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Effect of Silicate oxide (SiO_2) on Morphological, Dimensional Stability, and Strength Properties of Biopolymer Composites Reinforced with Wood Fibre

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Abstract: Moisture sorption and strength properties of SiO_2-modified bio-polyethylene blocks made from recycled polyethylene and fiber of *Gmelina arborea* at different proportional ratios were investigated. The morphological properties and chemical composition of the composites were also examined. The bio-polyethylene blocks made at a proportional ratio of 80/15/5 (SiO_2/polyethylene/wood) were denser than others before and after exposure. All blocks except 30/65/5 act negatively to water absorption after 1 day and 7 days, respectively. The study revealed that a strong interfacial adhesion bond exists between materials used for bio-polyethylene blocks at 80/15/5, 70/25/5, and 30/65/5 due to no voids, no fiber pullout, and SiO_2 fallout. The tensile-fractured revealed that bio polyethylene blocks made at a proportional ratio of 30/65/5 exhibited better stress transfer to give higher strength and modulus. The bio-polyethylene blocks attained good compressional strength at 40 % and 60 % SiO_2 content. The spectra band at 1376 to 1384 cm^{-1} and 1083-1035 cm^{-1} shows that the O-H bond for cellulose and Si-O stretching vibration was present after production. The compatibility of wood fibers with SiO_2 in the composition of polymer composite is a great innovation that could solve the problems of plastic pollution in our environment. Production of bio-polyethylene blocks for pavement will reduce the adverse effects of wood and polymer wastes on the environment in most cities worldwide.

Keywords: bio-plastic interlock; *Gmelina arborea*; morphology; mechanical; pollution; silicate oxide.

1. Introduction

Biocomposite, an amalgamation of two or more components materials [1] reinforced with natural fibers, synthetic materials, and nanoparticles in its matrix [2], has emerged as a popular value-added construction material for specific applications in the market [1]. This arises from unique properties ranging from excellent stiffness, biodegradability, lightweight, improved density, lower cost with improved sustainability, exceptional strength, flexural

rigidity, high durability, and fireproof and non-corrosive characteristics [2-5]. Nanoparticles such as Silicate oxide (SiO_2) have prospects in producing bio-composites with remarkable qualities such as improved strength and durability performance. These exceptional qualities have made this composite product find its way into various applications, including structural construction, aerospace, automobile, packaging, mechanical, biomedical, and furniture industries [2,6-8].

The utilization of green, sustainable materials for construction and architectural applications in light of heavy reliance on conventional raw materials, including cement, granite, and sand [9], has called for a concerted paradigm shift toward green, eco-friendly practices [10,11]. The ever-increasing build-up of environmental wastes globally, limited landfill spaces, inadequate disposal mechanisms, and emission of unwanted gases accompanying incineration processes [12] coupled with rising construction costs [9,13] have compelled scientists to find alternative sustainable and environment-friendly construction materials [14,15]. These sustainable materials are cheaper, abundant, locally, and readily available in contrast to the depleting conventional materials used in construction industries [16], particularly in the production of paving units for walkways.

In Nigeria today, the most common types of walkways are those constructed with the use of concrete and stones. Most walkways are found in residential and public areas. These are produced from the same composite production materials as concrete [17]. However, the surfacing, method of application, and production and installation cost of interlocking floor pavers are believed to have the inherent strength and aesthetic nature accompanied by their lightness. The structural strength and intrinsic beauty of interlocking floor pavers make them compete favorably with the traditional solid concrete and black asphalt used for walkways and road construction [18]. However, using environmental wastes and local materials to produce value-added interlocking pavement is considered a proactive solution to addressing important environmental issues and sustainable growth. Composite interlocking pavement is expected to be characterized by high compression resistance, especially in areas of high foot traffic [17]. This, therefore, necessitated the investigation into the suitability of silicate oxide (SiO_2) as reinforcement with wood fiber for the production of biopolymer composites intended for functional walkway use. Developing biocomposites from recycled plastic wastes, wood fiber, and silicate oxide (SiO_2) to produce eco-friendly interlocking paving units is an innovative approach with great potential in managing environmental wastes and providing construction materials for low-cost buildings in rural and urban areas. It, therefore, becomes expedient to understand the behavior of physical and strength properties as well as the chemical reaction of silicate oxide with synthetic plastic and wood fiber concerning utilization.

2. Materials and Methods

Materials such as recycled polythene embalmed dihydrogen monoxide, particles of *Gmelina arborea*, and Silicate oxide were employed in this study. The recycled polythene embalmed dihydrogene monoxide was packed from DFRIN bottled water factory at Forestry Research Institute of Nigeria (FRIN), Ibadan, Oyo State, Nigeria. Silicate oxide (SiO_2) was collected from the experimental plot of the soil section also at FRIN. The wood particles were derived from the conversion of *Gmelina arborea* logs extracted from the forest reserve at FRIN Research Station, Onigambari, Ibadan, and milling was done at the sawmill section of the Department of Forest Products Development and Utilization, FRIN.

2.1. Materials preparation and sample production.

The SiO_2 employed was thoroughly sieved with a wire mesh size of 1.0mm to produce fine powder and remove unwanted stones or larger particles that are unnecessary. The SiO_2 was oven-dried at 103ºC to attain 2 % moisture content. The agglomerator machine milled the recycled polythene embalmed dihydrogen monoxide into powder form. The fine powder of recycled polythene embalmed dihydrogen monoxide was thoroughly screened with magnets and a wire mesh sieve of 1.00 mm to remove any form of metal or unwanted elements. The powder-recycled polythene embalmed dihydrogen monoxide was later oven-dried at a temperature of 45ºC to remove any available water. The sawdust of *Gmelina arborea* was also screened with a wire mesh sieve of an equal dimension of 1.00 mm to produce wood flour (powder form). The same wire mesh sieve dimension was adopted to obtain homogenous particles. Before sample production, varying quantities of SiO_2, polyethylene, and wood powder were proportionately weighed at 90/5/5, 80/15/5, 70/25/5, 60/35/5, 50/45/5, 40/55/5, and 30/65/5 (Sand/polymer/wood) weight to weight basis within the constant nominal density of 2.64 g/cm^3 with mold volume of 1,026 cm^3 to produce bio-polyethylene blocks. These materials were thoroughly mixed and fed into a single screw extruder of temperature range 110 to 120ºC to produce compounded molten material, which was injected into a metal mold of size 19 cm by 9 cm by 6 cm (length x breadth x height) and pressed under 30 tons hydraulic presser to form rectangular bio-polyethylene blocks (Plate 1). The bio-polyethylene blocks were removed from the molds after passing through the cooling process to harden and cut into specific specimen sizes to determine properties.

Plate 1. Samples of bio-polyethylene blocks.

2.2. Properties determination.

2.2.1. Procedure for FTIR.

A Perkin Elmer Fourier Transform Infra-red spectrometer with a broad-spectrum range between 4000 cm-1 and 400 cm^{-1} was used to confirm the existing prominent functional groups in the bio-polyethylene blocks. This was done to confirm the chemical compositions in the bio-polyethylene blocks. The chemical compositions of the fiber or other fillers in polymer composites interpret the possible chemical inter-reactions in the matrix, and this can be effectively identified using FTIR [19]. 200 mg of the materials in pelletized form were added with Potassium bromide (KBr) and inserted into the Spectrophotometer cell for

characterization. KBr was used in this study as a standard because of is an attribute not to produce peaks within the frequency range.

2.2.2. Physical properties (porosity).

The ability of the samples to withstand or resist moisture exposure was determined following the ASTM D570-98 standard. The specimen size of 1.2 cm x 1.2 cm x 18 cm was conditionally dried in an electric oven at a temperature of 50^{o}C for 24 h; this was to remove any unwanted water from the samples and allow them to attain constant weight in desiccators. The weight and thickness of the samples were taken after being removed from desiccators and immersed in deionized water of 25^{o}C under laboratory conditions for 0 hr (control), 24 hours, and 168 hours. After a completed duration of moisture exposure, the weight and thickness of the samples were taken to determine the porosity (density, water absorbed, and thickness changes).

2.2.3. Mechanical properties.

Flexural and tensile properties of the samples were done following ASTM 790, in which the specimen for each varying proportion and at different durations of moisture exposure was subjected to a force on the universal testing machines (UTM) of model WDW 5000 at 50 KN with 100 mm support span. Each specimen was supported with two rollers at the extreme ends and loaded at the center. The forward movement of the machine led to a gradual load increase until failure occurred. At the point of failure, the force exerted on the specimen and the specimen dimension were recorded to determine the strength and modulus for each sample.

2.2.4. Scanning Electron Microscopy (SEM).

Scanning electron microscope (SEM), available at the University of Ibadan, Oyo State, Nigeria, examined the fracture surface of fillers (SiO_2 and wood flour) in formed polymer composites. Each sample was sputter-coated with gold-palladium and then observed under the SEM of model JEOL JSM-7600F operated at 5 kV. The test was carried out at various magnifications ranged 58X to 304X. This examination was done to examine the arrangement of fiber to fiber to SiO_2 surface morphology, fibers pull out, and fiber polyethylene interface.

3. Results and Discussion

3.1. Morphological properties.

The micrographs of the tensile-fractured obtained for each bio-polyethylene block, which explained the interfacial bonding between the matrix and fiber and SiO_2, are shown in Figure 1. The microstructure of the samples showed in the SEM images of fracture surfaces for variations of 80/15/5, 70/25/5, and 30/65/5 (SiO_2/polymer/sawdust) weight to weight basis in % were shown at a magnification of 304×, the presence of voids was seen but no fiber pullout and no sand fallout (Figures 1a, 1b, and 1f). As shown in Figures 1c, 1d, and 1e the SEM images of fractured surfaces of bio-polyethylene blocks of varying proportions of 60/35/5, 50/45/5, and 40/55/5 (SiO_2/polymer/sawdust) revealed a close matrix-fiber surface without any sign of fiber pull out within the materials, and this show that bio-polyethylene blocks have better-compacted surfaces. It was observed that all the samples showed good morphological properties due to the strong interfacial adhesion between the fiber, SiO_2 (mixture of wood flour

and sand), and polymer matrix. This observation might be due to the increase in polyethylene to fillers, and better encapsulation of fillers was witnessed to reduce the presence of surface voids. The result of the findings in this study cannot be disconnected from the careful pretreatment processing observed in the line of production, which led to a good homogenous mixture of all materials used for the production of bio-polyethylene blocks.

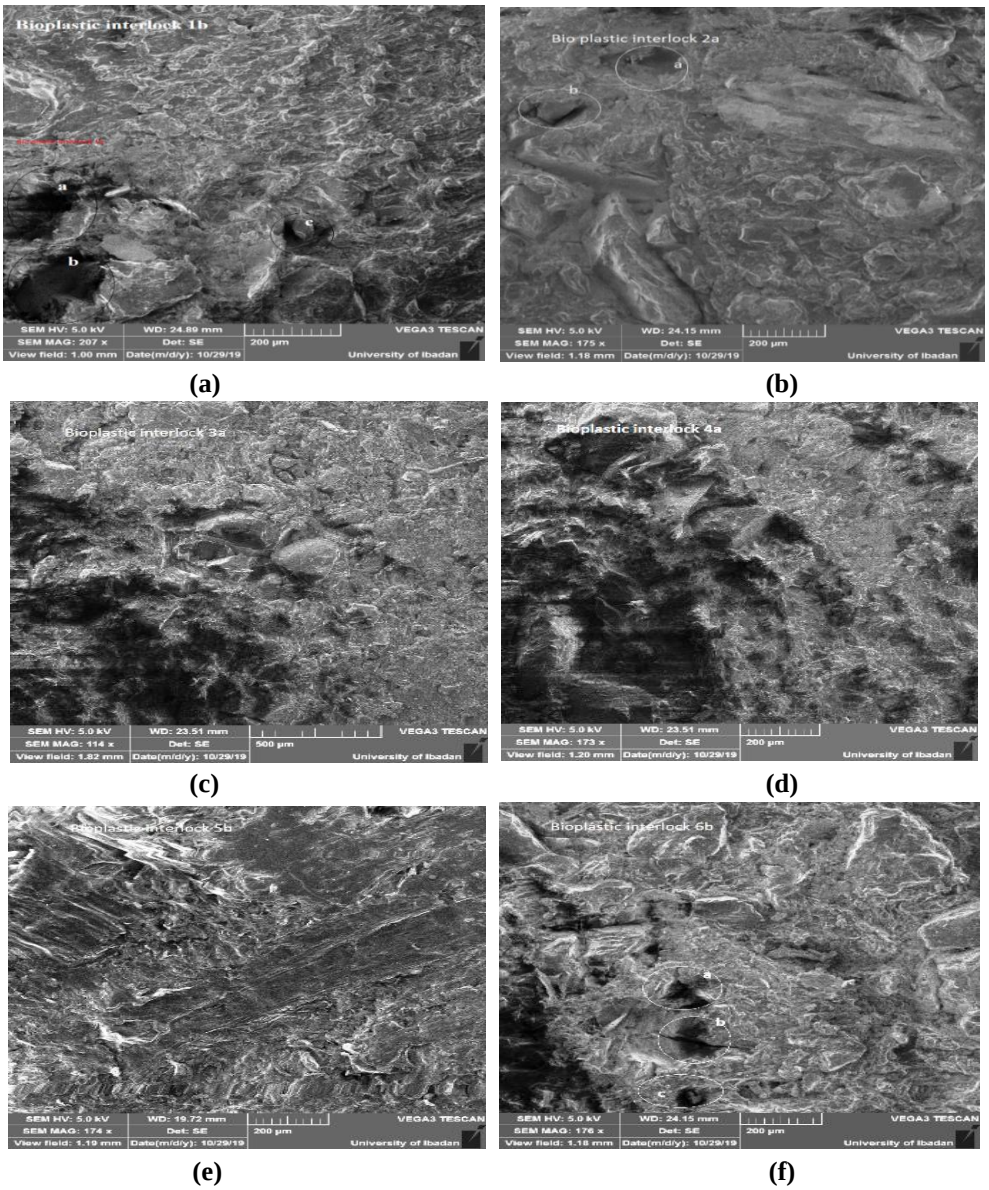

Figure 1. SEM images (×304) of a fractured surface of variation of SiO_2/polymer/sawdust) weight by weight basis in % (a) Bio-polyethylene block of 80/15/5; (b) Bio-polyethylene block of 70/25/5; (c) Bio-polyethylene block of 60/35/5; (d) Bio-polyethylene block of 50/45/5; (e) Bio-polyethylene block with 40/55/5; (f) Bio-polyethylene block with 30/65/5.

3.2. Chemical composition of bio-polyethylene blocks.

The weak bands 3779 cm^{-1} can be ascribed to the stretching vibration of the free alcohol (-OH) group. This band was observed in all the FTIR spectra for all the samples at varying proportions of SiO_2/polymer/sawdust (Figure 2). Jannah et al. [20] mentioned that the broad and sharp band observed at 3415 to 3421 cm^{-1} can be attributed to the stretching vibration of hydrogen-bonded alcohols. The bands 2921, 2922, and 2925 cm^{-1} were ascribed to C-H bond as the presence of cellulose [21]. The bands 1717 to 1736 cm^{-1} observed in the spectra are

attributed to the carbonyl group present in the cellulose; this confirms the presence of lignocellulosic material used even after compounding the particle mix. The broad and pronounced peaks from 1619 to 1621 were assigned to H-O-H intermolecular stretching vibration of absorbed moisture present in the reinforcement (both sand and wood flour), according to the findings of Toledano *et al*. [22]. The bands observed at 1376 to 1384 cm^{-1} were attributed to O-H bond of the cellulose. The pronounced (doublet) band at 1083-1035 cm^{-1} is characteristic of Si-O stretching vibration [23]. The FTIR result confirms the presence of a mixture of wood flour and sand in the interlock as reinforcement.

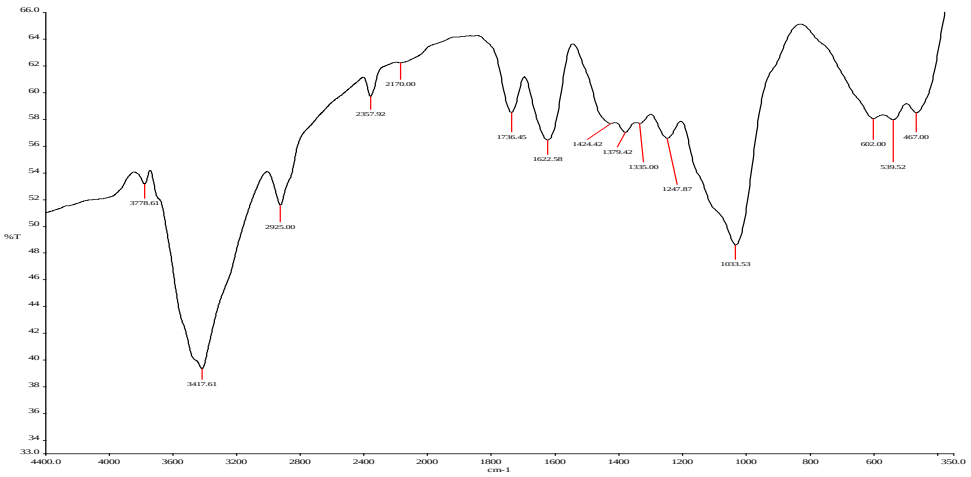

Figure 2. The FTIR spectra show the band in the bio-polyethylene block.

3.3. Porosity.

The outcome of the dimensional behavior of the bio-polyethylene blocks is illustrated in Figures 3a, 3b, and 3c after subjecting them to a water soak test for 0 hr (control), 24 hours, and 168 hours. The values obtained after 24 hours of exposure ranged from 1.07 to 1.66 g/cm^3, -1.33 to 9.97 %, and -29.56 to 10.26 % for density, water absorption, and thickness swelling, respectively (Figures 3a, 3b, and 3c). When the period of exposure was extended to 168 hours, the values obtained ranged from 1.03 to 1.50 g/cm^3, -26.21 to 0.73 %, and -27.00 to 0.97 % for density, water absorption, and thickness swelling, respectively (Figures 3a, 3b, and 3c). As observed in Figure 3, bio-polythylene blocks made at 80/15/5 had the highest density values before and after exposure, while 30/65/5 had the lowest density values, which gradually decreased as the exposure period increased. All the other bio-polyethylene blocks followed the same trend. The density values decreased as the exposure period increased (Figure 3a). The bio-polyethylene blocks at 80/15/5 had more SiO_2 than the others. SiO_2 is naturally bulky and heavier, and when forcefully pressed together with plastic and fiber under high pressure, the resulting composite will be denser and harder. However, as the SiO_2 content reduces, the density of the composite is also reduced (Figure 3a). The water intake for all the bio-polyethylene block specimens was very low and increased as the period extended to 24 hours, decreasing tremendously as it stretched to 168 hours of exposure (Figure 3b). During the periods of 24 hours and 168 hours, all the blocks except 30/65/5 maintained a uniform absorption trend, which was relatively low. The other bio-polyethylene blocks recorded a negative trend, indicating they desorbed moisture and shrank instead of absorbing and swelling (Figures 3b and 3c). This observation may result from strong interfacial adhesion between the fiber and SiO_2 (a mixture of wood flour and sand) and the polymer matrix, which acted as moisture resistance.

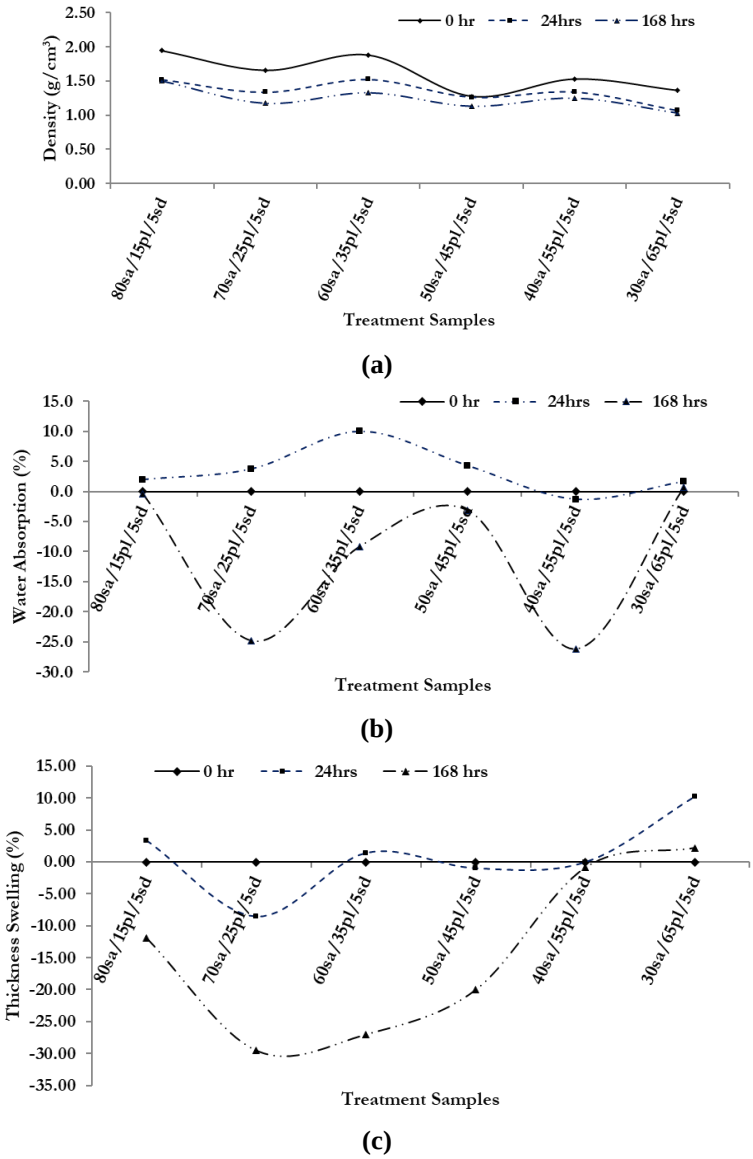

Figure 3. Effect of SiO_2 on physical properties: (a) Density (g/cm^3); (b) Water Absorption (%); (c) Thickness swelling (%) of bio-polyethylene blocks.

3.4. Mechanical properties.

The mean values for strength properties ranged from 540.67 to 2050.07 N/mm^2, 7.37 to 22.43 N/mm^{2,} and 9.88 to 24.88 N/mm for modulus of elasticity, modulus of rupture, and compressional strength, respectively. The samples' strength properties remained the same before and after exposure (Figures 4a, 4b, and 4c). The effect of SiO_2 was greater in a bio-polyethylene block, having less SiO_2 content loading. Among the bio-polyethylene blocks, the sample made at 30/65/5 had the highest values for modulus of elasticity and modulus of rupture, followed by bio-polyethylene blocks made at 70/25/5, 50/45/5, 80/15/5, and 40/55/5. When a gradual increase in SiO2 content was added, the flexural rigidity and elasticity decreased due to a decrease in stress transfer from the matrix to the fiber and SiO_2. There was increased flexural rigidity and elasticity in the bio-polyethylene block made at 30/65/5 because the quantity of the SiO2 added to the matrix to fiber was little. There was sufficient interfacial bonding to transfer the load from the matrix to the fibers.

Meanwhile, for compressional strength, bio-polyethylene blocks at 40/55/5 and 60/35/5 had the highest compressional strength values, followed by 70/25/5, 50/45/5, 30/65/5, and the

least value was found in 80/15/5 (Figure 4c). The effect of SiO_2 was quite different in the case of the samples. The values at 40 and 60 % SiO_2 might be due to the modification in the microstructure of the surrounding matrix; the particle size of the homogenous particle size increased the matrix–fiber surface, fiber agglomeration, dispersion, adhesion, fiber distribution, and orientation and volume/weight fraction of the particles. This occurrence is in line with the report of Mirzababaei *et al*. [24] that an increase in fiber content results in increased fiber-to-fiber cohesion due to more contact points in the structural matrix of the composite. Also, adding nanoparticles such as SiO_2, as reported by Rahman *et al*. [25], enhances the interfacial bonding between the biocomposite matrix.

The analysis result for physical and strength properties (Table 1) showed significant differences among the samples made at different proportional quantities for physical and strength properties.

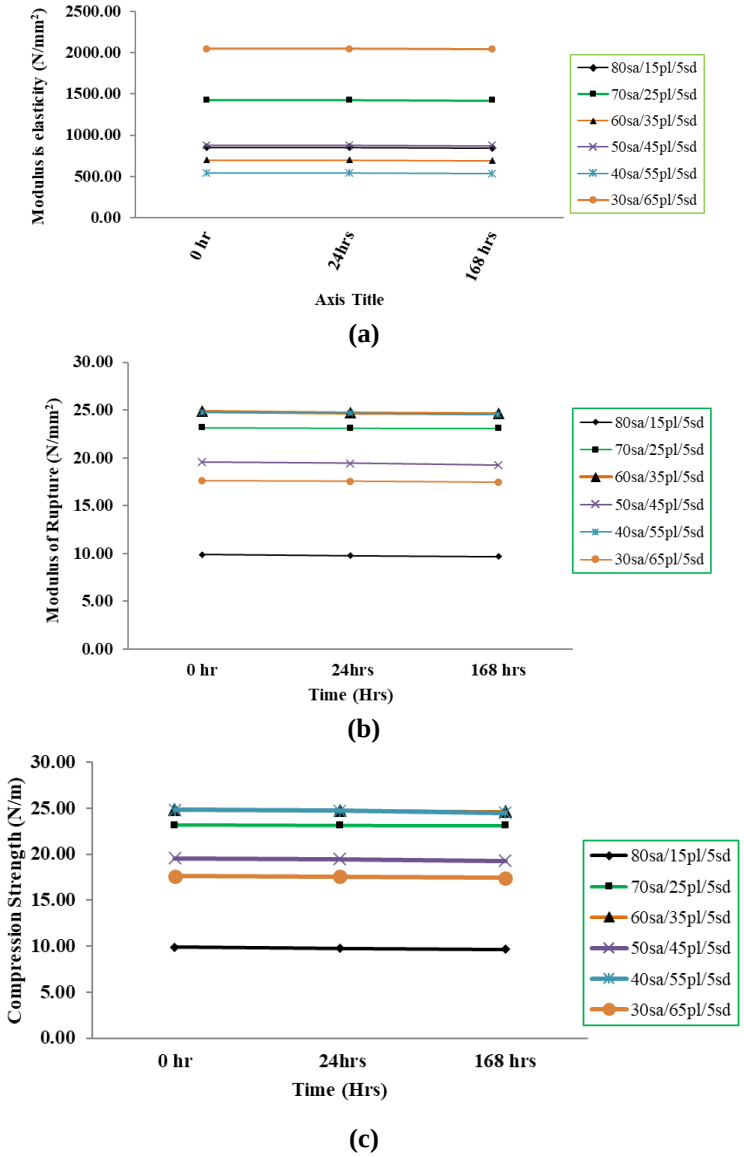

Figure 4. Effect of SiO_2 on mechanical properties: (a) Modulus is elasticity (N/mm^2); (b) Modulus is rupture (N/mm^2); (c) Compression strength (N/m) of bio-polyethylene blocks.

Table 1. Mean values obtained for physical and strength properties of bio-polyethylene blocks.

Performance evaluation	SiO_2/Polymer/sawdust Proportional Mixture						Pooled mean
	80/15/5	70/25/5	60/35/5	50/45/5	40/55/5	30/65/5	
Observed density (g/cm^3)	1.94^a	1.35^d	1.88^b	1.26^e	1.53^c	1.36^d	1.55± 0.27
Density @ 24 hrs (g/cm^3)	1.52^b	1.66^a	1.52^b	1.13^d	1.34^b	1.07^c	1.37 ±0.22
Water absorption after 24 hrs (%)	1.95^c	3.71^d	9.97^f	4.26^e	-1.33^a	1.64^b	3.37±3.55

Performance evaluation	SiO_2/Polymer/sawdust Proportional Mixture						Pooled mean
	80/15/5	70/25/5	60/35/5	50/45/5	40/55/5	30/65/5	
Thickness swelling after 24 hrs (%)	3.33^{e}	-29.56^{a}	1.41^{d}	-20.01^{b}	0.00^{c}	10.26^{f}	-5.76±14.52
Density @ 168 hrs (g/cm^3)	1.50^{a}	1.17^{e}	1.33^{b}	1.28^{c}	1.25^{d}	1.03^{f}	1.26±0.15
Water absorption after 168hrs (%)	-0.45^{e}	-24.82^{b}	-9.19^{c}	-3.14^{d}	-26.21^{a}	0.73^{f}	-10.51±11.39
Thickness swelling after 168 hrs	-11.98^{b}	-8.51^{bc}	-27.01^{a}	-0.97^{cd}	-0.89^{cd}	2.17^{d}	-7.87±11.15
Modulus of elasticity (N/mm^2)	851.87^{c}	1426.87^{b}	699.76^{cd}	880.39^{c}	540.67^{d}	2050.07^{a}	1074.94±546.30
Modulus of rupture (N/mm^2)	7.37^{d}	14.73^{c}	12.75^{c}	17.48^{c}	13.08^{d}	22.43^{a}	14.64±4.86
Compression strength (N/mm)	9.88^{c}	23.1^{ab}	24.88^{a}	19.55^{ab}	24.8^{a}	17.62^{b}	19.98±6.09

Means in the same row having different superscripts are significantly different ($p \leq 0.05$)

4. Conclusions

The bio-polyethylene block panels designed for pavement applications were formulated from sawdust, recycled polyethylene, and SiO_2 (Sand) as reinforcement using extruding and compression methods. Bio-polyethylene blocks were prepared at varying proportions of SiO_2/polymer/sawdust. Each bio-polyethylene block sample was tested for porosity and strength before and after cumulative exposure to moisture for 192 hours. After a period of 192 hours, all the blocks except 30/65/5 maintained their absorption trend and were relatively low in values. The other bio-polyethylene blocks recorded negative values, showing that instead of absorption and swelling, they desorbed moisture and ank. The micro graphical features of the fractured tensile samples displayed the presence of void without fiber pullout or sand fallout from the matrix, indicating a good inter-bonding relationship between the reinforcers (fiber and sand) and the matrix (polymer). It has also been confirmed that the FTIR spectra band identified the presence of cellulose and Si-O in all the samples. As the content of the SiO_2 increases, the flexural rigidity and elasticity of the bio-polyethylene blocks decrease except at 30 %. Bio-polyethylene block made at 30/65/5 had the highest strength and modulus of the others but low compressional values. However, blocks made at 40/55/5, 80/15/5, and 60/35/5 for pavement application will be of good use. This study has confirmed that wood fiber and SiO_2 (sand) can be compounded with recycled polythene embalmed dihydrogen monoxide to produce a hard structural product, and it will also serve as a solution to the menace caused by sawdust and recycled polythene embalmed dihydrogen monoxide to the environment as pollutants. This study will form a guideline for any interested manufacturers willing to invest in producing bio-polyethylene blocks for commercial purposes.

The experimental results provided in this study will help develop technology for producing bio-polyethylene blocks for pavement applications. It will also help reduce the environmental problems created by plastic and sawdust in society. The outcome of this study can serve as an alternative to concrete interlock. It will also be important if more investigation can still be carried out on different soil types, sizes, polymer types, wood species, and low proportional ratios.

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Conflicts of Interest

The authors declare no conflict of interest.

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