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Hybrid Polymer Composites Reinforced with Doum Palm Fibres/Sandglass and their Mechanical Properties

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ABSTRACT

Hybrid fiber-reinforced polymer composites have emerged as a subject of growing interest in both academic and industrial research. This study explored the use of alkali-treated *Hyphaene thebaica* (Doum) fibers and sandglass (mineral silica) as reinforcements within a high-density polyethylene (HDPE) matrix. 5% fiber content was maintained across all formulations, while varying levels of mineral filler were incorporated. The composite materials were fabricated through melt compounding followed by compression molding. Mechanical properties were evaluated according to ASTM standards. Optimal tensile, flexural, compressive, impact, and hardness values achieved were 19.80 MPa, 20.02 MPa, 82.04 MPa, 1.33 J/m², and 43.60 Vickers Hardness (HV), respectively. Except for flexural performance, the hybrid composites demonstrated superior mechanical behavior over neat HDPE. Scanning electron Microscopy (SEM) analysis revealed uniform filler dispersion and enhanced interfacial adhesion in the 90% HDPE / 5% Sandglass SG / 5% Doum palm fibres DF sample. Include the implication of these values, conclusion, and recommendation.

Keywords: *Hyphaene thebaica*, sandglass, composites, hybrid, mechanical

INTRODUCTION

Fillers are usually added to polymer matrices to achieve goals which include; improvements of stiffness, thermal and mechanical properties, material cost reduction among others. Polymers, particularly thermoplastics are extensively used as matrix materials because they are easily process (mouldable), have good mechanical strength and have light weight [1]. Polymer matrix is the continuous phase in which reinforcement materials are embedded and bind together to bring out the strength and shape of materials. Sandglass, which is predominantly made up of silica (SiO_2), is a naturally abundant mineral found widely in the environment. Mineral silica consists of silicon and oxygen atoms which occur in various crystalline forms or polymorphs [2]. Natural silica which is also known as mineral silica, can be prepared by precipitation or

fumed and fused methods [3]. Silica serves as a reinforcing filler in numerous fields, including plastics, ceramics, electronics, and concrete [4]. Mineral silica may be used as reinforcement in a particle form or after ground to powdered form (silica flour). It has attractive features over other mineral fillers such as excellent brightness, inexpensive and thermal stability at high temperatures [5].

Large amount of biomass and agricultural-based by-products are abundant in nature, and considered as potential sources of lignocellulosic materials for many applications in diverse areas such as textiles, construction, automotive and medicinal applications [6]. The attractive properties of natural fibers as reinforcement materials include light weight, biodegradable, reduce tool wear; low-cost which make them suitable in the preparation of composite materials [7].

Previous studies explored how varying amounts of Doum palm fiber affect the mechanical and thermal performance of low density polyethylene (LDPE) - based composites. Enhanced mechanical properties of composite were found at 30wt% fiber loading. However, the thermal properties decreased with increased of added Doum fiber [7]. The mechanical strength of epoxy resin reinforced silica nanoparticle was evaluated [8]. They found that addition of 5% silica improved the stiffness and tenacity of polymer composite [9]. In Nigeria, Doum fibers are abundant in the Northern and Southern regions and serve as a source of income for farmers. In spite of the abundance of Doum fibers, their use as reinforcement was negligible. Therefore, Doum fibers as bio-reinforcement can enhance its economic value.

In spite of the reported potential of natural fibres and silica-based fillers as reinforcement materials, limited studies have investigated their combined effect in a high-density polyethylene matrix. Previous studies have mainly focused on the use of Doum palm fibre in low-density polyethylene composites or the incorporation of silica particles into polymer and glass-fibre systems. These studies have demonstrated improvements in selected mechanical properties; however, the effect of combining mineral micro-silica with alkali-treated *Hyphaene thebaica* fibre in HDPE has not been adequately established. In particular, there is insufficient information on how varying the proportions of micro-silica and treated Doum fibre influence the mechanical performance of the resulting hybrid composites and whether the combined reinforcements can produce a synergistic improvement in properties. This gap is important because the utilization of abundant Doum fibre and locally available silica-containing sand glass could provide a relatively low-cost and sustainable approach to improving the performance of HDPE-based composite materials.

Therefore, the present study seeks to address this gap by investigating the effect of mineral micro-silica and alkali-treated *Hyphaene thebaica* fibre on the mechanical properties of HDPE hybrid composites.

MATERIALS AND METHODS

Materials

The recycled HDPE used as the polymer matrix was obtained from an industry in Batagarawa Local Government Area, Katsina State, Nigeria. The mineral silica was obtained from Babban mutum, Baure Local Government Area, Katsina State. Raw *Hyphaene thebaica* fibre was collected from local field near Kayauki village along Daura road, Katsina State, and NaOH was gotten from a scientific supplies company.

The equipment used for this research are; vacuum oven (Cole and Parme, Chicago Illinois 60648), Jaw crusher (Retsch masch Nr.70992), Ball milling machine (Kera b.v. 057748), Two roll mill (CP 5183 North Bergen U. S. A), Compression molding machine (DT 8679-7585, Wenzhou Zhingang, China), Tensile properties tester (Instron 3366, USA), Flexural strength tester (Universal material testing machine Cat Nr. Model: 26), Impact resistant tester (Charpy impact testing machines Cat. Nr. Model: 412), Hardness testing machine (Vickers Hardness Tester MV1-PC, Mh-v CM. 07/2012-1329) and FTIR (4000-6500 Happ-Genzel).

Doum palm fibre pre-treatment

Initially, the raw Doum fibers were rinsed with clean water to eliminate dirt and impurities. The cleaned fibers were subsequently oven-dried at 60 °C for 48 hours before being ground into smaller particles suitable for further processing.

Alkali treatment

A total of 200 grams of dried fiber was immersed in 500 mL of a 5% (w/v) sodium hydroxide solution. This mixture was maintained at room temperature for 48 hours in a 1000 mL beaker. Following treatment, the fibers were thoroughly washed with distilled water to remove residual alkali and then neutralized using a 1 wt.% acetic acid solution. The neutralized fibers were again dried in an oven at 80 °C for 48 hours [10].

Preparation of composites

Hybrid composites were produced using a combination of melt compounding and compression molding. Recycled HDPE granules, varying proportions of mineral silica (5%, 7.5%, 10%,

12.5%, and 15% by weight), and a constant 5% by weight of alkali-treated Doum fiber were blended. The components were mixed in a two-roll mill for 5 minutes to ensure uniform distribution. The homogenized mixture was then transferred into a steel mold (dimensions: 150 × 120 × 5 mm) coated with a releasing agent. Compression molding was performed at 160 °C under a pressure of 5 N/mm² for 15 minutes. After molding, the composite samples were conditioned in an oven at 70 °C for 48 hours before mechanical testing [11].

Fourier transform infrared (FTIR) analysis

The Fourier Transform Infrared analysis of the samples was carried out using an Agilent Technologies Cary 360 FTIR spectrometer. The samples were analyzed to identify the characteristic functional groups present in the alkali-treated *Hyphaene thebaica* fibre, mineral micro-silica, HDPE and the prepared hybrid composites. The FTIR spectra were recorded over the selected wavenumber range, and the characteristic absorption bands were identified and used to assess changes in the chemical structure of the materials.

Tensile test

Tensile strength testing followed ASTM D638 standards, employing specimens with dimensions of 100 × 10 × 5 mm and a gauge length of 40 mm. Testing was conducted using a TM2101-T7 Tensile Strength Test Machine at a crosshead speed of 2 mm/min with a 100 kN load force.

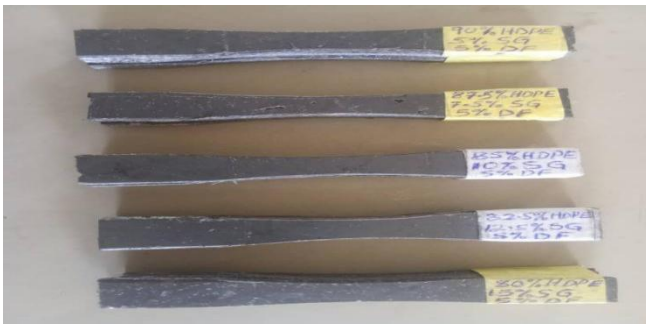


Plate 1: Tensile test samples

Flexural strength test

Three-points bending test was used to study the flexural strength of the composite samples according to ASTM D-790. The flexural tests were done using universal materials testing machine (model; Cat. Nr.261). The test sample dimensions were 100 × 30 × 5 mm (length, width and thickness). The span length was 80 mm apart at a 0.5 mm/min strain rate.

Impact strength test

Impact resistance was evaluated using the ASTM D256 standard with notched specimens. Testing was conducted using a Norwood Charpy Impact Tester (Model 6957) with a capacity of 15 J. Sample dimensions were 100 × 10 × 5 mm.

Compressive strength test

Compressive strength was measured following ASTM D6641 procedures. Tests were carried out on an Electronic Universal Testing Machine (Model WDW-100KN) using samples of dimensions 20 × 20 × 10 mm at a crosshead speed of 2 mm/min.

Hardness test

The hardness test adhered to ASTM D-384 standard using a Vickers hardness testing machine (model MV1-PC) using a diamond indenter. The machine load of 0.3Kgf at 15 seconds was used for each of the sample whose dimension was 30 × 30 × 5 mm (length, width and thickness).

RESULTS AND DISCUSSION

Fourier transform infra-red analysis of *Hyphaene thebaica* fiber

Figure 2 illustrates the FTIR spectra of untreated and alkali-treated *Hyphaene thebaica* fibers. The absorption peak observed at 1028.74524 cm^{-1} corresponds to C–O stretching vibration in cellulose and hemicellulose. Absorption peak at 1237 cm^{-1} indicates C–O stretching in acetyl or aromatic ether groups present in lignin. Absorption peak at 1513 cm^{-1} was assigned to C=C aromatic vibrations in lignin. The medium peak at 1617 cm^{-1} linked to C=O stretching vibrations indicating the presence of carbonyl groups in lignin and is confirmed by the peak at 860 cm^{-1}. The peak at 2899 cm^{-1} indicates C–H stretching vibrations, in cellulose, hemicellulose, and lignin. A broad peak at 3280.05730 cm^{-1} is attributed to O–H stretching vibrations, this confirms the presence of hydroxyl groups in cellulose and lignin. In the alkali-treated sample, the disappearance of the 1735 cm^{-1} peak indicated the removal of hemicellulose, pectin, and surface waxes [12]. Removal of components such as waxes, pectin, hemicellulose, and lignin in the treated fibre enhanced compatibility and mechanical performance is associated with improved fiber-matrix interaction, enhancing composite compatibility and mechanical integrity.

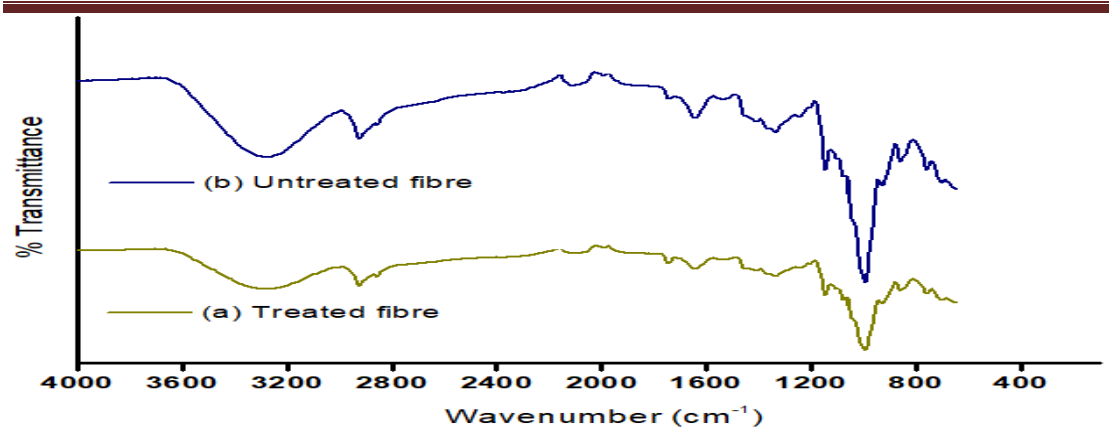


Figure 2: FTIR spectra of (a) NaOH treated fibre and (b) untreated fibre

Tensile strength

As shown in Figure 3, the tensile strength improved significantly with the incorporation of Doum fiber and sandglass, peaking at 19.80 MPa for the 90% HDPE / 5% SG / 5% DF composite. The increase is attributed to effective stress transfer at the fiber-matrix interface and uniform dispersion of reinforcements. However, increasing sandglass content to 15% resulted in diminished tensile strength, likely due to filler agglomeration and reduced bonding efficiency. All reinforced samples outperformed the neat HDPE matrix, indicating enhanced tensile properties through hybridization. These observations are consistent with previous findings [13].

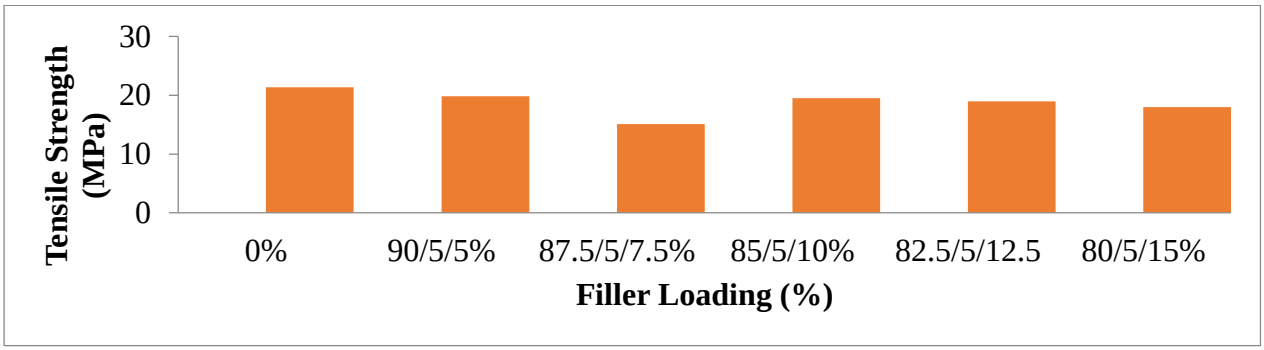


Figure 3: Tensile Strength of *Hyphaene thebaica* Sandglass reinforced high density polyethene hybrid composites

Elongation at break

The elongation at break decreased with higher sandglass content, as shown in Figure 4. The unreinforced HDPE sample had the highest elongation of 19.35%, while the lowest (9.49%) occurred in the composite with 87.5% HDPE / 5% DF / 7.5% SG. This trend is likely due to

increased matrix rigidity and reduced polymer chain mobility caused by filler addition. Reduced ductility with higher filler loadings is consistent with trends observed by Muktari et al [14].

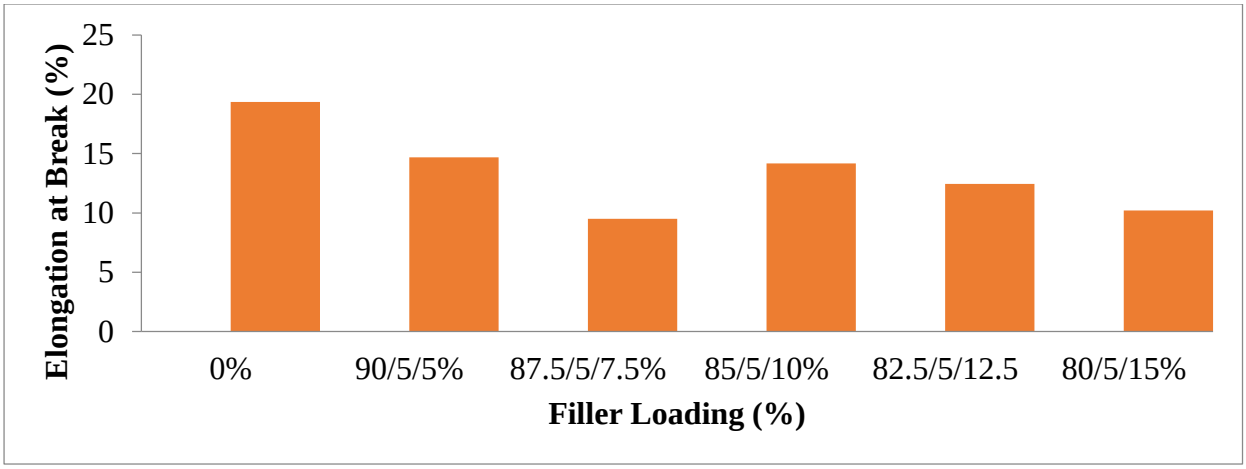


Figure 4: Elongation at break of Doum fibre / Sandglass reinforced High density polyethene Hybrid composites

Tensile modulus

Figure 5 reveals a progressive increase in tensile modulus with rising filler content. It showed an increased with increase filler loading from 0% to 15% sandglass / 5% doum fibre. It was revealed that the tensile modulus of 80% HDPE / 5% DF / 15% SG wt% composites were higher than that of the unfilled polymer (0%). The highest tensile modulus was observed with 80% HDPE / 5% DF / 15% SG wt% loading at 1.759 GPa and the lowest was seen with 0% at 1.103 GPa. The stiffer matrix is ascribed to enhanced rigidity from filler reinforcement. Similar trends in tensile modulus have been reported by Pai and Jagtap [15].

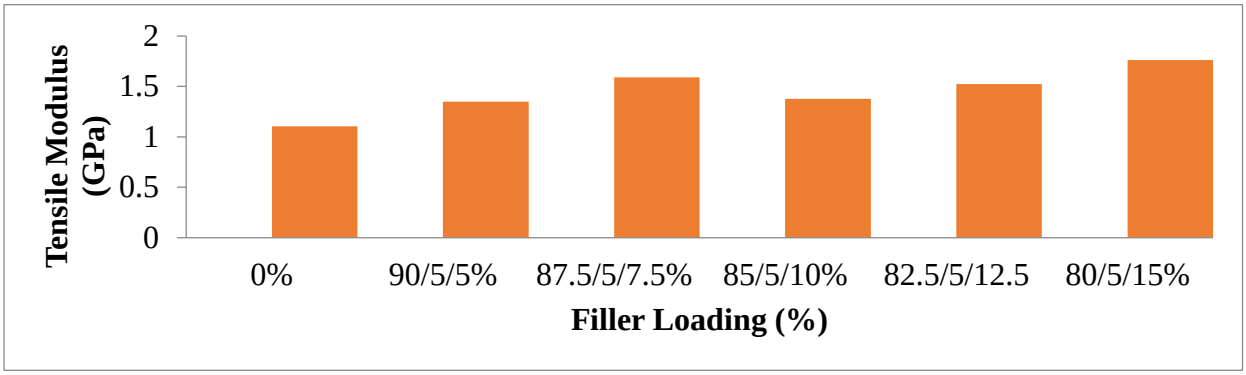


Figure 5: Tensile modulus of Doum fibre/Sandglass reinforced High density polyethene hybrid composites

Flexural strength

Flexural strength provides material's ability to resist failure under bending loads (3-point bending test). The composites flexural strength varied from 20.02 to 18.90 MPa as presented in Figure 6. The addition of sand glass and doum fibre decreased the flexural strength in comparison to the neat polymer matrix (HDPE). The least flexural strength was observed at 82.5% HDPE / 5% DF / 12.5% SG wt% with 18.90 MPa. This shows that the addition of sandglass to the polymer matrix increased the stiffness of the composites due to reduction in polymer molecular chain mobility caused by the incorporated sandglass particle. This is due to weak adhesion between the sandglass, matrix phase and fiber. The addition of high percentage of sand glass did not positively influence the flexural strength of the composites. This behavior parallels earlier findings [16]. Highest flexural strength was observed at 90% HDPE / 5% SG / 5% DF wt% with 20.02MPa. This could be related to the extent of excellent inter mingling between the good fibre / matrix and the two fillers interfacial interaction. This was similarly observed by Bessadok et al [13].

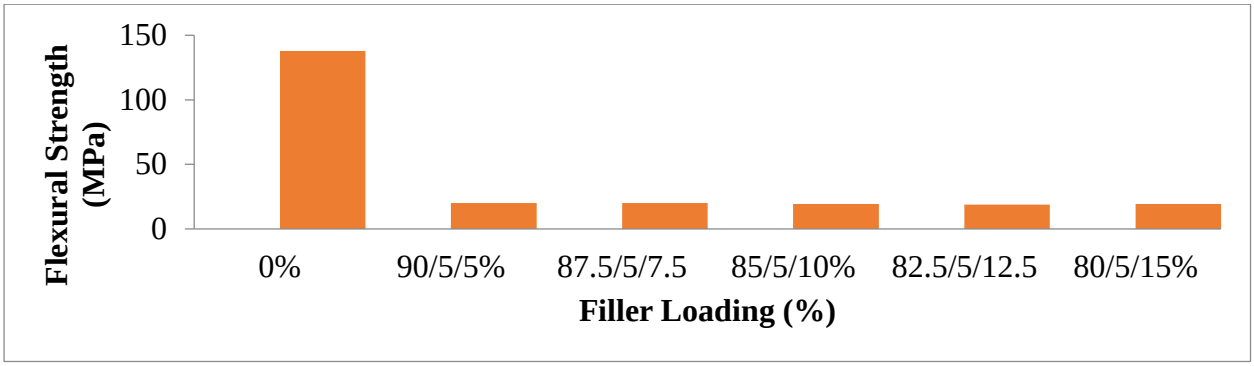


Figure 6: Flexural Strength of Doum fibre/Sandglass reinforced high density polyethene hybrid composites

Flexural modulus

These results shown in Figure 7 display an increase with increase in sandglass particles and doum fibre content. 80% HDPE / 5% DF / 15% SG wt% composite had flexural modulus of 8310.756 MPa while 5% sandglass, 5% doum fibre and 90% HDPE had flexural modulus of 4384.592 MPa. Higher flexural modulus with 80% HDPE / 5% DF / 15% SG wt% was due to an increase in the stiffness of the material as a result of restriction in polymer molecular chain mobility. Addition of rigid filler such as sandglass into the matrix increased the rigidity of the composite. Hybridization of natural and synthetic fibers in a composite increases the flexural modulus of the material. This is in-line with the findings of Praveena et al [17]. The lower

flexural modulus with 90% HDPE / 5% SG / 5% DF wt% was attributed to free movement of the polymer molecular chains.

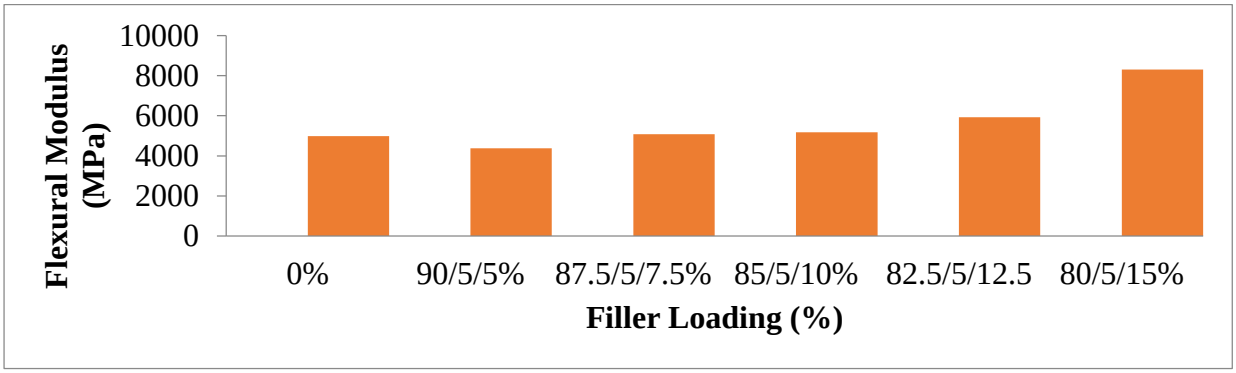


Figure 7: Flexural modulus of Doum fibre/Sandglass reinforced high density polyethene hybrid composites

Compressive strength

Compressive strength refers to ability of material to resist compression forces without failing. The compressive strength results of the composite samples were shown in Figure 8. The results showed that the best compressive value (82.04 MPa) was obtained at 80% HDPE / 5% DF / 15% SG wt%. This property is attributed to high reinforcing ability of sandglass at 15% loading and synergism occurring between the two reinforcements [18]. Lowest compressive strength was seen with unfilled polymer at 26.71 MPa due to absence of reinforcing materials to absorb and share the stress transferred by the polymer matrix. A drop in compressive strength was observed at 85% HDPE / 5% DF / 10% SG wt% and 82.5% HDPE / 5% DF / 12.5% SG wt% with 33.58 MPa and 40.80MPa respectively. This could be due to formation of voids during processing.

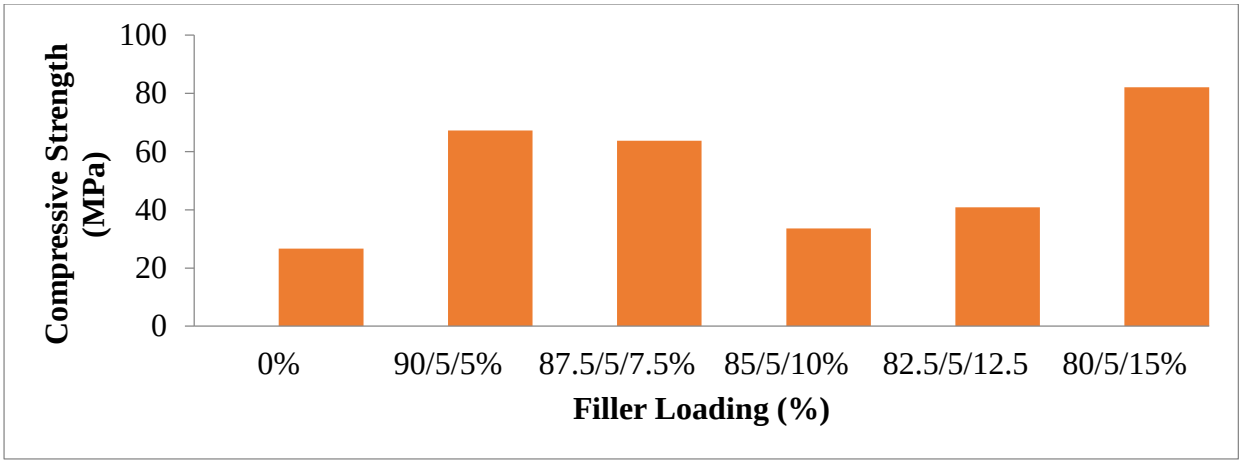


Figure 8: Compressive strength of Doum fibre/Sandglass reinforced High density polyethene hybrid composites

Impact strength

The impact test was carried out to evaluate the energy absorbed by material by sudden applied stress. The impact strength of the fabricated composites was presented in Figure 9. Composite sample with 85% HDPE / 5% DF / 10% SG wt% had the highest impact strength of 1.33 J/m^2 while the neat polymer matrix had impact strength of 0.88 J/m^2. The higher impact strength at 85% HDPE / 5% DF / 10% SG wt% fiber loading could be attributed to better intermingling and synergism between the two reinforcement materials and good fibre / matrix interfacial interaction [19]. The testing revealed that composites produced with 80% HDPE / 5% DF / 15% SG wt% exhibited lower impact strength. However, the quantity of sandglass particles which is more brittle than doum fibre drastically affects the impact strength of the composites thus, lowering the impact strength [17].

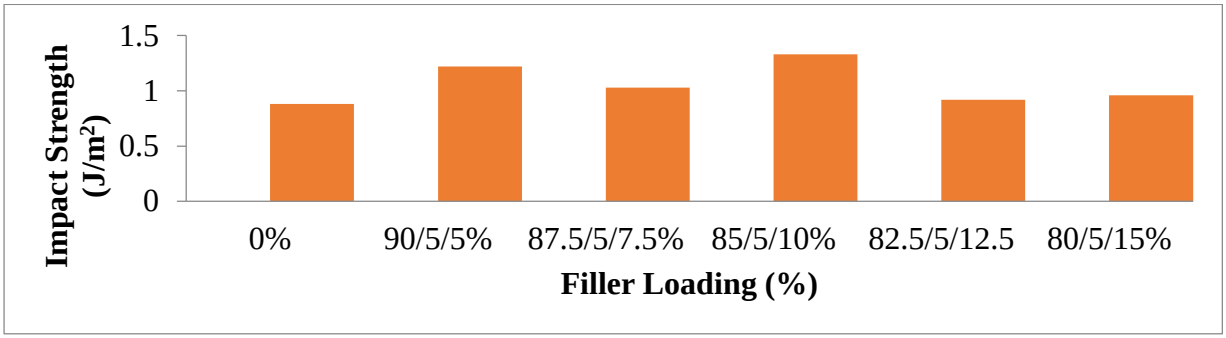


Figure 9: Impact Strength of Doum fibre/Sandglass reinforced High density polyethene hybrid composites

Hardness test

The hardness test results of the composites were presented in Figure 10. It was observed that the hardness value (HV) increased linearly with increased of sandglass loading. The least hardness value of 18.7HV was obtained at 90% HDPE / 5% SG / 5% DF wt%. which was higher than the neat polymer matrix. Increase in sandglass resulted in the increase in the hardness values of the composite, thus decreased the penetration of the indenter on the surface of the composite. This agreed with findings reported by El-Wazery [20]. Highest hardness values were observed with 80% HDPE / 5 DF / 15% SG wt%. The addition of 15% sandglass particles and 5% doum fibre to 80% HDPE matrix led to an increase in hardness values to 43.6HV due to an increase in the stiffness of the composites.

The increase in the hardness values of the composites is an indication of good bonding between polymer and fillers, reducing polymer molecular chain mobility. It has been reported in the literature [21].

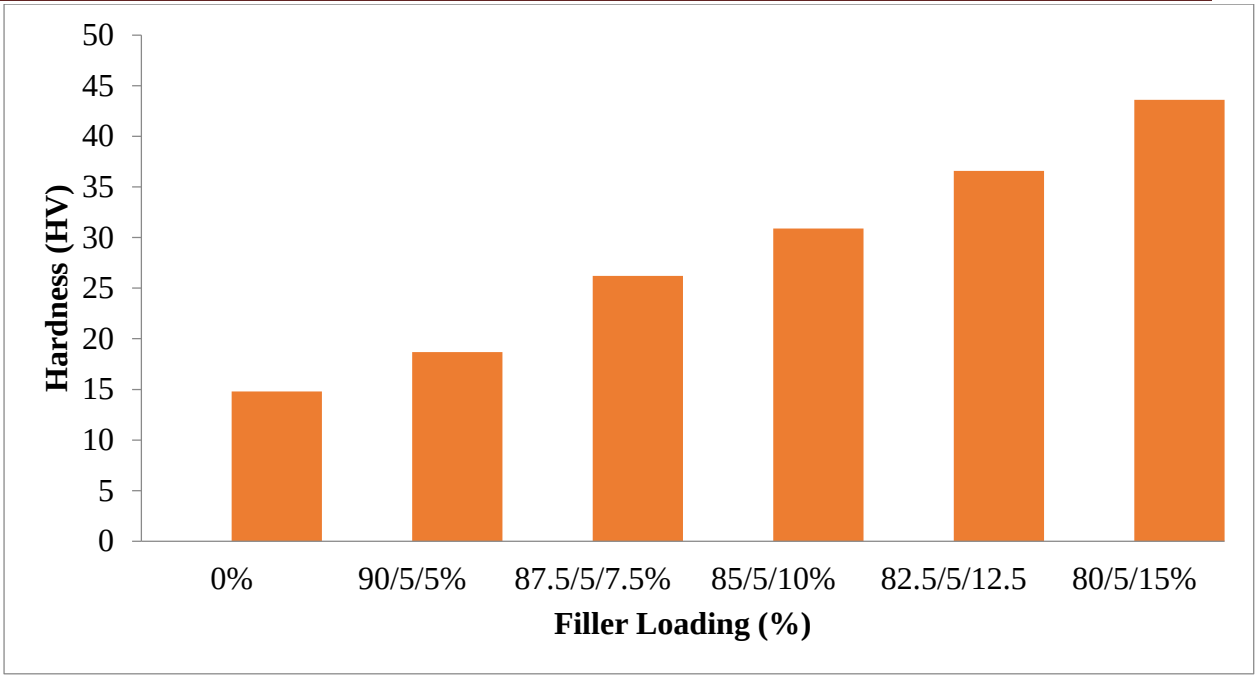


Figure 10: Hardness of Doum fibre/Sandglass reinforced high density polyethene hybrid composites

Morphological studies

The SEM micrograph in Plate 2 reveals a uniform dispersion of the sand glass fillers and doum fibre within the high density polyethylene matrix for the 90% HDPE / 5% SG / 5% DF wt%. This shows the maintenance of good interfacial interaction between the matrix and the fibre / filler particles. This factor gave a positive influence on the mechanical properties such as tensile (19.80 MPa) and flexural strength (20.02 MPa) for the 90% HDPE / 5% SG / 5% DF wt%.

There is a poor and irregular dispersion of sand glass particles / doum fibre for the 87.5% HDPE / 7.5% SG / 5% DF wt% loading (Plate 2), showing particle agglomeration within the matrix. The tensile fractured micrographs samples confirmed the 90% HDPE / 5% SG / 5% DF wt% filler / fibre loading (Plate 1) having the best tensile strength and flexural strength properties with stronger interfacial bounding between the high density polyethylene matrix and sun glass particle / doum fibre.



Plate 1: SEM Micrographs of 90 HDPE / 5 SG / 5% DF at x 500 magnification

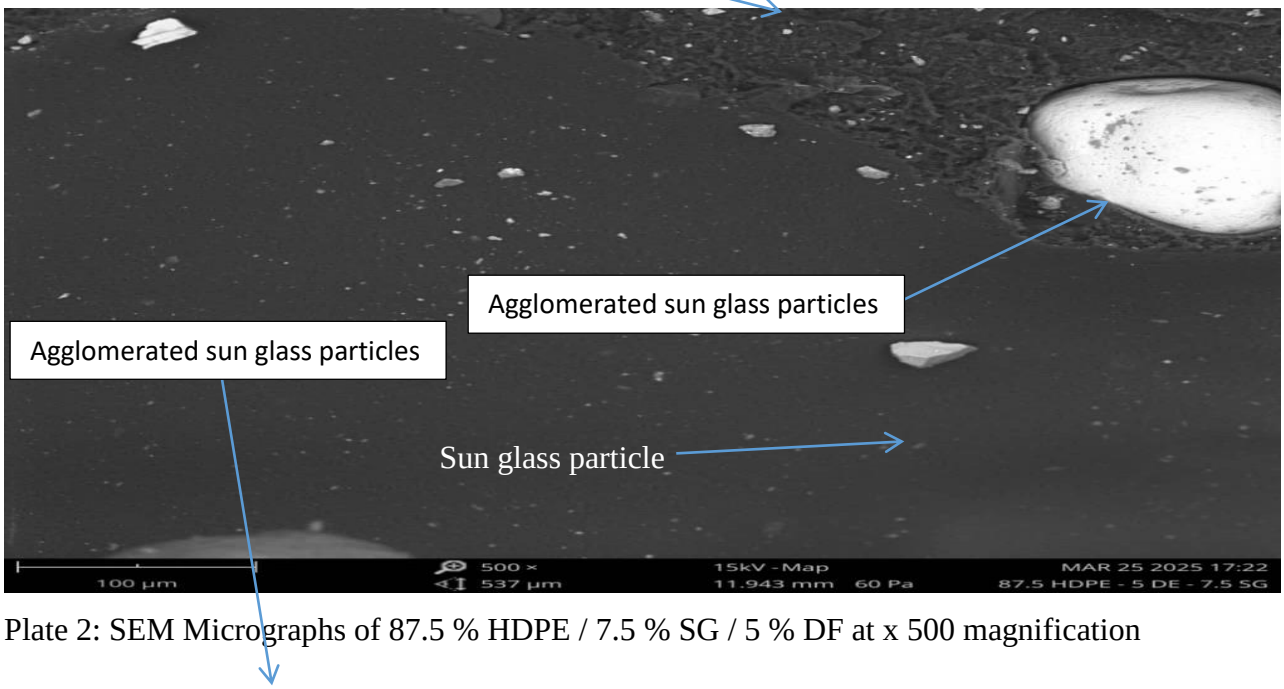


Plate 2: SEM Micrographs of 87.5 % HDPE / 7.5 % SG / 5 % DF at x 500 magnification

CONCLUSION

Hybrid composites consisting of natural mineral silica (sandglass), recycled HDPE and alkali treated Doum fibre were prepared and mechanical properties evaluated. Removal of lignin, hemicellulose and pectin was achieved using alkaline solution and confirmed by FTIR analysis. The improved mechanical properties of the composites were attributed to good interfacial adhesion and better intermingling and synergism between the fiber and the polymer matrix. Tensile and flexural properties were best at 90% HDPE / 5% DF / 5% SG wt% suggesting that the loading of sand glass and doum fibre as a filler should not be beyond 90% HDPE 5% DF /

5% SG wt% for the attainment of best tensile and flexural properties. Highest impact strength was obtained at 85% HDPE / 5% DF / 10% SG wt%. The composite′s compressive strength and hardness increased even up to 80% HDPE / 5% DF / 15% SG wt% loading.

This work revealed the hybridisation of sand glass and doum fibre for the production of lightweight composites materials with reasonable mechanical properties such as tensile and flexural at 90% HDPE / 5% DF / 5% SG wt% indicates a good potential for minimum-load bearing applications.

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