INVESTIGATION OF MECHANICAL PERFORMANCE OF *BORASSUS FLABELLIFER* SPROUT FIBER REINFORCED POLYMER COMPOSITES

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Natural fibers have been extensively used for many decades. This work investigates the suitability of *Borassus flabellifer* sprout fiber, a new class of fibers, as reinforcement in polymer matrix composites. *Borassus flabellifer* sprouts are also called palm sprouts. The fibers were extracted by the water retting method and treated with 5% sodium hydroxide (NaOH) to remove the impurities present in the fiber to achieve better bonding with the matrix. Scanning electron microscopic images of raw and alkali treated *Borassus* sprout fibers were studied. Composite specimens were made with 20, 25, 30 and 35 volume % of treated and untreated palm sprout fibers, respectively, in a polyester matrix by the hand layup technique and by the compression molding technique. Tensile strength, flexural strength, compression strength, impact strength, hardness and water absorption of sample specimens were determined. Experimental results showed that the composite specimens with 35 volume % of treated palm sprout fibers as reinforcement performed better in all aspects. They have 30.34% higher tensile strength, 34.47% higher flexural strength, 3.14% increased compression strength and 15.56% better impact strength and 7.6% less water absorption than the composite plates reinforced with 35% untreated palm sprout fibers. Thus, the composites showed adequate mechanical properties to be considered for specific applications.

Keywords: natural fibers, polymer matrix, chemical treatment, palm sprout, mechanical properties, compression molding

INTRODUCTION

Structural models used in infrastructure consider not only the composites strength, but also their light weight, energy absorption and ease of installation.[1-2] Coir fibers have advantages of lower cost, availability, easy processing, high elongation at break and low elastic modulus.[3-4] It is evident that the properties of composite materials are largely dependent on the properties of its constituent materials and their orientation within the matrix.[5] Fiber reinforced composites are used in various structural applications due to their high strength, high stiffness and light weight.[6-8] Using natural fibers as reinforcement is gaining popularity due to their sustainability. Natural fiber reinforced polymer composites possess enormous advantages, such as biodegradability, low weight, easy processing and excellent mechanical properties.[9-12] Natural fiber reinforced composites are also called biocomposites due to their biodegradability, and are classified as partially or completely green composites. In the last decade, a number of research works have reported the superior characteristics of natural fibers.[13-18]

Most of the earlier research has focused on material properties, fiber processing methods, composite fabrication techniques and the effect of matrix on the mechanical properties of the composites.[19-20] Research evidenced that the composites having natural fiber as reinforcement have low intrinsic mechanical properties, in comparison with those with synthetic fiber, whereas the applications of both types of fibers are similar.[21-22] Studies focusing on identifying the suitability of natural fiber reinforced composites for structural applications, like civil infrastructure, are however, limited. Natural fiber composites have intrinsic properties that could make them suitable for structural applications when their mechanical properties are reliable, predictable and well explored. For civil infrastructural applications, one of the important properties is compressive strength, showing the ability of materials to resist the load due to gravity. Hanamanagouda *et al*. examined the mechanical properties of composites reinforced with 5, 10, 15, 20, and 25% by volume of jute fiber. The composite specimens were produced by the hot compression molding technique, and the impact, flexural and tensile strength were tested. Their results demonstrated that the composites may be used for manufacturing structural components.[23] It is evident that the composites with a polyester matrix up to 40 vol% reinforcements have higher tensile strength and Young's modulus.[24]

This work focuses on examining the mechanical properties of polyester matrix based composites reinforced with treated and untreated palm sprout fiber, with different fiber volume fractions, such as 20, 25, 30, 35% reinforcement, the remaining representing the matrix percentage.[30] Investigating the fiber volume fractions in natural fiber composites is essential to optimize the mechanical performance, control density, improve cost efficiency, enhance the manufacturing process and maximize the sustainability of the composites. The experimental results were used to compare the mechanical properties of palm sprout fiber reinforced polyester matrix composites with different fiber volume fractions.

EXPERIMENTAL

Extraction of fibers

Borassus flabellifer sprouts underwent a week-long submersion in water. These sprouts primarily consist of starch, which absorbs water and undergoes a process called retting. After being taken out of the water, the palm sprouts were carefully compressed to eliminate the starch. The fibers were subsequently washed by hand multiple times with clean water until all the starch adhering to them was visibly eliminated. Next, the fibers were extracted and left to dry in sunlight for an hour to remove any remaining moisture. Delicate compression was employed to separate the dried starch from the fibers. *Borassus flabellifer* sprouts and the extracted fibers are shown in Figure 1.

Alkali treatment of fibers

The dried fibers of the palm sprout underwent a treatment using a 5% NaOH solution for approximately 30 minutes at room temperature. Subsequently, the fibers were rinsed with deionized water to eliminate any NaOH residue on their surface. Next, the fibers were neutralized by applying a 2.5% HCl solution at room temperature for a duration of 24 hours.[25] The purpose of the alkali treatment is to eliminate impurities adhering to the fibers and create a rough surface. This roughness enhances the bonding between the fibers and the matrix, allowing for better transmission of applied force.

Scanning electron microscopy (SEM)

Scanning electron microscopy (SEM) is a highly efficient tool for analyzing the surface characteristics of fibers.[37] To investigate the variations in surface morphology between untreated and alkali-treated fibers, SEM images were captured. Images of raw and alkali-treated fibers, as well as composite specimens subjected to tensile testing, were obtained at various magnifications to examine their microstructure.


(a)


(b)

Figure 1: *Borassus flabellifer* sprout (a) and raw sprout fibers (b)

The SEM images were acquired using a JEOL-JSM-6390 machine model. Carbon coating was applied to enhance the conductivity of the samples. The process involves depositing a thin layer of carbon onto the sample surface, which improves the conductivity and minimizes charging effects during SEM imaging.

Preparation of composites

Unsaturated polyester resin with catalyst methyl ethyl ketone peroxide (MEKP) was used as matrix and cobalt octoate was used as accelerator. Untreated and 5% sodium hydroxide (NaOH) treated palm sprout fibers with uniform length of 30 mm and random orientation were used as reinforcement.[26] The composite specimens were prepared using polyester resin as matrix and palm sprout fibers in random orientation by combining the hand layup and the compression molding techniques.[27] The molding press was preheated, and the thoroughly mixed fibers and matrix were poured into the mold cavity and the required pressure of 10 MPa was applied. Composite specimens were removed from the mold after 24 hours, to enable the polyester matrix to cure and bond with the fibers, then they were visually inspected for any defects, like voids, delamination and fiber pull-out. Tests were conducted for six identical composite samples for each combination and the average results were presented for each combination.[28] The various combinations of sample specimens prepared were composed of 20, 25, 30 and 35 wt% of reinforcement and the remaining percentage of matrix, for both raw and alkali treated *Borassus flabellifer* sprout fibers, respectively.

Mechanical testing

The following tests were carried out on composite laminates as per ASTM standards to explore their mechanical performance. The different tests and their corresponding ASTM standards are given in Table 1.

Table 1
ASTM standards used for testing

Test performed	ASTM Standard	Reference
Tensile test	ASTM D 3039	29
Flexural test	ASTM D 790-03	32
Impact test	ASTM D 256-06	30
Compression test	ASTM D 695-02	31
Hardness test	ASTM D 785-98	33
Water absorption test	ASTM D 570-98	34

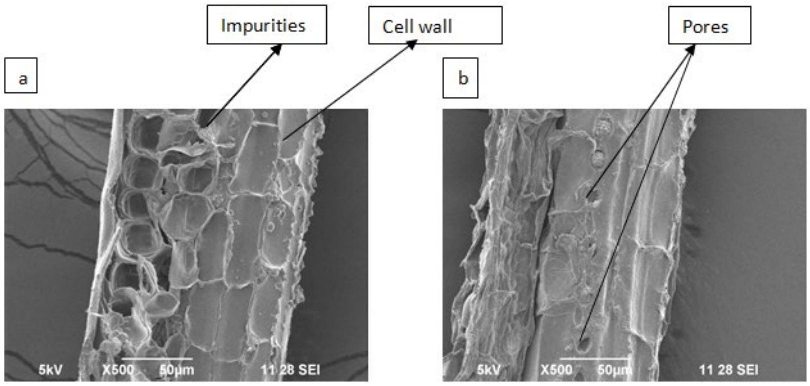

Figure 2: (a) Untreated palm sprout fibers, and (b) 5% alkali treated palm sprout fibers

RESULTS AND DISCUSSION

Surface morphology of palm sprout fibers

Figure 2 displays the surface morphology of *Borassus flabellifer* sprout fibers before and after the treatment with a 5% alkali solution. In the untreated fibers (Fig. 2a), the presence of non-cellulosic components and hemicelluloses can be observed on the fiber surface. However, after the treatment, the waxes, lignin, and hemicelluloses were effectively removed, resulting in a rough fiber surface. This removal of impurities revealed the presence of pores on the fiber surface (Fig. 2b). As a result, the contact area of the fiber increases when used for reinforcement in composites.

Tensile strength

Tensile strength is the maximum stress that a material can withstand when stretched or pulled before breaking. The composite specimens were tested at a crosshead speed of 1 mm/min. The tensile performance of various composite specimens is shown in Figure 4. From the figure, it can be seen that the tensile strength is higher for the composite specimens reinforced with treated palm sprout fibers. By increasing the volume of fiber, the tensile strength also increases, due to the tendency of the reinforcements to withstand the applied load.[26] The specimens, containing treated fiber as reinforcement in the ratio of 35%, have 30.14% better tensile strength than the untreated specimens. The strong fiber matrix interlocking in alkali treated specimens leads to better performance. The alkali treated fibers are also more flexible than the raw fibers. The sample tensile test specimens are shown in Figure 3.

Flexural strength

Flexural strength is also known as modulus of rupture or bend strength or transverse rupture strength. It is the stress in a material just before it yields in flexure tests. This test is conducted at a crosshead speed of 2.5 mm/min. The flexural performance of composite specimens is presented in Figure 5. It can be noted that the composite specimens incorporating treated palm sprout fibers as reinforcement shows better performance. The flexural strength increases with the increase in fiber volume due to the tendency of the fibers to absorb more stress before failure. Treated fibers are free from impurities and have better bonding with the matrix,[9] this is the reason for the 34.47% better performance of composite specimens with 35% volume of treated fibers as reinforcement. The treated fibers underwent shrinkage and became tougher, which contributed to improved strength values.

Figure 3: Tensile test specimens before and after testing

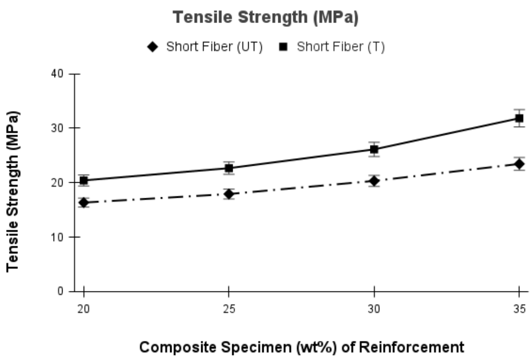

Figure 4: Tensile strength of composite specimens incorporating untreated (UT) and treated (T) palm sprout fibers

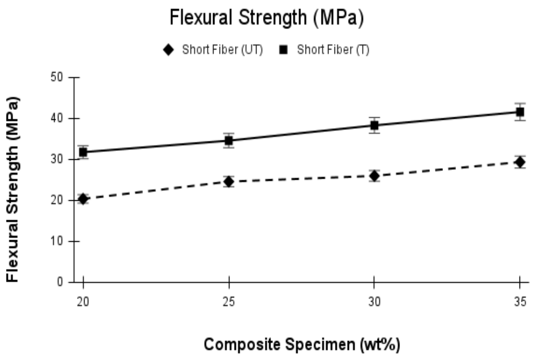

Figure 5: Flexural strength of composite specimens incorporating untreated (UT) and treated (T) palm sprout fibers

Impact strength

The impact energy refers to the minimum force per unit area required to cause fracture in a material. It represents the amount of energy that a material can endure when subjected to a sudden load. The impact specimens were sanded off with emery cloth to ensure that there were no out of plane notches. The test specimens were Charpy V-notched to induce a known point of stress. The specimens were held horizontally and the pendulum was released to strike the back side of the V-notch to predict the temperature dependent brittle–ductile shift of a material. The test specimen's failure surface was examined: if it is flat and smooth, the failure is brittle; on the other hand, if the failure surface is fibrous, the failure is ductile.

The impact strength of various composite laminas was presented in Figure 6. Composite specimens containing 35% by volume of treated and untreated palm sprout fibers presented impact strength of 0.97 J and 0.83 J, respectively. It can be understood that, by increasing the fiber volume, the impact strength increases as the fibers distribute the applied load.[34] Removal of hemicelluloses during the alkali treatment enhanced the interfacial bonding between the fiber and the matrix, which, in turn, leads to better impact strength. The impact test involves a pattern of crack initiation and growth in the matrix. The absorption of energy occurs as a result of fiber–matrix debonding and fiber pull-out, and the impact strength is greatly influenced by the strength of the interface between them.

Compression strength

Figure 7 presents the effect of fiber weight (%) on the compressive strength of the composite plates. The compressive strength of a material or structure is its tendency to withstand loads tending to reduce size and it is a key factor in the design of structures.[31] There is an increase of 3.14% in compressive strength for composite laminates reinforced with treated palm sprout fibers. It can be noted from Figure 7 that there is only a little difference in the compressive performance of the composites with treated and untreated fiber reinforcements, under the applied compressive load. Hemicelluloses and other impurities present in the fiber were washed away during alkali treatment, which exposes the maximum fiber surface for better fiber matrix bonding.

Hardness

Hardness refers to the ability of a material to withstand abrasion, indentation and scratching. Figure 8 shows the hardness of composite specimens. The maximum hardness obtained – of 84 HRRW – was recorded for the composite specimens with 35 wt% of treated fibers, due to the homogeneous distribution of the matrix. A material's hardness is related to the matrix used, but also to the intermolecular bonding of the matrix with the fibers.[36]

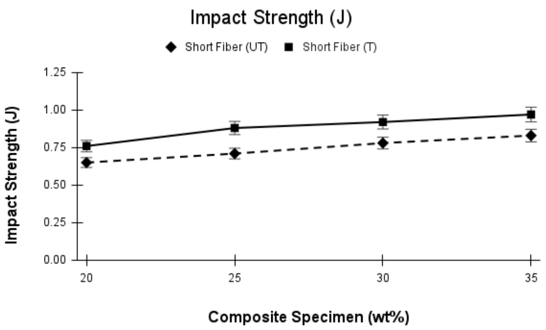

Figure 6: Impact strength of composite specimens with untreated (UT) and treated (T) palm sprout fibers

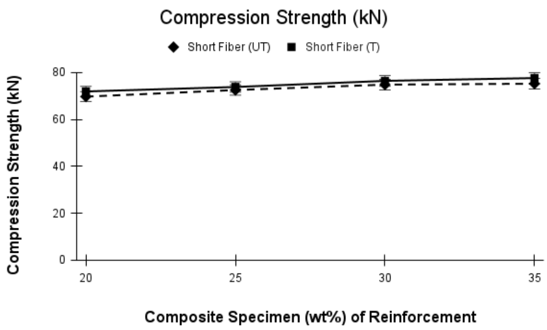

Figure 7: Compression strength of composite specimens with untreated (UT) and treated (T) palm sprout fibers

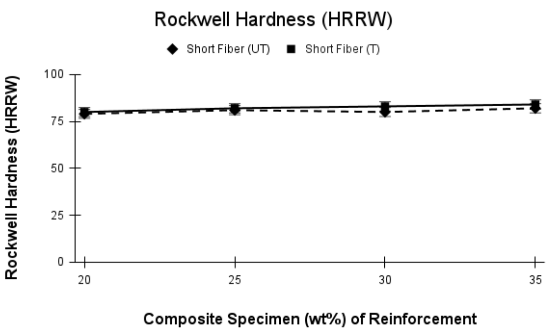

Figure 8: Hardness of composite specimens with untreated (UT) and treated (T) palm sprout fibers

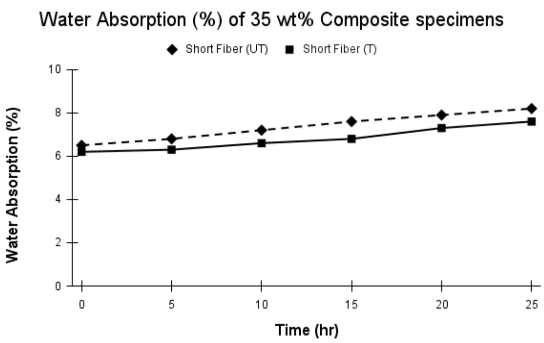

Figure 9: Water absorption % of composite specimens with untreated (UT) and treated (T) palm sprout fibers

Water absorption

The water absorption test was used to explore the behavior of composite specimens in marine atmosphere. Water absorption tests were conducted only for the composite specimens reinforced with 35 wt% of treated and untreated palm sprout fiber reinforced polyester composites, as the materials with this loading performed better in the mechanical tests. Water absorption values were calculated by the relation below:[35]

Water absorption %, $W = \left(\frac{w_t - w_0}{w_0}\right) X100$ (1)

where w_o is the weight of the composite specimen before immersion, and w_t is the weight of the composite specimen after immersion for a particular period of time.

It may be observed from Figure 9 that the percentage of water absorption in composite specimens with 35 wt% of treated fibers is lower than in the composites with untreated fibers. This may be explained by the fact that the chemical treatment decreased the hydrophilicity of the fibers.

Surface morphology of tensile test specimens

The surface morphology of the untreated and treated tensile test specimens with 35 vol% reinforcement is shown in Figure 10. The SEM images display the fractured surface of specimens subjected to tensile testing. The untreated fibers have less bonding with the matrix, hence fiber pull-out is visible in the scanning electron microscopy images. Figure 10 (a) reveals the presence of voids caused by fiber pull-out and fiber breakage, indicating weak adhesion between the palm sprout fiber and the matrix. Meanwhile, the cell walls of palm sprout fibers are visible in the treated tensile specimens (Fig. 10b), as the chemical treatment removed the impurities. Enhanced adhesion between the fiber and the matrix is achieved through chemical treatment of the fibers prior to composite preparation. This treatment decreases the occurrence of fiber pull-outs and improves the transmission of stress between the fiber and the matrix, resulting in enhanced tensile strength. It can be observed that the NaOH treatment increases the degree of interaction between the fiber and matrix, hence the composite specimens with treated palm sprout fibers performs better in all aspects.

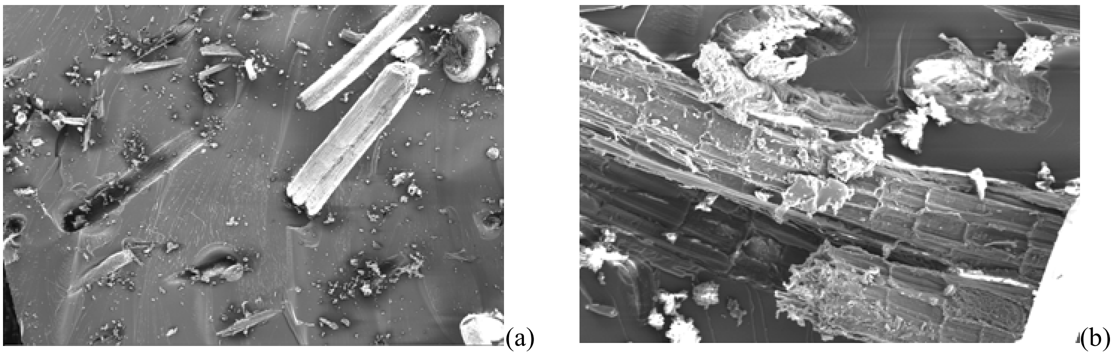

Figure 10: SEM images of tensile test specimens formed with the incorporation of (a) untreated and (b) treated palm sprout fibers

CONCLUSION

This work reports the potential of *Borassus flabellifer* sprout fibers, an unexplored type of natural fibers, to be used as reinforcement in polyester matrix composites. Scanning electron microscopy images of raw and 5% NaOH treated fibers showed that the impurities, such as waxes, lignin, and hemicelluloses were removed after the alkali treatment. It was observed that the chemical treatment of fibers led to better bonding with the polyester matrix, and the experimental results confirmed the suitability of these fibers for incorporation in a polymer matrix. By increasing the fiber volume up to 35% with chemically treated palm sprout fibers, the tensile, flexural, impact, compression strength and hardness of the composites also increased, while the water absorption percentage decreased. The tensile strength of 31.84 MPa and 23.45 MPa, flexural strength of 41.56 MPa and 29.34 MPa, impact strength of 0.97 J and 0.83 J, compression strength of 77.6 kN and 75.2 kN, and hardness values of 84 HRRW and 82 HRRW were recorded for composite specimens with 35 vol% of treated and untreated *Borassus flabellifer* sprout fibers, respectively. The water absorption % of the composites specimens with 35 vol% of treated and untreated palm sprout fibers for 24 hours was 7.6% and 8.2%, respectively. Experiments were performed by further increasing the percentage of reinforcement to 40%, 45% and 50%, but the mechanical properties showed a decreasing trend, which can be explained by lack of adequate bonding with the matrix. It is known that higher fiber volume fractions can lead to inadequate matrix coverage, resulting in poor interfacial bonding and reduced composite strength. Other reasons why the reinforcement percentage is limited in natural fiber composites may be that higher volume fractions can lead to fiber agglomeration or clustering, and can increase processing difficulties, causing fiber breakage or excessive void formation. All of these negatively affect the overall mechanical performance of the composites.

By keeping the reinforcement percentage within the optimal range, natural fiber composites can achieve a good balance between strength, stiffness, and other desired properties, while maintaining processability and structural integrity. Hence, it can be concluded that the fiber volume fraction of 35 wt% as reinforcement allows achieving good mechanical performance of the composites. Thus, palm sprout fibers can be potentially used in the development of polymer matrix composites for lower weight and high strength applications.

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