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Experimental Investigation of Physical and Mechanical Properties of Okro Bast Fibre/Epoxy Resin Composites

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Abstract

In recent years, the use of polymer composites derived from organic resources has significantly increased across various industries. This shift is largely driven by environmental concerns and the health risks associated with the production and disposal of traditional synthetic fibers. Natural fibers have gained popularity as reinforcement materials in polymer matrix composites due to their numerous advantages, including low cost, widespread availability, low density, favorable mechanical properties, environmental friendliness, high stiffness, and biodegradability.

In the present study, OBF (organic-based fibers) were treated with a 5% sodium hydroxide solution and then incorporated into epoxy resin (ER) as the matrix material. Composites were fabricated using varying OBF weight fractions of 3%, 6%, 9%, 12%, and 15% as filler material. The preparation and testing of the composites followed ASTM standards. To evaluate the physical and mechanical performance of the composites, tests were conducted for water absorption, tensile strength, hardness, impact resistance, and flexural strength.

Keywords: Epoxy Resin, Okro bast fiber, Filler Loading, Polymer composite

Introduction

The rising concerns about global warming and diminishing petroleum reserves have encouraged researchers to explore natural fibers as sustainable bio-fillers in thermosetting and thermoplastic polymers. Compared to synthetic fibers, natural fibers offer various benefits, including cost-effectiveness, high strength, low density, biodegradability, and greater flexibility during extraction and processing, as reported by Sathish and his co-workers [1]. Due to their eco-friendly nature, natural fibers support the development of a green economy by enhancing energy efficiency and reducing carbon emissions when used in composites.

However, natural fibers often show poor mechanical performance in composites because of incompatibility with polymer matrices. This issue can be addressed through polymer matrix modifications or by incorporating additional fillers, which significantly improve the mechanical behavior of the composites. Fibers such as okro, flax, ramie, cotton, hemp, kenaf, sisal, bamboo, and jute are now commonly used as reinforcements in place of synthetic fibers.

Okro (Abelmoschus esculentus), also called Hibiscus esculentus, belongs to the mallow (Malvaceae) family, which includes species like hibiscus and cotton. It is a tall-growing, warm-season crop suited to diverse soil types and widely cultivated across Asia, Africa, the Caribbean, and the southern America, known by various names such as lady's finger, gumbo, and bhindi its origin is believed to be the Abyssinian region, covering parts of Ethiopia, Eritrea, and Sudan. Okro is the only vegetable crop in the Malvaceae family with significant applications in the food industry.

Vegetable fibers have a complex structure due to their hierarchical composition, consisting mainly of cellulose along with hemicellulose, lignin, pectin, waxes, and water-soluble substances. Lignin and pectin function as natural bonding agents. According Shamsul, and Arifuzzaman [2], okro bast fiber (OBF) contains approximately 67.5% cellulose, 15.4% hemicellulose, 7.1% lignin, 3.4% pectin, 3.9% waxes and fats, and 2.7% water.

Arrifulzaman and co-workers showed that increasing the content of OBF in phenol formaldehyde resin (PFR) composites improves tensile strength, Young's modulus, and flexural strength up to an optimal filler content of 29% [3]. Beyond this point, excessive fiber reduces mechanical performance. The hydroxyl groups in OBF also increase water absorption and contribute to poor bonding with hydrophobic matrices like PFR. However, surface treatments such as alkali treatment or bleaching enhance the fiber's compatibility with the matrix and improve the composite's mechanical properties.

The overall strength of natural fiber-reinforced composites depends not only on the matrix but also on several factors, including fiber orientation, fiber-matrix compatibility, filler content, and aspect ratio. Accordingly, this research aims to investigate the impact of okro bast fiber fillers on the mechanical and physical properties of epoxy-based composites.

2. Materials and Method

Extraction of Fiber

Okro stems were sourced from a small farm located in Gwarzo Local Government Area of Kano State. The fibers were extracted using the water retting technique. The okro bark was stripped into ribbon-like bundles and submerged in a water bath. Light pressure was applied to ensure the bark remained fully immersed for a period of 10 days, allowing the natural binding substances such as pectin, lignin, cellulose, and hemicellulose to break down and soften.

After the 10-day retting period, the bark was removed and thoroughly washed with clean water to separate the pulp from the fibers. The extracted fibers were then shredded and combed to obtain finer strands. These were air-dried at room temperature for 15 days. Once dried, the fibers were cut into short lengths of approximately 1.5 cm and subsequently treated with a sodium hydroxide solution. These treated fibers were then used in the preparation of composite samples.

Table 2.1. Formulation table of UOBF and TOBF/ER Composites

S/N	Material	Source
1	Okro Bast Fibre	Getso, Gwarzo Local Government, kano state
2	Sodium Hydroxide	Steve moor, Kwangila, Zaria
3	Acetic Acid	Steve Moor, Kwangila Zaria
4	Epoxy Resin, Hardener (Hy-951)	Epochem, 18 Adeshina Street, behind holy trinity hospital Ikeja, off Obafemi Awolowo Way Ikeja, Lagos State Nigeria.

Table 1.2. Source and Machine Models

S/N	Machine	Model	Source
1	Flexural Strength Tester (Universal Testing Machine	M500-50CT equip with win test analysis version 4.1.6	Dept of mechanical engineering, Bayero University Kano (BUK)
2	Tensile Testing Machine	Instron 3366 Instron Co,Ltd	Dept of Polymer and Textile Engineering, Ahmadu Bello University Zaria. (ABU)
3	Impact Testing Machine: Resil Impactor	Ceast 363	Dept of Metallurgical and Material Engineering, Ahmadu Bello University Zaria (ABU)
4	Hardness Testing Machine (Vickers Hardness)	MVI-PC, Mh-v CM07/2012-1329	Shell Chair Laboratory. Dept of Mechanical Engineering, Ahmadu Bello University Zaria (ABU)

Alkaline Treatment of Okro Fiber

Treatment of Okro Bast Fiber is 5% sodium hydroxide solution was prepared by dissolving sodium hydroxide in distilled water. The okro fibers were then immersed in this solution and treated at a temperature of 60°C for two hours with continuous stirring. After the treatment, the fibers were taken out and thoroughly rinsed with water. To neutralize any remaining alkali, the fibers were soaked in a 1% acetic acid solution, followed by a final rinse with distilled water. The treated fibers were then left to dry at room temperature.

Table 2.1. Formulation table of UOBF and TOBF/ER Composites

S/N	UOBF (wt%)	TOBF (wt%)	ER (wt%)	Total
1	0	0	100	100
2	3	3	97	100
3	6	6	96	100
4	9	9	91	100
5	12	12	88	100
6	15	15	85	100

UOBF= untreated okro bast fibre, TOBF= treated okro bast fibre, ER= epoxy resin

2.3. Fabrication of Okro Bast Fiber Composites

Short okro bast fibers were utilized in the preparation of the composites using the hand layup method. This process involved manually mixing different weight percentages of okro bast fiber (OBF) fillers 3, 6, 9, 12, and 15wt% with epoxy resin to create uniform blends. The blending was done by hand stirring for 10 to 15 minutes, after which a hardener was added. The resin-to-hardener ratio used was 2:1. Once the filler was thoroughly mixed, the blend was poured into a glass mold (200 mm × 100 mm × 4 mm) lined with aluminum foil to act as a release agent. The mixture was left to cure at room temperature for 24 hours before being demolded. The cured composites were then cut into specific shapes for testing rectangular strips for general testing (Impact, hardness and flexural test) and dog-bone shapes for tensile testing.

2.4. Characterization of the Composites

The characterization of the composites was performed in line with ASTM standards for testing of materials the composites were conditioned at room temperature and then subjected to various test

2.4.1. Physical Property

Water absorption was carried out according to ASTM D570. The samples were conditioned in an oven at 45 °C for 72 hours. Then, placed inside desiccators for 24 hours and finally weighed (W1) using a metler weighing balance. The weighed samples were then immersed in a plastic container containing water for 24 hours. The samples were removed from the water, wiped with a clean cloth to eliminate moisture, then re-weighed (W2) and the process continues for thirty days.

2.4.2. Mechanical Properties

The tensile test was carried out using a tensile properties tester (YG026D Multifunctional Electronic Fabric Strength Machine) according to ASTM D638 with a maximum force of 10 KN. The sample's dimensions were 100 x15 x 4 (mm) in length, width, and thickness respectively. A cross– head speed of 2 mm/min was used. The test specimens were held in the grips of the testing machine and tightened evenly and firmly to prevent any slippage as the test commenced. The resistance and elongation of the specimens were detected and recorded by the load cell until a failure or rupture occurred. From the tensile test, tensile parameters (tensile strength (breaking point), elongation at break, and tensile modulus) were determined and recorded.

2.4.3. Izod Impact Test

The Impact test is usually carried out to determine the energy needed to initiate fracture and continue until the specimen is broken at a certain point in time. It is a test that determines the resistance of the material to impact from a moving pendulum. The Izod test is used to identify the overall toughness of a material. The procedure involves specimens made with a notch which produces stress and concentration that increases the possibility of brittle failure. The notch in the specimen reduces or minimizes plastic deformation and direct fracture of the part behind the notch. The specimen is clamped into the fixture with the notched side facing the edge of the pendulum. The pendulum is allowed to hit the specimen. The Izod impact test was performed as per ASTM D256 with a standard specimen size of 64 mm x 1.27 mm x 4 mm. Impact strength is measured by dividing impact energy in joule by the thickness of the specimen. The greater number indicates the toughness of the material.

2.4.4. Hardness Testing (Vickers Hardness)

Vickers Hardness testing machine was utilized to determine the hardness of composites. The hardness testing procedure followed the ASTM 2240 standard, providing guidelines for the Vickers Hardness test Samples with parallel flat surfaces were used for the hardness testing. The sample (30x30mm) was placed on the anvil (or avail) of the Vickers hardness testing machine The dial on the apparatus was adjusted to zero under a minor load of 10 kg the major load of 60 kgf (kilogram-force) was immediately applied by releasing the trip lever. After 15 seconds, the major load was removed. The specimen was allowed to recover for 15 seconds the hardness test was repeated three times to ensure consistency and reliability of the results. An average value of each test result was calculated based on the three repetitions.

2.4.5. Flexural Strength

The flexural test was carried out in accordance with ASTM D790 (2010) using a Universal Testing Machine. This test evaluates a material's resistance to bending by determining its flexural strength and modulus. A three-point bending setup was used, where the specimen was placed on two supports and a load was applied at the center. The test measures the force required to bend the sample under these conditions. Each specimen was tested five times to ensure accuracy, and the flexural strength was calculated using the formula provided in the corresponding equation 1.

$$F = \frac{3PL}{2bd^2}$$

Flexural strength = F = Maximum load applied on the test specimen

L= is the span length of the sample (mm) (gauge length);

P = the load applied (N)

b = the width of the specimen (mm)

d = Thickness of specimen tested (mm) respectively

3. Results and Discussion

3.1. Physical Properties

Water absorption is one of the physical parameters carryout to find out the quantity of water absorbed by the composites; water absorption test was carried out to find out the quantity of water absorbed for 30(thirty) days. Water absorption depends on certain parameters such as matrix, fibre content/filler loading, method of fabrication and environment/ weather condition. Water absorption of treated and untreated OBF/ER composites as shown in figure3.1.

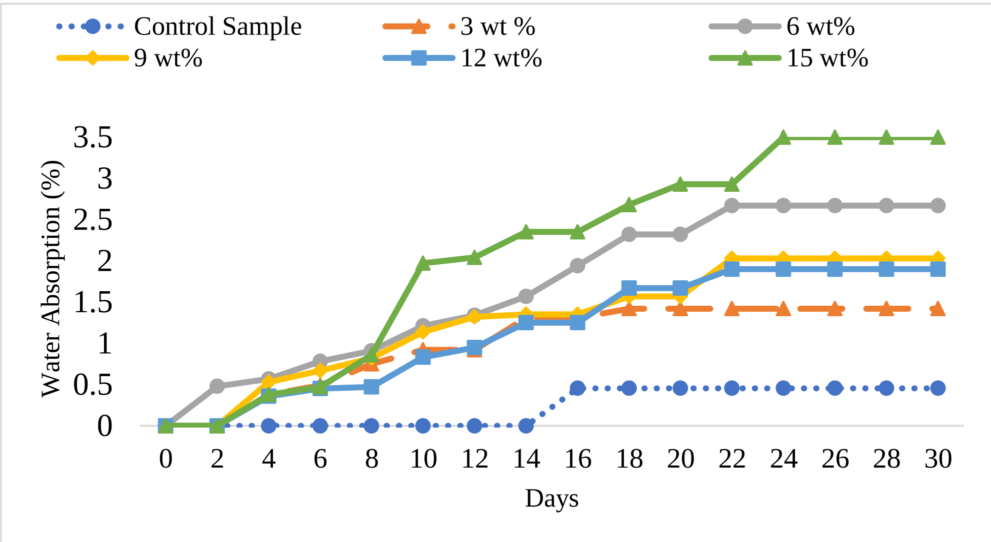

Figure 3.1. Water Absorption of Untreated Okro Bast Fibre/Epoxy Resin Composites

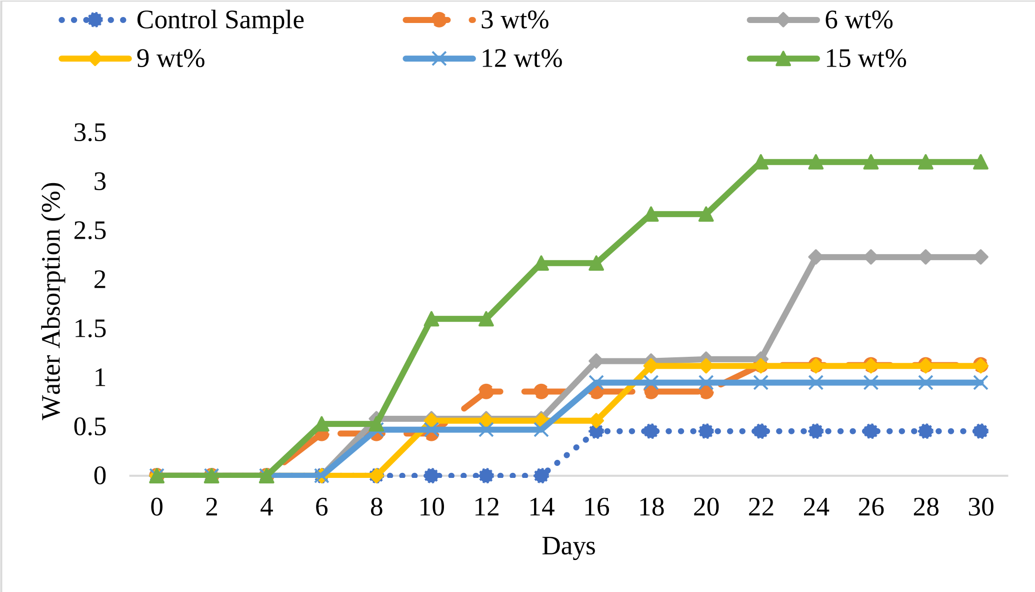

Figure 3.2. Water Absorption of Treated Okro Bast Fibre/Epoxy Resin Composites

Water absorption by the fiber is likely caused by the presence of hydroxyl groups, which attract water molecules through hydrogen bonding. This occurs because natural fibers are hydrophilic, in contrast to polymers, which are generally hydrophobic. Both untreated and alkali-treated composites initially showed an increase in water absorption within the first 48 hours, eventually reaching a saturation point between 24 to 30 days. Maximum water uptake was recorded as 3.72% for untreated composites and 3.37% for alkali-treated composites at a 15% fiber weight fraction.

This pattern of water absorption follows Fickian diffusion behavior, where the rate of water penetration is directly related to the concentration gradient, leading to a steady absorption until equilibrium is achieved. The hand lay-up method often introduces imperfections or voids into the material, which can facilitate water ingress. Okro bast fiber, being a natural and hydrophilic material, contains cellulose with hydroxyl groups that contribute to its water-absorbing nature.

The reduced water absorption observed in the alkali-treated fiber composites is attributed to decreased hydrophilicity caused by the treatment. Sodium hydroxide (NaOH) treatment modifies the fiber surface by removing or altering hydrophilic functional groups like hydroxyl (-OH), which decreases the fibers' affinity for water, resulting in less water absorption by the composite. Similar observations were made by Madhusudhan and co-workers [4], and Isa and research partners [5].

Additionally, Arifuzzaman and his research partners studied okra bast fiber-reinforced phenol formaldehyde resin composites and found that treated composites with 30 wt.% filler showed lower water absorption compared to untreated ones [3]. This was attributed to improved fiber wettability within the polymer matrix, which limited water accumulation.

3.2. Mechanical Property

Tensile strength of a material is the maximum amount of stress a material can withstands before failure. Five (5) specimens were examined for each loading of the reinforcement as presented in figure 3.3.

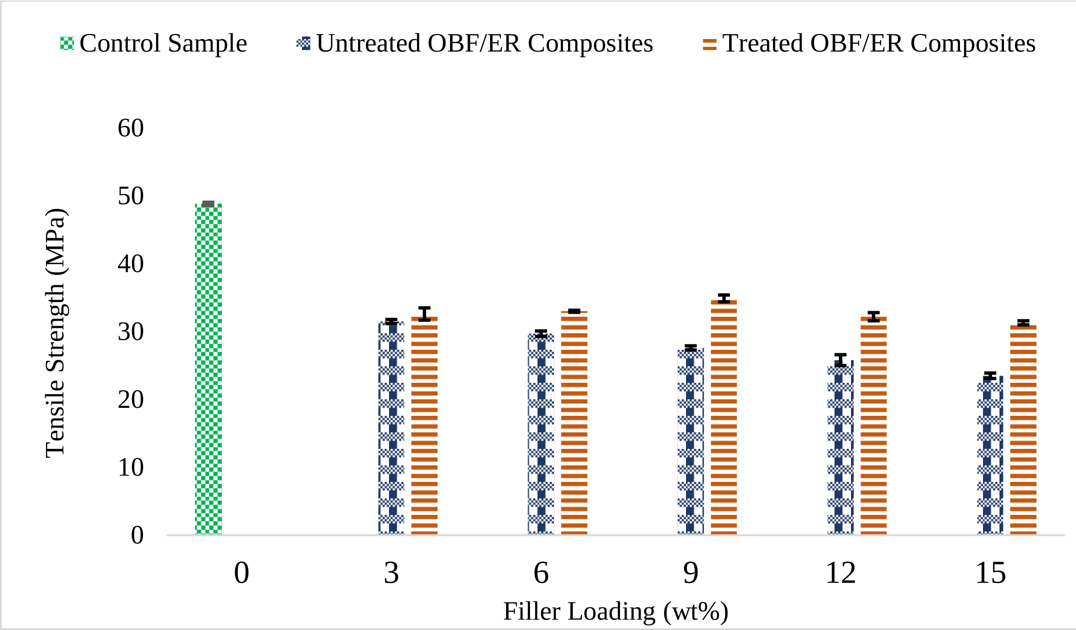

Figure 3.3. Tensile Strength of Untreated and Treated OBF/ER Composites

The tensile strength of untreated okro bast fibre/epoxy resin (OBF/ER) composites was observed to be lower compared to the control sample and certain alkali-treated composites. An increase in fibre loading led to a decline in tensile strength in the untreated composites, which is likely due to inadequate fibre-matrix bonding caused by remaining cementing substances. Comparable results were reported by Sule and research partners who linked the reduced strength in untreated composites to poor interfacial adhesion and non-uniform stress transfer resulting from fibre clustering within the matrix [6]. Similar result was obtained by Ali and research partners in their findings on studies of physical and mechanical properties of unsaturated polyester resin hybrid composites reinforced with jute fibre and maize cob particles [2].

Zin and research partners reported that untreated pineapple leaf fibre exhibited lower tensile strength than its treated counterpart [7]. The application of alkali treatment led to an increase in the tensile strength of PALF/epoxy composites until it peaked, after which further treatment diminished fibre strength due to the excessive removal of waxy coatings and lignin. In a similar manner, sodium hydroxide treatment of okro bast fibre improved its tensile performance by creating a rougher surface, which facilitated stronger adhesion with the epoxy resin.

According to Gassan and Bledzki [8], alkali treatment interfered with hydrogen bonds in the chemical structure of the fibres, thereby increasing the fibre surface roughness, which in turn promotes the crystallinity index of fibres, enhancing the formation of hydrogen bonds between cellulose chains and chemical bonding between the fibres and the matrix of the composites. This is in line with the result obtained by Cao and his co- workers in their findings on the mechanical properties of biodegradable composites reinforced with bagasse fibre before and after treatment [6].

Furthermore, tensile strength is influenced by factors such as filler volume fraction, the quality of adhesion between the filler and matrix, the uniformity of filler dispersion, and the presence of surface defects. The observed increase in the tensile strength of OBF/ER composites may be attributed to improved mixing during fabrication, resulting in enhanced interaction or stronger interfacial bonding between the fibre and the matrix. Conversely, as filler content increased, a decline in tensile strength was observed particularly at 12% and 15% filler loadings likely due to weaker adhesion at the fibre-matrix interface. This poor bonding created vulnerable points within the composites, reducing their ability to withstand tensile forces.

Higher filler loading can weaken the bond between the matrix and filler, leading to voids and reduced tensile strength, as reported by Tezara and co-workers [9] and supported by Ayyavoo and his research partners [10] and Sudhakar and his research partners [11].

3.3. Tensile Modulus

Tensile modulus, or Young's modulus, measures a material's stiffness and resistance to deformation. A higher modulus indicates increased rigidity and reduced ductility, often due to stiffening effects within the composite as reported by Bello and co-workers [5].

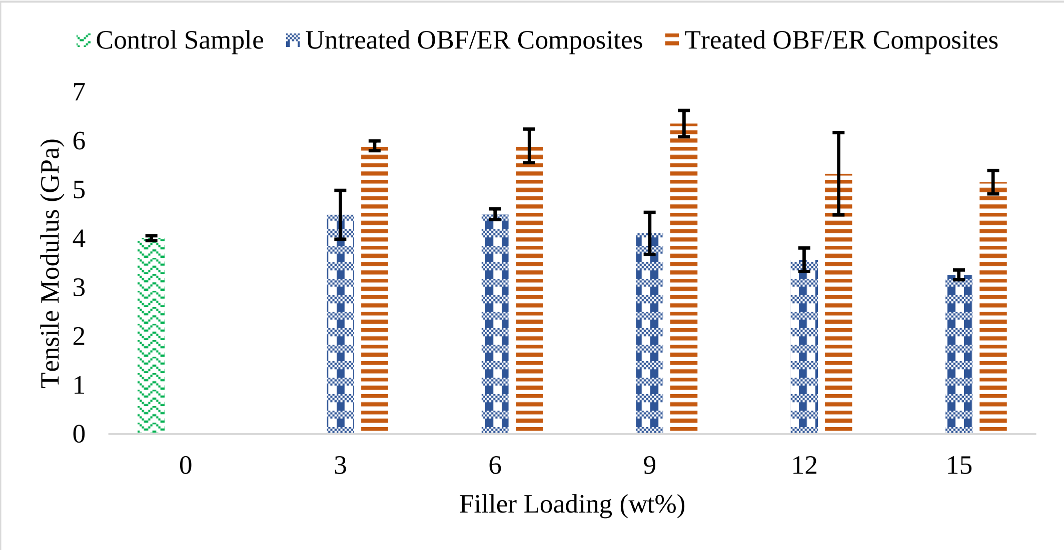

Figure 3.4. Tensile modulus of Untreated and Treated OBF/ER composites

From figure 4 above, the results indicated that the tensile modulus of treated okro bast fibre/epoxy (TOBF/ER) composites increased with filler loading, peaking at 9% with a maximum value of 6.35 GPA. This was significantly higher than the control epoxy resin sample, which had a modulus of 4.01 GPA. The increase in stiffness is attributed to the reinforcing effect of the okro bast fibre (OBF), which enhances the rigidity of the composites. According to Nitya [11], composites with high tensile modulus and strength result in more rigid structures. The improved modulus in treated composites is due to enhanced interfacial bonding between the fibre and matrix, requiring more stress to cause failure. The modulus values for treated OBF/epoxy composites at 3, 6, 9, 12, and 15 wt% were 5.90, 5.90, 6.35, 5.33, and 5.15 GPA, respectively all higher than the control. The increase in tensile modulus following fibre treatment reflects stronger filler-matrix adhesion. Compared to untreated composites, the treated samples showed notable improvements, with percentage increases varying across different filler loadings. Similar trends were observed by Bello and his co-workers [5].

A reduction in modulus was observed in the untreated okro bast fibre/epoxy resin (OBF/ER) composites, with values declining as filler content decreased, reaching a peak modulus of 4.5 GPA at 6% filler loading. However, significant decreases were recorded at 12% and 15% filler contents, likely due to uneven fibre dispersion within the matrix, which weakened interfacial adhesion and increased the likelihood of stress concentrations, leading to early composite failure. Ahmad and his research partners [12] noted that variations in modulus across different studies could be due to differences in fibre and matrix weight fractions, as well as the fibre types used. Saira and his co-workers [13] found that alkali treatment enhances both tensile strength and modulus in hemp fibres, attributing this to the partial removal of lignin and hemicellulose, which increases the crystallinity and rigidity of the fibres. The removal of these components enables the microfibrils to relax and realign along the fiber's main axis, forming a stiffer structure. Increasing NaOH concentration further eliminates lignin and hemicellulose, creating more space for microfibril rearrangement. In untreated OBF, the presence of hemicellulose, lignin, and other impurities hinders fibre-matrix adhesion, leading to weaker bonding and reduced mechanical performance.

3.4. Impact Strength

The impact strength of a material is the capacity of the composites material to resist to shock during deformation. The formed composites have moderate impact strength after the addition of the OBF into the polymeric matrix.

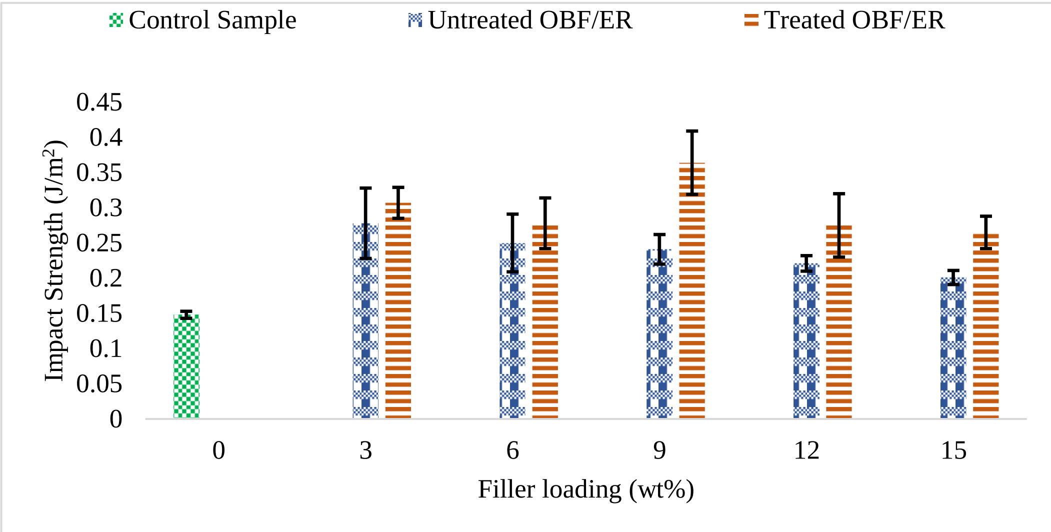

Figure3.5. Impact Strength of Untreated and Treated OBF/ER Composites

From the result above, it was evident that the treated okro bast fibre (OBF) composites exhibited better performance compared to the untreated OBF/epoxy resin (ER) composites. In the untreated samples, impact strength declined as filler content increased. This reduction was likely caused by poor compatibility between the filler and matrix, as well as void formation and fibre agglomeration at higher filler loadings. In contrast, the treated OBF/ER composites demonstrated an increase in impact strength with rising filler content, which can be attributed to the enhanced fibre surface roughness from alkaline treatment, leading to improved mechanical interlocking. Suradi and co-workers [14] also observed similar improvements in their study on oil palm bio-fibre composites, where treated fibres delivered better impact strength than untreated ones. For treated OBF/ER composites, the optimal impact strength (0.36 J/m) was recorded at 9% filler loading. However, further increases in filler content led to a drop in impact strength, with values of 0.27 J/m and 0.26 J/m at 12% and 15% loadings, respectively, making them the lowest among all tested composites.

3.5. Hardness Test

Hardness is the measure of wear resistance of any materials to surface indentation, which also serve as a function of stress required to produce a specific type of deformation and values obtain are used to evaluate or estimate the mechanical strength of each composite.

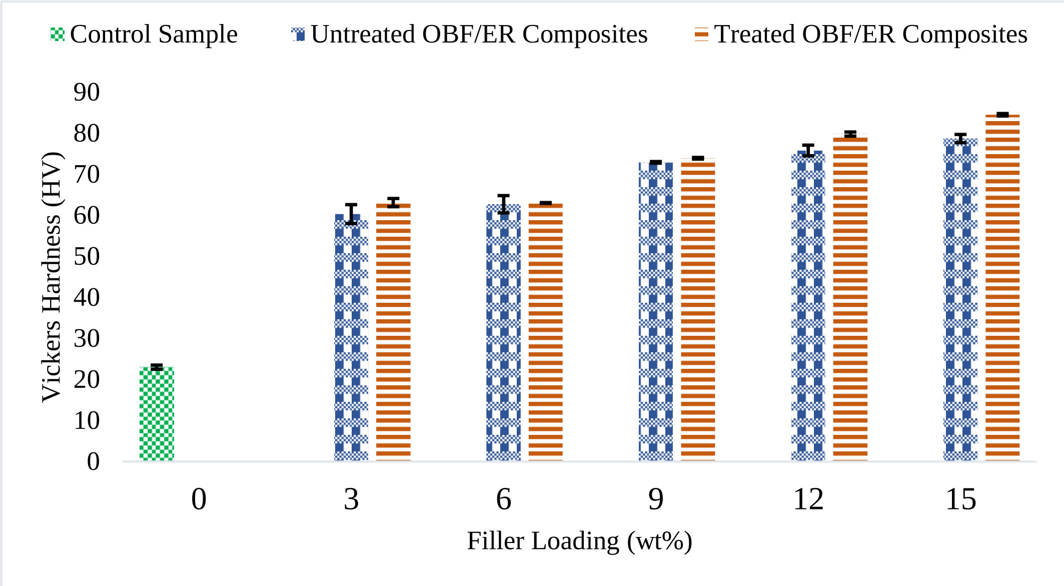

Figure 3.6. Hardness of Untreated and Treated OBF/ER Composites

Figures 3.6 show the hardness values of treated and untreated OBF/UPR and OBF/Epoxy composites. It was observed that the hardness value of all the treated and untreated composites of OBF/UPR and OBF/ER increases with an increase in fibre content. Hence the highest value indicates greater resistance of the composites to indentation an increase in hardness value of treated OBF/ER composites was noticed with an increase in filler loading content with the observed values of 63 to 84.5 Hv all values observed greater than that of the control/Neat sample and the untreated OBF composites. The increase in hardness value could be attributed to the increase in stiffness and the dispersion of the fibres into the matrix, minimization of voids, and stronger interfacial bonding between the matrix and the fibre as a result of the treatment this is similar to the findings of). 15% filler loading of the treated OBF/ER exhibits the highest value. The decrease in hardness value could be attributed to poor/weak interfacial bonding between the OBF/ER composites. On the introduction of OBF into the epoxy matrix air may be trapped inside which leads to micro crack formation in the interface under loading and non-uniform stress transfer due to the fibre agglomeration in the matrix [15]. The values for untreated OBF/ER are lower than that of treated OBF/ER composites. This shows that the surface modification has increased the fibre stiffness and enhanced the interfacial bonding between the filler and the polymer matrix. According to Rajeshkumar [16], the hardness value of treated Phoenix sp. fibre was found to be higher than the untreated fibre reinforced polymer composites the observed increase could be due to the increased stiffness and enhanced interfacial bonding in the treated fibre reinforced composites he also said that when the natural fibre is treated with a higher concentration of sodium hydroxide will damage fibre leading to weak interfacial bonding between the filler and polymer matrix. A similar result was reported by Sudhakar and co-workers [17] in their findings on the Study of Mechanical Properties of Bamboo fibres before and after Alkali Treatment.

3.6. Flexural Strength

The results indicate that epoxy composites reinforced with sodium hydroxide-treated okro bast fibre exhibit better flexural properties than those made with untreated fibres. This suggests that the alkali treatment enhanced the fibres adhesion characteristics, leading to improved wettability and stronger bonding between the fibre and the polymer matrix.

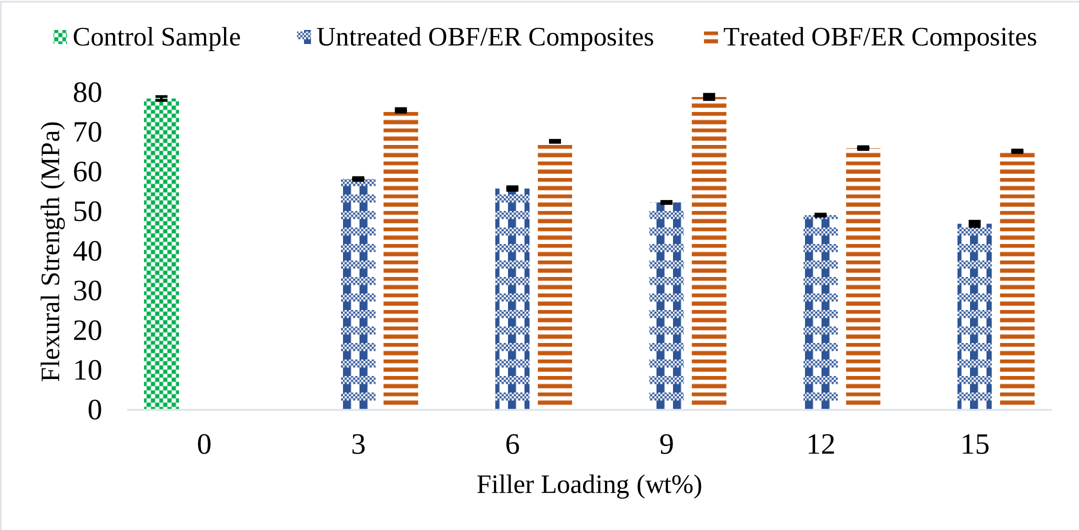

Figure 3.7. Flexural Strength of Untreated and Treated OBF/ER Composites.

The flexural strength of treated okro bast fibre (TOBF)/epoxy composites increased with rising fibre content, peaking at 78.9 MPa at 9 wt% filler loading. This improvement is likely due to enhanced interfacial bonding, which facilitates efficient stress transfer between fibre and matrix. Surface modification from alkali treatment may also contribute by roughening the fibre surface, promoting better mechanical interlocking. Similar trends were observed by Sugiman and his co-workers [18], Nadendla [19], and Silas & Timothy [20], who reported increased flexural strength and modulus with fibre treatment and filler loading. However, beyond 9, at 12 and 15w% filler loading, flexural strength declined likely due to weak bonding and poor stress transfer, leading to voids and structural weaknesses. Ojha and co-workers also observed a similar decline in strength at higher filler loadings [21].

4. Conclusion

Composites made from okro bast fibre (OBF) and epoxy resin were fabricated using the hand lay-up method, with a focus on both untreated and alkaline-treated fibres. The results indicated that incorporating OBF improved the mechanical performance of the composites. Hardness increased with higher filler loading for both treated and untreated samples, while water absorption was significantly lower in treated composites. The treated OBF/ER composites showed peak tensile, flexural, and impact strength at 9wt% filler loading. These composites are suitable for non-structural applications such as ceiling and partition boards. Overall, the study highlights the potential of converting agricultural waste like okro bast fibre into valuable, functional materials.

Contributions

All the authors have contributed equally.

Conflict of Interest Statement

The authors declare that they have no known conflict of interest.

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