Mechanical Properties Characterization of Water Hyacinth ("Emboch") Plant for Use as Fiber Reinforced Polymer Composite

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Abstract. The aim of the research work reported in this article is to fabricate water hyacinth fiber reinforced polyester composites and characterize its mechanical properties. The fiber material was extracted manually after collecting the water hyacinth plant from Lake Koka in the Oromia Region, Ethiopia. Once the extraction was done, the fiber was treated by a chemical in different sodium hydroxide concentration, used for the improvement of bond and interfacial strength of the water hyacinth fiber. The composite of water hyacinth fiber is fabricated with polyester resin, using hand lay-up methods in different fiber/matrix ratios. The mechanical properties of the specimens were then measured according to ASTM standard recommendations experimental tests such as tensile, flexural and compressive tests were conducted on the prepared composite material samples. The results show that 20% fiber content is around optimum content for best mechanical behavior and all the mechanical properties are satisfactorily improved when the water hyacinth polyester composite is chemically treated using NaOH. Therefore, using water hyacinth fibers as reinforcement in a polymer matrix, it has been proved that successful composites can be developed.

Keywords: Natural fiber · Water hyacinth fiber · Polyester resin · Hand lay-up fabrication · Mechanical property

1 Introduction

Composite materials are combinations of two or more materials with different physical and chemical properties at distinct interfaces [1]. These materials have been in industrial applications for thousands of years. The most important reason for the selection of composite materials is the versatility in their properties including specific strength, high-temperature resistance, high specific modulus, and low thermal conductivity [2]. Among the areas where composite materials are widely used, the aerospace industry, marine sector, chemical industries, automotive industry, construction, electrical, and other application areas [3, 4] can be mentioned.

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The fibers used in reinforced composite materials can be classified as natural fibers and synthetic fibers [5]. Natural fibers are simple fibers found in plants and animals. Their advantages include high strength, durability, low thermal conductivity, lightweight, corrosion resistance, and dimensional stability [6]. The common drawback of almost all natural fibers is their relatively low dimensional stability, high moisture adsorption, and incompatibility with the binder matrix. Thus, chemical treatments and immersion techniques are needed to improve their mechanical performance [7]. The typical chemical treatments used on natural fibers are Alkali treatment, Acetic acid (CH_2COOH), Isocyanate, Silane treatment, Benzoylation, Peroxide, and other types of chemical treatments that are used for refinement of the natural fibers [8]. At present, many types of natural fibers are being investigated as reinforcement in the polymer matrix, including flax, hemp, jute straw, sisal, raphia, banana fiber, pineapple leaf fiber, and so on [9]. Table 1 shows the chemical composition and mechanical properties of selected plant fibers [10, 11]

Table 1. Chemical composition and mechanical properties of plant fibers.

Fiber	Hemicelluloses (Wt. %)	Cellulose (Wt %)	Lignin (Wt %)	Density (g/cm^3)	Tensile strength (MPa)
Sisal*	10–14	66–78	10–14	1.5	511–635
Hemp	17.9–22.4	70–74	3–5.7	1.48	690
Flax	18.6–20.6	71	2.2	1.5	345–1035
Bamboo	20.5	34.5	26	0.6–1.1	140–230
Jute	16	67	9	1.2	393–773

* The origin of sisal fiber is from leaves while the rest are from stem

One of the natural fiber sources is water hyacinth (WH), which contains lignocellulose materials. The water hyacinth (Eichhorniacrassipes) is a free-floating aquatic plant, a native of the Amazon basin, and belongs to the Pontederiaceae family, with different growth habits under different environmental conditions [12]. This plant is a noxious weed that has attracted worldwide attention because large water hyacinth mats prevent the transfer of oxygen from the air to the water surface or decrease oxygen production by other plants and algae [13]. The plant doubles its surface area indoors within two weeks, sometimes in a week. Water hyacinth covers 80% of Lake Victoria [14]. In Lake Tana, in Northern Ethiopia, water hyacinth recently invaded over 30% of the shoreline of the North-eastern part of the lake's shores [15].

Water hyacinth plant is used in animal feed and animal production, organic fertilizer (green manure or compost) or mulching materials, for making paper, biogas production, and the like. The use of this plant, for instance in Indonesian, as a raw material for handicraft and processed in a bag, basket, and tablecloth are the motivations of this study, which is aimed to convert this plant into engineering applications. Only limited previous studies and investigations are reported on the capabilities of this plant as a source of fiber and reinforcements to manufacture composite materials. For instance, Sawpan et al. [16] reported that the tensile strength of chemically treated (NaOH) fibers can be increased compared with the untreated hemp fiber. The reason is densification of fiber cell walls for the removal of the non-cellulosic components during treatment. The study reported by Bhuvaneshwari et al. [17] proved that the water hyacinth fiber has excellent absorbency, elongation and medium strength. The Scanning Electron Microscope (SEM) analysis shows that the fibers contain many hollow pores which can hold moisture and are suitable for high absorbency materials such as wipes and napkins.

Thus, the research reported in this article focuses on using this unwanted weed for useful engineering applications. Characterization of the mechanical properties of this plant as a source of fibers for composite materials demands an extensive research because the strength properties are affected by several parameters such as altitude, water quality, and water content. Thus, the current study aims only to develop some level of understanding on the possible applications of water hyacinth fiber as reinforced polyester composite as a source of fiber under limited conditions. A particular attention is given to the chemical treatments of WH fibers to improve the interfacial bonding between the WH fibers and the matrix.

2 Materials and Methods

The water hyacinth fiber was collected from Koka Lake in the Oromia region, Ethiopia and Phthalic Anhydride based TOPAZ-1110 TP unsaturated polyester resin with Luperox® K10 catalyst (purchased from World fiberglass engineering plc, in Addis Ababa, Ethiopia) was used as the matrix. Polyester resin, whose physical properties are given in Table 2, is the most widely used resin type particularly in the marine industry. This resin is low-cost and easily available in local market.

Table 2. Physical properties of polyester resin.

	Properties					
	Density (g/cm^3)	Tensile strength (MPa)	Modulus of elasticity (MPa)	Elongation (%)	Flexural strength (MPa)	Flexural modulus (MPa)
Value	1.2	50	3000	2.5	60	3000

To extract the fiber, the water hyacinth plant was collected and the root and leaves were separated from the stalk using knives. The stalk was then washed using tap water to remove dirt particles and soaked in water for seven days to remove lignin, any adhering dirty and hemicelluloses. The soaked fiber was washed by tap water and then dried. The steps used to collect the plant and extract the fiber are shown in Fig. 1.

According to the literature, treating the natural fibers with alkali solution has a good effect on their mechanical behavior. The chemical treatment was performed according to the following steps:

- Measuring the dry fiber and Sodium hydroxide (NaOH) amount according to the rule of mixture,
- Mixing the measured NaOH with distilled water,
- Soaking the fiber into alkali solution at room temperature for 3 h, and
- Washing the fiber thoroughly in distilled water.

Samples of fibers, both untreated and treated are given in Fig. 2.

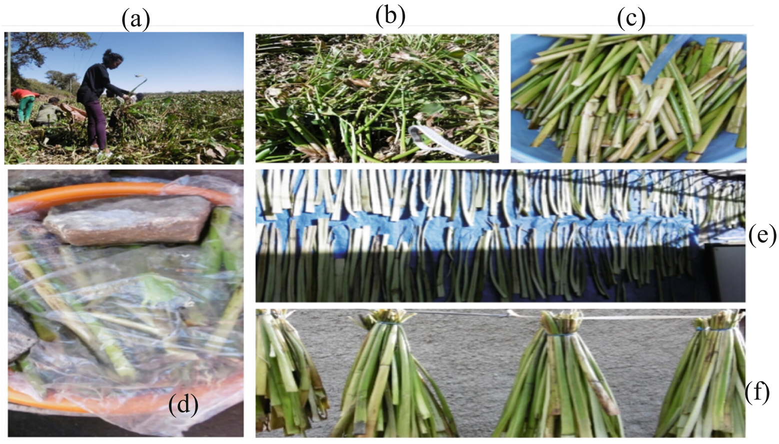

Fig. 1. (a) Harvesting water hyacinth from Koka (b) sample of collected water hyacinth (c) washing samples by tap water (d) soaking in water (e) and (f) drying in open air.

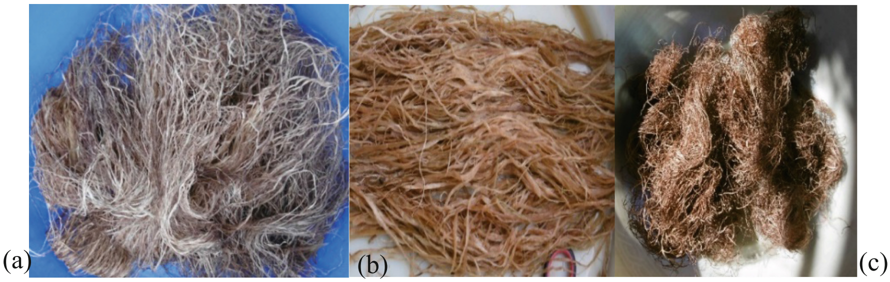

Fig. 2. (a) Untreated fiber (b) 10% NaOH treated fiber and (c) 20% NaOH treated fiber

The test specimens were then prepared by using the hand lay-up method. This involved mixing the resin and the hardener, putting a plastic in the bottom and smearing a wax to remove adhesion between the sample and the mold, and finally, putting the mold in hydraulic pressing machine. The fibers collected and prepared according to the procedure presented above are then prepared for three types of tests according to the recommended ASTM standards (1) tensile test – ASTM D-3039/D-3039M [18], (b) flexural test – ASTM D-790 [19] and (c) compression test – ASTM D-695 [20].

To calculate the density of the water hyacinth, Pycnometer method was used. A Pycnometer flask with a capacity of 50 ml, oven-dry temperature at 105 °C and a sensitive balance were employed. The density was measured at Food Technology Laboratory of Addis Ababa University, Ethiopia.

First the mass of empty pycnometer flask was measured and record as m_o, then the flask was filled to 1/3rd volume with chopped fiber and its mass was measured and recorded as m_1. Then, distilled water was added to the fiber-containing flask and measured (m_2) and the mass of distilled water was calculated ($m_3 = m_2 - m_1$). The density of distilled water varies depending on the temperature in the laboratory. Thus, for 20 °C, the density is 1.00 g/cm^3. Based on the recorded masses, mass fiber ($m_o - m_1$) and measured volumes distilled water and the flask, the density of the chopped fiber was calculated. Finally, the pycnometer flask was dried for 20–30 min in an oven at 90–105 °C respectively before the next test.

3 Results and Discussions

3.1 Density

The density of water hyacinth was measured according to the procedure outlined in Sect. 2. The experiment was repeated five times and the average value was calculated. The linear density of untreated water hyacinth fiber was found to be 0.812 g/cm^3. When compared with the density of other natural fibers, hyacinth fiber is lower than the density of bamboo 1.20 g/cm^3 [21] but greater than Kenaf (core) 0.1- 0.2 g/cm^3 [22]. The density of natural fibers determines their application, for instance light weight applications prefer materials with low density.

According to the work reported by Bhuvaneshwari et al. [23], the density of water hyacinth is 1.37 ± 0.05 g/cm^3, and the density varies because of the drying temperature and moisture content of the fiber.

3.2 Tensile Tests and Results

To evaluate the in-plane tensile properties of the material, six different test groups were prepared with 5 test specimens each. The test groups are designated as follows:

1.. WHS1(T): Water hyacinth fiber reinforced polyester size one composite with fiber/matrix ratio of 30/70,
2. WHS2(T): Water hyacinth fiber reinforced polyester size two composite with fiber/matrix ratio of 30/70,
3. WHR20wt%(T): Water hyacinth fiber reinforced polyester composite with fiber/matrix ratio 20/80,
4 WHR10wt%(T): Water hyacinth fiber reinforced polyester composite with fiber/matrix ratio 10/90,
5. WHT20%(T): 20% NaOH treated water hyacinth fiber reinforced polyester composite, and.
6. WHT10%(T): 10% NaOH treated water hyacinth fiber reinforced polyester composite.

The tests were conducted at room temperature of 20 °C. For each test specimen, a cross-sectional area of 125 mm^2 was used. The tensile tests were conducted with focus on investigating the effects of cutting size, which are 10 mm and 2.5 mm for WHS1 (T) and WHS2 (T) respectively, fiber/matrix ratio (i.e. fiber content) and the chemical treatment of the composite on the stress-strain distribution (tensile strength). Table 3 shows the average values obtained from the tests.

Table 3. Tensile test results of the tested untreated sample groups.

Specimen	Peak load (kN)	Max. deformation (mm)	Max tensile strength (MPa)
WHS1(T)	0.21	5.62	1.68
WHS2(T)	1.38	6.52	11.28
WHR20wt%(T)	1.07	5.31	8.56
WHR10wt%(T)	0.78	4.28	6.24

As can be observed from the table (Table 3), higher average maximum tensile stress has been registered for the size two fiber contained composites (WHS2(T)) compared with the size one composite (WHS1(T)). In other words, the tensile strength of samples in the WHS2 group is about 85% higher than those in the WHS1 group. This can be attributed to the effect of fiber cutting size, 10 mm and 2.5 mm respectively, and this demonstrates the effect of weak internal interaction of large fiber size and an inability of a large fiber size to withstand the load transferred from the matrix. For the sake of better visualization, the comparison of the effect of the cutting size on the stress – strain distribution is plotted in Fig. 3(a). The tensile strength result obtained for size 2 water hyacinth fiber reinforced polyester composite in the current work (11.28 MPa) is close to the result obtained by Abral et al. [24], which is 14.9 MPa. The other observation is that fiber orientation is important for the performance of natural fiber composites where unidirectional long fiber or mat composites have higher tensile strength properties compared with randomly distributed short fibers.

Furthermore, to investigate the effect of fiber content on the tensile strength properties of the composite materials, the stress – strain distribution of the composites with fiber/matrix ratio of 30/70, 20/80 and 10/90 are plotted in Fig. 3(b). The plots show a clearly noticeable difference because of the fiber content. Though no particular trend is observed, the fiber/matrix ratio of 20/80 has the highest tensile strength compared with the rest in the comparison and this may be as a result of proper fiber distribution and dispersion that facilitated the strength of the composites. The plots also show that the fiber content highly influences the tensile strain. Composites with higher fiber content sustain higher strain.

The comparative results for the untreated (WHUT(T)) and alkali treated (WHT20%(T) and WHT10%(T)) fiber reinforced polyester composites are given in Table 4 and plots of the stress-strain distribution are given in Fig. 4. The results indicate that alkali treatment affects the tensile strength of the water hyacinth fiber reinforced polyester composite material. Treatment with higher percentage of alkali content leads to higher tensile strength and higher strain at failure.

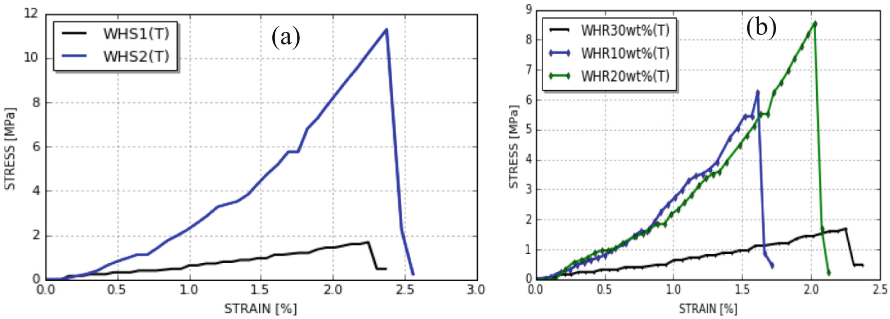

Fig. 3. Stress-strain distributions as functions of effects of (a) cutting size (WHS1(T) vs. WHS2(T)), and (b) fiber content (WHR30wt %(T), WHR20wt %(T) and WHR10wt %(T))

Table 4. Tensile test results of treated and untreated fiber reinforced polyester composites

Specimen	Peak load (kN)	Max. deformation (mm)	Max tensile strength (MPa)
WHUT(T)	0.21	5.92	1.68
WHT20%(T)	0.55	6.28	4.4
WHT10%(T)	0.45	5.08	3.6

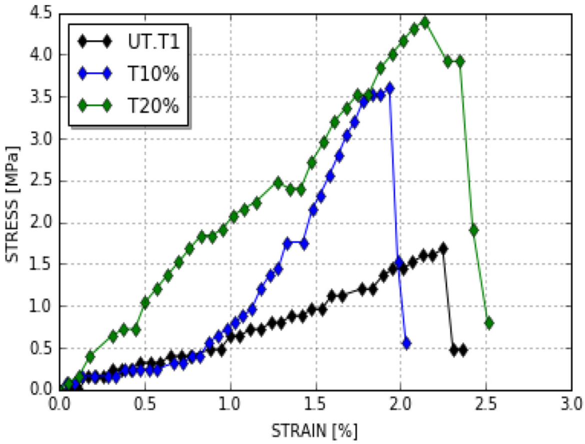

Fig. 4. Stress-strain distributions as functions of effects of alkali treatment

3.3 Flexural Test (3-point Bending Test)

Flexural strength is defined as a material's ability to resist deformation under load. The test is commonly conducted by a 3-point bend test, which generally promotes failure by inter-laminar shear. For this case, the test was conducted on 5 different test groups using 5 test specimens each. The test groups are designated as follows:

1. WHR30wt%(B): Water hyacinth fiber reinforced polyester composite with fiber/matrix ratio of 30/70,
2. WHR20wt%(B): Water hyacinth fiber reinforced polyester composite with fiber/matrix ratio of 20/80,
3. WHR10wt%(B): Water hyacinth fiber reinforced polyester composite with fiber/matrix ratio of 10/90,
4. WHT20%(B): 20% NaOH treated water hyacinth fiber reinforced polyester composite,
5. WHT10%(B): 10% NaOH treated water hyacinth fiber reinforced polyester composite.

Similar to the tensile test case, the flexural tests were conducted at room temperature of 20 °C. For each test specimen, a cross-sectional area of 125 mm^2 was used.

As the values given in Table 5 show, the maximum force and flexural strength was found in the sample with 20% alkali (NaOH) treated composite (i.e. sample WHR20wt%(B)). The results also indicate that the 20% fiber content among the untreated has highest load carrying capacity and flexural strength among the untreated composites. Furthermore, the 20%NaOH treated composite has 13.33% higher load carrying capacity than the 10%NaOH treated water hyacinth fiber reinforced polyester composite. The results, in general, show that chemical treatment improves the performance of the composite. This agrees with the work of Rokbi et al. [25] who studied the effect of NaOH treatment on natural fibers and identified that the flexural strength of treated composites improves likely due to bonding of the fiber with polyester matrix interaction.

Table 5. Tensile test results of the tested untreated sample groups.

Chemical treatment	Specimen	Max. force (kN)	Flexural strength (MPa)
Untreated	WHR30wt%(B)	70	26.6
	WHR20wt%(B)	340	137.70
	WHR10wt%(B)	270	109.35
Treated	WHT20wt%(B)	150	57.15
	WHT10wt%(B)	130	49.53

3.4 Compression Test

For this test, five different test groups were prepared with 5 test specimens each. The test groups are designated as follows:

1. WHR30wt%(C): Water hyacinth fiber reinforced polyester composite with fiber/matrix ratio of 30/70,
2. WHR20wt%(C): Water hyacinth fiber reinforced polyester composite with fiber/matrix ratio of 20/80,
3. WHR10wt%(C): Water hyacinth fiber reinforced polyester composite with fiber/matrix ratio of 10/90,
4. WHT20%(C): 20% NaOH treated water hyacinth fiber reinforced polyester composite,
5. WHT10%(C): 10% NaOH treated water hyacinth fiber reinforced polyester composite.

In accordance with the recommended standards, the specimens with the dimension of 25 mm × 12 mm × 3.2 mm were used and the tests were conducted at room temperature of 20 °C. Table 6 gives the test results.

Table 6. Compressive strength test results.

Chemical treatment	Sample group	Peak load (kN)	Max. deformation (mm)	Max tensile strength (MPa)
Untreated	WHR30wt%(C)	2.10	0.67	35.0
	WHR20wt%(C)	6.39	1.66	106.50
	WHR10wt%(C)	5.94	2.26	99.00
Alkali treated	WHT20wt%(C)	2.52	1.43	42.00
	WHT10wt%(C)	2.44	2.17	40.67

Comparative stress-strain distribution for the untreated composites showing effect of fiber content on the compressive strength is given in Fig. 5(a). As the plots clearly show, highest compressive strength is obtained for 20% fiber ratio, similar to the previous test results for tensile and flexural tests. In a similar fashion as before, the failure strain decreases with increasing fiber weight percentage.

Furthermore, Fig. 5(b) indicates that alkali treatment has significant effect on the compressive strength of the water hyacinth fiber reinforced polyester composite material compared with the untreated water hyacinth fiber reinforced polyester composite (WHUT(C)). In general, the stress - strain plots indicate nonlinear segments caused by stick-slip behavior at the fiber-matrix interface.

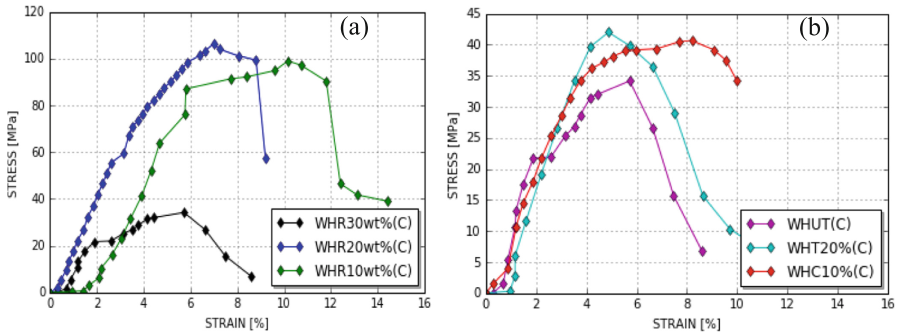

Fig. 5. Stress-strain distributions as functions of effects of (a) fiber content and (b) alkali treatment on compressive strength.

4 Conclusions

This article presented the study conducted on water hyacinth fiber reinforced polyester composite that was successfully extracted from the plant and fabricated. The article focused on limited mechanical properties of the composite which are studied using tensile, flexural and compression tests. Influences of parameters such as fiber cutting size, fiber content and alkali treatment are investigated in each case. The fiber cutting size is observed to improve the results of tensile strength. In general, it has been observed that the fiber content affects the results of tensile strength, compression, and flexural strength. It seems that fiber content of about 20% weight is optimum for all cases considered in the study. In addition, higher alkali (NaOH) treatment improves the mechanical properties because of better interface adhesion between the water hyacinth fiber and the polyester resin.

Future works of this research will focus on characterization of the mechanical properties with respect to different extraction methods, curing time and chemical treatment methods. Further investigations on hardness and impact properties will also be investigated.

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