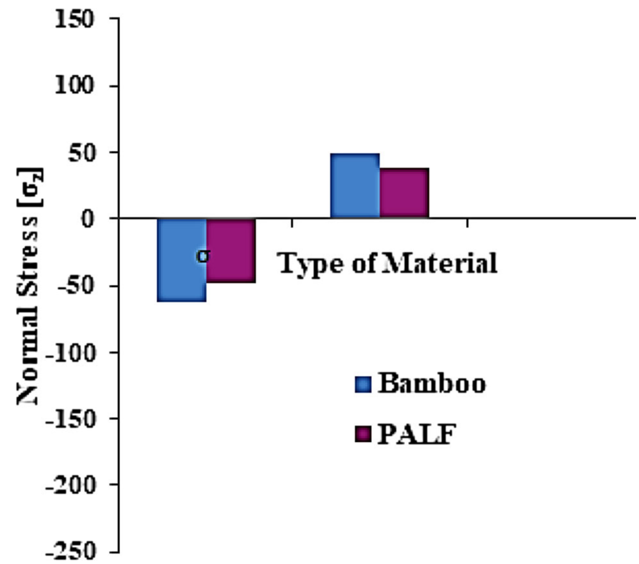


Fig. 13 Variation of σ_z

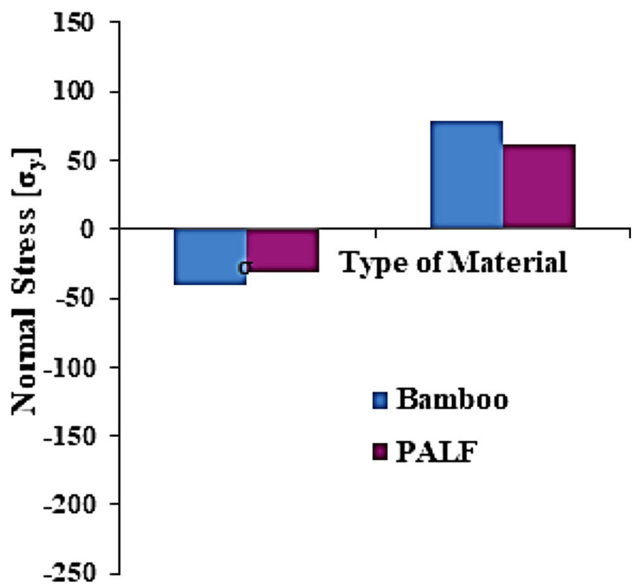


Fig. 12 Variation of σ_y

6 Finite element studies

Simulation studies were conducted to investigate the effects of bamboo fiber-reinforced composites and PALF (Pineapple Leaf Fiber) reinforced composites on normal and shear stresses. The finite element method was employed to achieve this research objective. The geometry, loading, and boundary conditions remain consistent with those considered in the experimental studies. [24, 52–54]. A geometrical model with the same dimensions as those utilized in the experimental studies has been generated within the finite element software Ansys. This model has a length of 100 mm, a width of 25 mm, and a thickness of 3 mm. The material properties required for the analysis are provided in Table.1. The finite element (FE) model is subjected to simply supported boundary conditions, and the maximum displacement obtained from the experimental results is imposed on the FE models. (Fig. 9). The finite element mesh is generated using the SOLID 186 element. A mesh convergence test is performed by progressively increasing the number of elements to ensure consistent results. The converged finite element models are then utilized to derive the results.

Normal and shear stresses (σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{xz}) in bamboo fiber-reinforced neem shell resin composites and PALF (Pineapple Leaf Fibre) reinforced neem shell resin composites are analyzed using finite element models.

Figure 10 depicts the contours of normal and shear stresses (σ_x, σ_y, σ_z, τ_{xy}, τ_{yz}, τ_{xz}) within the composite under discussion.

Figures 11, 12 and 13 show the change of normal stress in longitudinal and transverse directions (σ_x, σ_y, σ_z) of bamboo fiber-reinforced neem shell resin and palf fiber-reinforced neem shell resin composite. The maximum magnitude of normal stress (σ_x) is observed in the longitudinal direction (along the x-axis) of the bamboo fiber-reinforced neem shell resin composite compared to the PALF (Pineapple Leaf Fiber) reinforced neem shell resin composite. This is because when the load is applied perpendicular to the fiber direction, the fibers are designed to bear the majority of the load, and in this case, all the fibers are aligned along the x-direction. As a result, the maximum stresses are generated in the x-direction due to the axial alignment of the fibers.

Figures 14, 15 and 16 show the change of shear stress in in-plane and out-of-plane bamboo and palf fiber reinforced neem shell resin composite. When compared to out-of-plane

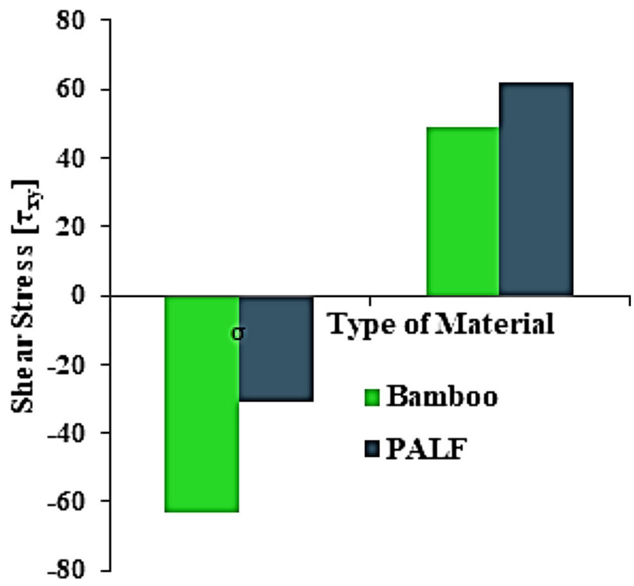


Fig. 14 Variation of τ_{xy}

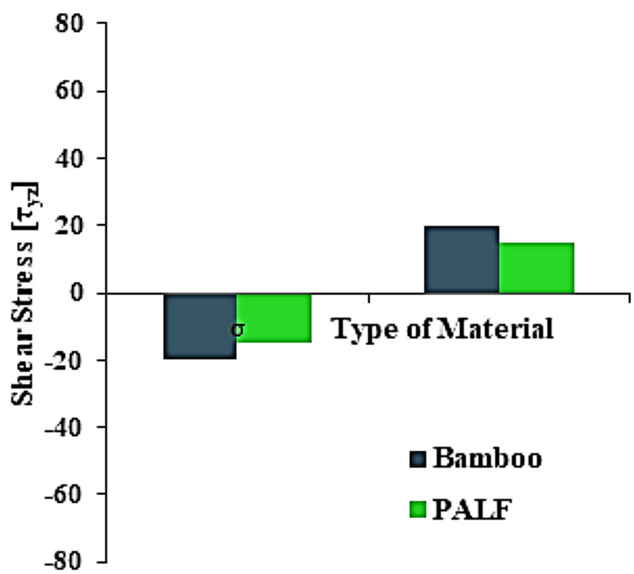


Fig. 15 Variation of τ_{yz}

shear stress, the magnitude of in-plane shear stress is more in both the bamboo fiber-reinforced neem shell resin composite and the palm fiber-reinforced neem shell resin composite. Furthermore, the bamboo fiber-reinforced neem shell resin composite exhibits the greatest magnitude of in-plane shear stress.

In a three-point bending test, the load is applied within the plane of the composite material, which is typically the XY plane. When the bamboo fibers are aligned in this plane, they can more effectively transfer the load along the length of the fibers. This alignment allows the fibers to bear a significant portion of the applied load, leading to higher magnitudes of in-plane shear stress than out-of-plane shear stresses.

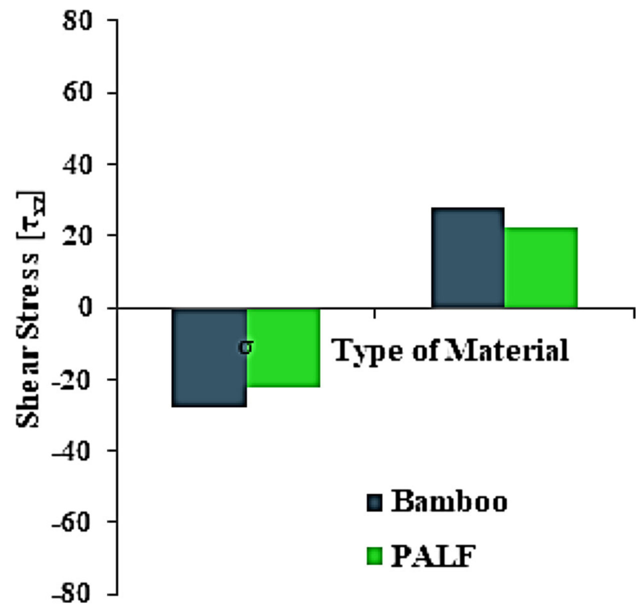


Fig. 16 Variation of τ_{xz}

7 Conclusions

The study focused on determining the flexural strength, flexural modulus, and impact strength of a completely biodegradable natural fiber-reinforced composite with a natural matrix. Bamboo and palm fibers were chosen as the reinforcing fibers, while neem shell resin was used as the matrix material. The study revealed the following conclusions:

- Composite specimens were successfully prepared using bamboo fiber and neem shell resin, as well as palm fiber and neem shell resin, with varying weight fractions of fiber.
- The flexural strength of the palm fiber-reinforced composite was found to be higher compared to the bamboo fiber-reinforced composite. Furthermore, the alkaline treatment applied to the composites had a significant effect on their flexural strength and flexural modulus, as observed in the current study.
- The research showed that adding 10% bamboo fiber with 8% NaOH treatment significantly improved flexural strength by 111.02%. In PALF fiber reinforced composite, using 2% NaOH treated PALF fiber at 15% weight fraction notably enhanced strength by 125.6%.
- For bamboo fiber composites, the optimal flexural modulus is achieved with a 10% weight fraction and 2% NaOH treatment. Similarly, PALF shows its highest modulus at 15% weight fraction and 2% NaOH treatment.
- The impact strength of bamboo and PALF-reinforced composites is tested with varying fiber weight fractions and % NaOH treatments. Higher weight fractions enhance shock

resistance. NaOH percentage also affects impact strength. Bamboo composite's peak improvement is seen at 4% NaOH treatment, while PALF composite responds well to 2% NaOH treatment.

- Finite element analysis results were utilized to analyze the prepared composites for normal and shear stresses under actual loading conditions. In-plane shear stresses were found to be higher, while normal stresses in the longitudinal direction exhibited higher values due to the inherent properties of the natural fibers considered in the present work.

In this work, fully biodegradable natural fiber and natural matrix fiber-reinforced composites are tested, and flexural strength, flexural modulus, and impact strength are predicted with respect to the weight fraction of the fiber and fiber treatment. Further, FE analysis is performed to understand the normal and shear stresses. However, these findings are limited to the input features considered for the study. Suggesting the appropriate application for the prepared material and maintaining its mechanical properties will be the scope of future work.

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