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Research Article

Influence of *Urena lobata* Fibre Treatment on Mechanical Performance Development in Hybrid *Urena lobata*: Fibre/Gypsum Plaster Composites

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Autogenous shrinkage is related to the chemistry and changes in the internal structure of the cement concrete paste on drying. This problem of drying shrinkage in early stages that occur without any moisture transfer to the surrounding environment has triggered the incorporation of fibres in the cement concrete matrix to fill the micropores and control cracking (autogenous shrinkage). This study aimed at investigating the potential use of *Urena lobata* (UL) fibre as microreinforcement in enhancing mechanical properties of hybrid UL-fibre/gypsum cement composites used for plasters. The fibre was harvested from the coastal region of Cameroon and treated with 0.06 M NaOH over different periods. Dispersion of treated fibre bundles in the composite (at Wt. % UL-fibre dosages of 0, 1.5, 2.5, and 3.5) was facilitated by blending with the cement paste which also helped to improve interfacial bonding between the fibre and the cement matrix. The moisture/water absorption and flexural properties within the hardened cement matrix were quantitatively assessed, and it was observed that the incorporation of treated fibre accelerated the hydration process. The test results showed an increment in compressive strength and reduction in autogenous shrinkage for the hybrid UL fibre/gypsum cement composites, while lower percentage additions (less than 2.5%) of untreated fibre appeared to have adverse effects on specimens. It was observed that properly dispersed (blended) treated UL fibres filled the fine pores in the cement matrix by providing an additional nucleation site that resulted in a denser microstructure, which in turn enhanced the strengths and limited the autogenous shrinkage.

1. Introduction

Gypsum is a naturally occurring mineral with the chemical formula $CaSO_4.2H_2O$, known as calcium sulphate dihydrate. There exist three hydration levels: anhydrate with the chemical formula $CaSO_4$, dihydrate with the chemical formula $CaSO_4.2H_2O$ (gypsum), and hemihydrate with the chemical formula $CaSO_4.1/2H_2O$ (plaster). Gypsum produced from hemihydrates essentially occurs in two forms α-hemihydrates and β-hemihydrates. Their reactivity with water and the strength of the hydration product of these two forms of hemihydrate are different. However, infrared and diffraction studies show no differences in their structures. The brittleness of the hydration product of α-hemihydrates mitigates its uses as a construction material, and hence, β-hemihydrates are widely used. The low density and high porosity of β-hemihydrates contribute to the fire-proofness and acoustic performance, regulating the humidity of walls. Plaster of Paris is mainly composed of β-hemihydrates, has gained great industrial importance, and has prompted several researchers to undertake studies on the hemihydrate of calcium sulphate [1]. Plaster has been used in residential, commercial, and industrial buildings as wall panels, partitions, and boards which have

emerged as unique construction materials due to lightness and easy application. They have favorable formability and excellent appearance, apparently very brittle with low tensile strength and strain capacity. Volume changes in plaster are generally not attributed just to drying of concrete but also to drying shrinkage in early stages that occur without any moisture transfer to the surrounding environment. This volume decrease is termed autogenous shrinkage and is related to the chemistry and changes in the internal structure [2]. Autogenous shrinkage should be controlled as it leads to cracking. In high-strength concrete, low water-binder ratio and inclusion of natural admixture, e.g., silica fume, result in a substantial drop in the internal relative humidity value of the paste specimen during sealed hydration [3]. This volume change in relative humidity is directly related to the autogenous shrinkage, which results in flexural effects due to restraint from the aggregates. Microfibers and nanofibers have been tried with success as means of reinforcement in cementitious composites at the microlevel [4], and yet some cementitious composites have shown flaws at the nanoscale where fibre reinforcement failed [5]. Glass and sisal fibres are best known for their industrial use with plaster. Fibre glass has high mechanical strength (from 2500 to 4600 MPa tensile strength at break [6]) and good resistance to high temperatures but it has drawbacks such as high cost, high density (around 2.5), skin itching, or respiratory irritation at the first time of handling [7]. Sisal, a plant fibre, biodegradable and renewable, has been used to give the plaster reinforcement desired for everyday applications with reduced costs and risks. In view of encouraging the use of an entirely ecological plaster composite, a necessary diversification of the nature of the vegetable reinforcement is required so as to ensure high availability or easy accessibility to reduce or even cancel the cost of importation of sisal fibre. *Urena lobata* (UL) is a possible source of natural fibres for use in reinforcement of plasters. *Urena lobata* is an annual shrub or perennial growing in various ecological habitats. The annual shrub varies in its physical profile; adventitious forms are low, spreading and branched, reaching 0.5 to 2.5 m high, while cultivated forms are erect, weakly branched, and reaching 5 m high. Fresh stalks of UL produce 3 to 7% of Russian Liberian fibres. They are thin, supple, flexible and lustrous, and creamy white or pale yellow. They resemble jute more than other jute substitutes, such as Kenaf (*Hibiscus cannabinus L.*) and Roselle (*Hibiscus sabdariffa L.*). They can be spun on machines for jute without any adjustment. The cells of the Liberian fibres are 0.8 to 9 mm long, with a diameter of 9 to 34 μm. A preliminarily study of UL fibres in our laboratory indicated that the fibres were on averaged 2.5 mm long and 21.6 μm wide, with a lumen width of 10.9 μm. Fibre composition data indicate a large variation in cellulose (63 to 87%) and lignin (7 to 12%) content. Fibre strands from wild plants are generally only about 1 m long, compared to about 2 m long on average for fibre strands from cultivated plants. The morphology of the fibre indicates the presence of silica, lignin, and hemicellulose, whose presence is greatly affected by chemical treatment methods. Therefore, prior to vulgarization of the use of UL fibre for plaster reinforcement, it was necessary to establish the best method of treatment and the physical and mechanical properties of the fibres produced. The reinforcing efficiency of the natural fibre is related to the nature of cellulose and presence of lignin, as well as silica. The main components of natural fibres are cellulose (α-cellulose), hemicelluloses, lignin, pectins, and waxes. The degree of polymerization (DP) is around 10000. Each repeating unit contains three hydroxyl groups whose ability to form hydrogen bond plays a major role in directing the crystalline packing and also govern the physical properties of cellulose. The crystal nature (monoclinic sphenodic) of naturally occurring cellulose is known as cellulose 1. Cellulose is resistant to strong alkali (17.5 wt %) but easily hydrolyzed by acid to water soluble sugars. Cellulose is relatively resistant to oxidizing agents. Hemicellulose forms the supportive matrix of cellulose microfibrils whereas hemicellulose is very hydrophilic, soluble in alkali, and easily hydrolyzed in acids [8]. Lignin is a complex hydrocarbon polymer with both aliphatic and aromatic constituents. They are insoluble in most solvents and cannot be broken down to monomeric units. Lignin is totally amorphous and hydrophobic in nature, and it is the compound that gives rigidity to the plants. Lignin has been found to contain five hydroxyls and five methoxy groups per building unit. Pectin is a collective name for heteropolysaccharides. They provide flexibility to plans. Waxes make up the last part of fibres, and they consist of different types of alcohols [9]. Savastano et al. [10] presented the results of experimental studies of resistance-curve behaviour and fatigue crack growth in cementitious matrices reinforced with natural fibres such as sisal, banana, and bleached eucalyptus pulp. Fatigue crack growth was observed to occur in three stages: an initial decelerated growth, a steady-state growth, and a final catastrophic crack growth. In the case of the composites reinforced with sisal and banana fibres, most of fatigue life was spent in the second stage of steady-state crack growth. The results showed that fatigue crack growth in the composites occurred via matrix cracking, crack deflection around fibres, and crack bridging by uncracked fibres and ligaments, whilst fibre pullout was also observed. The fatigue performance of sisal/epoxy composites was also studied by Towo and Ansell [11, 12], and they looked into the effect of surface modification on the fatigue performance of the composite. The results showed that a NaOH surface treatment has a significant effect on the tensile modulus and strength of the material, but the fatigue life is not highly influenced, especially in low stress levels. Their conclusion states that the behaviour of sisal fibre composites is similar to that of conventional synthetic fibre composites and static and fatigue strengths are suitably high for many commercial applications.

2. Materials and Methods

2.1. Materials. 0.06 M solution of sodium hydroxide (caustic soda), plastic hand gloves, bark from the stems of UL plant removed manually using a tool knife, and all other ordinary

laboratory equipment such as simple thermometers and glass wares were used.

2.2. Methods

2.2.1. Methods of Extracting UL Fibres. Two fibre extraction methods were used, namely, direct and indirect extraction methods. The direct extraction method made use of neither instruments nor chemicals, while the indirect extraction method made use of instruments such as machines and chemicals.

In the direct (retting) method of extraction, bark from the stems of UL plant removed manually using a tool knife was immersed in running water for three weeks, while the constituents (matrix) of the bark degraded leaving the fibres which was hand washed to eliminate the waste. The fibres extracted were smooth, clean, and could be identified as fibres. On the contrary, in the indirect method of extracting, bark from the stems of UL plant removed manually using a tool knife were immersed in a 0.06 M sodium hydroxide solution at room temperature and boiled at 100°C for 20 mins [13]. The fibres obtained were washed under running water to eliminate waste, and the resulting fibres were dewaxed and preserved for characterization.

2.2.2. Determination of Lignin, Holocellulose, Hemicellulose, and Cellulose. Lignin was determined according to the Klaxon method. The fibres were dried at 105°C and treated with 72% by weight sulphuric acid (H_2SO_4) in the ratio of 1 g fibre per 15 ml of solution with frequent stirring using a glass rod at a temperature of 4°C in a refrigerator over a period of 5 min (when the sample completely soaks in the acid). The samples were hydrolyzed for 2 h at room temperature, while stirring every 5 min to ensure complete mixing and wetting. The residue was transferred into a 1000 ml flask and diluted to a 3% acid concentration with 560 ml of distilled water. This was placed on a heating mantle, attached to a reflux condenser and allowed to heat for 4 h. Finally, the hydrolysis solution was removed, filtered through a sintered glass, and washed thoroughly with hot distilled water, and the residue was collected dried and weighted [14].

To determine the holocellulose content, the fibres were heat treated at 90–95°C for 90 min with 0.7% $NaClO_2$ solution buffered at a pH value of 4, while maintaining the fibre liquor ratio at 1 : 50. Finally, 2% sodium metabisulphite solution was added to the fibres and allowed for 15 min (to reduce the chlorite action), washed thoroughly with distilled water, and dried in an oven for 2 h and weighed. The fibres treated with sodium chlorite are called chlorite holocellulose or bleached fibres [14].

The dried chlorite holocellulose was treated in 24% KOH solution for 4 h, while occasionally stirring in the liquor (ratio of 1 : 100). By this treatment, hemicellulose goes into the solution, and the cellulose separated by filtration is washed thoroughly with 2% acetic acid solution and then with distilled water. The product was dried, and the amount by weight of cellulose is the weight difference between the holocelluloses and hemicelluloseas [14].

2.2.3. Physical Treatment of UL Fibres. The physical parameters (density, length, and diameter) of the fibre were measured and recorded.

(1) Moisture Absorption Rate of the Fibres. The samples were dried in an oven at a temperature of 75°C ± 5°C for two hours. Five different samples of mass 0.5 g were taken in each case (for 2 hrs, 4 hrs, 7 hrs, and 11 hrs), and this was done to reduce the error margins. The procedure consisted of putting already weighed samples in a perforated plastic basket with salty water beneath it in a separate vessel, while ensuring that the two were not in physical contact. The unit was placed in a moisture-proof enclosed system, so as to avoid air (which contains water molecules) from getting in contact with samples. Specimens were taken out of the enclosed system and weighed to the nearest 0.001 g within 1 min of removal time. The moisture absorption rate of each specimen was calculated by the weight differently.

2.2.4. Preparation of Specimen Composites. Each batch of mixture gave twelve blocks of the composite material. Seven batches were produced with different percentages' ratio of fibre plasters which gave 84 blocks of composites for flexural tests. Two different methods of mixing were evaluated (the plaster-fibres' bundle and the plaster/defibrillated fibres), and in each case, the molds were lubricated for easy demolding of the samples.

(a) Mixing

The total mixing proportion percent of the sample formulation is shown on Table 1.

(b) Plaster/fibre bundles' mixture

In order to attain maximum compaction of the beams for maximum strength, the samples were mixed for seven minutes immediately from the moment water was poured into the mold. Stirring was done for five minutes to ensure homogeneity in the mixture. After the seventh minute, the composites were viscous for pouring into the mold, and after 48 hours, demolding was done, while samples were identified following the wt. % fibre dosage in the hybrid composite.

(c) Plaster/defibrillated fibre bundles' mixture

In this method, the fibres were mixed with plaster (1.5% and 2.5% of fibres) and blended using a mechanical grinding machine. This mixture was further mixed with water and molded. 48 hours later, demolding was done following the same process, while samples were identified following the wt. % fibre dosage in the hybrid composite.

2.2.5. Flexural Characterization of Hybrid Fibre/Gypsum Composites. A three-point bend test was conducted on all the composite samples with the help of a flexural machine (RMU serial 1461288), and the loading arrangement is shown in Figure 1. An increasing axial load was applied by the specimen until failure occurred to obtain the maximum

Table 1: Sample formulation.

Architecture	*A* Random		*B* Random		*C* Random		*D* Random	
Fibres	%	*M* (g)	%	*M* (g)	%	*M* (g)	%	*M* (g)
	1.5	6	2.5	10	3.5	14	0	0
Plaster	98.5	394	97.5	390	96.5	386	100	400
Total	100.0	400	100.0	400	100.0	400	100.0	400

flexural load. The specimen dimensions and weights were taken before the testing.

Specimens were tested for flexural strength by applying increasing axial load (continuous axial load). The specimen was placed between two supports (fixed) and the third mobile force in the middle until failure occurred and the maximum load and extension for failure was recorded. The calculation of the modulus of elasticity (E), flexural strength, shear strength, specific modulus, and specific strength was obtained using the formulae stated on equation (3). The modulus of elasticity gives us the resistance of the composites beam, while the specific modulus is the elastic modulus per mass density of a material. It is also known as the stiffness to weight ratio or specific stiffness. The flexural strength of a composite is the maximum tensile stress that it can withstand during bending before reaching the 63 breaking point. The test was repeated ten times for each composite type and the mean value reported.

From the 3-point bending test,

$$\begin{aligned} \text{Modulus} &= \frac{F_{\text{max.}}}{46\Delta L \cdot l} L^3, \\ E &= \frac{\Delta}{\mathscr{E}}, \\ \text{Flexural strain, } \mathscr{E} &= \frac{6h\Delta L}{L^2}, \\ \text{Flexural stress, } \Delta &= \frac{3FL}{2bh^2}. \end{aligned} \tag{1}$$

For a rectangular cross-section where L is the span length of the sample (mm),

$$\text{Specific stress} = \frac{\text{stress}}{\text{density}}. \tag{2}$$

The data recorded during the three point bend test is used to evaluate the shear strength also.

The shear strength values are calculated as follows:

$$\text{Shear strength} = \frac{3F}{2bha^4}, \tag{3}$$

where $F_{\max}$: maximum load (N), l: distance between the two supports (mm), E: modulus of elasticity (MPa), I: moment of inertia (mm^4), Δl: maximum deflection (mm), σ_f: flexural strength, b: the width of the specimen (mm), and h: the thickness of the specimen (mm).

2.2.6. Water Absorption of Our Composite. The determination of water absorption (WA) was performed on five different samples in each case to reduce the error margins. The water absorption tests were conducted by immersing the specimens in a water bath at room temperature for different durations. The specimens were reweighed within a period of one minute following removal from water. These specimens were weighed regularly, and the water absorption percent is calculated in the following equation:

$$\text{Water absorption\%} = \frac{(\text{weight of we sample} - \text{weight of dry sample}) \times 100}{\text{weight of wet sample}}. \tag{4}$$

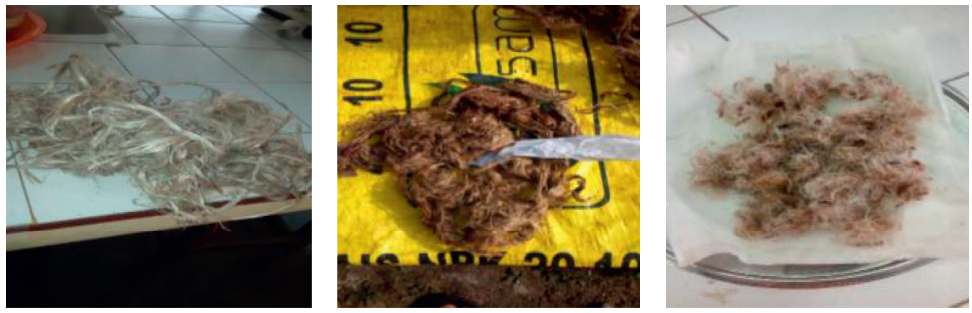
The water absorption rate of each specimen was calculated by the weight difference.

3. Result and Discussion

3.1. Physical Characteristics of the Fibres. The fibre obtained from the two methods, as shown in Figure 2, was physically different in colour, length, and diameter. Fibre length was measured to learn about the strength, evenness, and appearance. The fibre length range varied in different sizes, which were obtained during the fibre extraction, and few of the fibre bundles were broken during extraction process. The fibre obtained by the retting method was white in colour and 1 m long, while that obtained from the chemical method (using sodium hydroxide) was brown in colour and 60 cm in length. These results show that the length of the single fibre is equal to the length of the sheath [15]. The fibre diameter was measured to know the uniformity of width. The average fibre diameter was 0.22 mm and 0.15 mm for fibres obtained by the retting method and chemical method (using sodium hydroxide), respectively. All the fibre bundles were found to be equal in diameter revealing uniformity in the fibres' width which indicate quality and flexibility [16]. These results indicated that chemical treatment, especially using sodium hydroxide, leads to fibrillation which causes the breaking down of the composite

(a) (b) (c)

Figure 1: Face views of the flexural test machine. (a) Face view. (b) Side view. (c) Loading arrangement.



(a) (b) (c)

Figure 2: Fibres obtained from (a) washing, (b) treatment with caustic soda, and (c) dewaxed fibres.

fibre bundle into smaller fibres. Mercerization reduces fibre diameter, thereby increasing the aspect ratio which leads to the development of a rough surface topography that results in better fibre matrix interface adhesion and an increase in mechanical properties [17]. Moreover, mercerization increases the number of possible reactive sites and allows better fibre wetting. Mercerization has an effect on the chemical composition of the flax fibres, degree of polymerization, and molecular orientation of the cellulose crystallites due to the loss of cementing substances such as lignin and hemicellulose which were removed during the mercerization process.

$$\text{Fiber} - \text{OH} + \text{NaOH} - \text{Fiber} - \text{O}^{-}\text{Na}^{+} + \text{H}_2\text{O}. \quad (5)$$

The dewaxed fibre shown in Figure 2(c) represents 91.54% of the fibres recovered, while 8.46 percent was lost during the dewaxing process as wax. The percentages by composition of cellulose, hemicellulose, and lignin shown in Table 2 are comparable to the compositions of these components in other plant fibres. The high percentage of cellulose in UL 73.2 is even higher than that in sisal fibres that has been in use for the reinforcement of gypsum plaster composites.

3.2. Water and Moisture Absorption Rate. The water absorption rates for the treated and untreated fibres are shown in Table 3, and the graph for the water absorption rate, presented in Figure 3, indicate that chemical treatment influences the rate at which the fibres absorb water (all the treated fibres absorb less water relative to the untreated fibres). This observation is attributed to the removal of lignin and hemicellulose; when the content of either hemicelluloses or lignin is reduced progressively by chemical treatment, the capillary properties of hemp fibres are improved, i.e., capillary rise height of modified fibres is increased up to 2.7 times in relation to unmodified fibres. Furthermore, hemicelluloses' removal increases the moisture absorption and decreases the water retention values of hemp fibres, while lignin removal decreases the moisture absorption and increases the water retention ability of hemp fibres [18]. Thus, the longer the fibre is treated with the chemical, the greater the effect and the lesser the fibre water absorption rate.

3.2.1. Moisture and Water Absorption for Physically Treated Fibres. The physical test on the fibres obtained through the direct method represented in Figure 4 and Table 3 showed that the fibres treated (by heating and wetting) for 11 hours had less rate of water absorption which was 37.13% opposed to 2 hours (63.38%), 4 hours (61.73%), and 7 hours (60.66%) duration of treatment. Similar result was obtained for moisture absorption in which the fibres treated (by heating and wetting) for 11 hours had less rate of moisture absorption which was 9.52% opposed to the 2 hours (30.55%), 4 hours (26.63%), and 7 hours (24.82%) duration of treatment. The water and moisture absorption rates of the

Table 2: Chemical composition of the UL fibre compared with fibres from other sources.

	Cotton	Jute	Lin	Ramie	Sisal	UL
			[47; 48]			
Cellulose	82.7	64.4	64.1	68.6	65.8	73.2
Hemicellulose	5.7	12.0	16.2	13.1	12.0	10.6
Lignin	—	11.8	2.0	0.6	9.9	16.2

Table 3: Water and moisture absorption rates for the treated and untreated fibres.

Time (hrs.)	Average water A R	Standard deviation	% improvement of relative water absorption	Moisture A R	Standard deviation	% improvement of relative water absorption
UT	76.47	0.22	0	49.56	2.59	0
2	63.32	0.26	17.12	30.55	3.25	38.31
4	61.73	0.54	19.28	26.63	3.09	46.27
7	60.66	0.22	20.68	24.82	4.07	49.92
11	37.13	9.44	51.45	9.42	1.81	80.79

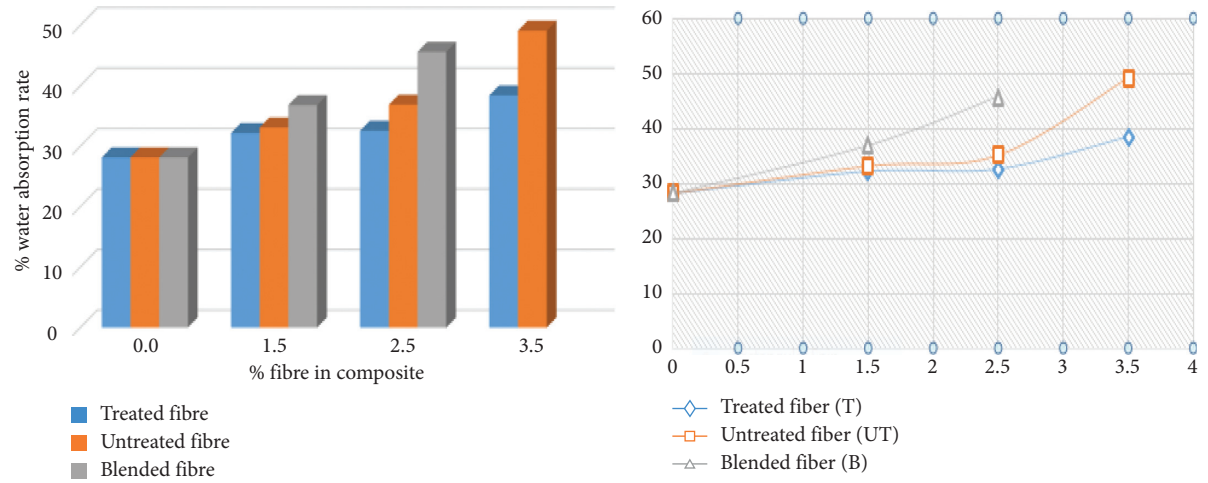


Figure 3: Water absorption rate of the reinforced hybrid fibre/gypsum plaster composite at different wt. % fibre dosages.

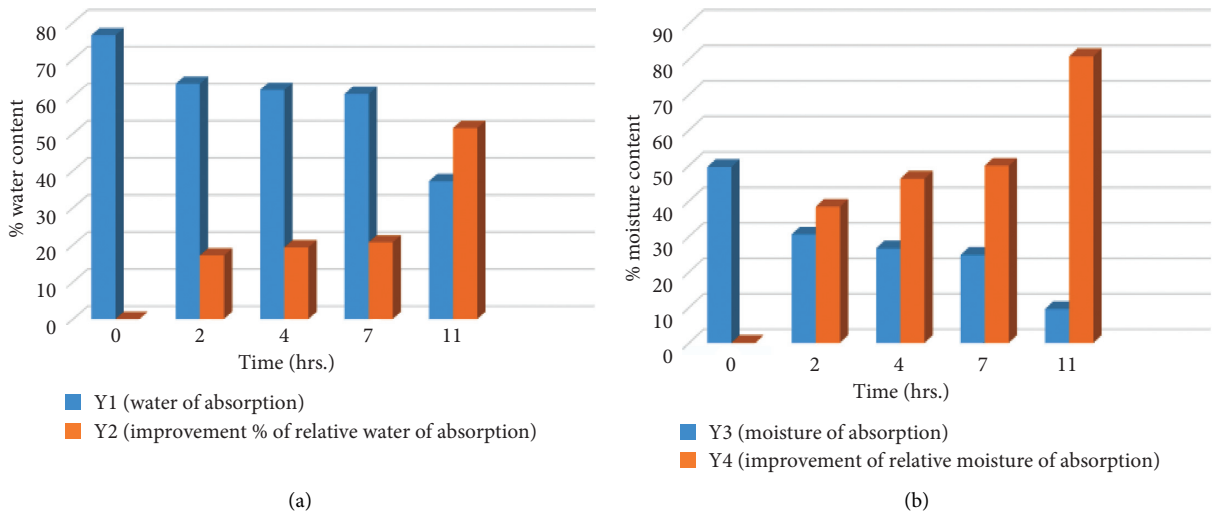


Figure 4: (a) Water absorption/% improvement (water) absorption rates for the treated fibres as a function of treatment length of time. (b) Moisture absorption/% improvement (moisture) absorption rates for the treated fibres as a function of treatment length of time.

untreated fibres were found to be 76.47% and 49.56%. These results show that prolonged treatment of fibre by heating and wetting reduces the rate of water absorption.

3.3. Water Absorption Rate of the Reinforced Hybrid Fibre/Gypsum Plaster Composite. Figure 3 shows internal relative water absorption rate values for all specimens at varying wt. % fibre dosages. The specimen with the blended fibres showed the highest water absorption rate with evaluated wt. % fibre dosage approximately 61.9% and 23.5% greater (at 2.5% and 1.5% fibre dosages, respectively) in the water absorption rate compared to the reference specimen (plaster composites). The specimen with untreated fibre at 2.5 wt. % fibre dosage showed 25.6% greater increase in the water absorption rate of the reinforced hybrid fibre/gypsum plaster composite compared to the reference specimen, while the specimen with 3.5% and 1.5% fibre dosages of untreated fibre showed 74.5% and 17.5% water absorption rate compared to the reference one. Greater increase compared to the reference specimen indicated that smaller additions result in greater hydration rate of plaster. In the case of blended fibre, the individually dispersed fibres had decreased the number of fine pores in the specimen, which resulted in a reduction of capillary stresses and ultimately lower autogenous shrinkage. Pretreatments of the fibres with 0.06 M NaOH can clean the fibre surface, chemically modify the surface and stop the moisture absorption process, and increase the surface roughness [19]. However, specimens with treated and untreated fibres produced a relatively lesser increase in the water absorption rate to that of the blended fibres which could be attributed to the smaller internal pore structure in the paste and the relative inability of treated and untreated fibres to fill the fine pores due to agglomerates and bundles of fibres resulting from poor dispersion. Indeed, according to the Kelvin equation, small pore sizes reduce radii of the water meniscus resulting in quick decrease of the internal relative humidity, which ultimately induces stress and enlarge shrinkage.

3.4. Flexural Characterization

3.4.1. Rupture Stress for Reinforced Hybrid Fibre/Gypsum Plaster Composites. The addition of UL fibre has affected the rupture stress of composite paste specimens. The values were measured with increased dosage in wt. % of treated, untreated, and blended fibre bundles.

The addition of UL fibre has affected the rupture stress of composite paste specimens. The values were measured with increased dosage in wt. % of treated, untreated, and blended fibre bundles. Figure 5 shows rupture stress for hybrid fibre/gypsum composites reinforced at varying amounts of fibre (by wt. % of binder) for the different treatment. The maximum rupture stress was achieved in samples with blended fibre. The specimens had 48.7% and 71.5% higher rupture stress than the reference specimens at 1.5% and 2.5% dosages, respectively. Also, the other specimens at relatively higher dosages showed higher rupture stress as compared to the reference specimens. The specimens from untreated fibre showed a 4.5% and 40.1% higher rupture stress than the reference specimens at dosages of 2.5% and 3.5%, respectively, and also, at dosage 3.5%, the specimens from the treated fibre showed a rupture stress of 6.0% greater than the reference specimen. The plausible reason for this effect is that the blended fibre bundles were more uniformly dispersed in the plaster paste so that the individual fibres acted as pores, filled the pore space between the gypsum grains with hydration phases, and reduced the capillary porosity. The reduction in porosity leads to a denser microstructure than that of the reference mix. Due to their small size, fibres provide very large reactive surface areas that can provide additional nucleation site. The homogeneous distribution of fibre results in fewer mesopores than that of the control mix. The interfacial bond between the hydration product and fibre depends on the surface energies of fibre and hydrated product. The size effect of fibrillates increases the interface between fibres and the hydrated matrix, and this was improved by bridging effect and well dispersed fibre which improved the reinforcement in the specimen. Good adhesion at the interface means that the full capabilities of the composite can be exploited and leaves it resistant to environmental attacks that may weaken it, thus increasing its life span. Sufficient adhesion between the polymer and the fibres results in good mechanical properties of the natural fibre-reinforced polymer composites. The decrease in rupture stress for the 1.5% dosage fibres in specimens from treated and untreated fibre bundles can be related to the inadequate dispersion as well as presence of agglomerates and bundles of fibres around plaster grains hindering the formation of the hydration product resulting in a weak bond. Also, fibrillates may not be wetted adequately thus causing pullout resulting in the formation of cracks. However, these results improve as the wt. % fibre dosage of the treated fibre increases in the hybrid composite, and similar results have been reported with carbon nanotubes [20]. The overall properties of the fibres depend on the individual properties of each of its components. Hemicellulose is responsible for the biodegradation, moisture absorption, and thermal degradation of the fibre. On the contrary, lignin (or pectin) is thermally stable but is responsible for UV degradation of the fibre. On average, natural fibres contain 60–80% cellulose, 5–20% lignin (or pectin), and up to 20% moisture. Therefore, removal of lignin and hemicellulose improves the performance of the fibre in the composite. On a composite, the properties of the fibres are combined with those of the matrix, which is responsible to transfer the external loads to the stiff fibres through shear stresses at the interface as well as keep the fibres together in a specific structural form. Thus, the properties of the composite are a combination of the properties of the ingredients.

The addition of the UL fibre has affected both the modulus of elasticity and deflection of composite paste specimens. Figure 6 shows the modulus of elasticity of hybrid fibre/gypsum plaster composites reinforced with varying amounts of fibre (by wt. of binder) for different treatments, while Figure 7 shows deflection of the reinforced hybrid fibre/gypsum plaster composite at different wt. % fibre dosages for different treatments. The values

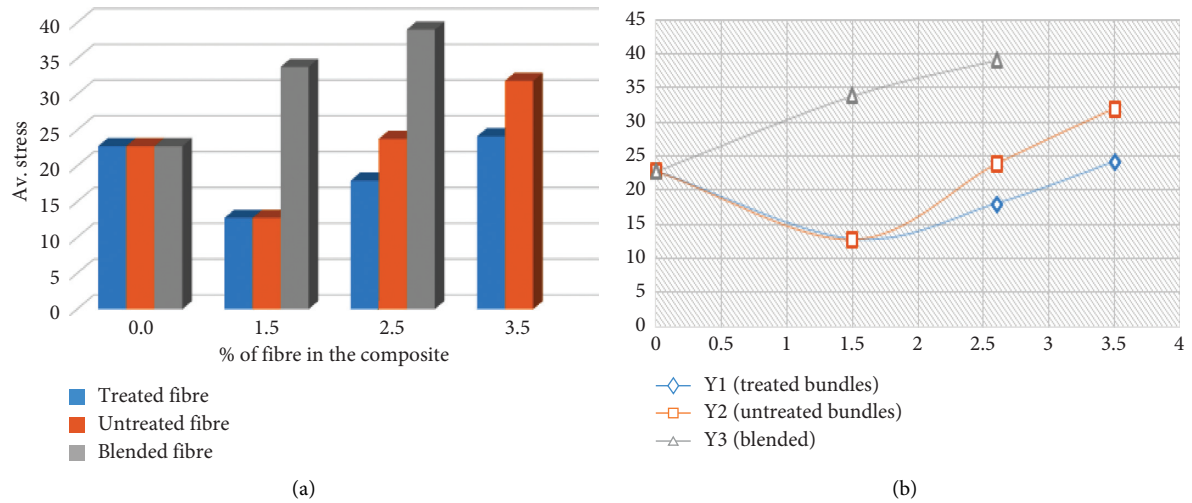


Figure 5: Rupture stress of the reinforced hybrid fibre/gypsum plaster composite at different wt. % fibre dosages.

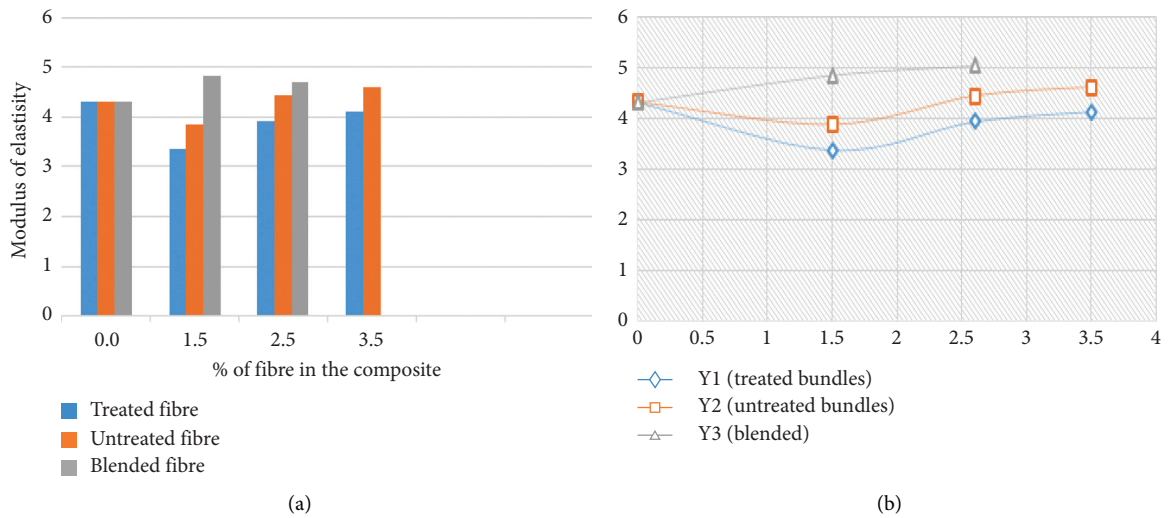


Figure 6: Modulus of elasticity of the reinforced hybrid fibre/gypsum plaster composite at different wt. % fibre dosages for different treatments.

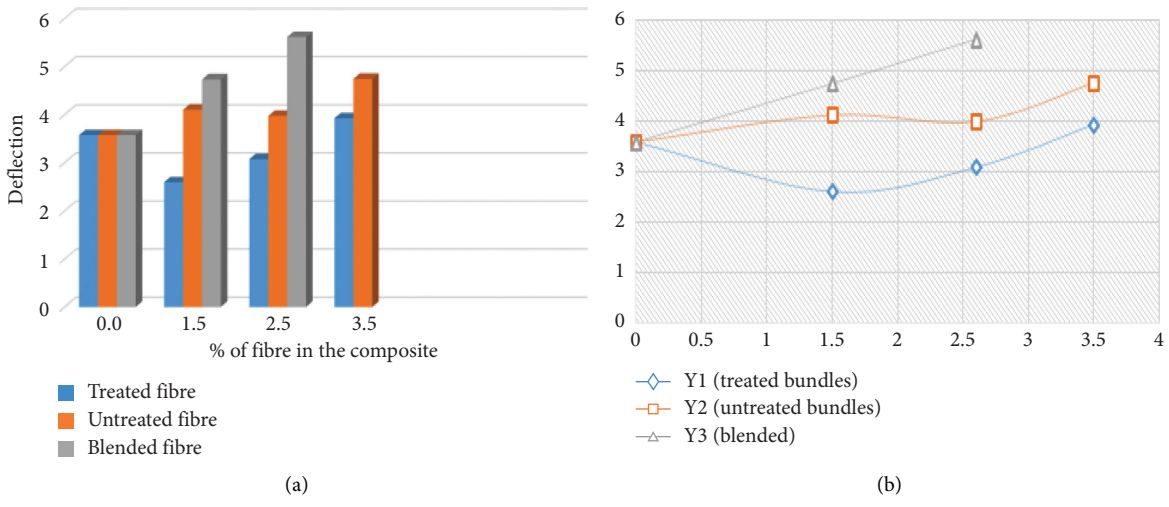


Figure 7: Deflection of the reinforced hybrid fibre/gypsum plaster composite at different wt. % fibre dosages for different treatments.

were measured with increased dosage in wt. % of treated, untreated, and blended fibre bundles. The maximum modulus of elasticity and deflection were achieved in samples with the blended fibre. The specimens had 12.6% and 17.2% higher modulus of elasticity than that of reference specimens at 1.5% and 2.5% wt. % fibre dosages, respectively.

Also, the untreated specimens at relatively higher dosages showed higher modulus of elasticity and deflection compared to the reference specimens. The specimens from the untreated fibre showed a 2.5% and 6.9% higher modulus of elasticity than the reference specimens at wt. % fibre dosages of 2.5% and 3.5%, respectively. The blended fibre bundles were more uniformly dispersed in the plaster paste so that the individual fibres might act as pores and fill the pore space between the gypsum grains with hydration phases and reduce the capillary porosity. Furthermore, the reduction in fibre size effect caused by mercerization increases the aspect ratio and consequently enhances the fibre matrix interface adhesion resulting in better mechanical properties.

4. Conclusion

The effect of the water to the properties is highly influenced by the fibre content, matrix, and mainly the temperature. Increase in the fibre weight fraction in the composite produced an increase in the rupture stress, elastic modulus, deflection, and tensile strength, and similar results were reported in literature [21]. However, the elastic modulus of the composites increases with the increase of the volume fraction, but only up to a certain level. The results also showed that (as in glass fibre composites) the impact strength increases with increasing fibre length. Literature reports [22] showed that this increase continued until a plateau level is reached. After that level, the impact performance drops depending on the pretreatment of the fibres and the adhesion of the fibre/matrix interface. In effect, a NaOH surface treatment has a significant effect on the elastic modulus and strength of the material, but the fatigue life is not highly influenced, especially in low stress levels, and the behaviour of UL fibre composites generated from the NaOH pretreated fibre is similar to that of sisal fibre composites which have static and fatigue strengths suitably high for many commercial applications. Thus, UL fibres have demonstrated high mechanical and thermal properties which offer them the ability to prevent cracks' growth (autogenous shrinkage) at the microscale. The mechanical properties of the hybrid fibre/gypsum plaster composite are enhanced by the blended NaOH pretreated fibre. This process is cost effective, eases manufacture, and generates performant products with the desired product geometry.

Data Availability

The data used to support the findings of the study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

References

[1] M. Sophia, N. Sakthieswaran, and O. Ganesh Babu, "Gypsum as a construction material- a review of recent developments," *International Journal for Innovative Research in Science & Technology*, vol. 2, no. 12, pp. 2349–6010, 2016.

[2] H. Justnes, E. Sellevold, B. Reyniers et al., "The influence of cement characteristics on chemical shrinkage," *Autogenous Shrinkage of Concrete*, pp. 71–80, E&FN Spon, London, UK, 1999.

[3] M. Jensen and P. F. Hansen, "Autogenous deformation and change of the relative humidity in silica fume-modified cement paste," *ACI Materials Journal*, vol. 93, pp. 539–543, 1996.

[4] G. Fischer and V. C. Li, "Effect of fiber reinforcement on the response of structural members," *Engineering Fracture Mechanics*, vol. 74, no. 1-2, pp. 258–272, 2007.

[5] M. S. Konsta-Gdoutos, Z. S. Metaxa, and S. P. Shah, "Multi-scale mechanical and fracture characteristics and early-age strain capacity of high performance carbon nanotube/cement nanocomposites," *Cement and Concrete Composites*, vol. 32, no. 2, pp. 110–115, 2010.

[6] M. Singh, C. L. Verma, M. Garg, S. K. Handa, and K. Rakesh, "Studies on sisal fiber reinforced gypsum binder for substitution of wood," *Research and Industry*, vol. 39, pp. 55–59, 1994.

[7] M. Karina, H. Onggo, and A. Syampurwadi, "Physical and mechanical properties of natural fibers filled polypropylene composites and its recycle," *Journal of Biological Sciences*, vol. 7, no. 2, pp. 393–396, 2008.

[8] J. J. Maya and D. A. Rajesh, "Recent developments in chemical modification and characterization of natural fiber- reinforced composites," *Polymer Composites*, vol. 29, no. 2, pp. 187–207, 2008.

[9] S. Hattalli, A. Benaboura, F. Ham-Pichavant, A. Nourmamode, and A. Castellan, "Adding value to Alfa grass (*Stipa tenacissima* L.) soda lignin as phenolic resins 1. Lignin characterization," *Polymer Degradation and Stability*, vol. 76, no. 2, pp. 259–264, 2002.

[10] H. Savastano Jr., S. F. Santos, M. Radonjic, and W. O. Soboyejo, "Fracture and fatigue of natural fiber-reinforced cementitious composites," *Cement and Concrete Composites*, vol. 31, no. 4, pp. 232–243, 2009.

[11] A. N. Towo and M. P. Ansell, "Fatigue of sisal fibre reinforced composites: constant-life diagrams and hysteresis loop capture," *Composites Science and Technology*, vol. 68, no. 3-4, pp. 915–924, 2008.

[12] A. N. Towo and M. P. Ansell, "Fatigue evaluation and dynamic mechanical thermal analysis of sisal fibre-thermosetting resin composites," *Composites Science and Technology*, vol. 68, no. 3-4, pp. 925–932, 2008.

[13] S. Kalia, A. Dufresne, B. M. Cherian et al., "Cellulose-Based bio- and nanocomposites: a review," *International Journal of Polymer Science*, vol. 2011, Article ID 837875, 35 pages, 2011.

[14] B. Victorine Namondo, J. Foba-Tendo, E. Peter Etape, and R. W. Maçedo Krause, "Potential of blended biomass feedstock from some species of raffia palm (*Raffia farinifera*, *Raffia hookeri* and *Raffia vinifera*) and oil palm empty fruit bunch (OPEFB) from Cameroon," *African Journal of Pure and Applied Chemistry*, vol. 12, no. 4, pp. 25–33, 2018.

[15] W. E. Morton and J. W. S. Hearle, *Physical Properties of Textile Fibres*, Butterworth and Company, London, UK, 1975.

[16] S. Msahli, F. Sakli, and J.-Y. Drean, "Study of textile potential of fibres extracted from Tunisian *Agave americana* L." *AUTEX Research Journal*, vol. 6, no. 1, pp. 9–13, 2006.

[17] K. Joseph, L. H. C. Mattoso, R. D. Toledo et al., "Natural fiber reinforced thermoplastic composites," in *Natural Polymers and Agrofibers Composites*, E. Frollini, A. L. Leao, and L. H. C. Mattoso, Eds., pp. 159–201, Embrapa, San Carlos, CA, USA, 2000.

[18] B. M. Pejic, M. M. Kostic, P. D. Skundric, and J. Z. Praskalo, "The effects of hemicelluloses and lignin removal on water uptake behavior of hemp fibers," *Bioresource Technology*, vol. 99, no. 15, pp. 7152–7159, 2008.

[19] J. Summerscales, N. Dissanayake, A. Virk, and W. Hall, "A review of bast fibres and their composites. Part 2—composites," *Composites Part A: Applied Science and Manufacturing*, vol. 41, no. 10, pp. 1336–1344, 2010.

[20] G. Y. Li, P. M. Wang, and X. Zhao, "Mechanical behavior and microstructure of cement composites incorporating surface-treated multi-walled carbon nanotubes," *Carbon*, vol. 43, no. 6, pp. 1239–1245, 2005.

[21] H. L. Bos, J. Müssig, and M. J. A. van den Oever, "Mechanical properties of short-flax-fibre reinforced compounds," *Composites Part A: Applied Science and Manufacturing*, vol. 37, no. 10, pp. 1591–1604, 2006.

[22] S. K. Garkhail, R. W. H. Heijenrath, and T. Peijs, "Mechanical properties of natural-fibre-mat-reinforced thermoplastics based on flax fibres and polypropylene," *Applied Composite Materials*, vol. 7, no. 5-6, pp. 351–372, 2000.