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# Mechanical Properties and Water Absorption of Epoxy Composites Reinforced with Treated Long Hair Fiber for Sustainable Manufacturing

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**ABSTRACT**

This study focused on exploring the alternative fibers that not only serve as substitutes for synthetic ones, but also offer ease of availability, cost-effectiveness, biodegradability, and superior specific properties. Extensive research suggests natural fibers can meet these desired criteria when replacing synthetic fibers. Here pig hairs were examined as suitable reinforcement for epoxy polymer and investigated the mechanical properties and water absorption for sustainable manufacturing. Pig hair was treated with NaOH solution and incorporated into an epoxy resin matrix at varying weight percentages (10% to 40%). Experimental results showed that the composites having 30wt% fiber exhibit the highest tensile modulus which is 65% higher and flexural modulus which is 122% higher than the value of the control sample. As the fiber loading increases impact strength also increases which is found to be 7 times higher than the control sample for 40wt% fiber loading. The water absorption resulted that after 40 days, the 10 wt% pig hair fiber composites absorbed only 2.5% water, while the highest water absorption was 9.01% for the 40 wt% sample. SEM analysis confirms robust interfacial bonding between pig hair fibers and epoxy matrix, which suggests that the product of the composites may be suitable for automobile, marine, and shed manufacturing Industries.



## 1. Introduction

For the last several years, extensive research has been dedicated to exploring new classes of materials and their diverse applications. The discovery of synthetic plastics facilitated the manufacturing of components for automobiles, aircraft, wind turbines, and more. It became apparent that the inherent low strength of plastic materials limited their ability to effectively transmit loads. This limitation spurred heightened scientific interest in fiber-based composites to bolster the load-bearing capacity of plastics. The concept of fiber reinforcement in composites is not entirely novel; the first fiber-reinforced composite was developed before 1940. However, it was during World War II that the applications of such composites significantly

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increased because of the demand for lightweight materials in fighter aircraft. Composite materials research underwent a transformative shift in the 1970s with the advent of synthetic fibers and various resin formulations [1]. This epochal development fundamentally altered the trajectory of research endeavors, opening up new avenues for enhancing the mechanical properties and performance of composite materials. Consequently, the quest for advanced fiber-reinforced composites gained renewed momentum, driven by the pursuit of materials capable of meeting the increasingly demanding requirements of diverse industries and applications. Greater attention is being directed towards enhancing the mechanical properties of plastics by incorporating synthetic fibers into various polymers. Synthetic fibers, such as glass fiber and carbon fiber, exhibit excellent mechanical strength, making them the most utilized reinforcement materials in various applications such as automobile, airplane, and ship manufacturing industries [2]. Although synthetic fibers exhibit favorable properties, their non-biodegradable nature and associated health risks pose ecological challenges. Consequently, there is a huge demand to explore alternative fibers that not only serve as substitutes for synthetic ones but also offer ease of availability, cost-effectiveness, biodegradability, and superior specific properties. Extensive research suggests that natural fibers can meet these desired criteria when replacing synthetic fibers[3].

The gradual variation in material properties offers distinct advantages over conventional composites, making it highly suitable for a wide range of applications. The current research emphasizes identifying suitable natural fibers, matrix agents, and adhesive enhancement techniques that can achieve the desired mechanical strength for diverse industrial applications. Natural fibers are typically classified into three categories: plant-based, animal/human-based, and mineral-based. Plant-based fibers are derived from the leaves, fruits, stems, or seeds of plants, while animal/human-based fibers include materials such as hair, wool, feathers, and silk. Mineral fibers encompass substances like asbestos, graphite, and glass fibers [4].

Due to its affordability, low density, minimal health risks, reduced pollution, eco-friendliness, and biodegradability, developing a new composite by reinforcing natural fibers can be considered both cost-effective and environmentally beneficial [5]. These advantages strongly justify further research into natural fiber-based polymer composites and promote their wider commercial application across various industries. With the growing demand for composite materials, research into various fiber-reinforced composites has notably surged, as evidenced by the increasing number of publications, articles, and books in this field over the past decade [6-9]. Natural fiber-reinforced polymer composites have demonstrated outstanding performance across a wide range of applications. Notably, they have been utilized in automotive components, food packaging, wood plywood production, pipes and tanks, reinforced cement concrete structures, medical equipment, and even domestic applications [10].

In recent decades, there has been growing global interest in utilizing waste materials to enhance the properties of polymer composites. Hair exhibits notable qualities such as elasticity, smoothness, strength, and softness, primarily due to its cortex keratin. This keratin forms long chains that are compressed into a strong yet flexible structure, significantly contributing to the flexibility of composite materials. Hair fibers also demonstrate remarkable tensile properties, indicating significant potential for a wide range of applications. However, further investigation into the physical and chemical properties of hair fibers, particularly their tensile characteristics, is essential to advance their utilization in both domestic and industrial contexts [11-17]. The average tensile strength of pig hair from various breeds is approximately 14.05 cN/tex or 126.45 MPa, which is slightly lower than that of human hair (150-220 MPa). Nevertheless, Young's modulus of pig hair is satisfactory at 6.39 GPa, which is higher than that of human hair, ranging from 1.74 to 4.39 GPa [13], [18], [19]. Additionally, the compressive strength of concrete blocks has been found to be satisfactory when pig hair is incorporated as a fiber reinforcement material [20].

Pig hair, a notable by-product of pig farming, is already used in various industries such as chemicals, pharmaceuticals, dyes, and biodiesel production. However, its potential remains underutilized for improving the mechanical properties and durability of polymer composites, while also addressing environmental concerns associated with the global pork industry. In this research, pig hair is employed as a fiber-reinforcing material due to its favorable tensile strength, high Young's modulus, biodegradable nature, widespread availability, and low cost as a by-product of pig slaughterhouses [13, 14].

The mechanical properties of natural fiber-reinforced polymer composites are influenced by several key factors. These include the selection of fibers and matrix materials, the interface strength between fiber and matrix, the dispersion of fibers within the matrix, the manufacturing methods employed, porosity levels, and fiber orientation [21] [19]. Understanding and optimizing these factors are crucial for the development of high-performance composite materials suitable for a wide range of industrial applications. Researchers have explored the feasibility of utilizing hair fibers as reinforcement in polymer composites, leveraging their abundant availability, cost-effectiveness, and potential to reduce environmental impact. The manufacturing methods for composites are diverse and are determined by the materials used and the desired properties of the final product. Common manufacturing techniques include Hand Lay-Up, Spray-Up, Vacuum Bagging, Pultrusion, Compression Molding, Filament Winding, Injection Molding, and Additive Manufacturing (3D Printing)[22, 23].

Research findings indicate that the chemical modification of natural fibers facilitates improved adhesion between the matrix and natural fibers through chemical reactions[24]. Several studies have explored the effects of chemical treatment on natural fibers. The inherent hydrophilic nature of natural fibers contrasts with the hydrophobic nature of matrices, resulting in weak bonding at the interfaces of natural fiber composites. Chemical treatment alters the inherent hydrophilic behavior of fibers, thereby enhancing the adhesion properties between the matrix and fibers. Various chemical treatment methods have been explored, including alkaline treatment, silane treatment, acetylation, benzoylation, peroxide treatment, maleated coupling agents, sodium chlorite treatment, acrylonitrile grafting, isocyanate treatment, stearic acid treatment, permanganate treatment, triazine treatment, oleoyl chloride treatment, and fungal treatments[8], [25-28].

Numerous research papers have been published on hair fiber-reinforced polymer composites[11-17], [29-35]. However, after conducting a thorough study, it was found that no work has been done specifically on pig hair fiber-reinforced polymer composites. Therefore, it was decided to focus on the following objectives:

- Fabrication of pig hair fiber-reinforced polymer composites using epoxy resin as a binding agent
- Fabrication of pig hair FRPC using hand layup and cold compression techniques
- Evaluation of the mechanical properties of pig hair fiber-reinforced composites
- Evaluation of the water absorption behavior of pig hair fiber-reinforced composites

This study specifically examines the influence of fiber loading on the mechanical properties and water absorption behavior of epoxy polymer composites reinforced with treated long pig hair fibers.

## 2. Materials and Methods

In this study, pig hair, a natural fiber, was used in the fabrication of composites with fiber loadings ranging from 10% to 40% by weight. To enhance the properties of the fibers, they were treated with a NaOH solution. A specific procedure was followed for the treatment of the fibers.

### *2.1. Reinforcement and Matrix Material*

In this research, commercially available pig hair of the Ghungroo breed was sourced from Achrol, Jaipur, Rajasthan (India). The analysis revealed three distinct regions within the pig fibers, similar to those observed in other types of fibers like animal and human hair [36], [37]. These regions include the outermost thin cuticle, a thick cortex situated between the cuticle and the medulla, and a central medulla, as shown in Figure 1. The lengths of the fibers obtained ranged from 75 to 100 mm.

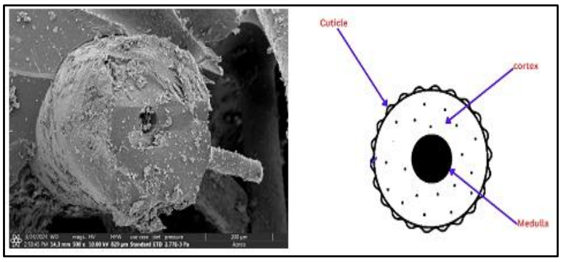


**Fig. 1.** SEM Image of Pig Hair Fiber and its Cross-section

Epoxy has been chosen as the matrix material for this study, specifically Epoxy LY556 and its corresponding hardener HY-951. Epoxy is selected for its excellent mechanical properties, as detailed in Table 1.

**Table 1.** Physical properties of Epoxy resin [31]

| Epoxy Resin Property | Value |
|---|---|
| Density, $g/cm^3$ | 1.1-.1.4 |
| Tensile Strength, MPa | 35-100 |
| Impact Strength J/cm | 0.3 |
| Elongation , % | 1-6 |
| Compressive Strength, MPa | 100-200 |
| Elastic Modulus, GPa | 3-6 |
| Cure Shrinkage, % | 1-2 |
| Water Absorption, (24 Hrs at 20ºc) | 0.1-0.4 |

### *2.2. Treatment of Fiber*

Before incorporating pig hair fibers as reinforcements in the composites, a comprehensive cleaning process was undertaken. The fibers were first washed with a solution of distilled water and detergent, followed by sun-drying for three days to remove impurities such as oil and pigments. Next, the fibers underwent chemical treatment to enhance wettability, improve interfacial bonding strength with the epoxy matrix, and reduce moisture absorption. The chemical treatment involved immersing the fibers in a 0.25 M NaOH solution in a water bath maintained at 60°C for one hour. After treatment, the fibers were neutralized with acetic acid, rinsed, and washed multiple times with distilled water to remove any residual NaOH. Finally, the fibers were oven-dried at 60°C for one hour to ensure complete drying. This meticulous cleaning and treatment process was designed to optimize the performance and compatibility of the pig hair fibers within the composite material.

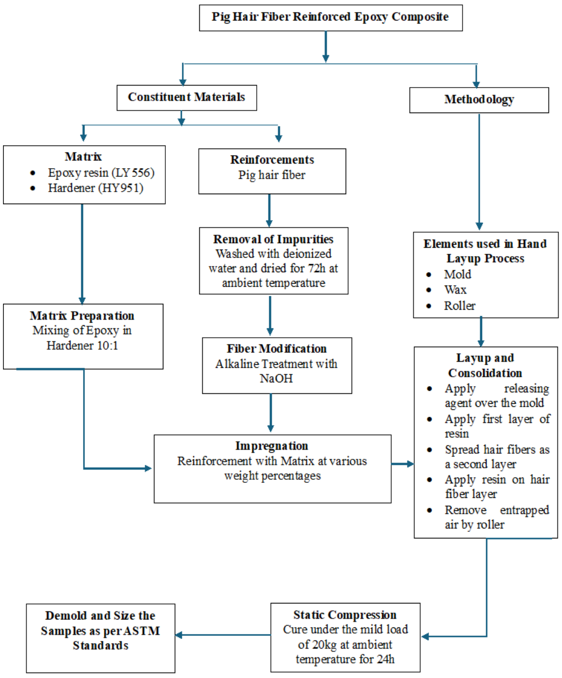


**Fig. 2.** Flow chart: Pig hair Fiber-reinforced Epoxy Polymer Composite sheet fabrication process

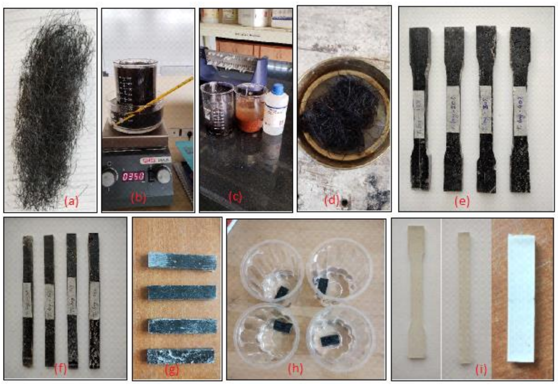


**Fig. 3.** Preparation of Treated Long Pig Hair fiber reinforced Epoxy Composite (a) Long Pig Hair, (b) Treatment with 0.25M NaOH, (c) Neutralized the fibers from Acetic Acid, (d) Drying process, (e) Tensile Test Samples, (f) Flexural Test Samples, (g) Impact Test Samples, (h) Water Absorption Test Samples, (i) Control Samples

The flow chart of the treated long pig hair fiber-reinforced epoxy composites and the preparation of samples are shown in Figure 2 and Figure 3.

### 2.3. Fabrication of Composite

The fabrication process of the composite materials involved creating a plate measuring 300 mm × 150 mm with a laminate thickness of 5 mm using the hand layup method. To facilitate easy removal of the specimen, a uniform layer of wax was applied across the entire surface of the molding box. Additionally, a releasing agent containing polyvinyl acetate was applied to both the upper and lower surfaces of the molding box prior to the molding process. A dwell time of 20 minutes was allowed for the molding box to dry before proceeding. Four different fiber compositions by weight percentage (wt%) were fabricated, as detailed in Table 2. Epoxy resin and its corresponding hardener HY 951 were mixed at a weight ratio of 10:1. Pig hair fibers were randomly incorporated into the epoxy matrix. The molds were constructed using plywood, silicone rubber, and lamination sheets. Epoxy resin was first poured into the mold, followed by the uniform distribution of fibers and additional resin application. The mold was then sealed with another lamination sheet and plywood and cured under a 20 kg load for 24 hours before demolding. Specimens for dynamic mechanical analysis were prepared in accordance with ASTM standards. A schematic diagram of the experimental setup is shown in Figure 4.

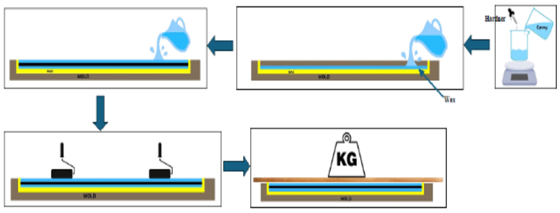


**Fig. 4.** Schematic diagram of the experimental setups used for the experiment

The fiber content ranged from 10 wt% to 40 wt%, while the epoxy resin content varied from 90 wt% to 60 wt%. Before fabrication, the required quantities of fibers and resin were calculated based on the selected weight fraction and fiber composition [31].

## 3. Sample Characterization

To evaluate the mechanical properties of polymer composites, several tests are performed, including impact strength tests, water absorption tests, and density analysis. These analyses provide valuable insights into the performance and behavior of composite materials in real-world applications.

**Table 2.** Weight percentage of fibers and resin for composite creation

| Sample Name | NaOH Treated Pig Hair | Composition |
|---|---|---|
| Control | Pure Epoxy | 100wt% Epoxy Resin |
| TLPH10 | Treated Long Pig Hair | 10wt%TLPH+90wt% Epoxy Resin |
| TLPH20 | Treated Long Pig Hair | 20wt%TLPH+80wt% Epoxy Resin |
| TLPH30 | Treated Long Pig Hair | 30wt%TLPH+70wt% Epoxy Resin |
| TLPH40 | Treated Long Pig Hair | 40wt%TLPH+60wt% Epoxy Resin |

### *3.1. Density Analysis and Faction of Voids*

The density of a composite material is determined by both the polymer matrix and the reinforcing fibers. Density analysis entails examining the interaction between the matrix and reinforcing fibers. These materials play a pivotal role in transforming industries by offering lightweight, robust, and adaptable solutions. To calculate the density of a polymer composite, it is essential to consider the densities of its constituent components, such as the resin, fibers, etc. By understanding the density of each component and their relative proportions within the composite, engineers can accurately predict and optimize the overall density of the composite material.

- Experimental Density:

The experimental density (ρe) of the samples was found in accordance with ASTM D1895. Density was computed using the following formula, based on the average data collected from three replicate samples.

$$\rho_e = \frac{m}{v} \tag{1}$$

where "m" represents the mass of the composites measured with an analytical balance, and "v" indicates the volume of the composites derived from their dimensions (length × width × thickness) measured using a digital caliper [38].

- Theoretical Density

To calculate the theoretical density of the composite material, the following equation is used. It expresses the density of the composite material in terms of the volume fractions of its constituents, formulated as:

$$\rho_c = \rho_f V_f + \rho_m V_m \tag{2}$$

where $\rho_c$ = Theoretical Density of Composite, $\rho_f$ = Density of Fiber, $\rho_m$= Density of Matrix, $V_f$= The volume fraction of Fiber and $V_m$= Volume fraction of Fiber

The equation for calculating the fraction of voids% is as follows:[32]

$$Fraction\ of\ voids\ (\%) = \frac{\rho_c - \rho_e}{\rho_e} \times 100 \tag{3}$$

where $\rho_c$ = Theoretical Density of Composite and ρe = experimental density

The above formula was used to determine the void percentage by comparing the theoretical and experimental densities.

### *3.2. Tensile Test*

Tensile testing was conducted utilizing a computerized universal testing machine, employing a crosshead speed of 1 mm per minute, and measuring a gauge length of 50 mm. The preparation of composite sample specimens adhered to the standards outlined in ASTM D638, which governs the evaluation of tensile strength [39]. These specimens were securely positioned within the grips of the universal testing machine for the duration of the test.

Tensile strength was determined using the following formula:

$$\text{Tensile Strength } (\rho) = \frac{Maximum\ Load\ Applied\ (N)}{Cross\ Section\ Area\ of\ Specimen\ (mm^2)}\ N/mm^2 \tag{4}$$

This standardized testing procedure ensures accurate and consistent measurement of tensile strength, providing valuable data on the mechanical properties of the composite materials.

Tensile Modulus was calculated using the following formula.

$$\text{Tensile Modulus } (\rho_m) = Stress/Strain \tag{5}$$

where $Stress = \frac{Load}{Area}$ and $Strain = \frac{\Delta L}{L}$ , $\Delta L = Change\ in\ length (Displacement)$ and $L = Gauge\ length\ (mm)$

### *3.3. Flexural Strength*

The flexural strength of a material reflects its ability to withstand deformation under bending forces. To assess this property, a flexural test was performed using the 3-point bending setup as per the ASTM D790 standard [39]. In this test, a load was applied at the midpoint of the beam until the specimen fractured. The load at the breaking point, along with the dimensions of the sample, was employed to calculate the flexural strength of the composite using the following formula:

$$\text{Flexural strength } (\rho_f) = \frac{3FL}{2wt^2} \quad (6)$$

where σf =Flexural strength (N/mm$^2$), F= Load (N), L= length or span (mm), w= width (mm) and t= thickness respectively

The Flexural Modulus of the composite was calculated using the following formula.

$$\text{Flexural Modulus } (E) = \frac{L^3F}{4dwt^3} \quad (7)$$

where L = Span length(mm), F = Load(N/mm$^2$), d= Displacement(mm), w & t = width and thickness of composite(mm).

### *3.4. Impact Test*

The impact test assesses a material's capacity to withstand or absorb impact or shock loading, typically by quantifying the energy absorbed during fracture. The Izod impact test was performed on the specimen in accordance with the ASTM D256 standard at room temperature [39].

$$Impact\ Strength = \frac{Energy\ Absorbed\ (J)}{Area\ of\ Composite\ (mm^2)} \quad (8)$$

### *3.5. Water Absorption*

The Water Absorption test was conducted in accordance with the ASTM D570 standard. Each composite sample was immersed in distilled water, and their weights were measured at regular intervals of time until reaching the saturation point at room temperature. The percentage moisture absorption was calculated as the ratio of the increase in mass of the specimen to its initial mass. This standardized procedure provides valuable insights into the water absorption behavior of composite materials, crucial for assessing their durability and suitability for various applications [40].

Mathematically, this was calculated using the following equation.

$$\%\ Absorption = \frac{W_t - W_d}{W_d} \times 100 \quad (9)$$

where, $W_t$ = Wet Weight and $W_d$ = Dry Weight

Thickness swelling is a metric that quantifies the alteration in thickness of a composite material subsequent to immersion in distilled water. It offers valuable indications regarding the extent of the expansion or swelling the material undergoes due to water absorption. The measurement of thickness swelling in the composite is conducted using a micrometer with a minimum resolution of 0.01 mm. The Thickness Swell (TS) of the sample is determined by employing the following equation.

$$TS(\%) = \frac{\delta_f - \delta_i}{\delta_i} \times 100 \quad (10)$$

where $\delta_i$ and $\delta_f$ are the initial and final thickness of the composite specimen after immersion in the distilled water[41].

### *3.6. Scanning Electron Microscopy (SEM)*

Scanning Electron Microscopy (SEM) analysis offers visual evidence of the microstructure of the composite. The morphological examination of alkali-treated hair fiber composites was carried out using a scanning electron microscope operating at an acceleration voltage of 0-30 kV. The fractured surfaces of the composite samples were utilized for this analysis. To aid imaging, a thin layer of gold coating was applied.

## 4. Results and Discussion

For each weight percentage of the developed composites, three samples were tested. The average results from these tests were calculated and used to represent the typical response of each composite variant.

### *4.1. Density of Treated Long Pig Hair Reinforced Composites*

The density of the developed pig hair-reinforced composites was determined experimentally, and the values closely aligned with the theoretical density. The average experimental density for each composite sample is presented in Table 3. A comparison with pure epoxy revealed that the inherent flow ability of pure epoxy facilitated the automatic removal of voids. However, during the fabrication of composites using the hand layup process, some air particles were trapped despite efforts to minimize voids with rollers. This led to the formation of weaker sections within the composite.

The results show that epoxy composites with 10 wt%, 20 wt%, 30 wt%, and 40 wt% pig hair content exhibit slightly lower densities than the theoretical values, likely due to the presence of voids within the composites [38]. Similarly, the experimental density of pure epoxy, serving as the matrix material, is closer to the theoretical density. Furthermore, the observed density is lower compared to that of conventional materials [33].

**Table 3.** Theoretical Vs Experimental Density

| Sample Name | Theoretical Density of Composite $\rho_c$ (g/cm³) | Average Experimental Density of Composite $\rho_e$ (g/cm³) | Fraction of voids (%) |
|---|---|---|---|
| Control | 1.15 | 1.15 | 0.94% |
| TLPH10 | 1.17 | 1.15 | 1.28% |
| TLPH20 | 1.18 | 1.16 | 1.37% |
| TLPH30 | 1.20 | 1.17 | 1.86% |
| TLPH40 | 1.21 | 1.19 | 2.03% |

### *4.2. Tensile Behavior of Developed Treated Long Pig Hair Reinforced Composites*

Figures 5 and 6 illustrate the tensile strength and tensile modulus of epoxy-based composites reinforced with treated long pig hair. The results show an initial decrease in tensile strength at 10 wt%, followed by a peak at 30 wt%. Beyond this point, further increases in fiber content lead to a decline in tensile strength [17]. The peak value of 49.46 MPa is observed in composites containing 30 wt% pig hair and 70 wt% epoxy, likely due to improved load transfer from the matrix to the fibers. This tensile strength of 30 wt% pig hair fiber reinforced polymer composite found near to the tensile strength of human hair fiber reinforced polymer composite at 7 wt% fiber loading [42]. More natural fiber incorporation reduces the pure epoxy requirements which make the composite biodegradable nature. The tensile strength is primarily influenced by the interfacial adhesion between the fibers and the matrix. However, at 40 wt% pig hair content, the interfacial bonding weakens due to insufficient resin, which may result in delamination between the pig hair layers[33], [35].

Figure 6 illustrates the tensile modulus, reflecting the stiffness of the developed composites under tensile loads. All composites exhibited higher tensile moduli compared to pure epoxy, which served as the control under identical experimental conditions [43]. A significant reduction in modulus was observed in the 30-40 wt% fiber reinforcement range, with the highest value occurring at 20 wt%.

The observed decrease in tensile modulus in the 30-40 wt% fiber-reinforced composites may be attributed to factors such as fiber agglomeration, resulting from experimental imperfections that hinder proper fiber dispersion.

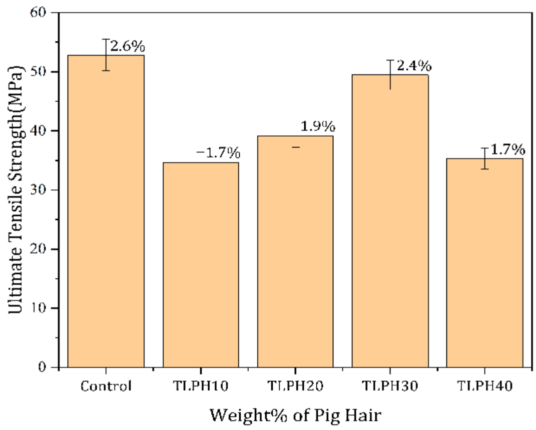


**Fig. 5.** Tensile Strength: Treated Long Pig Hair Fiber Reinforced Epoxy and Control

Optimal fiber dispersion promotes strong interfacial bonding and minimizes voids, whereas fiber agglomeration exacerbates these issues.

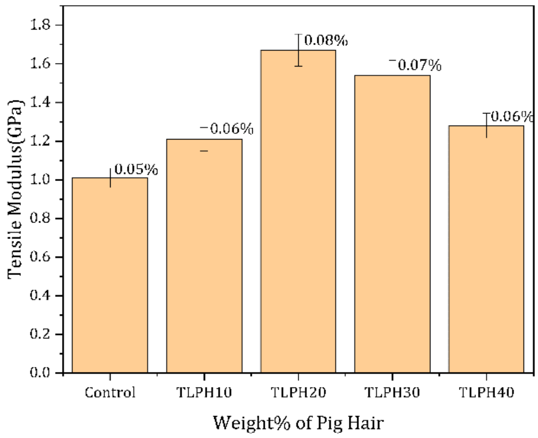


**Fig. 6.** Tensile Modulus: Treated Long Pig Hair Fiber Reinforced Epoxy and Control

Notably, the 20 wt% fiber-reinforced composite exhibited the highest tensile modulus of 1668.59 MPa (1.67 GPa), compared to the control sample's modulus of 1008.34 MPa (1.01 GPa)[35].

### *4.3. Flexural Strength of Developed Treated Long Pig Hair Reinforced Composites*

Figure 7 presents the flexural strength results for both neat epoxy and epoxy composites reinforced with pig hair. Research indicates that the flexural strength of natural fiber-reinforced composites increases proportionally with fiber content until reaching an optimal level [2]. Neat epoxy demonstrates a flexural strength of 101.20 MPa. The incorporation of pig hair at 30 wt% enhances flexural strength, with the composite containing 30 wt% pig hair and 70 wt% epoxy exhibiting the highest flexural strength of 89.86 MPa among all tested laminate compositions. However, beyond the 30 wt% threshold, the flexural strength of reinforced epoxy composites declines. Specifically, at 40 wt% pig hair content, a reduction in flexural strength is observed, likely due to insufficient resin, leading to poor interfacial bonding between the hair mat and epoxy [26]. Under load, the specimens experience delamination on the bottom side opposite the applied load.

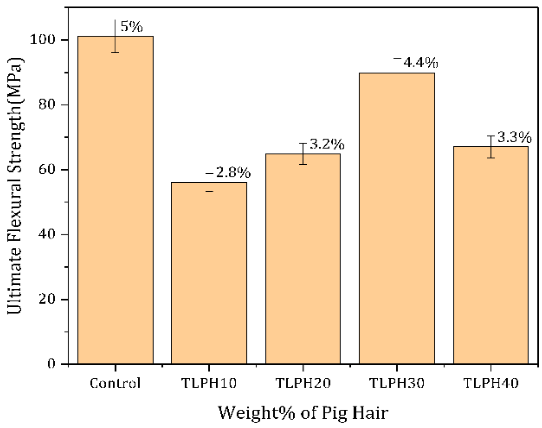


**Fig. 7.** Flexural Strength: Treated Long Pig Hair Fiber Reinforced Epoxy and Control

Figure 8 illustrates the flexural modulus of both the developed composites and the control sample.

Consistent with the trend observed in Figure 6, most of the developed composites show improved flexural modulus compared to the control sample[43]. However, exceptions are noted in the 20 wt% and 40 wt% treated fiber-reinforced composites, which exhibit lower flexural moduli. This deviation may be attributed to uniform load distribution within the fibers as fiber content increases, allowing for more efficient load-bearing. This observation aligns with the findings in Figure 6. Notably, the composite with 30 wt% fiber content demonstrated the highest flexural modulus at 3979.47 MPa (3.98 GPa), followed by the 10 wt% treated pig hair fiber-reinforced composite at 3967.19 MPa (3.97 GPa). In contrast, the control sample registered a flexural modulus of 1789.80 MPa (1.79 GPa). These results indicate that the fibers were well-dispersed, enhancing interaction with the matrix and improving fiber-matrix interfacial adhesion, which directly increased the flexural modulus [44]. Such enhancement may not be as pronounced at lower fiber weight fractions.

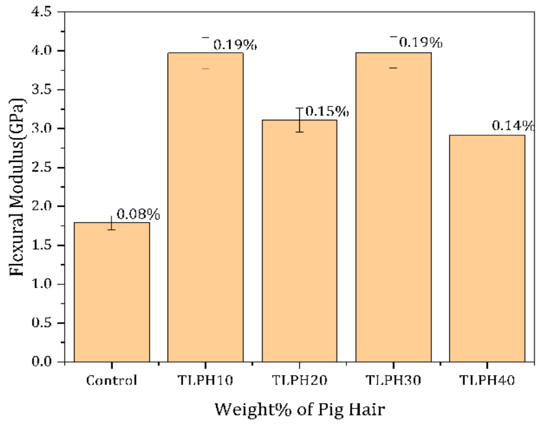


**Fig. 8.** Flexural Modulus: Treated Long Pig Hair Fiber Reinforced Epoxy and Control

In general, the trend indicates that flexural modulus tends to increase with higher fiber content, highlighting the advantage of using higher weight fractions in the fabrication of pig hair fiber-reinforced epoxy composites to achieve superior flexural strength and stiffness.

### *4.4. Impact Energy Behavior of Developed Treated Long Pig Hair Reinforced Composites*

An experimental assessment was conducted to investigate the Izod impact strength of both epoxy and epoxy composites reinforced with pig hair. The findings revealed a distinct pattern: impact strength increases with the weight percentage of pig hair up to 40 wt%, as depicted in Figure 9.

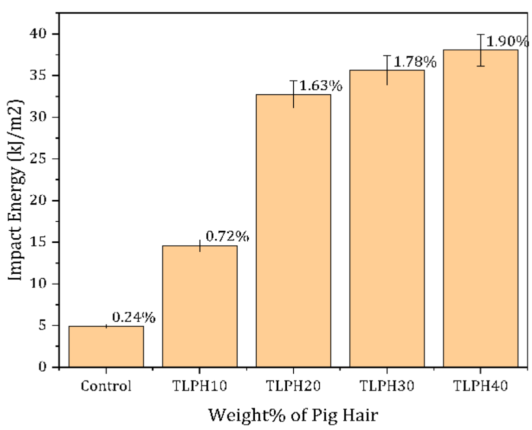


**Fig. 9.** Impact Variation: Treated Long Pig Hair Fiber Reinforced Epoxy and Control

Notably, for composites comprising 40 wt% pig hair and 60 wt% epoxy, the highest impact energy required for specimen fracture in the Izod tests was recorded at 38.05 kJ/m² (38,050 J/m²). Here lowest Impact strength achieved by 10 wt% of pig hair loading 14.58 kJ/m² (14580 J/m²) which is higher than a human hair with 10 wt% fiber loading[42]. Similar observations have been documented in previous studies examining impact energy in Polymer Matrix Composites [34].

The increase in impact strength with the rising weight percentage of pig hair up to 40 wt% can be attributed to the reinforcing effect of the pig hair fibers within the material matrix. As the weight percentage of pig hair increases, more fibers are dispersed throughout the matrix, enhancing its mechanical properties, including impact strength [12]. However, beyond 40 wt%, there may be diminishing returns or other factors that limit further improvements in impact strength.

### *4.5. Water Absorption and Thickness Swelling Examination Of Developed Treated Long Pig Hair Reinforced Composites*

Table 4 presents the outcomes of water absorption tests on composites reinforced with treated pig hair fibers. Natural fibers are known for their pronounced hydrophilicity, meaning that higher fiber content typically leads to increased moisture absorption. This correlation is supported by the increasing moisture absorption trend shown in Figure 10 with a rising fiber fraction [40].

Initially, a high rate of moisture absorption was observed within the first 24 hours and, subsequently, every 10 days. This can be attributed to the chemical treatment, which alters the hair's structure, potentially increasing its porosity and accelerating water absorption. After approximately 30 days, the rate of water absorption stabilized as the fibers reached saturation, making further significant absorption unlikely [2].

**Table 4.** Water Absorption Percentage

| Sample Name | Day0 | Day1 | Day2 | Day3 | Day10 | Day20 | Day30 | Day40 |
|---|---|---|---|---|---|---|---|---|
| Control | 0.00% | 0.22% | 0.27% | 0.33% | 0.38% | 0.43% | 0.43% | 0.43% |
| TLPH10 | 0.00% | 0.73% | 1.04% | 1.30% | 1.98% | 2.34% | 2.50% | 2.50% |
| TLPH20 | 0.00% | 1.33% | 2.26% | 3.02% | 4.35% | 4.97% | 5.24% | 5.46% |
| TLPH30 | 0.00% | 1.94% | 3.02% | 3.81% | 5.18% | 6.26% | 7.16% | 7.70% |
| TLPH40 | 0.00% | 2.10% | 3.48% | 4.50% | 6.06% | 7.27% | 8.29% | 9.01% |

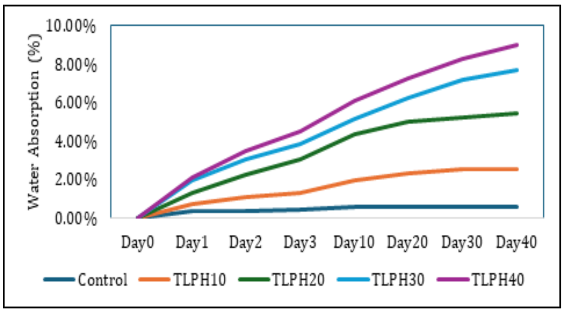


**Fig. 10.** Water absorption: Treated long pig hair fiber reinforced composites.

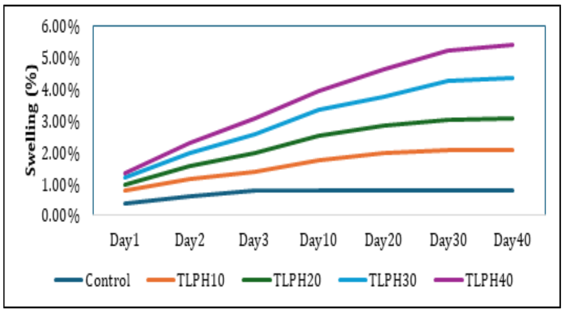


**Fig. 11.** Swelling Variation: Treated long pig hair fiber reinforced composites.

In contrast, the reduced size of the fiber fraction and subsequent enhanced dispersion enable superior encasement of the fibers within the matrix. This significantly reduces the rate at which water permeates into the fibers, ultimately enhancing resistance to absorption. As previously explained, however, the composite reinforced with 40wt% treated pig hair fiber exhibited the lowest resistance to water absorption and displayed the highest hydrophilicity among all the composite samples[40], [41].

Nevertheless, it is noteworthy that even after 40 days, only 2.5% water was absorbed by the 10wt% pig hair fiber composite, and the maximum water absorption was also limited to 9.01% by the 40wt% pig hair fiber composite. Due to its low water absorption behavior, the thickness swelling behavior of the pig hair fiber was also found to be satisfactory as illustrated in Table 5.

Composites with 40wt% pig hair exhibited greater thickness swelling compared to pure epoxy as depicted in Figure 11. This increased swelling in composites can be ascribed to water absorption, which results in expansion of both the fibers and the epoxy matrix. However, with time, water can infiltrate between the fibers and the epoxy matrix, eventually reaching saturation [7], [40].

**Table 5.** Swelling Percentage

| Sample Name | Day1 | Day2 | Day3 | Day10 | Day20 | Day30 | Day40 |
|---|---|---|---|---|---|---|---|
| Control | 0.40% | 0.60% | 0.80% | 0.80% | 0.80% | 0.80% | 0.80% |
| TLPH10 | 0.79% | 1.18% | 1.38% | 1.77% | 1.96% | 2.06% | 2.06% |
| TLPH20 | 0.98% | 1.57% | 1.96% | 2.55% | 2.84% | 3.04% | 3.08% |
| TLPH30 | 1.19% | 1.98% | 2.57% | 3.36% | 3.75% | 4.25% | 4.35% |
| TLPH40 | 1.35% | 2.32% | 3.09% | 3.96% | 4.63% | 5.21% | 5.41% |

### *4.6. Scanning Electron Microscopy (SEM) Image Analysis*

Here Scanning Electron Microscopy (SEM) is utilized to investigate various aspects of surface morphology in composites, including fiber-matrix bonding, presence of voids, micro-cracks, crack propagation, and fiber agglomeration. SEM image depicts observations in long fiber composites, emphasizing a robust attachment between pig hair fibers and the epoxy polymer matrix, indicating superior interfacial bonding as shown in Figure 12. This strengthened bonding enhances adhesion between the fiber surface and the matrix, thereby enhancing the mechanical properties of long fiber-reinforced composites[29].

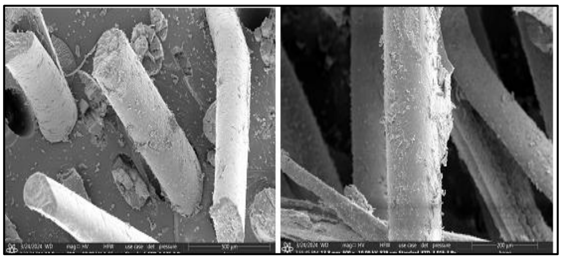

**Fig. 12.** SEM Image of Un-treated and treated Long Pig Hair Fiber

Here is an image comparing SEM visuals of untreated and treated hair fibers, highlighting the difference in surface roughness. The treated hair strand exhibits the increased surface roughness seen in the SEM image. The roughness suggests better adhesion and strengthening treatments, leading to enhanced durability and resilience compared to the untreated strand.

## 5. Conclusions

In this study, we investigated the mechanical and water absorption properties of pig hair, with a focus on tensile, flexural and Impact strength performance.

- Optimal tensile strength was achieved at 30 wt% pig hair reinforcement, with a decline beyond this point due to weakened interfacial bonding. The tensile modulus peaked at 20 wt% reinforcement, emphasizing the importance of proper fiber dispersion for maximizing mechanical properties.
- Flexural strength and modulus improved with 30 wt% reinforcement, demonstrating better fiber-matrix interaction, but properties declined with further reinforcement due to poor bonding.
- Impact strength increased with pig hair content up to 40 wt%, showcasing the reinforcing effect of pig hair fibers.
- The study of water absorption and thickness swelling revealed higher moisture absorption with increasing fiber content due to natural fibers' hydrophilicity. Chemical treatment initially increased absorption rates but stabilized after 30 days, with satisfactory thickness swelling behavior.

### *5.1. Limitations of Work*

Despite the promising results, this study does have some limitations that need to be addressed. These limitations mainly pertain to the fabrication process and the inherent properties of natural fibers.

- The density of pig hair-reinforced composites closely matched theoretical values, indicating successful fabrication despite some voids, particularly during hand layup, which weakened sections of the composites.
- Voids introduced during the hand layup process, despite efforts to minimize them, weakened certain sections of the composites.

- Inadequate interfacial bonding in composites with higher fiber content led to reduced mechanical properties.
- Water absorption was higher with increased pig hair content due to the hydrophilicity of natural fibers.

*5.2. Comparison with Other Studies*

- The tensile strength and Flexural Strength align with similar studies on human hair fiber-reinforced composites, but this study showed that pig hair fibers offer better impact resistance at higher fiber content compared to human hair fibers [42].
- Epoxy resin reinforced with conventional fibers like glass or carbon offers higher strength but lacks the environmental benefits and cost-effectiveness of pig hair reinforcement.
- Unlike studies focusing solely on synthetic fibers, this work showcases the advantages of natural fibers in applications requiring moderate mechanical properties with added sustainability.

The study underscores the importance of balanced reinforcement content for optimal mechanical performance in composite materials. Pig hair-reinforced composites demonstrate properties that can be suitable for applications in the automobile, marine, and shed manufacturing industries. Future research could focus on refining fabrication techniques to minimize voids and improve interfacial bonding. Additionally, combining this fiber with other materials like synthetic fibers, natural fibers, nano-clay or ceramic to create hybrid composites could further improve performance and reliability [45-47]. Overall, this study contributes valuable insights into the mechanical behavior and potential applications of pig hair-reinforced composites.

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## Conflicts of Interest

The author declares that there is no conflict of interest regarding the publication of this article.

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