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EXPLORING THE MECHANICAL PROPERTIES AND WATER ABSORPTION BEHAVIOR OF KERATIN FIBER-REINFORCED EPOXY COMPOSITES: INSIGHTS INTO SUSTAINABLE MANUFACTURING

Kachhot Deepak[1*], Dewangan Rishi[2], Rinawa Motilal[3], Dwivedi Umesh Kumar[4]

[1,2]Department of Mechanical Engineering, Amity University Rajasthan, Jaipur, India
[3]Department of Mechanical Engineering, Govt. Engineering College Jhalawar, Jhalawar, India
[4]Department of Applied Science, Amity University Rajasthan, Jaipur, India

[1]https://orcid.org/0000-0001-6329-2619, [2]http://orcid.org/0000-0002-1973-6726, [3]http://orcid.org/0000-0001-7561-227X, [4]http://orcid.org/0000-0002-8990-2275

E-mail: [1]*deepakkachhot27@gmail.com, [2]rdewangan@jpr.amity.edu, [3]motilal.rinawa@gmail.com, [4]ukdwivedi@jpr.amity.edu

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ABSTRACT

This study investigates the mechanical properties and the water absorption behavior of Keratin fiber-reinforced epoxy composites. The Keratin fibers were used as reinforcement with epoxy. Samples were prepared using the Hand lay-up method, having different amounts of reinforcement. The samples were characterized for their mechanical behavior as per ASTM standards. The tensile strength peaks found at 30wt% declined thereafter due to weakened interfacial bonding. Enhanced tensile moduli observed with fiber loading peaked at 30wt%. Flexural strength and modulus raised to 30wt%. Izod impact strength increased consistently with higher percentages, reaching a maximum of 40wt%. Density values closely matched with theoretical values, with epoxy composites demonstrating lower densities. The positive aspect is found that even after 40 days, only 4.04% of water was absorbed by the composite containing 40wt% fiber which shows the hydrophobic nature of the composite. Certainly, the thickness swelling behavior is notably adequate, owing to the low water absorption characteristics exhibited by fiber composite. This research highlights the significance of Keratin fibers composite in the field of automobile, shed manufacturing, and Marine products manufacturing industry.

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I. INTRODUCTION

Since few decades, lot of research are going on to find out the new class of materials and their applications. In 19th century, synthetic plastic was used to manufacture the parts for automobile, aircraft, wind turbine and so on. Due to the low strength of plastic, it is found that, its parts are not able to transmit the full load, this limitation increased the scientists focus on to do the research on fiber-based composite to enhance the load transmitting capacity of plastic. Synthetic fibers show good mechanical strength due to this glass fiber and Carbon fibers are the most used synthetic fiber for reinforcement materials and still used in various applications like in automobile, aero-plane, ship manufacturing industries etc. Although synthetic fibers show good properties results but due to non-biodegradable properties and health hazards, it creates ecological problems. Due to this reason, there is a need to find the new alternative fibers which can not only substitute of existing one but also it should be easily available, cost effective, bio-degradable and should have high specific property[1]. This research was focused on finding the appropriate natural fiber, matrix agent and adhesive property enhancement techniques through which desired mechanical strength can be achieved, which can be used for various industrial applications.

Generally natural fibers are categorized into three divisions: plant based, animal/human based, and minerals based. Plant based fibers are extracted from leaves, fruits, stems or seeds of the plants, animal/human-based fibers are like hairs, wool, feather, silk etc. and asbestos, graphite, glass fibers etc. are categorized under the mineral fibers[2] [3]. Due to their less cost, low density, minimal health hazards, less pollution, eco-friendly and bio-degradable nature, if a new composite is developed through reinforcement, it would not only be beneficial for

environmental concern but also would be economical[4]. These advantages are sufficient to lead the research on the natural fiber-based polymer composite and increase the commercial utilization of these in different industries. The property of natural fiber depends on their physical nature, age of the plant, chemical composition of the fiber and some other additives like wax, ash present in it etc.[5]

The utilization of waste materials to augment or enhance the characteristics of polymer composites has garnered considerable research interest worldwide in recent decades[2], [6], [7]. Hair is known for its elasticity, smoothness, strength, and softness, attributes primarily attributed to its cortex keratin. The long chains of cortex keratin are compressed to create a regular structure that is both strong and flexible. This inherent flexibility is a key factor in enhancing the flexibility of the composite material. Hair can be used as a fiber reinforcing material in composites due to its high tensile strength, non-degradable material, abundantly available and hair is obtainable at a very low cost as a waste material[2].

Keratin, a significant by-product of pig farming, finds various applications in industries such as chemicals, pharmaceuticals, dyes, and biodiesel production.[8]. Recycled Keratin may have promising opportunity to enhance the mechanical properties and durability of polymer composites while simultaneously addressing environmental concerns within the global pork industry. From the study it is found that the Mechanical Property of the Natural fiber reinforced Polymer composite depends on Fiber selection, Matrix selection, Interface strength, Fiber dispersion, Manufacturing Method, Porosity and Fiber orientation.[9].

N. H. Mohan et al.[8] have explored the potential of Keratin fibers as reinforcement in polymer composites, leveraging their widespread availability, cost-effectiveness, and potential to mitigate environmental footprints. Methods for manufacturing composites vary widely depending on the materials involved and the desired properties of the final product. Several common manufacturing methods include Hand Lay-Up, Spray-Up, Vacuum Bagging, Pultrusion, Compression Molding, Filament Winding, Injection Molding, Additive Manufacturing (3D Printing). ([1], [2], [10], [11]

From the study it is found that chemical alteration of natural fibers enhances the adhesion between the matrix and natural fibers through chemical reactions. Numerous studies have investigated the impact of chemical treatment on natural fibers[12], [13], [14]. The distinct 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 improving adhesion properties between the matrix and fibers[15], [16]. Various chemical treatment methods have been explored, including alkaline treatment, silane treatment, acetylation, benzoylation, peroxide treatment, malleated coupling agents, sodium chlorite treatment, acrylonitrile grafting, isocyanate treatment, stearic acid treatment, permanganate treatment, triazine treatment, oleoyl chloride treatment, and fungal treatments.

II. MATERIALS AND METHODS

II.1 MATERIALS

Keratin fiber i.e. Pig hair procured from local pig farmers at Achrol, Jaipur, Rajasthan, India. The fiber was examined under a light microscope, pig fibers exhibit three distinct regions[17]. These regions include the outermost thin cuticle (measured 0.28 to 0.32 mm), the central medulla (measured 0.36 to 0.39 mm), and a thick cortex (measured 0.40 to 0.46.mm) situated between the cuticle and the medulla. The fibers obtained in the lengths ranged from 75 to 100mm. Here Chopped fibers(4-5mm) were used for reinforcement[18]. Keratin Fiber was used as reinforcement and the matrix was Epoxy and Hardner in fabrication of natural fiber composite. To enhance fiber bonding characteristics, a NaOH solution was used for fiber treatment. The density of used Pig hair was 1.6 g/cm³. Physical properties of Pig hair are mentioned in Table 1.

Table 1: Physical properties of Pig Hair

Keratin Properties	Value
Tensile strength (cN tex^{-1})	14.05
Young's modulus (Gpa)	6.39
Maximum load at rupture(N)	9.2–13.8
Extensibility	31.53%
Average Mid-Section diameter (mm)	0.16
Average Length (mm)	35.7
Aspect Ratio	249
Water Absorption (%)	95
Surface Roughness (µm)	0.104
Density of Keratin (g/cm^3)	1.59– 1.88

Source: [19], [20].

Epoxy demonstrates good mechanical Properties, here Epoxy (LY556) and hardener (HY-951) were employed as matrix material. Physical properties of Epoxy resin are listed in Table 2.

Table 2: Physical properties of Epoxy resin.

Epoxy Resin Property	Value
Density, g/cm³	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

Source: [21].

Before started the development of composites, Keratin fibers underwent a thorough cleaning process. These were washed with distilled water and detergent, then sun-dried for one week to eliminate impurities. Subsequently, the fibers underwent chemical treatment to enhance wettability and improve interfacial bonding between the fibers and the matrix.

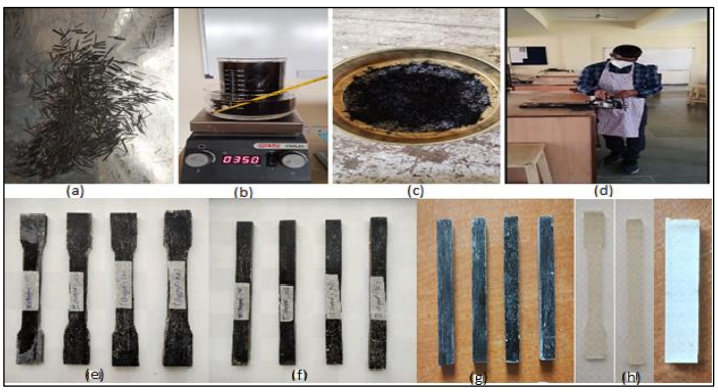

Figure 1: Preparation of Treated Chopped Keratin fiber reinforced Epoxy Composite (a) Chopped Keratin Fiber (b) Treatment with 0.25M NaOH (c) Drying process (d)Cutting samples as per ASTM standards (f) Tensile Test Samples (g) Flexural Test Samples € Impact Test Samples and (h) Control Samples.

Source: Authors, (2024).

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. Afterward, the fibers were rinsed multiple times with distilled water to remove any residual NaOH solution adhering to the fiber surface and then dried in an oven at 60°C for one hour.[22], [23].

II.2 FABRICATION METHOD OF COMPOSITE

Before starting fabrication, the quantities of fibers and resin needed for composite creation were calculated based on the selected weight fraction and fiber composition. The fiber weight percentage(wt%) ranged from 10wt% to 40wt%, while the epoxy resin varied from 90wt% to 60wt%. Molds were prepared using plywood, silicone rubber, and lamination sheets. To facilitate the easy removal of the specimen, a wax layer was evenly applied to the entire surface of the molding box. Additionally, a releasing agent comprising polyvinyl acetate was also applied to both the upper and lower surfaces of the molding box before initiating the molding process. A dwell time of 30 minutes was taken to dry before proceeding the fabrication process. A solution of epoxy resin and hardener with weight ratio of 10:1 was prepared. Chopped fibers were randomly sprinkled onto the first layer of epoxy matrix. The remaining mix was poured onto the mold, followed by uniform distribution of fibers. The mold was then closed with another lamination sheet and plywood and cured under a 20 kg load for 24 hours before demolding. Composite sheets (300 mm × 150 mm) were fabricated with a laminate thickness of 5 mm, by utilizing the hand layup method in four different wt% of fiber loading as mentioned in Table 3.

Table 3: Weight percentage of fibers and resin for composite creation.

Sample Name	NaOH Treated Keratin	Composition
TCPH10	Treated Chopped Keratin Fiber	10wt%TCPH+90wt % Epoxy Resin
TCPH20	Treated Chopped Keratin Fiber	20wt%TCPH+80wt % Epoxy Resin
TCPH30	Treated Chopped Keratin Fiber	30wt%TCPH+70wt % Epoxy Resin
TCPH40	Treated Chopped Keratin Fiber	40wt%TCPH+60wt % Epoxy Resin

Source: Authors, (2024).

II.3 TESTING AND CHARACTERIZATION OF COMPOSITE

To investigate the mechanical properties of polymer composites Tensile Test, Flexural Test, Impact Test, Water Absorption Test and Density Analysis were conducted after cutting the samples as per the ASTM standards as shown in Figure 1, The following methods were used to determine the values of various tests.

II.3.1 Tensile test

Tensile testing was performed using a computerized universal testing machine with a crosshead speed of 1 mm per minute, measuring a gauge length of 50 mm. The composite sample specimens were prepared according to the standards outlined in ASTM D638 for evaluating tensile strength.[24] The specimens were then securely positioned within the grips of the universal testing machine for the duration of the test. Tensile strength is calculated using the following formula.

$$\rho = \frac{Load\ (N)}{Original\ Cross\ Section\ Area\ (mm^2)}\ N/mm^2 \quad (1)$$

Tensile Modulus was calculated using the following formula.

$$\rho_m = \frac{Stress}{Strain} \quad (2)$$

Here $Stress = \frac{Maximum\ Load}{Cross\ section\ Area\ of\ Specimen}$ and $Strain = \frac{\Delta L}{L}$, $\Delta L = Change\ in\ length(Displacement) and\ L = Gauge\ length\ (mm)$

II.3.2 Flexural Strength

The flexural strength of a material demonstrates its resistance to deformation caused by bending forces. To evaluate this property, a flexural test was conducted using the 3-point bending setup in accordance with the ASTM D790 standard[25]. During the test, a load was applied at the midpoint of the beam until the specimen fractured. The load at the breaking point and the dimensions of the sample were utilized to compute the flexural strength of the composite using the following formula.

$$\rho_f = \frac{3FL}{2wt^2} \quad (3)$$

where σ_f =Flexural strength (N/mm^2), F= Load (N), L= length or span (mm), w= width (mm) and t= thickness respectively Flexural Modulus of the composite was calculated using the following formula.

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

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

2.3.3 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.

$$Impact\ Strength = \frac{Energy\ Absorbed\ (J)}{Area\ of\ Composite\ (mm^2)} \quad (5)$$

II.3.4 Relative Density analysis

The density of a composite material is influenced by both the polymer matrix and the reinforcing fibers. Density analysis involves understanding the interplay between matrix and reinforcing fibers. These materials continue to revolutionize industries by providing lightweight, strong, and versatile solutions. To calculate the density of a polymer composite, we need to consider the densities of its individual components (resin, fibers, core, etc.).

Measured Density:

The measured density (ρ_e) of the samples was determined following the guidelines outlined in ASTM D1895.

Density was calculated using the subsequent formula, utilizing the average data obtained from three replicate samples.

The formula for density is- Density $\rho_e = \frac{M_C}{V_C}$

Where, M_c = represents the mass of the composites measured using an analytical balance (Gram), V_c = indicates the volume of the composites derived from their dimensions (length*width*thickness) measured using a digital caliper[26]

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:

$$\rho_c = \rho_f V_f + \rho_m V_m$$

Here

ρ_c = Density of Composite, ρ_f = Density of Fiber, ρ_m= Density of Matrix, V_f= Volume fraction of Fiber and V_m= Volume fraction of Fiber

The equation for calculating the volume fraction of voids is as follows:[27].

$$V_f = \frac{\rho_c - \rho_e}{\rho_e} \quad (6)$$

II.3.5 Water Absorption and Thickness Swelling Examination

Water Absorption test was accomplished according to ASTM D570 standard. All the composite samples were dipped in distilled water and their weight was measured at regular intervals of time up to saturation point at room temperature. The ratio of increase in mass of the specimen to the initial mass is given as the percentage moisture absorption.[28]

Mathematically, it was calculated using the following equation.

$$\%\, Absorption = \frac{W_t - W_d}{W_d} \times 100 \quad (7)$$

Where, W_t = Wet Weight and W_d = Dry Weight

Thickness Swelling measures the change in thickness of the composite material after it has been soaked in distilled water. It provides insights into how much the material expands or swells due to water absorption. The measurement of the composite's thickness swelling was performed using a micrometer with a minimum resolution of 0.01 mm. To determine the Thickness Swell (TS) of the sample, the following equation was utilized [29].

$$TS(\%) = \frac{\delta_f - \delta_i}{\delta_i} \times 100 \quad (8)$$

where δ_i and δ_f are the initial and final thickness of the composite specimen after immersion in the distilled water.

IV. RESULTS AND DISCUSSIONS

IV.1 RELATIVE DENSITY ANALYSIS

Theoretical density was calculated as discussed in 2.3.4. The experimental values of density closely aligned with theoretical values. The average value of density for each composite is illustrated in Tables 4. The findings revealed that epoxy composites containing fibers at 10wt%, 20wt%, 30wt% and 40wt% exhibit slightly lower densities than the theoretical values. This variance may be attributed to the presence of voids content within the composites[26].

The composites were fabricated via the hand layup process, despite the use of rollers to mitigate voids, some air particles become trapped. This occurrence may leads to the formation of weaker sections within the composite.

Table 4: Theoretical vs Experimental Density of Composite.

Sample Name	Theoretical Density of Composite ρ (g/cm^3)	Average Experimental Density of Composite ρ (g/cm^3)	Fraction of voids (%)
TCPH10	1.17	1.15	1.2%
TCPH20	1.18	1.16	1.3%
TCPH30	1.20	1.17	1.7%
TCPH40	1.21	1.19	1.9%

Source: Authors, (2024).

IV.2 TENSILE BEHAVIOR ANALYSIS

Tensile strength and Tensile Modulus of epoxy-based composites reinforced with Keratin fiber are illustrated in Table 5. The findings revealed that up to 30wt% the tensile strength was increased, and peaking was found at 30wt% as shown in figure 2. Beyond this threshold, however, further increments lead to a decline in tensile strength. The peak value recorded stands at 35.24 MPa for composites containing 30wt% Keratin Fiber and 70wt% Epoxy.

Table 5: Tensile strength and Tensile Modulus of epoxy-based composites reinforced with Keratin Fiber.

	Sample	Ultimate Tensile Strength (MPa)	Average Ultimate Tensile Strength (MPa)	Tensile Modulus (MPa)	Average Tensile Modulus (MPa)
TCPH10	1	20.04	21.16	1155.74	1227.32
	2	20.62		1227.67	
	3	22.81		1298.56	
TCPH20	1	30.15	31	1216.42	1270.01
	2	30.97		1258.85	
	3	31.88		1334.77	
TCPH30	1	34.68	35.24	1385.12	1416.42
	2	35.93		1472.63	
	3	35.12		1391.52	
TCPH40	1	21.44	22.52	1342.14	1411.72
	2	23.25		1490.28	
	3	22.87		1402.74	

Source: Authors, (2024).

Strength is predominantly governed by the interfacial adhesion between the fiber and the matrix. Notably, at 40wt% Keratin Fiber content, the interfacial bonding weakens due to resin material inadequacy. This deficiency prevents proper resin penetration, leading to potential delamination between Keratin Fiber layers.

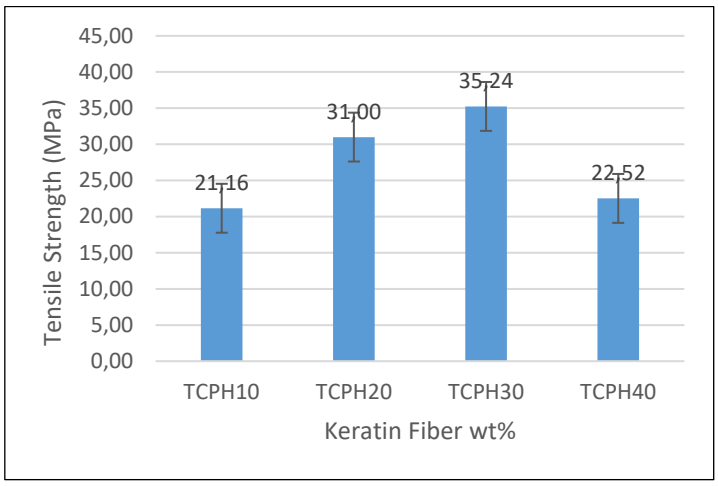

Figure 2: Tensile Strength: Chopped Keratin Fiber Reinforced Epoxy.
Source: Authors, (2024).

Figure 3 illustrates the tensile moduli, reflecting the stiffness of the developed composites under tensile loads. Notably, the moduli exhibited significant enhancement within the range of 10-40wt% fiber reinforcement, reaching an optimum value at 40wt%. The apparent decline in tensile modulus observed in the 40wt% fiber reinforced composites may be attributed to fiber agglomeration and the less amount of matrix present over the region that deteriorates the binding between fibers. Occasional fiber agglomeration, stemming from experimental imperfections that hinder fiber dispersion, can lead to these defects. Since optimal fiber dispersion is known to facilitate good interfacial bonding and minimize voids by ensuring complete fiber encapsulation by the matrix, fiber agglomeration tends to exacerbate these issues. Notably, the 30wt% fiber reinforced composite exhibited the highest tensile modulus of 1416.42 MPa.

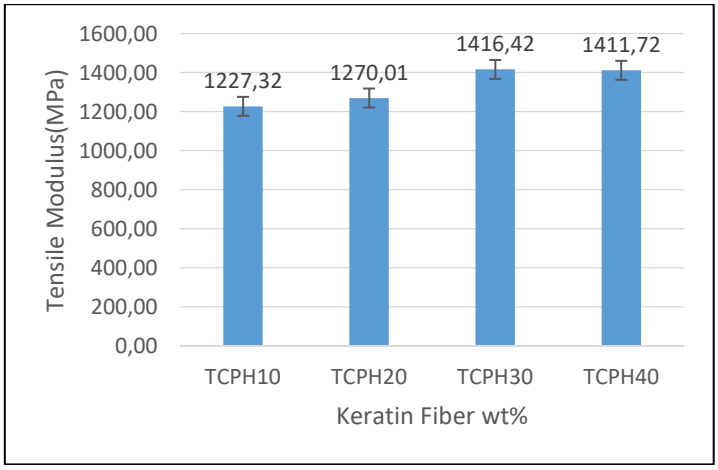

Figure 3: Tensile Modulus: Chopped Keratin Fiber Reinforced Epoxy.
Source: Authors, (2024).

IV.3 FLEXURAL STRENGTH ANALYSIS

The flexural strength and Flexural Modulus results for both neat epoxy and Keratin Fiber-reinforced epoxy composites are depicted in Table 6. Neat epoxy exhibits a flexural strength of 101.29 MPa. The inclusion of Keratin Fiber up at 30% by weight increase in flexural strength.

Table 6: Flexural strength and Flexural Modulus of epoxy-based composites reinforced with Keratin Fiber.

	Sample	Ultimate Flexural Strength (MPa)	Average Ultimate Flexural Strength (MPa)	Flexural Modulus (MPa)	Average Flexural Modulus (MPa)
TCPH10	1	46.83	47.36	1991.29	2029.51
	2	47.37		2010.44	
	3	47.88		2086.81	
TCPH20	1	56.05	56.64	3109.18	3193.73
	2	56.62		3198.47	
	3	57.24		3273.54	
TCPH30	1	75.42	74.80	3956.41	3889.61
	2	74.31		3820.90	
	3	74.68		3891.53	
TCPH40	1	62.83	62.09	3688.25	3623.84
	2	62.16		3614.87	
	3	61.29		3568.41	

Source: Authors, (2024).

Notably, the composite comprising 30% Keratin Fiber demonstrates the highest flexural strength recorded at 74.80 MPa among all laminated compositions tested. However, the 40% Keratin Fiber threshold in reinforced epoxy composites leads to a decline in flexural strength, a reduction in flexural strength is attributed to resin material deficiency resulting in inadequate interfacial bonding between the hair mat and epoxy. Under load application, specimens experience delamination on the bottom side opposite to the applied load.

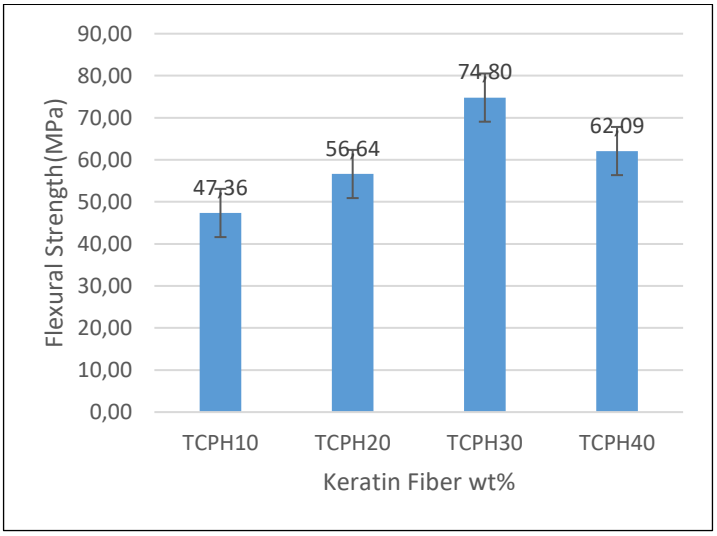

Figure 4: Flexural Strength: Chopped Keratin Fiber Reinforced Epoxy.
Source: Authors, (2024).

Figure 5 depicts the flexural modulus of both the developed composites. The trend observed in Figure 4, most of the developed composites exhibit improved flexural. This reflects that with increasing fiber contents Tensile modulus increased. This could be attributed to the uniform load distribution within the fibers as the fiber content increases to bear the load more efficiently. This observation aligns with the findings in Figure 5. Notably, the composite with a 30wt% fiber content demonstrated the highest flexural modulus at 3889.61 MPa, followed by the 20wt% Keratin fiber reinforced composite at 3193.73 MPa. These results indicate well-dispersed fibers with enhanced interaction with the matrix, thereby improving the fiber-matrix interfacial adhesion and

directly increasing the flexural modulus. Such enhancement may not be as pronounced with lower fiber weight fractions.

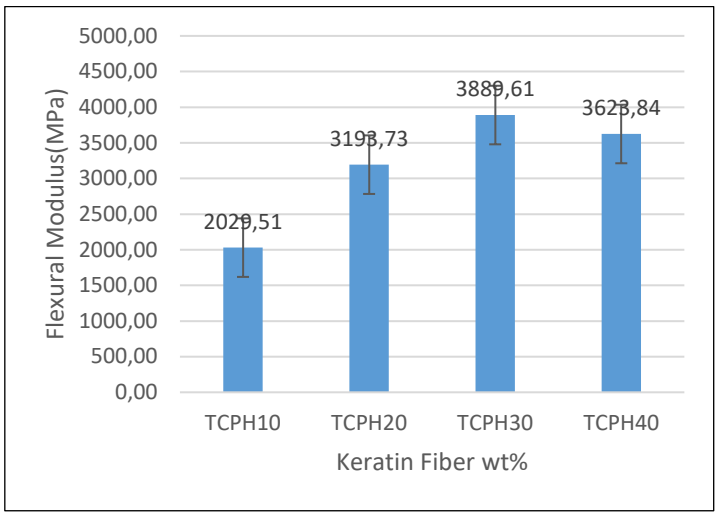

Figure 5: Flexural Modulus: Chopped Keratin Fiber Reinforced Epoxy.
Source: Authors, (2024).

Overall, the trend suggests that flexural moduli tend to rise with increasing fiber content, highlighting the preference for higher weight fractions in the development of Keratin fiber reinforced epoxy composites to achieve superior flexural strength and stiffness.

IV.4 IMPACT ENERGY ANALYSIS

Experimental evaluation was conducted on Izod impact strength of Epoxy and Keratin Fiber-reinforced epoxy composites depicted in Table 7. The results revealed a clear trend: impact strength increases with the rise in weight percentage of Keratin Fiber up to 40wt%, as illustrated in Figures 7, respectively.

Table 7: Impact Energy absorbed by epoxy-based composites reinforced with Keratin Fiber.

	Sample	Impact Energy(J/mm^2)	Average Impact Energy(J/mm^2)
TCPH10	1	4.16	4.14
	2	4.13	
	3	4.12	
TCPH20	1	5.02	4.99
	2	4.97	
	3	4.99	
TCPH30	1	7.7	7.77
	2	7.76	
	3	7.84	
TCPH40	1	9.84	9.87
	2	9.91	
	3	9.87	

Source: Authors, (2024).

Notably, for composites containing 40wt% Keratin Fiber and 60wt% epoxy, the maximum impact energy required for specimen fracture in the Izod tests were recorded at 9.87 J/mm^2, respectively. Previous studies have similarly illustrated such events through examinations of impact energy in Polymer Matrix Composites[30].

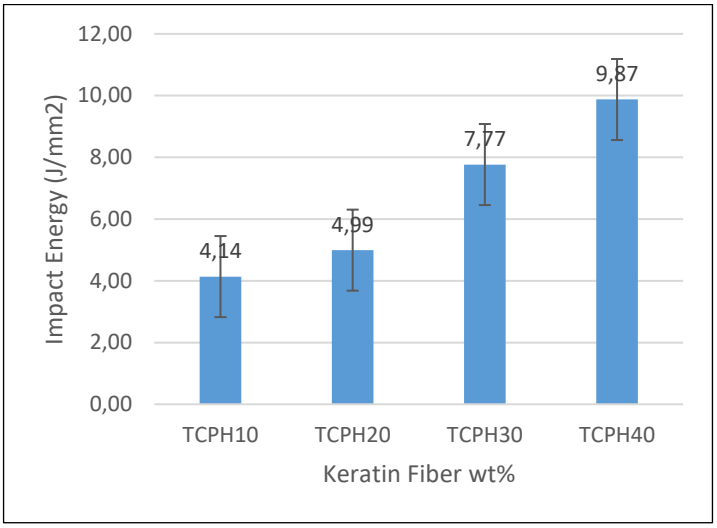

Figure 6: Impact Variation: Treated Chopped Keratin Fiber Reinforced Epoxy and Control.
Source: Authors, (2024).

The increase in impact strength with the rise in weight percentage of Keratin Fiber up to 40wt% can be attributed to the reinforcement effect provided by the incorporation of Keratin fibers into the material matrix. As the weight percentage of Keratin Fiber increases, more fibers are dispersed throughout the matrix, effectively reinforcing it and enhancing its mechanical properties, including impact strength. Beyond 40wt%, however, there may be diminishing returns or other factors coming into play that limit further improvements in impact strength.

IV.5 WATER ABSORPTION AND THICKNESS SWELLING EXAMINATION

The outcomes from doing water absorption tests on the treated Keratin fiber reinforced composites are illustrated in Table 8. It is well-established that natural fibers exhibit high hydrophilicity, meaning that a higher fiber content leads to greater moisture absorption, as confirmed by the increasing moisture absorption trend depicted in Fig. 8 as fiber fraction increases.

Table 8: Percentage of Water Absorbed by Composite.

Sample Name	Day 0	Day 1	Day 2	Day 3	Day 10	Day 20	Day 30	Day 40
TCPH 10	0.00 %	0.27 %	0.49 %	0.71 %	1.15 %	1.32 %	1.32 %	1.37 %
TCPH 20	0.00 %	0.51 %	0.92 %	1.16 %	1.62 %	1.94 %	2.03 %	2.08 %
TCPH 30	0.00 %	0.82 %	1.23 %	1.59 %	2.28 %	2.87 %	3.14 %	3.28 %
TCPH 40	0.00 %	0.91 %	1.32 %	1.68 %	2.45 %	3.17 %	3.63 %	4.04 %

Source: Authors, (2024).

Initially, the higher moisture absorption rate was observed within the 24 hours. It can be attributed to chemical treatment which alters the hair's structure, potentially increasing its porosity and allowing it to absorb water more readily. After around 20 days, the rate of water absorption starts to stabilize as the hair reaches a saturation point where it can no longer absorb significant amounts of additional water.

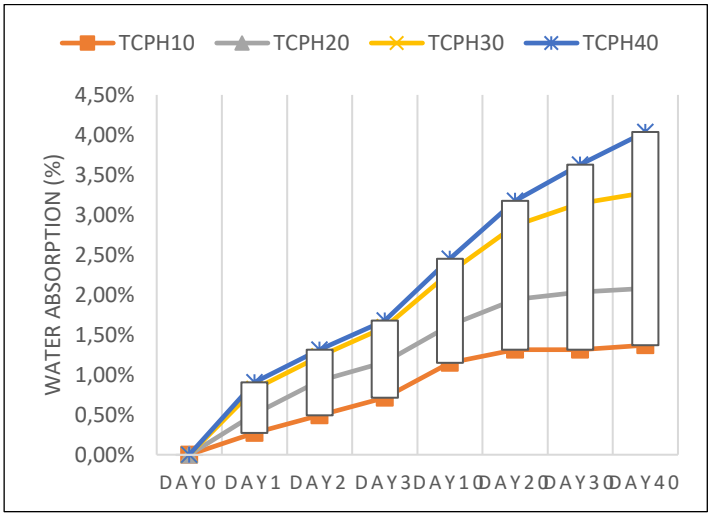

Figure 7: Water absorption: Treated Chopped Keratin fiber reinforced composites.
Source: Authors, (2024).

On the contrary, the reduced size of the fiber fraction and subsequent enhanced dispersion facilitate superior encasement of the fibers within the matrix. This significantly diminishes the rate at which water permeates into the fibers, ultimately enhancing the resistance to absorption. Conversely, as elucidated earlier, the composite reinforced with 40wt% treated Keratin fiber exhibited the lowest resistance to water absorption and displayed the highest hydrophilicity among all the composite samples. Here the good thing is that even after 40 days only 1.37% water absorbed by 10wt% Keratin fiber composite and maximum water absorption was also good as 4.04% by 40wt% Keratin fiber composite. Due to its less water absorption behavior of the Keratin fiber, its thickness swelling behaviors was also found quite sufficient as illustrated in Table 9.

Table 9: Percentage of thickness swelling due to water absorption by Composite.

Sample Name	Day1	Day2	Day3	Day10	Day20	Day30	Day40
TCPH10	0.49 %	0.68 %	0.88 %	1.36 %	1.56 %	1.56 %	1.56 %
TCPH20	0.58 %	0.78 %	0.97 %	1.75 %	1.95 %	1.95 %	1.95 %
TCPH30	0.60 %	1.00 %	1.20 %	2.00 %	2.20 %	2.20 %	2.20 %
TCPH40	0.80 %	1.29 %	1.49 %	2.39 %	2.69 %	3.59 %	3.69 %

Source: Authors, (2024).

The 40wt% Keratin Fiber composites gave higher values of thickness swelling, followed by pure epoxy as depicted in Fig. 9. The higher values of thickness swelling for composites can be attributed to water absorption, causing the fibers and epoxy matrix to expand. However, over time, water can also penetrate between the fibers and the epoxy matrix, leading to saturation.[29]

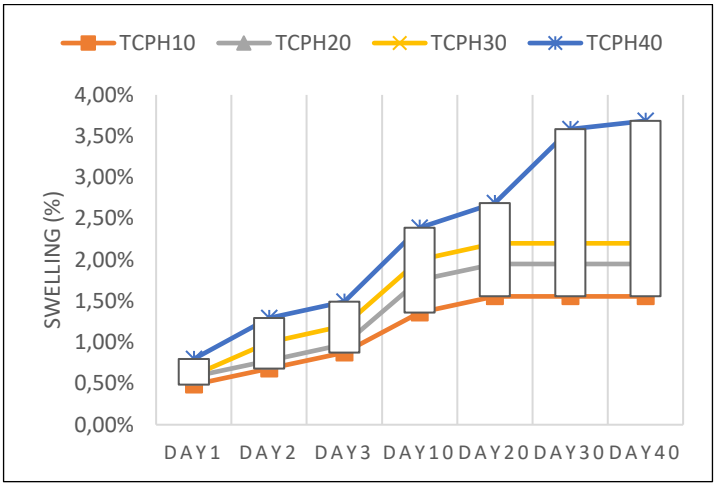

Figure 8: Swelling behavior: Treated Chopped Keratin fiber reinforced composites.
Source: Authors, (2024).

IV.6 SCANNING ELECTRON MICROSCOPY (SEM) IMAGE ANALYSIS

In this context, Scanning Electron Microscopy (SEM) is employed to examine different facets of surface morphology within composites. This includes analyzing fiber-matrix bonding, identifying voids, microcracks, observing crack propagation, and assessing fiber agglomeration. SEM image reveals the observations in Treated chopped Keratin fiber composites highlight a strong attachment between fibers and matrix, suggesting superior interfacial bonding depicted in Fig. 10. This enhanced bonding enhances adhesion between fiber surface and matrix, consequently improving the mechanical properties of treated chopped fiber-reinforced composites.

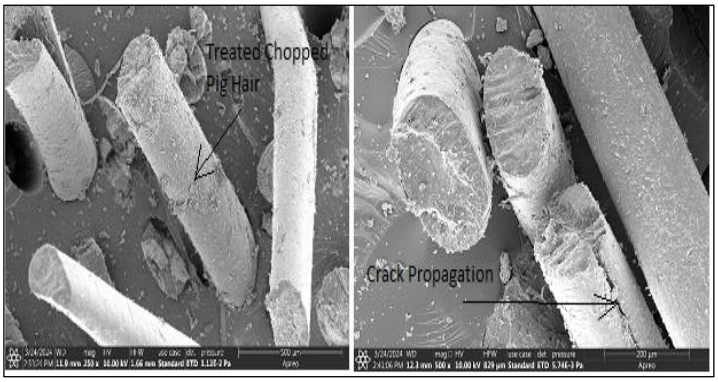

Figure 9: SEM: Bonding between the Treated Chopped Keratin Fiber with epoxy polymer.
Source: Authors, (2024).

V. CONCLUSIONS

The study investigates the tensile, flexural, and impact strengths of epoxy composites reinforced with Keratin fiber. Due to weaker interfacial bonding, tensile strength declined after reaching its peak of 35.24 MPa at 30 weight percent fiber content. Even with the sporadic fiber aggregation, the tensile modulus improved as well, reaching 1416.42 MPa at 30% weight percentage. At 30wt%, flexural strength rose to 74.80 MPa; however, because of insufficient resin bonding, a drop occurred with a larger fiber content. At 30wt%, the flexural modulus peaked at 3889.61 MPa. The impact energy of composites with 40wt% Keratin Fiber was found to be the greatest, measuring 9.87 J/mm².

Impact strength increased steadily as Keratin Fiber content increased, reaching a peak at 40wt%. Tests on water absorption revealed a direct correlation between moisture uptake and fiber content, which stabilized after 20 days. Although 40wt% Keratin Fiber composites had the most hydrophilicity but still managed water absorption and swelling, higher fiber content composites showed superior resistance to absorption.

Density measurements revealed that voids caused minor departures from theoretical values; Keratin Fiber composites had densities that were lower than expected. The composites showed notable improvements in mechanical performance and hydrophobic qualities, which qualified them for use in maritime, construction, and automotive applications.

IX. AUTHOR'S CONTRIBUTION

Conceptualization: Umesh Kumar Dwivedi
Methodology: Deeapk Kachhot, Umesh Kumar Dwivedi
Investigation: Deeapk Kachhot
Discussion of results: Moti Lal Rinawa
Writing – Original Draft: Deeapk Kachhot, Rishi Dewangan
Writing – Review and Editing: Deeapk Kachhot, Rishi Dewangan, Moti Lal Rinawa, Umesh Kumar Dwivedi
Resources: Kachhot Deepak, Dewangan Rishi, Rinawa Motilal, Dwivedi Umesh Kumar
Supervision: Rishi Dewangan, Moti Lal Rinawa, Umesh Kumar Dwivedi
Approval of the final text: Kachhot Deepak, Dewangan Rishi, Rinawa Motilal, Dwivedi Umesh Kumar

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