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Physicomechanical Properties of Sustainable Wood Plastic Composites of Tropical Sawdust and Thermoplastic Waste for Possible Utilization in the Wood Industry

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Abstract

This work investigated and quantified the physicomechanical properties of flat-pressed wood plastic composites produced with recycled polyethylene terephthalate, recycled polyethylene and sawdust derived from selected tropical timbers, namely, *Nauclea diderrichii*, *Brachystegia eurycoma*, *Erythrophleum suaveolens* and *Prosopis africana*, for possible utilization in the wood industry. The compounding of the polymer blends of the precursor plastics, namely recycled PET (rPET) and recycled PE (rPE) with the sawdust (SD) from the selected timbers to produce the desired wood rPET/rPE composites was carried out via the flat press method. The characterization of the physicomechanical properties of the wood plastic composites (WPCs) produced, such as the density, hardness, flexural strength, ultimate tensile strength, elongation %, thickness swelling and water absorption capacity was carried out using methods based mainly on the European Committee for Standardization (CEN) and the American Society for Testing Materials (ASTM) standards. The results of the investigation on the resultant composites indicated that changes in the SD content affected the density of flat-pressed WPCs in line with literature. Generally, it was observed that as wood dust increased and PET content decreased, the density of composites decreased with some deviations as expected probably due to the anisotropic nature of the wood fillers. The analysis of variance (ANOVA) revealed that there was a statistically significant variation in the wood composites of *Nuclea diderichii* based on the physicomechanical values as the p-value (0.020) obtained was less than the critical level of $\alpha = 0.05$. It was also observed that the composite, Wood 1 Sample 5

(W_1S_5) which was composed of 40% rPE, 40% rPET and 20% SD (derived from *Nuclea diderichii*), had the highest percentage elongation (26.84%); the highest flexural strength (14.995 N/mm^2) and possibly the least carbon footprint in the environment. These properties of W_1S_5 suggest that it could therefore be the best option for the production of building materials like ceiling boards or floor skirting in the wood plastic composite industry. The results of these investigations have therefore indicated that the fabrication of WPCs from sawdust and rPET/rPE was technically feasible and had prospects for large scale production in the wood industry.

Keywords

Wood Plastic Composites, Density, Water Absorption Capacity, Cellulose, Sustainability, Recycle, Waste

1. Introduction

There is no gainsaying the fact as has been noted by some environmental scientists, that there is an urgent and immediate need to take care of our environment so that life on this planet earth could be sustained [1]. The accumulation of non-biodegradable waste and its disposal in oceans, sewers, or landfills leading to air, soil, and water pollution in the ecosystem has been raising serious public concerns [2]. Plastics are now the world's third-largest production material, accounting for more than 11% of the total municipal solid waste (MSW), second only to concrete and steel [3]. Post-consumer plastic materials like high density polyethylene (HDPE), low density polyethylene (LDPE), polyvinylchloride (PVC) and polyethylene terephthalate (PET) which form a major portion of global MSW pose serious threats to the environment [4]. PET, in particular, is one of the most utilized plastics in the globe and its continued accumulation in our environment makes the need to dispose of recycled PET (rPET) in an economical and productive manner, a necessity [5]. Likewise, Polyethylene (PE) which is also one of the most widely used thermoplastic materials in the production of electrical insulating appliances, pipes, sheets, containers and so on, due to its desirable qualities [6], equally constitutes an environmental problem. The need to properly dispose of recycled polyethylene (rPE) in an eco-friendly manner has thus become a major research issue [7]. Similarly, Chaharmahali, Tajvidi, and Najafi (2008) [8] observed that sawdust (SD) waste from wood processing industries also creates environmental pollution unless reprocessed for different applications like particle-board pulp or any other useful wood plastic composites (WPCs). SD has continued to pose serious hazards not only in manufacturing industries [9] but also in the area of waste management [10]. This is because their decomposition process takes relatively much time [11]. As a result of this environmental challenge, recycling has been proffered as the best way to reduce both solid plastic waste and carbon footprint in the environment in a sustainable

manner [9]. Fortunately, wood from which sawdust (SD) is derived is renewable, recyclable and biodegradable, with a good reinforcing potential in the composite matrix, when compared to other artificial fibers that can be combined with plastic like PET into useful WPCs [4].

Studies have been carried out the mechanical properties of WPCs prepared from different plastic wastes combined with different sawdust proportions of wood waste to formulate excellent properties and the best performance of the resultant composites [11]. This includes the use of relatively newer techniques in the WPC industry, like the flat press method which possesses among other advantages, higher productivity with lower pressure requirements which helps to keep the integrity of the wood structure intact [4] [12]. In spite of the extensive research with respect to the effect of sawdust components on WPC properties, there is still very limited work on the fabrication and properties of flat-pressed WPCs obtained from tropical sawdust and a blend of rPET/rPE at various mixing ratios [4] [12]. The limited information and data on the physicochemical, morphological, and structural properties of our local tropical timbers have also been reported as a factor militating against the growth of the WPC industry in the tropical region of Africa [13]. These lacunae necessitate further work in this area if the opportunities offered by the subsequent production of useful materials from the sawdust obtained from these tropical timbers are to be maximized with respect to the WPC industry. Further research will provide useful information on new sources of raw material for the WPC industry and their effect on the products [14]. This work investigated and quantified the physicomechanical properties of the wood plastic composites produced from the sawdust waste of selected tropical timbers, namely, *Nauclea diderrichii*, *Brachystegia eurycoma*, *Erythrophleum suaveolens* and *Prosopis africana* and thermoplastic MSW like recycled PET and rPE for possible utilization in the wood industry.

2. Materials and Methods

2.1. Sample Collection

Samples of the main trunks of four tropical timbers were obtained from various forests located in Ogwogo Nike in Enugu East of Enugu State, which is situated in the South Eastern part of Nigeria with the assistance of a well-trained government forestry official during the dry season. The selected timbers were: *Nauclea diderichii* (ubulu ani), *Erythrophleum suavolens* (inyi), *Brachystegia eurycoma* (achi), *Prosopis africana* (ugba). Recycled PET bottles and recycled PE (from sachet water packaging) were collected from homes and the environment in 3-3 areas of Onitsha, Nigeria. The collected timbers were pulverized using the sawing machine. They were milled and ground and passed through a sieve of 105 microns (mesh size) to remove impurities and then air-dried for 48 hrs. Clean consumer drinking water bottles and sachet bags collected were shredded by a shredding machine and a pair of scissors. The shredded plastics were air dried for 48 hours. The pulverized samples of the timbers and plastics are shown in **Figure 1**.

Figure 1. Samples of the pulverized starting materials: sawdust, rPE and rPET.

2.2. Sample Preparation: Compounding of the Blends by Flat Press Method

The composites were produced using a flat-press molding facility [12]. It comprises a digital temperature-controlled heater band of 500-watt capacity into which a cylindrical bronze mold (with lid) 80 × 50 mm outside dimension, and tapered internal dimension of 50 × 30 mm was fitted. A hand-operated hydraulic press coupled to a force load cell was applied to the blend and a digital force display was used to monitor the applied force/pressure during compounding. 20 g of each sample (constituting sawdust, rPE and rPET combined in fixed ratios to one another) was weighed. The selection (of 20 g) was based on the volume to weight ratio of the mold cavity. The respective weights of each constituent (sawdust, rPE and rPET) in each sample were therefore calculated based on 20 g total weight. **Table 1** shows the experimental design.

After weighing, the constituents were mixed in a high-speed blender at 6000 Revolutions per minute (RPM) for 5 minutes. Subsequently, the properly mixed material was poured into a bronze mold, whose internal surface was coated with a thin film of graphite, and then fastened to the heater band. The temperature, force and time were set at 125˚C, 3000 N and 30 minutes respectively. Compounding was initiated by turning the start button on the heater unit. The heating rate was set at 25˚C per minute. After about 5 minutes of start-up, a drop in the force was observed indicative of rPE melting. When the force dropped significantly to as low as 500 N, after 10 minutes, a final force of up to 1500 N was applied and left unattended to thereafter to prevent the spilling of the rPE from the mold. The start button was then turned off after the alarm from the timer signaled the expiration of the set 30 minutes and the mold was allowed to cool slowly for 60 minutes, after which the composite was freely removed, facilitated by the tapered internal cavity and the graphite mold wash. Samples of the composites produced are shown in **Figure 2**.

2.3. Experimental Procedures

2.3.1. Determination of Density

The composite blends were carefully weighed to determine their weights. For the determination of their various densities, the formula in (1) was used:

Table 1. Formulation for the various blends of wood sawdust (SD), rPE, rPET C_1 and C_2.

Sample (S_y)	rPE (%)	rPET (%)	(SD) %	Composite (W_xS_y)
S_1	20	70	10	W_1S_1
S_2	20	60	20	W_1S_2
S_3	20	50	30	W_1S_3
Control One (C_1)	20	80	----------	
S_4	40	50	10	W_1S_4
S_5	40	40	20	W_1S_5
S_6	40	30	30	W_1S_6
Control Two (C_2)	40	60	----------	

Note: rPE = Recycled Polyethylene, rPET = Recycled Polyethylened Terephthalate, SD = Sawdust or wood flour derived from the parent wood, W_x = Wood flour or sawdust (SD) of wood one (W_1), wood two (W_2), wood three (W_3), and wood four (W_4). S_y = Samples one to six (S_1 - S_6) of various combination % of rPE, rPET and SD, where subscript y = 1, 2, 3, 4, 5 and 6 e.g. W_1S_1 = Wood 1 sample 1 is the composite made from blending: 20% of rPE + 70% of rPET + 10% of SD (sawdust).

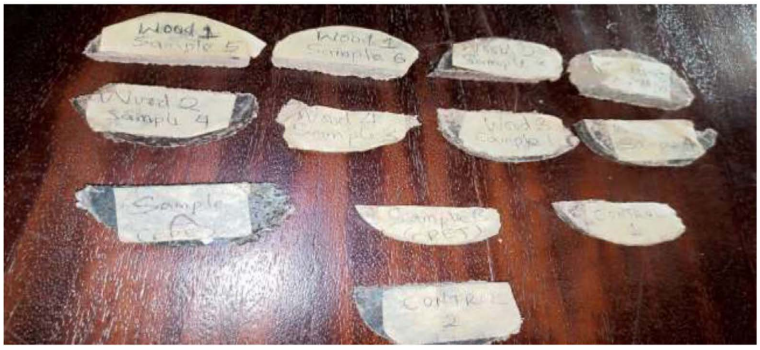

Figure 2. Samples of Some of the composites produced from SD, PE and PET blending.

$$\text{Density} = (\text{weight of sample})/\text{volume} \tag{1}$$

i.e. Density = Weight in grams (g)/Volume in cm^3.

But the formula for the volume of composite was that of a "tapered cone" as shown in **Figure 3**, because of the shape of the mold used in the production of the composite as can be deduced from Section 2.2 on the compounding of the blends [15]. In this case,

$$\text{Volume } (\text{V}) \text{ of composite sample } (\text{V}) = \frac{\pi\left(r^2 + rR + R^2\right)h}{3} \tag{2}$$

where r is the smaller radius of tapered cone in cm^3; R is the bigger radius in **Figure 3** and h is the height of the sample (in cm) in the mold.

2.3.2. Determination of Shore D Hardness

The determination of the hardness properties of composites **[16]** was carried out

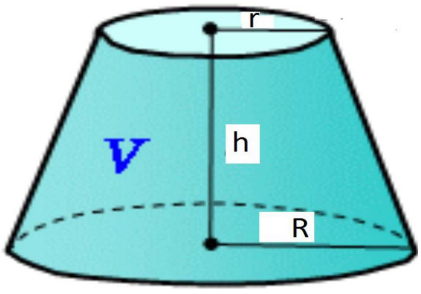

Figure 3. Volume of a tapered cone.

at room temperature using the CV instruments Shore D hardness tester apparatus in accordance with [17]. The applied load was equal to the 50 N and the depressing time of measuring was equal to the 5 s.

2.3.3. Determination of the Flexural Strength of Composites Produced [18]

Samples were cut into specimen of dimensions 30 mm × 11 mm × 9 mm in readiness for the test. The specimens were placed on two parallel positioned anvils and bent via a compression die. The specimen was not allowed to break during the process. The four parameters used were: Load at fracture (F_f), Length of the cross section (width, b), Width of the cross section (thickness, d) and distance between the support points (Span, L). The flexural strength of each composite sample was calculated using:

$$\sigma_{fs} = \frac{3F_f L}{2bd^2} \tag{3}$$

2.3.4. Determination of the Tensile Properties of Composites Produced

The tensile properties (ultimate tensile strength and elongation) were measured using Ametek Universal Digital Tensile Tester, Model EZ250 shown in **Figure 4**. The samples were prepared according to ASTM standards [19]. Raw data of applied forces with the corresponding increases in length were saved in the computer. The ultimate tensile strength and percentage of elongation were subsequently derived. The tensile strength also known as the ultimate tensile strength is the load at failure divided by the original cross sectional area as shown in Equation (4) and (5):

$$\text{Ultimate tensile strength}\left(\text{UTS}\right): \sigma_{\max} = P_{\max} / A_o \tag{4}$$

where $P_{\max}$ = load at failure, and A_o = original cross sectional area.

$$\text{Tensile strength} = \frac{\text{Peak Force } \left(\text{N}\right)}{\text{Width} \times \text{thickness}} \tag{5}$$

2.3.5. Determination of Thickness Swelling of Composites Produced

Six replicates of each composite with dimensions 50 mm × 50 mm were prepared. The specimens were oven dried at 103˚C ± 2˚C for 24 hours and measurements of thickness and weight were obtained. Thickness swelling is calculated as a percentage (%) using the equation,

Figure 4. Ametek EZ 250 universal tensile testing machine.

$$TS(\%) = \left[\left(T_0 - T_i \right) / T_i \right] \times 100 \quad (6)$$

where TS is thickness swelling (%), T_0 is wet thickness after water saturation for 2 until 24 hours (mm), and T_i is oven dried thickness (mm) [20].

2.3.6. Determination of Water Absorption Capacity of Composites Produced

The water absorption capacity at 25˚C and 75˚C was determined by the means of a thermogravimetric analyser (Hi-Res 2950). The WAC of each composite sample was determined with the aid of "Universal Analysis software 2000" and water absorption capacities of the composites determined from the curves.

3. Results and Discussion

The results of the physichomechanical properties viz: density, hardness, flexural strength, ultimate tensile strength, elongation %, and thickness swelling are presented in **Table 2** and **Figures 5-11**.

3.1. Density

The result of the densities of the wood-rPE/rPET composites produced is presented in **Table 2** and shown in **Figure 5** and **Figure 6**, respectively. The results showed that increase in the quantity of wood flour content affected the density of flat pressed WPCs in line with some recent studies [12]. From the results, the composites of *Prosopis africana*, W_4S_2 and W_4S_5 with SD-rPE/rPET mix ratios of 20:20:60 and 20:40:40 respectively, when compared to the other composites, had the two highest densities of 1.058 g/cm^3 and 1.017 g/cm^3 (respectively), while, W_3S_2 (0.801 g/cm^3) and W_3S_3 (0.803 g/cm^3) (composites of *Brachystegia eurycoma*) had the lowest densities. It was observed that the density of the SD-rPE/rPET composites decreased with the increase of SD percentage in the thermoplastic matrices from Sample Two (S_2) in W_1S_2 (0.970 g/cm^3) and W_4S_2 (1.0581 g/cm^3)

Table 2. Formulation for the various blends of wood sawdust (SD), rPE, rPET C_1 and C_2.

Composites	Density, g/cm^3	Hardness	Flexural strength, N/mm^2	UTS, N/mm^2	% Elongation	TS@ 25˚C (mm)	TS@ 50˚C (mm)	TS@ 75˚C (mm)
Wood One								
W_1S_1	0.825	47	0.750	0.791	9.269	0.10	1.24	0.80
W_1S_2	0.970	40	0.699	0.294	13.490	0.14	0.05	0.52
W_1S_3	0.948	30	0.636	2.011	7.995	0.09	1.28	1.18
W_1S_4	0.877	52	4.703	4.327	14.410	1.58	0.14	0.15
W_1S_5	0.899	54	14.100	3.309	26.650	0.08	0.23	0.18
W_1S_6	0.864	48	6.629	3.326	15.600	0.07	0.31	0.22
Wood Two								
W_2S_1	0.936	50	3.066	0.653	10.710	0.05	0.42	0.10
W_2S_2	0.860	43	1.391	0.552	13.100	0.09	0.23	0.13
W_2S_3	0.962	41	0.988	0.644	8.938	0.10	0.18	0.30
W_2S_4	0.831	45	4.070	1.708	11.400	0.13	0.09	0.07
W_2S_5	0.867	45	4.472	2.790	9.552	0.18	0.10	0.07
W_2S_6	0.830	50	2.905	2.036	9.162	0.21	0.25	0.34
Wood Three								
W_3S_1	0.811	43	1.592	0.585	7.044	0.07	0.25	0.19
W_3S_2	0.801	42	2.477	1.676	11.250	0.04	0.15	0.07
W_3S_3	0.803	44	1.471	0.723	14.530	0.1	0.39	0.52
W_3S_4	0.867	49	4.971	1.950	12.024	0.05	0.15	0.15
W_3S_5	0.838	45	2.930	1.554	10.033	0.28	0.15	0.25
W_3S_6	0.924	55	3.189	1.435	10.900	0.3	0.19	0.25
Wood 4								
W_4S_1	0.896	42	1.050	1.286	17.089	0.15	0.5	0.29
W_4S_2	1.058	56	1.975	1.620	7.910	0.2	0.48	0.09
W_4S_3	0.952	48	0.959	0.656	16.240	0.07	0.15	0.29
W_4S_4	0.870	50	0.769	1.169	5.764	0.07	0.59	0.33
W_4S_5	1.017	51	8.035	3.274	11.530	0.08	0.38	0.07
W_4S_6	0.876	47	1.051	0.796	25.180	0.13	0.28	0.10
Plastics								
PE	0.590	46	8.341	5.966	24.490			
PET	1.140	62	19.950	14.820	6.121			
C_1	0.916	46	4.643	1.978	11.170	0.24	0.10	0.26
C_2	0.928	51	11.190	3.557	9.766	0.12	0.03	0.32

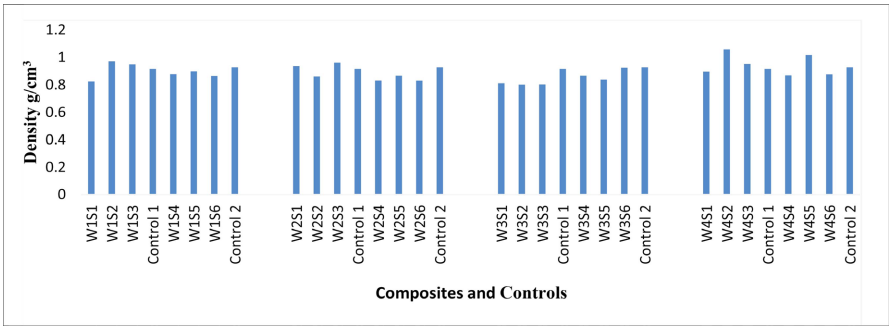

Figure 5. Densities (g/cm³) of the composites of the four woods studied compared with C1 and C2.

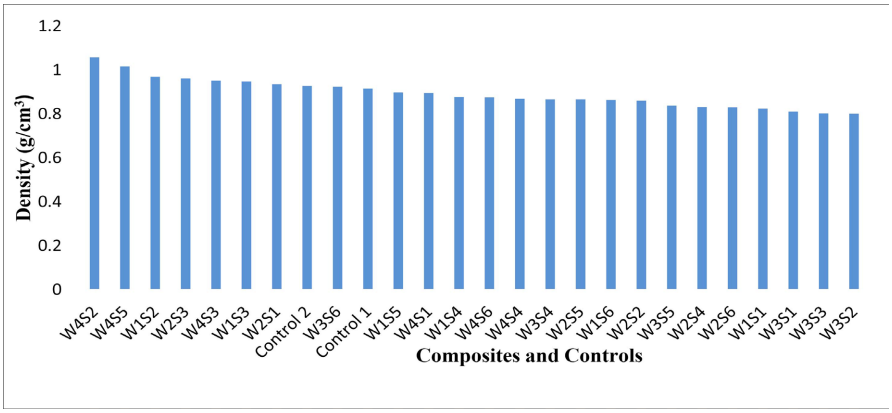

Figure 6. Densities (g/cm³) of the composites of the four woods studied in descending order of magnitude.

to Sample Three (S_3) in W_1S_3 (0.948 g/cm³) and W_4S_3 (0.952 g/cm³) respectively. This trend was also observed in the composites of W_2 and W_3 when going from Sample One (S_1) of W_2S_1 (0.936 g/cm³) and W_3S_1 (0.811 g/cm³) to Sample Two (S_2) of W_2S_2 (0.860 g/cm³) and W_3S_2 (0.801 g/cm³).

The decrease observed in the density of composites with an increase in the percentage of sawdust was in line with the literature which posited that the lower density of sawdust could be the cause of this reduction [4]. This means that the densities of the sawdust were actually enhanced by the plastic matrix which in turn is imparted with some level of biodegradability in line with the need to promote a sustainable environment [21].

In the case of Wood 2, it could be observed from **Figure 5** that all the densities of $W_2S_{1\text{-}3}$ (except in W_2S_2) were above the density of C_1 but the densities of $W_2S_{4\text{-}6}$ were well below the density of C_2. This showed that as the percentage of wood dust increased to 20%, the density also increased up to the optimum point (0.867 g/cm³). However, in Wood Two, 20% rPE (C_1) impacted more on the density of the composites than 40% rPE (C_2) in line with some work done elsewhere [12]. In the case of Wood Three, it was observed from **Figure 5**, that the densities of $W_3S_{1\text{-}3}$ decreased from 0.811 g/cm³ in W_3S_1 to 0.801 g/cm³ in W_2S_2 and finally to 0.802 g/cm³ in W_3S_3. All these values were below that of C_1. For

$W_3S_{4\text{-}6}$, the density decreased from 0.867 g/cm^3 to 0.838 g/cm^3 in W_3S_4 to W_3S_5, but increased to 0.924 g/cm^3 in W_3S_6. Apart from W_3S_6, the densities of W_3 samples were below C_1 and C_2. The relatively higher density observed for $S_{4\text{-}6}$ showed that formulation with 40% rPE impacted more on the densities of the composites than at 20% rPE. With respect to $W_4S_{1\text{-}3}$, it could be observed that the densities of the composites increased from 0.896 g/cm^3 in W_4S_1 to 1.058 g/cm^3 in W_4S_2 and decreased to 0.952 g/cm^3 in W_4S_3. Similarly, in $W_4S_{4\text{-}6}$, the densities of the composites increased from 0.870 g/cm^3 in W_4S_4 to 1.020 g/cm^3 in W_4S_5 and decreased to 0.876 g/cm^3 in W_4S_6. In both formulations, the density increased to the optimum point at S_2 and decreased as more wood dust was added. In Wood Four, the two formulations impacted positively on the density of the composites. Generally, as wood dust increased and rPET content decreased, the density of composites decreased except in W_1S_2. This may be due to poor binding arising from high rPET content in the composite according to some studies [22]. Furthermore, the decrease in the polymer content in the matrix slightly reduced the density values of the composite samples as a result of the viscoelastic behavior of wood fiber since the gaps in the lumens of lignocellulosic materials are crushed/jammed under high pressure and temperature [12]. For $S_{4\text{-}6}$, as wood dust increased, the density of composites also increased to an optimum point. This could be attributed to enhanced binding between wood dust and rPE, at low rPET content [23].

From our discussion so far, it could be observed that the density of the SD-PET/PE composites did not show any consistent pattern of increase or decrease with the increased SD percentage in the thermos-plastic matrices This implies that the increase in SD content alone is not the only factor responsible for impacting on the densities of the composites. Considerations of the chemical compositions of the parent woods from which the SDs were derived and the anisotropic nature of trees could be contributory factors as has been noted in the literature [24]. However, the key factor which is important for the production industry is that all the SD-rPET-rPE composites formulated in this study met the required standards for high density particleboard (>800 kg/m^3) by ANSI standards [25].

3.2. Hardness

Hardness is the ability of a material to maintain its physical features even in the face of applied force. The Shore D hardness values for the composites are presented **Table 2** and shown in **Figure 7** and **Figure 8**.

The results indicated that there was no particular order of increased or reduced hardness. The maximum hardness 56 Shore D was observed in W_4S_2, while minimum material hardness of 30 Shore D was observed in W_1S_3 as shown in **Figure 8**. Increase in material hardness is usually as a result of higher filler to matrix ratio [26], while decrease in material hardness could be as a result of poor adhesion at the interfaces between SD particles and polymer matrixes [27]. In this investigation, the range of values showed a decrease in hardness when compared

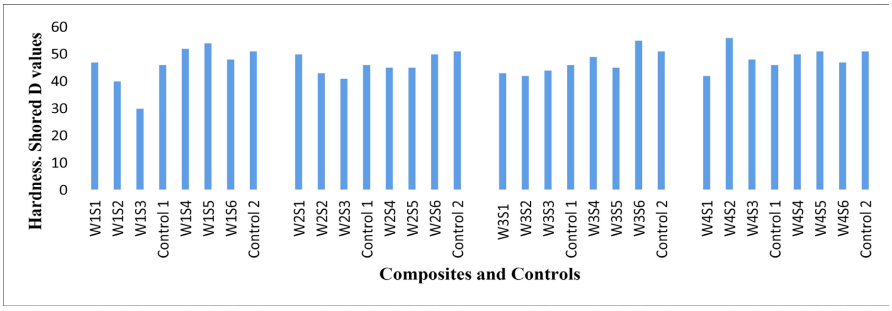

Figure 7. Hardness, shore D values of the composites of the four woods studied compared with C1 and C2.

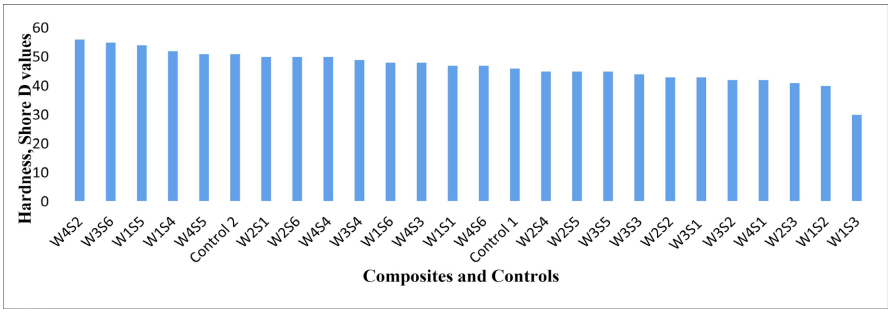

Figure 8. Hardness, shore D values of the composites of the four woods studied compared together with C1 and C2 in descending order of magnitude.

to the values attributed to PET (85-95) and PE (70-80) in the shored D scale as expected because of the incorporation of sawdust from wood [28].

3.3. Flexural Strength

The flexural strength of the composites of all four wood samples and their six different specimens with varying mixture ratio of rPET-rPE-SD are presented in **Table 2** and in **Figure 9** and **Figure 10**. W_1S_5 (14.995 N/mm^2) had the highest flexural strength across all the formulations. Very low flexural strength was observed in majority of other wood samples with W_1S_3 having the lowest value of 0.636 N/mm^2.

The reason for low flexural strength of various composites could be as a result of poor interfacial interaction between the polymeric matrixes and wood particles, not allowing efficient stress transfer between the three phases of the material (Zou, Fan and Chen, 2016) [29]. All composite of rPET-rPE-SD except the 40:40:20 mixed ratio could not produce values close to their respective controls (C_1 had 4.643 and C_2 had 11.192). The results of the investigation showed that the composites of 40% rPE binder gave improved flexural strength than that with 20% rPE. This might be attributed to good dispersion of SD in the rPE/rPET blend (Durmaz, 2022) [12]. The inconsistencies with regard to trends, of the effect on the increase of wood flour with respect to its effect on the bending strength of WPCs have been reported [30]. The variation in flexural strength of the composites was as the result of anisotropic nature of wood such that

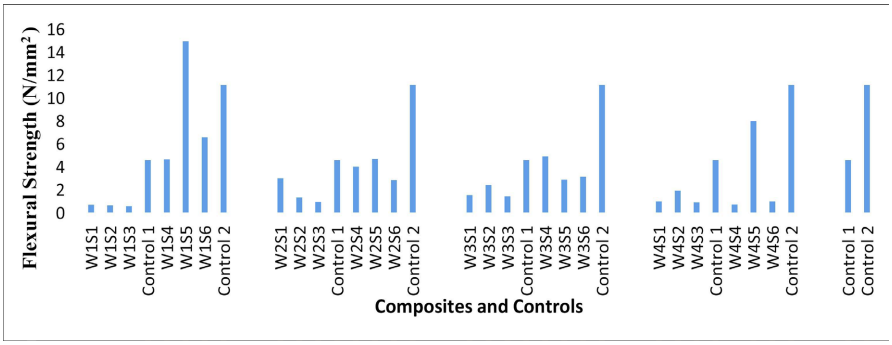

Figure 9. Flexural strengths, (N/mm²) of the composites of the four woods studied compared with C1 and C2.

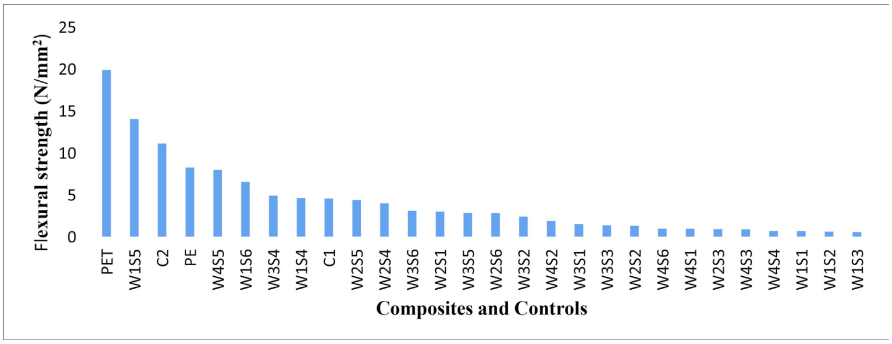

Figure 10. Flexural strength (N/mm²) of the composites of the four woods studied compared with their controls (C1 and C2) and plastic sources rPE and rPET in descending order of magnitude.

after a limit, load cannot be proportional to deformation [31]. Generally, as wood dust increased for $S_{1\text{-}3}$, with relatively higher PET content, flexural strength decreased as reported in some studies (Chaharmahali *et al.* 2008 [8], Ayrilmis and Jarusombuti, 2011 [32]; Durmaz, 2002) [13]. The decrease in bending strength of up to 58% was prominent after 50% of wood flour content, limiting the usability of WPC where high mechanical properties are vital (Durmaz, 2022) 13. Composite of W_2 (W_2S_1) had the best flexural strength at 20/70 rPE/rPET blend (10% wood dust). But at 40/40 rPE/rPET combination, $Wood_1$ (W_1S_5) gave the best flexural strength (14.995 N/mm²). It is worthwhile to note also that W_1S_5 that produced the highest of flexural strength (14.995 N/mm²), also produced the highest value in terms of percentage elongation of 26.65%. This is an indication that with the mixture of 20% SD of wood sample one (W_1) and 40% each of rPET and rPE, the composite will attain a very good flexural strength which is a major mechanical property of composite for resistance to bending. This property could be further improved by the addition of fillers like glass and carbon fibers [33].

3.4. Ultimate Tensile Strength (UTS)

The ultimate tensile capabilities of all six different specimens for all four wood samples under study are indicated in **Table 2** and in **Figure 11** and **Figure 12**

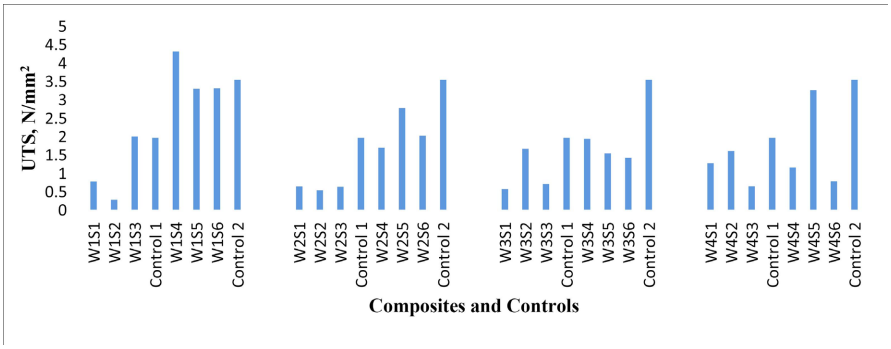

Figure 11. Ultimate Tensile Strength (UTS, N/mm²) of the composites of the four woods studied.

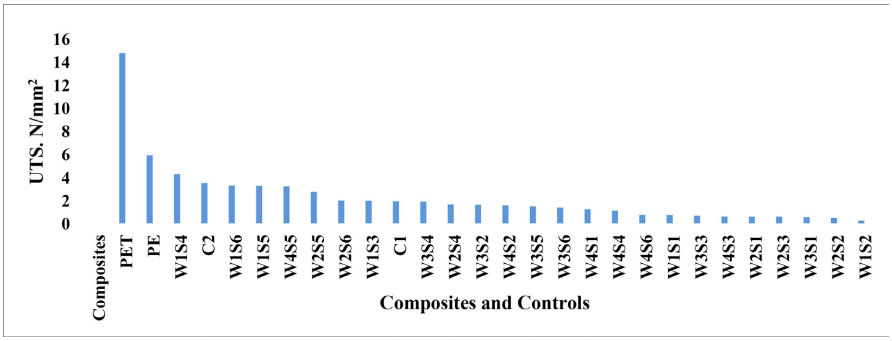

Figure 12. Ultimate tensile strength of the composites of the wood studied compared with C1, C2, PE and PET in descending order of magnitude.

respectively. It was observed that the UTS increased with an increase in both rPE and SD content as has been reported (Manaila, Stelescu, Craciun, and Ighigeanu, 2016) [34]. The UTS could be correlated with the density of composite materials as has been reported [35] With respect to Wood One Composite Samples ($W_1S_{1\text{-}3}$), it was observed that the UTS decreased from 0.99 N/mm² inW_1S_1 to 0.29 N/mm² in W_1S_2 and rose to 2.01 N/mm² in W_1S_3.

For $W_1S_{4\text{-}6}$, the UTS decreased from 4.32 N/mm² in W_1S_4 to 3.31 N/mm² in W_1S_5 and then to 3.32 N/mm² in W_1S_6. In the case of Wood 2 Composite Samples ($W_2S_{1\text{-}4}$), the UTS decreased from W_2S_1 to W_2S_3. For $W_2S_{4\text{-}6}$, the UTS increased from 1.70 N/mm² to 2.79 N/mm². The UTS of Wood 3 Composite Samples ($W_3S_{1\text{-}3}$) increased from 0.58 N/mm² in W_3S_1 to the optimum point of 1.67 N/mm² in W_3S_2, while for $W_3S_{4\text{-}6}$, it decreased from 1.950 N/mm² in W_3S_4 to 1.435 N/mm² in W_3S_6. For Wood Four Composite Samples ($W_4S_{1\text{-}3}$), a similar trend was obtained as in Wood Three ($W_3S_{1\text{-}3}$).

The highest UTS for $W_{1\text{-}4}S_{4\text{-}6}$, was obtained at W_1S_4 (14.32 N/mm²) while the least was 0.29 N/mm² in W_1S_2 (**Figure 11**). The highest value at W_1S_4 (14.32 N/mm²) was 220% greater than C_1 and 122% greater than C_2. Hence, W_1S_4 had the highest ability to withstand tearing due to tension than other wood species. The high value of W_1S_4 (14.32 N/mm²) could be attributed to the enhanced compatibility of 40/50% rPE/rPET and wood dust filler at 10% loading compared to 30% loading.

3.5. Elongation (%)

The results of the percentage elongation of the composites studied are presented in Table 2 and in Figure 13 and Figure 14.

The percentage elongation of these wood composites was generally above that of C_2. The highest percentage elongation for $S_{1\text{-}3}$ was in W_4S_1 (17.08%), which was 16.08% above C_1.

Similarly, the highest percentage elongation for $S_{4\text{-}6}$ formulation was at W_1S_5 (26.84%), which was 174.71% above C_2. This implied that W_1S_5 composite gave the greatest ductility and should have the greatest toughness. This showed that formulation involving 40% PE was superior in ductility than that with 20% PE as a binder. This is in line with the result of the flexural strength experiment discussed earlier in section 3.3. Statistical analysis of data confirmed the prime position of W_1S_5 in the scheme of things as well. The analysis of variance (ANOVA) revealed that there was a statistically significant variation in the wood composites of Wood 1 based on the Physico-mechanical values as the p-value (0.020) obtained was less than the critical level of $\alpha = 0.05$. Hence, to further determine which wood composites significantly varied across the group based on their physico-mechanical values, the multiple comparison test was performed and results obtained showed that W_1S_5 composites are significantly different from W_1S_1, W_1S_2, and W_1S_3 composites with p-value (0.018, 0.009 and 0.001) respectively. Thus, W_1S_5 had a significantly higher proportion of the desired physico-mechanical values compared to other wood composites.

3.6. Thickness Swelling

The results of thickness swelling (TS) are presented in Table 2 and in Figures 15-18.

Overall, it could be deduced that the TS did not follow any particular pattern of increase or decrease based on the ratio of SD-rPET-rPE mixture. The differences observed in TS of the composites can be attributed to variations in blending efficiency, wood percentages, density and pressing condition (Halligan, 1970) [36]. But it was observed that the SD-rPET-rPE composites having lower percentages of rPET-rPE were susceptible to the thickness swelling than those of panels having higher rPET-rPE content. This might be due to the increasing SD content in the WPC formulation.

Ayrilmis *et al.*, 2011 [32] reported that for thickness swelling and water absorption of WPCs, wood fibres were mainly responsible. The TS at room temperature (25˚C) ranged between 0.07 to 0.30 for composites with up to 30% of SD content. Averagely, the lower thickness swelling was found in composite mixtures with the following percentage ratio rPE 20% rPET 60% SD 20%. Wood has a critical surface energy in the range of 40 - 60 ml/m^2 (Gupta *et al.*, 2007) [37] which is higher than that of PET and PE. The large difference in surface energy between PET, PE and wood could make the various composite mixtures become hydrophobic. From the statistical analysis, it was observed that there was

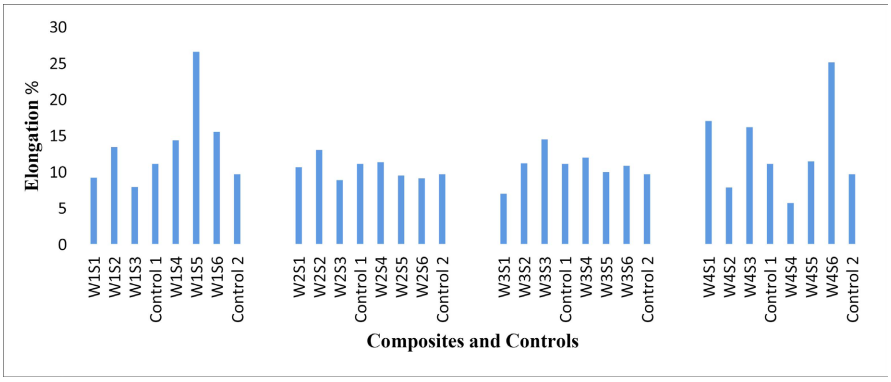

Figure 13. % Elongation of the composites of the four woods studied compared with their controls (C1 and C2).

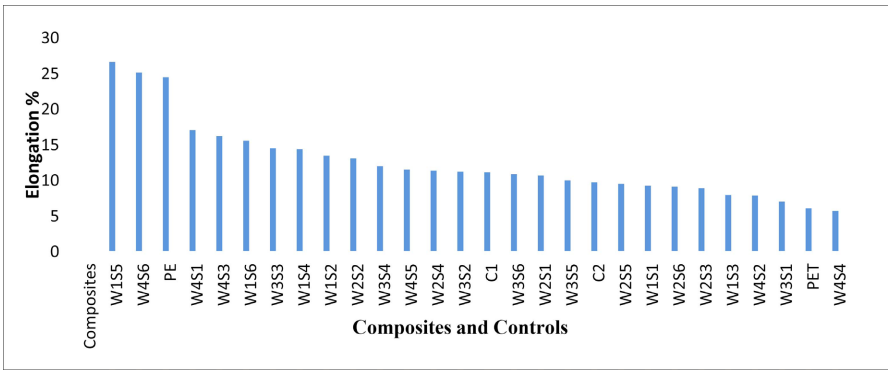

Figure 14. % Elongation of the composites of the four woods studied compared with their C1, C2, PE and PET in descending order of magnitude.

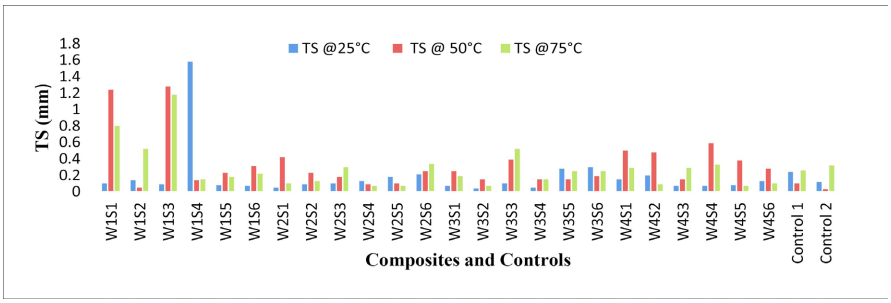

Figure 15. Thickness Swelling (TS) of the composites of the four woods studied compared with their controls C1 and C2).

no significant difference for all samples, that is the composites of Wood One through Wood Four ($W_{1\text{-}4}S_{1\text{-}6}$) at three different temperatures (25˚C, 50˚C and 75˚C) as their p-values were greater than the critical level of $\alpha = 0.05$ respectively.

3.7. Water Absorption Capacity (%)

The results of water absorption capacity of the composites are presented in Table 3 and in Figures 19-21. With respect to the Composites of Wood One ($W_1S_{1\text{-}6}$), it was observed that at 25˚C, WAC of $W_1S_{1\text{-}3}$ increased from 31.40% in W_1S_1 to a maximum of 47.04% in W_1S_2 and then decreased to a minimum of

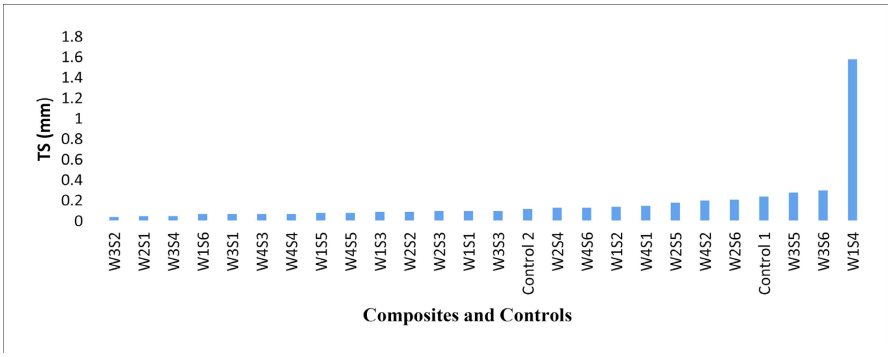

Figure 16. Thickness Swelling (TS) in mm at 25˚C of the composites of the composites of the four woods studied including C1 and C2 in ascending order of magnitude.

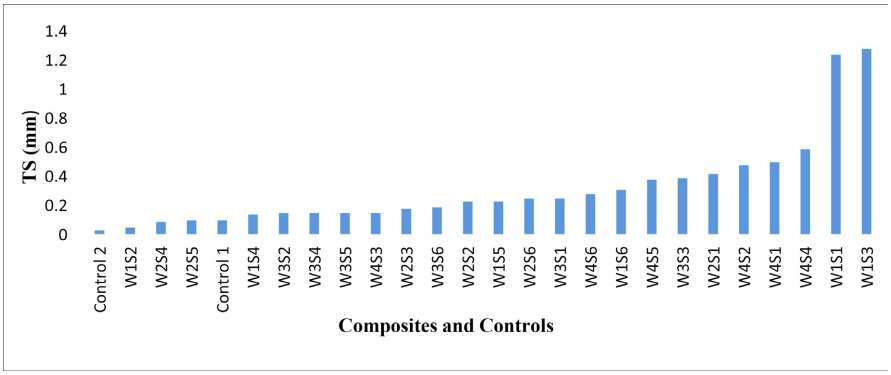

Figure 17. TS (mm) @ 50˚C of the composites of the Four Woods studied including C1 and C2 in ascending order of magnitude.

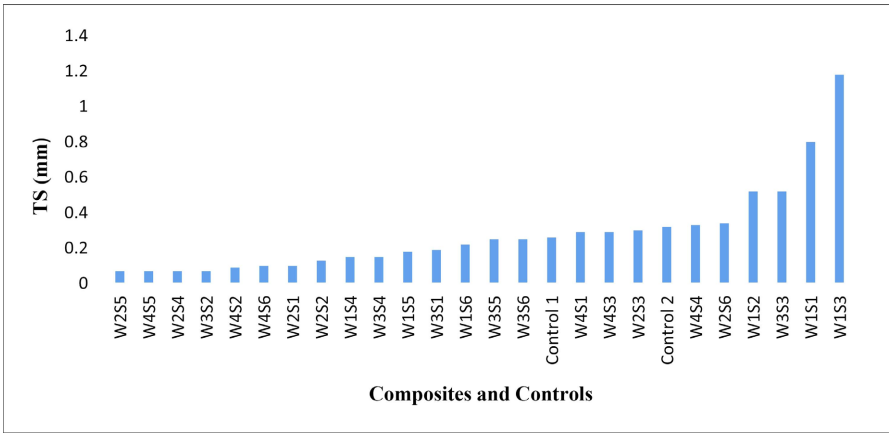

Figure 18. TS (mm) @ 75˚C of the composites of the four woods studied including C1 and C2 in ascending order of magnitude.

26.14% in W_1S_3. A similar trend was observed in $W_1S_{4\text{-}6}$, with a maximum WAC of 23.65% inW_1S_5. The highest water absorption capacity of the composites at 47.04% for W_1S_2 was 66.28% greater than C_1, while that of $W_1S_{4\text{-}6}$ which was highest at W_1S_5 was 16.81% greater than C_2. This shows that the composite containing 20% PE had more WAC and hence may be more porous and more prone to performance problem than the one containing 40% PE. A comparison of

Table 3. Water Absorption Capacity (WAC) of composites studied.

Composite	WAC 25˚C (%)	WAC @ 25˚C (mg)	WAC @ 75˚C %	WAC @ 75˚C (mg)
W_1S_1	31.40%	3.610	38.41%	3.507
W_2S_2	47.04%	5.786	13.29%	1.355
W_1S_3	26.17%	2.091	33.03%	3.570
W_1S_4	7.973%	0.759	12.38%	0.839
W_1S_5	23.65%	2.194	1.732%	0.097
W_1S_6	9.484%	0.468	2.482%	0.111
W_2S_1	26.76%	3.284	23.96%	3.887
$W_2 S_2$	22.36%	2.510	33.64%	4.581
W_2S_3	16.34%	1.224	28.02%	2.553
W_2S_4	21.52%	1.548	15.34%	1.413
W_2S_5	20.13%	2.804	29.92%	3.234
W_2S_6	27.05%	1.752	18.05%	1.355
W_3S_1	24.63%	3.056	33.04%	4.899
W_3S_2	30.15%	4.246	36.42%	5.460
W_3S_3	27.56%	1.426	40.27%	3.867
W_3S_4	1.059%	0.057	9.487%	0.418
$W_3 S_5$	20.27%	1.849	12.44%	0.776
W_3S_6	21.04%	1.440	8.945%	0.689
W_4S_1	40.67%	3.429	24.43%	3.113
W_4S_2	8.621%	0.733	17.40%	1.137
W_4S_3	9.755%	0.397	23.57%	2.132
W_4S_4	3.824%	0.251	29.99%	3.076
W_4S_5	3.937%	0.395	13.68%	1.019
W_4S_6	21.28%	1.470	42.58%	3.233
Control 1	28.29%	3.163	43.64%	4.827
Control 2	19.39%	1.601	9.554%	1.028

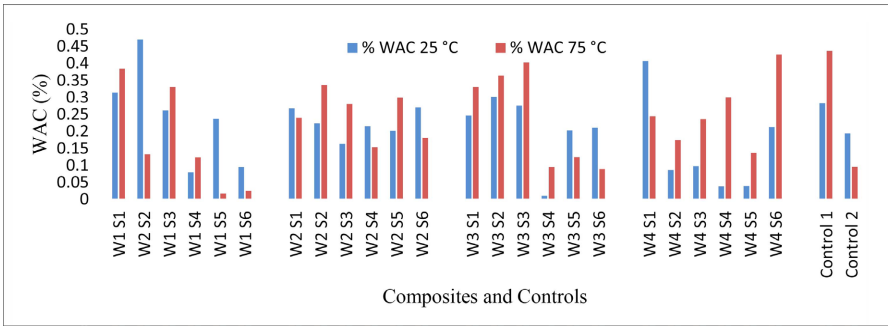

Figure 19. Water absorption capacity (WAC) % at 25˚C and 75˚C of the composites of the four woods studied compared with their controls (C1 and C2).

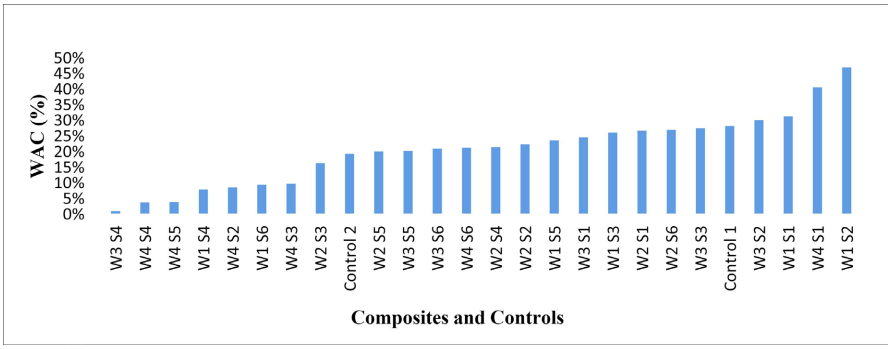

Figure 20. Water absorption capacity (WAC) % at 25˚C of the composites of the four wood studied in an ascending order of magnitude.

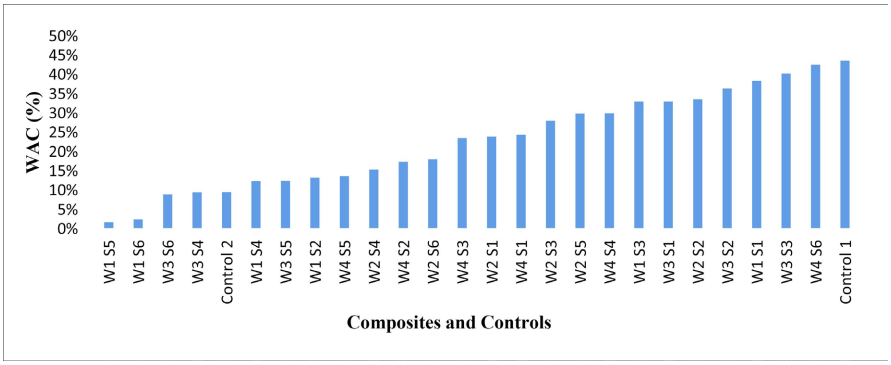

Figure 21. Water absorption capacity (WAC) % at 75˚C of the composite of the four woods studied in an ascending order of magnitude.

water absorption capacity for the composites of the four wood samples at the two temperatures 25˚C and 75˚C studied, showed that at 25˚C for $S_{1\text{-}3}$, the wood dust increased in the composites as the WAC increased with increase in SD in the composites for W_1 and W_3. But for W_2 and W_4, it decreased. Similarly, for $S_{4\text{-}6}$, as the wood dust increased, the WAC of the wood composites also increased for W_1 and W_3 but not for W_2 and W_4.

This showed that the two composite formulations for the wood species gave the same trend in water absorption. At 75˚C, it was observed that for $S_{1\text{-}3}$, as the wood dust increased in the composite, the WAC for composites of W_1 and W_4 decreased while those of W_2 and W_3 increased. The same trend was observed at $S_{4\text{-}6}$ compositions.

The increase in WAC of composites as wood dust increased has been evaluated. It was observed that as wood dust increased with a decrease in the volume fraction of PET, WAC also increased (Atoyebi, Adediran and Adisa, 2018) [38]. WAC of composites of wood tends to increase with wood dust loading because of the structural similarity between water and wood species. The ability of the composites to absorb water is attributed to the hydrophilic nature of SD particles. Wood which is the main content of SD is a hydrophilic porous composite which consists of cellulose, lignin and hemicellulose, polymers that are rich in functional groups such as hydroxyls, which readily interact with water molecules

by hydrogen bonding (Clemons, 2002) [39] and due to this reason, the WPCs have the potential ability to uptake water under humid condition (Adhikary *et al.*, 2008) [40]. On the other hand, the higher water resistance of composites can be attributed to the hydrophobic characteristics of both PE and PET, though they are semi-crystalline in nature. Composite materials are known to degrade when subjected to humid conditions, and therefore the humidity confounds the difficulty of determining the high strain rate behavior of composites. Nevertheless, it was noted that the trend for W_1 and W_2 in WAC with temperature was reversed in the two temperatures (25˚C and 75˚C) studied. However, in W_3 and W_4, such reversals did not occur. The reversal of trend in WAC with temperature may be attributed to a change in the structure of the composites at higher temperatures for W_1 and W_2 but not for W_3 and W_4. Overall, it could be deduced that the WAC did not follow any particular pattern of increase or decrease based on the ratio of SD-rPET-rPE mixture. The highest water absorption content of 47.04% was noticed in W_2S_2 at 25˚C and 42.58% was noticed in W_4S_4 at 75˚C, while the lowest water absorption content of 1.06% was observed in W_3S_3 at 25˚C and 1.73% was observed at 75˚C. Several researchers have found that water absorption by composites brings about a breakdown of matrix dominated quasi-static properties (Woldesenbet, Gupta and Vinson, 2002) [41]. Composites with high water absorption tend to decrease in performance with time (Nayak, Mahato, and Ray, 2016) [42]. In light of this argument, the results as shown in **Figure 20** and **Figure 21** a show indicate that sample W_1S_5 has the lowest water absorptive quality since it has the lowest average value for both 25% and 75% combined and thus could be the best among the rest in performance. Furthermore, this composite could be the most environmentally friendly since studies have indicated that it could have the least carbon footprint in the environment (Duruaku, Ajiwe, Okoye and Arinze, 2016; Duruaku et al., 2023) [43] [44].

4. Conclusion

From the results of this investigation, it could be stated that the densities of all the SD-rPET-rPE composites formulated in this study met the required standards for high density particleboard. It was also noted that the SD-rPET-rPE combination of 20:40:40 was the best formulation in terms of the mixing ratio for the production of flat-pressed WPCs. The composite W_1S_5, which was in this class (SD-rPET-rPE combination of 20:40:40), had on average, the most desirable physicomechanical properties as well as the least C footprint in the environment. These qualities would make this composite formulation derived from the timber species *Nauclea diderichii*, the most suitable for the production of sustainable ceiling boards or floor skirtings from municipal plastic wastes in the wood plastic composite industry.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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