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Property characterization of acacia tortilis for natural fiber reinforced polymer composite

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ABSTRACT

Eco-friendliness and availability of green fiber reinforced based composites attracted many as a potential replacement for non-biodegradable synthetic fiber. Green composites are biodegradable and less susceptible to health hazards during the utilization for engineering application. Furthermore, natural fibers tend for application of light weight engineering products and provide satisfactory mechanical properties that pose challenges on massive application of green fibers as reinforcement in composite structures. The main objective of this paper is to extract and characterize Acacia tortilis as natural fiber for green composite. ASTM standard for sample preparation and experimental testing of fiber bundles were used. After successful extraction of the fiber, chemical composition, density and tensile test of mechanical property were performed as well as effect of chemical treatment was studied for bundles of fiber and a promising result were obtained. Validation with published results indicates that acacia tortilis fiber can be considered as a potential natural fiber for the application as a green composite.

1. Introduction

Composites are heterogeneous materials, formed by the combination of two materials with different physical and chemical properties at distinct interfaces. The parent materials are generally differentiated as matrix phase and reinforcement phase. While the reinforcement is the load bearing member, the matrix bonds the reinforcing material together and distributes the load among them [1, 2].

Green composites emerged as promising alternatives to substitute synthetic composites. As natural fibers, they have substantial advantages such as abundance, light weight, high specific strength and modulus, cost effectiveness, biodegradability, renewability, ease of processing and the like [3–6].

There exist several ongoing studies focusing on plant fibers to investigate their capacity to substitute the synthetic fibers. The common plant's parts that are used as source of natural fiber are seeds, bark, leaf, stalks, grass, etc [7]. Forthermore, Sisal, Pineapple, Banana, Flax, Hemp, Jute, Ramie, Artichoke, Okra, Coir, Cotton, wheat, bamboo and grass are common plants studied as sources of natural fibers [3]. As different parts of the plant are used for natural fibers, they can be extracted by using different methods such as manual extraction, decortication, water retting and chemical retting [1].

Although, studies conducted on Acacia tortilis plant are limited, even those available studies mainly focused on applications for medical purposes of the plant and their particular values. As a result, Acacia tortilis, which is a major tree plant found in the arid and semi-arid parts of Africa and Middle East [8, 9], is not well studied for other purposes beyond its medication values. This tree type is one of a drought resistance species that grows in areas with average annual rainfall as low as 40 mm and as much as 1200 mm, and withstand higher temperature variation of 0^{O}c to 50^{O}c. Thus, it is native to arid and semi-arid parts of Ethiopia [10].

In addition, there are studies conducted on Acacia tortilis plant in terms of its usage for fuel wood, fodder, shade potentiality of improving soil fertility, nitrogen fixing and reforestation agent and its value of pharmaceutical and biological application for different purposes [11–14]. Yet, such plant is not well studied for its usage as a source of green fiber for composite structure reinforcement purpose.

The study reported in this article focuses on the extraction and mechanical property characterization of a novel Acacia tortilis fiber as natural fiber based green fiber reinforced polymer composites using mechanical testing. Following this introduction section, the article is divided into 3 main sections. Section 2 presents the materials and

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research methods used to investigate the extracted fiber from Acacia tortilis. It discusses the used extraction method, determination of material composition, measurement of physical properties, mechanical testing and mictostructure study using scanning microscopic. The experimental results are then discussed in Section 3 and finally Section 4 summarizes the conclusions drawn from the study.

2. Materials and methods

2.1. Materials

The Acacia tortilis bark for this study was collected from Modjo, Oromia region, in Ethiopia. Other materials and chemcials used include sodium hydroxide, ethanol, nitric acid, sulfuric acid and benzene. Pycnometer was used to determine the density of the fiber.

2.2. Extraction and treatment of acacia tortilis fiber

The bundles of Acacia tortilis plant were manually separated from the main tree by cutting the bark that contained fibers. Then, the fibers went through water retting process, illustrated in Fig. 1, and soaked in water for 24 days to facilitate the separation of fiber bundles and unwanted substances. The water was changed every seven days and at the end, it was washed before allowing to dry in open air.

Then Acacia tortilis fibers were alkali treatment at 10 wt% and 20 wt % concentration of sodium hydroxide. The diluted solution was stirred for 15 min continuously unidirectional to insure that all the alkali was diluted in the water. Then the required amount of fiber was soaked in the alkali diluted solution for 3 h before washing by water until clean water and whitish fiber was obtained. Finally, the treated fibers were allowed to dry in open air for five days, which was then ready for further study.

2.3. Determination of chemical compositions

The chemical compositions of natural fibers have a great influence on the mechanical and other properties of the fibers. Most studied chemical compositions of natural fibers are cellulose, hemicellulose, lignin and wax, but the amount of hemicellulose was not determined in this study. The fibers are allowed to dry in oven for 6 h under 105 °C to ensure the removal of any moistures and then it was powdered on wood milling machine and sieved on randomly selected sieve size of 250 μm. Then 1 g of the milled fiber sample for cellulose and lignin, and 2 g of wax were taken for each type of the chemical composition analysis. Kurschner and Hoffer method, ASTM D1106-56 and ASTM D 1107–56 was followed to calculate the content of cellulose, Lignin and wax in Acacia tortilis fibers.

2.4. Characterization of the physical properties

Density, ash and moisture contents are the selected physical properties considered in this study. The dried and powdered fiber are conditioned to 65% relative humidity and 29 °C temperature by putting in closed desiccators for 48 h. For moisture content, 2 g of conditioned sample was dried in oven at 100 °C for 2 h and then allowed to be cooled in desiccators containing silicon gel to room temperature, and the sample was weighed. The heating and cooling process was repeated until the difference of the two successive weights becomes less than 1 mg. Finally, the moisture content was calculated using the following equation.

$$Moisture\ content\ (\%) = \frac{Initial\ weight - Final\ weight}{Initial\ weight} * 100 \quad (1)$$

To determine the ash content, the empty crucible was ignited and covered in the muffle furnace at 600 °C for 10 min. Then it was cooled in desiccators containing silica until it gets to room temperature and its weight was measured. Then the crucible containing 1 g of the sample was put in muffle furnace at 600 °C for 2 h and cooled with silica gel to room temperature and weighed. The heating and cooling process was repeated until the difference of the two successive weights becomes less than 1 mg. Finally, the ash content is calculated using the following equation.

$$\begin{aligned} Ash\ content\ (\%) &= \frac{Initial\ sample\ weight}{Final\ ash\ weight} * 100\ \text{ash content}\ \ \% \\ &= \text{Initial sample weightfinal ash weight} * 100 \end{aligned} \quad (2)$$

The density of the untreated Acacia tortilis fiber was determined by following the pycnometer procedures where distilled water was taken as an immersion liquid and the density of Acacia tortilis fiber (ρATF) was determined using the following relation

$$\rho_{ATF} = \left(\frac{m_2 - m_1}{(m_3 - m_1)(m_4 - m_2)}\right)\rho_w \quad (3)$$

where m_1, m_2, m_3 and m_4 are masses (g) of empty pycnometer, pycnometer filled with fiber, pycnometer filled with distilled water, and pycnometer filled with fiber and distilled water, respectively and ρ_W stands for density of distilled water (g/cm^3).

2.5. Scanning electron microscopy analysis

The microstructure and composition of the fibers were studied using scanning electron microscopy (SEM), Gemini SUPRA 35VP equipped with EDAX Energy Dispersive X-ray Spectroscopy (EDS) detector. The EDS detector is silicon drift detector (SDD) that enable accuracy and precision than the older model. The EDS detector is used to identify elemental composition of the sample. For the analysis, pieces of Acacia tortilis are placed on a sample holder using a carbon tape. Surface of the sample is then coated with very thin palladium (Pd) layer. The coating was done to ground the electrons hitting the surface of the samples. The electron which are probing the Acacia sample are accumulated on the surface, if the sample is nonconducting material. If so, it is not possible to

Fig. 1. Fiber extraction and treatment.

do the analysis. Therefore, coating is needed for nonconducting samples to avoid charge/electron accumulation. This study did not include the Atomic force microscopy (AFM) experimental analysis.

2.6. Mechanical testing to characterize the fiber

Acacia tortilis fiber naturally exists in a layer form unlike other common natural fibers, which are in yarn form. The fiber was converted to yarn form manually to investigate its tensile properties. Since identification of numbers of yarn per each sample is difficult, sample count was considered for tensile investigation. Accordingly, the average count for each sample (Length divided by mass) is 1.9, which gives information about the number of yarns. The fiber diameter was measured before performing single fiber yarn tensile test according to ASTM D2256 standard. Successful tests were conducted on 10 test samples each for untreated, 10 wt% and 20 wt%NaOH treated acacia tortilis fiber separately. The tests were performed at room temperature with 500 mm gauge length and 500 mm/min test speed. The handmade fiber yarns that are used to determine the tensile properties are illustrated in Fig. 2.

3. Result and discussion

3.1. Extraction of fibers

The hand washing process assisted removal of foreign materials from the fiber surfaces. As shown in Fig. 3, the fiber geometry was not as expected, i.e. the geometry is in strand or yarn form as natural fibers that existed.

The geometry and appearance of the fibers naturally will affect the properties and application of the fibers. In the process, it was found difficult to get equal sized fibers and the separation of the layers takes time. This makes difficult to make different fiber orientations when fabricating the composite and perform single fiber test. When compared with other natural fibers, geometry and appearances like sisal, juncus effuses and agave americana; acacia tortilis fibers are expected to have lower strengthes. The alkali treatment enhanced the fiber separations and increased surface roughness that is supported by similar studies such as Luffa sponge fiber [15] and Borassus fruit fibe fibers [16].

3.2. Chemical composition and physical properties

The mechanical properties and degree of biodegradability of the natural fibers obviously depend on the content of chemical

Fig. 3. Geometry of Acacia tortilis fibers (a) Acacia fiber appearance, (b) magnified appearance.

Table 1
Chemical composition and density of Acacia tortilis fiber.

Cellulose, [%]	Lignin, [%]	Wax, [%]	Moisture content, [%]	Ash content, [%]	Density, [g/cm^3]
61.89	21.26	17.43	6.47	4.33	0.906

compositions. Acacia tortilis fiber contained 61.89% of cellulose that improved the tensile strength and rigidity of the fibers, as tabulated in Table 1. The sum total of the chemical compositions are greater than 100% due to the individual test was performed from separate sample sizes; 1 gram was used to determined the wax amount and 2 gram sample was used for lignin determination test (required cellulose free sample). The content of cellulose in Acacia tortilis fibers are equivalent with other bast fibers such as Prosopis Julflora Bast fiber, Coccinia Grandis L. bast fiber but lower and/or higher than that of hemp fiber and kenaf fiber. But, when compared with common natural fibers, the content of cellulose in Acacia tortilis fiber (61.89%) are lower than Sisal fiber (66.5%) [3], Flax fiber (66.5%), Hemp fiber (71%) and Jute fiber (65%) [17], as illustrated in Fig. 4.

The Acacia tortilis fibers contained higher concentration of Lignin (21.26%) that enhance the stability of the fiber structure and contributed to excellent rigidity but lowered the fiber strength. But, when compared with common natural fibers, Acacia tortilis fiber contained higher amount of Lignin compared to Kenaf fiber (14%) [17] and Sisal fiber (12%) [3]. The wax content contributes to improved bonding between

Fig. 2. Acacia fiber (a) Acacia tortilis raw fiber, (b) handmade acacia tortilis fiber yarn).

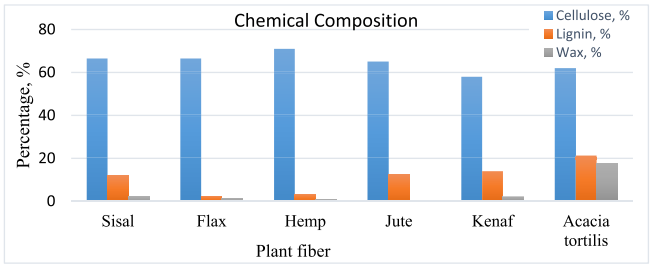

Fig. 4. Chemical composition of common natural fibers.

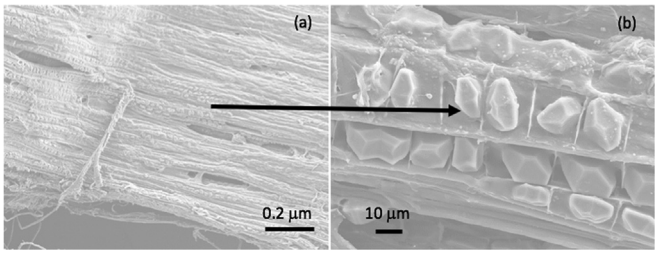

Fig. 6. (a) Fiber structure (b) high magnification image showing block (capsule)-like component.

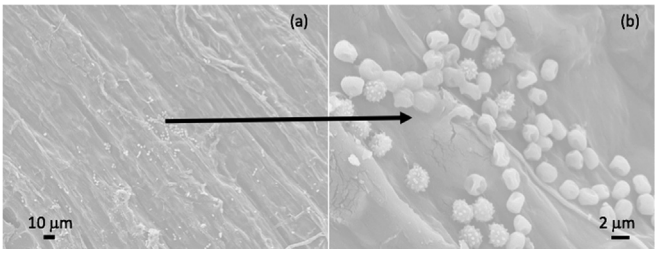

Fig. 7. View of spherical components at (a) low magnification (b) high magnification.

fibers and polymer matrix in composite adhesions. The wax content (17.43%) of Acacia tortilis fiber are much higher when compared to the common natural fibers such as Sisal fiber (2%) [3], Kenaf fiber (2.2%), Flax fiber (1.5%), Hemp fiber (0.7%) and Jute fiber (0.5%) as reported in Ref. [17]. Wax also improves interfacial bond between the fibers and polymer matrix during composites manufacturing [18].

Commonly, natural fibers have hydrophilic properties that are susceptible to moisture. The ash content (6.47%) in Acacia tortilis fibers affectes the applications of the fiber in humid environments. When compared with other natural fibers, Acacia tortilis fibers are observed to have less ash content (4.33%) than pineapple leaf fiber (4.5%) and palm leave fiber (9.0%). Density is the main criteria that determines the application of any material, especially natural fibers, with other combined properties. Comparably, Acacia tortilis fibers have lower density (0.906 g/cm^3) but this value is approximated with the density of other common natural fibers such as Bamboo (1.23 g/cm^3), Kenaf (1.18 g/cm^3) and Coir (1.20 g/cm^3), as reported in Ref. [19], but, lower than density of Flax (1.5 g/cm^3) and Jute (1.3 g/cm^3) [1]. A lower density implies that Acacia tortilis will have the capacity to substitute Jute fiber, Kenaf fibers, Coir fiber, Flax fiber and Bamboo fiber if they have comparable strength.

3.3. Scanning electron microscopy

The microstructural surface aspect of the fibers has a large aspect ratio (length to thickness ratio). The elemental composition of the sample analyzed with EDS is given in Fig. 5.

The main compositions of the Acacia tortilis fiber are Carbon and Oxygen. These two elements are nearly the same in weight percentage (43–44 wt %). It also consists of considerable amount of Calcium (12.61 wt %) and small amount of Sulphur (<1 wt %). The fiber also consists small traces of Silicon, Magnesium and Nitrogen. The concentration of Carbon and Oxygen are in the range of 24–28 wt% and 69–73 wt% respectively. Weight percentage revealed that Acacia tortilis fiber contains less carbon (42.591 wt%) and oxygen (40.509 wt %) content compared to Jute fiber (55.68 wt% and 43.89 wt%) and Cotton fibers (46.1 wt% and 53.9 wt %) [20]. But it has higher content of calcium (21.653 wt%) and negligible amount of nitrogen (0.593 wt %), magnesium (0.943 wt %), silicon (0.7 wt %) and Sulphur (0.6 wt %) with respect to other natural fibers. The acacia sample also consists spherical type components as shown in Fig. 6.

In between the bundles of the fibers, block/capsule like structures that measure about 20 µm on average are observed as illustrated o Fig. 6. The capsules investigated consist of variable amount of Calcium (36–62 wt %) and Oxygen (27–47 wt %). The rest of the concentration is Carbon, Sulphur and Magnesium. Such surface structure helps to enhance the adhesion force between the fibers and matrix during composite fabrication. They are also expected to hinder cracks on composites, prevent fiber-matrix separation and give the ductile properties to the composite.

The ball like components have an average diameter of about 2.5 µm, shown on Fig. 7 (b). Such ball like structures are expected to increase the bonding between the fiber to enhance the fiber strength. Also, those structures have the capacity of arresting internal cracks when the fiber undergoes microscopic failure that increased the bonding forces within fiber but needs further investigations.

3.4. Tensile properties

The maximum tensile strength of Acacia tortilis fibers has been determined as the maximum stress before the rupture and the Young's modules are determined from the stress-strain curves. Both tensile strength and Young's modulus are expected to be higher for Alkali

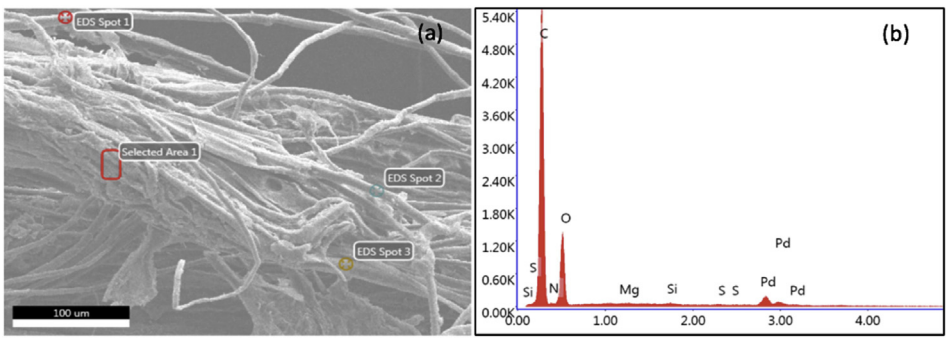

Fig. 5. EDS spot analysis (a) SEM image of individual fibers and (b) EDS spectrum from the fibers.

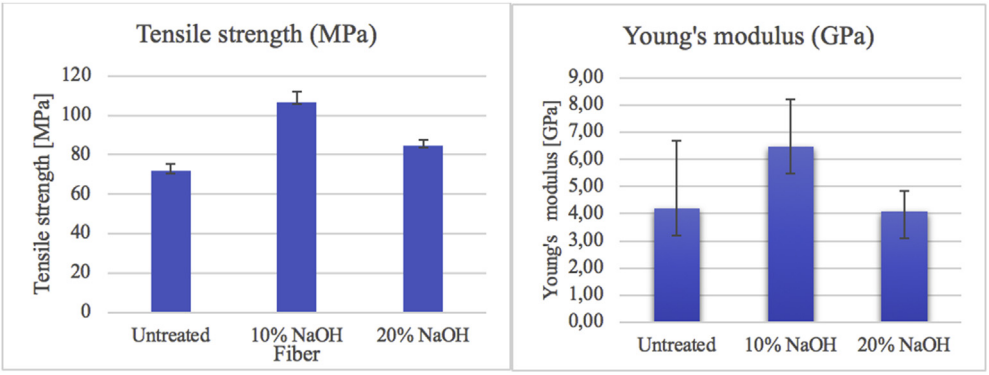

Fig. 8. Tensile properties (tensile strength and Young's Modulus) of Acacia tortilis fiber.

Table 2
Property of Acacia tortilis fiber yarn.

Specimens	Diameter [mm]	Max. force (F_{max}) [kN]	Tensile strength [MPa]	Young's modulus, E [GPa]	Elongation [%]
Untreated	0.48	2.28	71.63	4.21	1.33
10 wt % NaOH	0.54	3.32	106.81	6.47	1.50
20 wt % NaOH	0.4	2.63	84.76	4.10	1.90

treated fibers compared to the untreated Acacia tortilis fibers. The results depicted in Fig. 8 and Table 2 reveal that the tensile strength, Young's modulus and elongation of 10 wt% NaOH fiber showed better performance compared to untreated fiber by 45.61%, 12.78% and 53.68% respectively. But, the tensile properties showed decreasing effect when the fibers are treated by 20 wt % alkali compared to 10 wt % treated fibers. This result arises due to the diameter inconsistency, the diameter of 20 wt % alkali treated fibers are lowered by 25.9% compared to that of 10 wt % treated fibers. A fiber treated by 10 wt % alkali has 106.81 MPa tensile strength and 6.47 GPa Young's modulus while a tensile strength of 84.76 MPa and Young's modulus of 4.10 GPa has been scored for the 20 wt % treated fibers. Here, the average diameter used to conduct the tensile tests is not similar for untreated and treated fibers.

Higher content of cellulose would enhance the tensile strength as observed on similar natural fibers, such as bamboo, sisal and kenaf. But, the Lignin content residing in Acacia tortilis fibers (21.26%) negatively affected the tensile strength that leads to the weak strength of Acacia tortilis fiber. The tensile properties comparisons of common natural fibers are demonstrated on Fig. 9(a). The comparison shows that Acacia tortilis fiber has higher tensile performance than Ramie fiber (0.3 MPa) [21] and coir fibers (44 MPa) [19]. But, Acacia tortilis fibers are the weakest fiber compared with Jute fiber (393 MPa) [1]. Bamboo, Kenaf, Flax and Jute fibers exhibited better Young's modulus performance but Acacia tortilis fibers have better Young's Modulus compared with Coir fibers (Fig. 9(b)). This shows that Acacia tortilis fibers are used for application that require light weight and medium strength applications.

4. Conclusion

As part of this study, the Acacia tortilis bast fibers were extracted manually and treated by the water retting method successfully. The experimental results showed that Acacia tortilis fibers have 0.906 g/cm^3 density and 61.89% cellulose, which is good. The content of cellulose positively affecte the tensile properties of Acacia tortilis fibers but higher amount of Lignin reduces the expected fiber strength. The capsule like structure on the fiber surface increased surface roughness and will be expected to assist adhesion during composite making. The tensile properties of untreated and treated fibers are 71.63 MPa and 106.81 MPa respectively, which imply that alkali treatment improved the fiber's tensile properties by 49.1%. As most studies reported, alkali treatment improved the tensile properties of Acacia tortilis fibers. This study also showed that Acacia tortilis bast fibers have a potential to reinforce composite materials that can be used for the applications requiring light weight design combined with higher strengths.

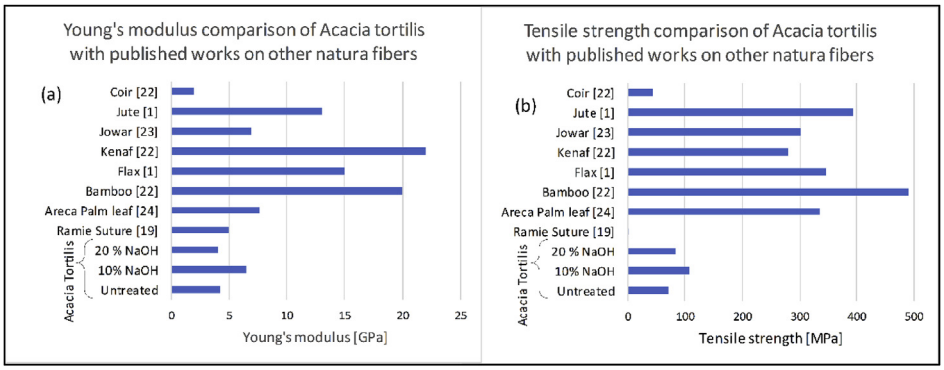

Fig. 9. Tensile properties of common natural fibers.

Declaration of competing interest

The authors declare that there is no conflict of interest regarding the publication of this article.

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