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Assessment of Properties of Composite Boards from Groundnut Shells and Sawdust for their suitability for Structural Applications

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HIGHLIGHTS

- Sawdust and groundnut shells created sustainable composite boards.
- Reusing waste reduces environmental impact.
- Composite boards have superior thermal properties.
- Boards are created inexpensively using waste to protect the environment.

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ABSTRACT

Groundnut shells and sawdust are generated in vast quantities yearly but under-utilized. In developing countries, this situation leads to their disposal by unplanned landfilling, indiscriminate dumping, or open burning as ineffective solid waste management systems persist. Such practices constitute severe environmental problems that need to be urgently tackled. In this work, composite boards were fabricated from groundnut shell particles (GSP) and sawdust particles (SDP) at varying volumetric proportions of 0%, 25%, 50%, 75%, and 100 % using Topbond as a binding agent. The boards were dried completely and then assessed for water absorption, bulk density, thermal conductivity, specific heat capacity, thermal diffusivity, thermal inertia, availability, and flexural strength. The results revealed improvement in the samples' thermal insulation performance as the SDP proportion increased from 0% to 100%. Though samples fabricated with 50 % each of the SDP and GSP exhibited a balance in the thermophysical and mechanical properties, all the samples could ensure better thermal insulation than conventional ceilings such as Isorel and plywood. Generally, the samples can be used as ceiling panels or partition elements in building design. This idea of utilizing groundnut shells and sawdust to develop composite panels for building purposes, as described herein, has been reported for the first time. It could help to ensure the construction of affordable and thermally safe buildings while solving the problems associated with their disposal.

1. Introduction

Shelter (house) is one of the basic needs of humans worldwide. Due to the constant rise in the cost of conventional building materials in recent years [1], there has been a growing interest in fabricating new materials to enhance affordable, sustainable, and thermally-safe housing development. Manufacturing of such materials is possible through the recycling of wastes. Waste is any unwanted item considered or regarded to have no usefulness again. It needs to be disposed of immediately without minding the effects of such disposal practices on the environment [2]. Observably, waste is generated by all sorts of means applied in human activities [3] and in direct proportion with population, socio-economic status, and urbanization level [4]. If this situation persists, municipal solid wastes will possibly increase and reach an overall generation quantity of 3.40 billion tons by 2050, as the World Bank estimates [5]. It is important to know about their properties to ensure that the new materials are selected for suitable applications.

In the agricultural sector, harvesting/processing crops is a typical activity from which various kinds of waste are generated. For example, when groundnut (Arachis hypogaea L.) is harvested and processed, its shells are usually considered waste. Groundnut shells can be used to produce biodiesel [6], bioethanol [7 - 9], enzyme [10, 11], and paper [12 - 14]. Other applications of the shells include the formation of carbon nano-sheet [15], dye degradation [16], preparation of lightweight concrete [17, 18],

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adsorption of heavy metals [19, 20], sculpture-making [21] as well as improvement of crop yields and soil properties [22, 23]. Tiwari [24] observed improvement in groundnut yield from 1095 kg per hectare to 2071 kg per hectare, with the likelihood of increased production from 3.73 million tons in 2018 to 5.1 million tons in 2019. Notably, groundnut is an excellent cash crop grown in more than 100 countries globally. Duc et al. [25] noted, its shell accounts for approximately 20% of the dried pod by weight, meaning that a significant amount is left after processing.

Industrial operations like timber processing generate sawdust as a waste material. In Nigeria, sawmills constitute more than 93% of wood processing industries [26]. Onochie [27] reported that sawmills in Nigeria produce over 1.7 million cubic meters of wood waste yearly. Various applications of sawdust reported in the literature include the preparation of lightweight concrete [28 – 30], the production of non-load bearing blocks [31 – 33], and mortar preparation [34]. Sawdust is used in agriculture for the improvement of soil properties [35, 36], treatment of wastewater [37, 38], calligraphy crafts [39], and as a source of energy for domestic cooking [40]. That notwithstanding, sawdust remains an under-utilized waste because a vast quantity of it is generated annually.

This study has been designed to examine the feasibility of recycling groundnut shells with sawdust into composite panels and assess the suitability of the fabricated materials for structural applications. To the authors' knowledge, no such study design has been reported in the literature. Due to ineffective solid waste management systems in less developed and developing countries [41 - 43], disposal of the aforementioned wastes is predominantly done by unplanned landfilling, open burning, or indiscriminate dumping. Any of these practices pose a serious threat to the environment and public health. Specifically, this work will use groundnut shells with sawdust to fabricate composite panels. Also, the thermophysical and mechanical properties of the developed materials will be evaluated to ascertain their suitability for structural applications. It is hoped that in addition to solving disposal problems, this study's findings would benefit engineers, researchers, material scientists, and manufacturers of building materials.

2. Experimentation

2.1 Materials

Groundnut shells, sawdust, potable water (from bore-hole), Topbond adhesive (General purpose white glue manufactured by PURECHEM Ltd), and a standard US sieve (with 2-mm openings) were some of the materials utilized in this study. Each of the waste materials (groundnut shells and sawdust) was obtained in large quantities within Uyo Local Government Area, Akwa Ibom State, Nigeria, lying between latitude 4^{o}32’’ and 5^{o}33’’ north and longitude 7^{o}35’’ and 8^{o}25’’ East.

2.2 Processing and Analysis of The Waste Materials

The groundnut shells and sawdust were soaked separately in water for 12 hours to remove the accompanying impurities like sand and other forms of dirt from them. After that, they were dried completely in the air before being subjected to pulverization using Agate mortar and pestle. This was followed by screening of each material using the sieve. The quantity of each screened material that passed the sieve was used in this work. Figure 1 shows the appearance of the processed materials (groundnut shell particles and sawdust particles) utilized. A reasonable quantity of each sieved material was analyzed for chemical composition following the method adopted by Mylsamy and Rajendran [44].

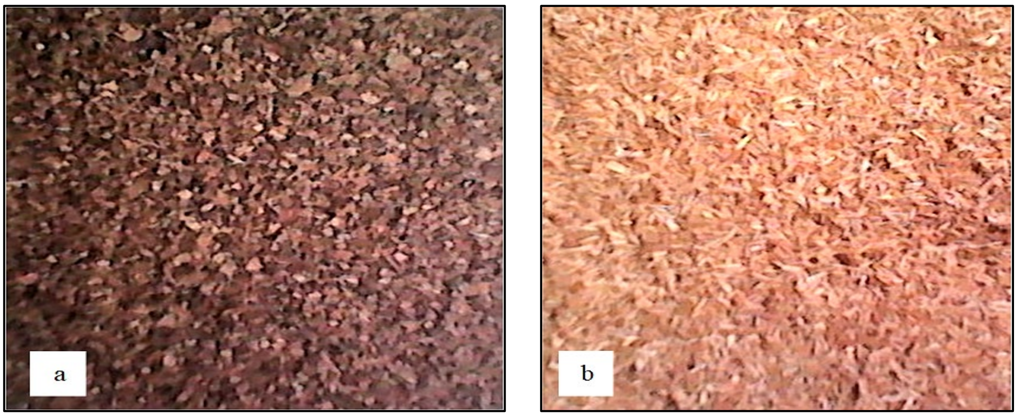

Figure 1: Processed materials (a) Groundnut shell particles (b) Sawdust particles

2.3 Fabrication of Test Samples

The remaining portion of each material was utilized to fabricate composites (test samples) by hand lay-up technique. Table 1 summarizes the proportions of the groundnut shell particles (GSP) and sawdust particles (SDP) adopted for the composite formulations in this research. The Topbond was applied as a binding agent at 25% by volume of each composite mix. Samples prepared for evaluation of thermophysical properties were cast in circular molds measuring 110 mm in diameter and 7 mm in thickness, and those meant for determination of mechanical properties were formed in molds with dimensions 160 mm x 125 mm x 14 mm. The samples were developed in triplicates and compacted using a laboratory-made compacting machine maintained at 5 kN. After 10 hours, they were demolding and then sun-dried to constant weight before being subjected to the various tests intended for them in this work.

Table 1: Composite mix design

Materials	Volumetric fraction (%)				
GSP	0.0	25.0	50.0	75.0	100.0
SDP	100.0	75.0	50.0	25.0	0.0

GSP= Groundnut shell particles; SDP = Sawdust particles

2.4 Properties Investigation

2.4.1 Bulk density and Water absorption

Each sample's mass was measured with a digital balance (S. METTLER – 600g). By using the Modified water displacement method, their respective bulk volumes were determined [45]. The data obtained were then used to compute the required bulk density, ρ thus [4, 46, 47]

$$\rho = \frac{M}{V} \tag{1}$$

where M = sample's mass and V = bulk volume of the sample.

In the case of water absorption assessment, the immersion method was used. The samples were first weighed and then immersed completely in water at 28°C [48]. After 24 hours, they were removed from the water and allowed to surface-dry before they were re-weighed. The data obtained were used to calculate water absorption [49, 50].

$$WA = \left(\frac{M_w - M_d}{M_d}\right) 100 \tag{2}$$

where M_w = mass of the surface-dry sample, M_d = sample mass prior to immersion, and WA = water absorption of the sample.

2.4.2 Specific heat capacity and Thermal conductivity

The specific heat capacity of the samples was investigated with the aid of SEUR'S apparatus [51]. Aluminum plate and plywood plate measuring 60 mm x 60 mm x 8 mm were used with the sample plate as heat exchange accessories. For temperature monitoring/measurement, three digital thermometers (Model No. 305, calibrated and equipped with a type-K probe) were employed. When the system attained thermal equilibrium during the heat exchange, the quantityQ_p of heat gained by the plywood plate and the amount Q_a of heat lost by the aluminium plate were calculated. Using the data obtained, the specific heat capacity, C was determined based on the relation.

$$C = \left(\frac{Q_a - Q_p}{M\Delta T}\right) \tag{3}$$

where ΔT = temperature rise of the sample under test.

In the case of thermal conductivity determination, Modified Lee – Charlton's Disc Apparatus Technique was used as detailed elsewhere [52]. An electric hotplate (Lloytron E4102WH) was employed as the heat source, and the cooling rate was modeled with the aid of Origin Software (Version 2019). The data obtained were applied to compute the required thermal conductivity, $k$as [53]

$$k = \left(\frac{Mcx}{A\Delta\theta}\right)\frac{dT}{dt} \tag{4}$$

ere M = mass of the disc, c = specific heat capacity of the disc, x = thickness of the sample, A = area of the sample's cross-section, $\Delta\theta$ = temperature across the sample's thickness and $\frac{dT}{dt}$ = rate of cooling of the disc.

2.4.3 Thermal diffusivity and Thermal inertia

The values obtained for each case's bulk density, specific heat capacity, and thermal conductivity were used to determine the samples' corresponding thermal diffusivity and thermal inertia. In the case of thermal diffusivity, the formula adopted for its calculation was [54 - 56]

$$\lambda = \frac{k}{\rho C} \tag{5}$$

where λ = thermal diffusivity of the sample

Also, the corresponding thermal inertia of the samples was obtained using the formula [46]

$$e = \sqrt{k\rho C} \tag{6}$$

2.4.4 Nailability and Flexural Strength

Nailability expresses the ability of a material to withstand nailing. In this study, the test for the nailability of the samples was performed with the aid of a carpenter's hammer and a 50-mm nail. The nail was driven with a hammer blow into the sample under test. The process was discontinued immediately when the sample developed a sign of a visible crack, or the nail penetrated it successfully. At that instant, nailability was computed as [57]

$$\cap_b = \left(\frac{h}{x}\right) 100\% \tag{7}$$

where $\cap_b$ = nailability of the sample, and h = depth of nail penetration in the sample, and x = thickness.

A Computerized Electromechanical Universal Testing Machine (WDW – 10) was used to obtain data for the determination of the flexural strength of each sample, and a three-point bending technique was adopted as outlined in the standard procedure [58]. During each test schedule, a test sample was placed on the flexure assembly of a machine and then loaded in the middle of the support span at a test speed of 1mm/min until the sample failed flexurally. At that instant, the maximum value of the load, P applied was used with the values of span length, L, sample's width, b, and thickness, x to compute the flexural strength, σ thus [57]

$$\sigma = \frac{3PL}{2bx^2} \tag{8}$$

All the samples were subjected to the tests intended for them in this work. The tests were performed at room temperature (with ± 1.0ºC variations). The results obtained for the triplicates were averaged for each formulation and tabulated with their corresponding standard error values.

3. Results and Discussion

3.1 Chemical Composition of The GSP and SDP

The results of the chemical composition analysis performed on the GSP and SDP are presented in Table 2, showing the proportions of various lignocellulosic constituents of the fibers. The cellulose, hemicelluloses, and lignin fractions in GSP are less than 10.81%, 3.55%, and 10.93%, respectively, compared to their percentages in the SDP. This simply portrays the fact that their degree of affinity for water is not the same.

Table 2: Chemical composition of the materials

Materials	Values for five determinations		
	Cellulose (%)	Hemicellulose (%)	Lignin (%)
GSP	38.02 ± 0.11	26.74 ± 0.16	19.21 ± 0.34
SDP	42.13 ± 0.25	27.69 ± 0.41	21.31 ± 0.29

3.2 Water Absorption Results

The results of the tests for thermophysical and mechanical properties carried out on the samples are presented in Table 3. Water absorption of the samples varies positively with the proportions of the SDP used. This may be because more cellulose is present in the SDP compared to the GSP. Meanwhile, the cellulose component of fiber is very hydrophilic [26], so as its proportion increases, the affinity of the fiber for water also increases. Even at that, the maximum mean value of water absorption obtained for the samples (31.04%) is far less than the standard upper limit (75%) stipulated for particleboards [59].

3.3 Bulk Density and Thermal Conductivity Results

It can also be seen that the sample made with 100% SDP has a lower bulk density than its counterpart fabricated using the GSP. Since the total volume of composite mix and fabrication conditions were maintained, SDP is lighter than GSP (though the lightness in this case is about 6.25%). Based on the classification standard for particleboards as outlined in [60], the samples (except the one containing 100% of the SDP, being of the least bulk density value) may be regarded as medium-density panels.

A sample with 100% SDP has a lower thermal conductivity value than its counterpart prepared using the GSP. There is a slight difference (about 2.76%) between their thermal conductivity values in this case. Because the samples are porous and completely dry, utilization of the SDP increases the volume of still air in the resulting sample. Since air is a good thermal insulant, the sample can restrict heat transmission more effectively than the similarly fabricated sample with the GSP. However, the mean values of thermal conductivity obtained for all the samples in this research fall between 0.023 Wm-1K-1 and 2.900 Wm-1K-1, the range recommended for heat-insulating and construction materials [61]. It can be deduced in this case that the highest mean thermal conductivity value (0.1632 Wm-1K-1) obtained for the samples is 94.37% less than the least acceptable thermal conductivity value for construction materials suitable for thermal insulation.

Gesa et al. [62] reported that conventional ceilings and/partition panels like Isorel and plywood have bulk densities of 898.25 kgm-3 and 589.47 kgm-3 with thermal conductivity of 0.4498 Wm-1K-1 and 0.1768 Wm-1K-1 respectively. Comparatively, this work's sample with the greatest bulk density is lighter than both conventional materials. Thus, the sample prefers selection and application as ceiling or wall partition material in buildings. This submission is supported by Hirst et al. 's [63] assertion that applying light materials in building design is advantageous. This is because such an undertaking can help reduce the weight of a building envelope by absorbing dead loads [64]. For thermal insulation, it can be deduced that among the studied samples, the most thermally conductive can retard heat by 63.72% and 7.69% better than the Isorel and plywood, respectively.

Figure 2 reveals that the samples' bulk density and thermal conductivity trend directly with each other but inversely with proportions of the SDP. This, plausibly, is because incorporating more SDP into the composite mix increases the volume of still air, thus leading to increased lightness and thermal insulation tendency of the samples. A similar observation was noted by Etuk et al. [46] in their study on heat transfer and mechanical properties of Saccharum Officinarum leaf boards.

3.4 Specific Heat Capacity and Thermal Diffusivity Results

Exposure of ceilings to photothermal heating is inevitable in building design. In this case, the results reveal thatincorporating more SDP into the composite mix yields a sample that can store more heat before the temperature of its unit mass changes by one Kelvin. At 25%, 50%, 75%, and 100% levels of SDP loading, the respective increment in the mean specific heat capacity value plays a critical role in influencing the thermal diffusivity of the samples. As seen in this case, thermal diffusivity decreases with increasing fractions of the SDP. This means that the speed at which the stored thermal energy diffuses within the samples and propagates temperature variation across the thickness of each sample can be lowered by increasing the SDP content in the composite mix.

3.5 Thermal Inertia Results

The thermal inertia value obtained for the samples further substantiates the submissions on their thermal diffusivity. For instance, an increase in the proportion of the SDP from 0% to 100% reduces the mean value of thermal inertia from 354.0 $Jm^{-2}K^{-1}s^{-½}$ to 346.1 $Jm^{-2}K^{-1}s^{-½}$, respectively. This shows a reduction in the resulting samples' tendency to release the absorbed heat to the surroundings readily. The average value of the thermal inertia of ceiling boards made from sugarcane leaves is 161.633 $Jm^{-2}K^{-1}s^{-½}$ [46]. As per this value, it can be deciphered that the samples in this study could exhibit better efficiency in heat retention and reluctance to share the same if applied as ceilings or wall partition panels in building design.

Table 3: Results of the thermophysical and mechanical tests

Composite mix (%) GSP:SDP	Water absorption, WA(%)	Bulk density, $\rho(kgm^{-3})$	Thermal conductivity, $k\ (Wm^{-1}K^{-1})$	Specific Heat capacity, $C\ (Jkg^{-1}K^{-1})$	Thermal diffusivity, $\lambda\ (10^{-7}m^2s^{-1})$	Thermal inertia, $e\ (Jm^{-2}K^{-1}s^{-1/2})$	Nailability, $\cap_b$ (%)	Flexural strength, $\sigma\ (N/mm^2)$
7.5	28.72 ± 0.04	526.8 ± 0.3	0.1632 ± 0.0008	1457.5 ± 0.2	2.126 ± 0.002	354.0 ± 0.1	100.0 ± 0.0	3.82 ± 0.03
25:75	29.01 ± 0.04	520.6 ± 0.2	0.1627 ± 0.0005	1474.1 ± 0.3	2.120 ± 0.002	353.4 ± 0.2	100.0 ± 0.0	3.52 ± 0.03
50:50	29.97 ± 0.03	512.9 ± 0.2	0.1606 ± 0.0004	1481.7 ± 0.2	2.116 ± 0.001	349.6 ± 0.4	100.0 ± 0.0	3.24 ± 0.04
75:25	30.68 ± 0.05	505.7 ± 0.3	0.1595 ± 0.0004	1495.6 ± 0.2	2.109 ± 0.002	347.3 ± 0.2	100.0 ± 0.0	2.69 ± 0.02
0:100	31.04 ± 0.03	493.9 ± 0.2	0.1587 ± 0.0007	1528.1 ± 0.3	2.103 ± 0.002	346.1 ± 0.2	100.0 ± 0.0	2.18 ± 0.03

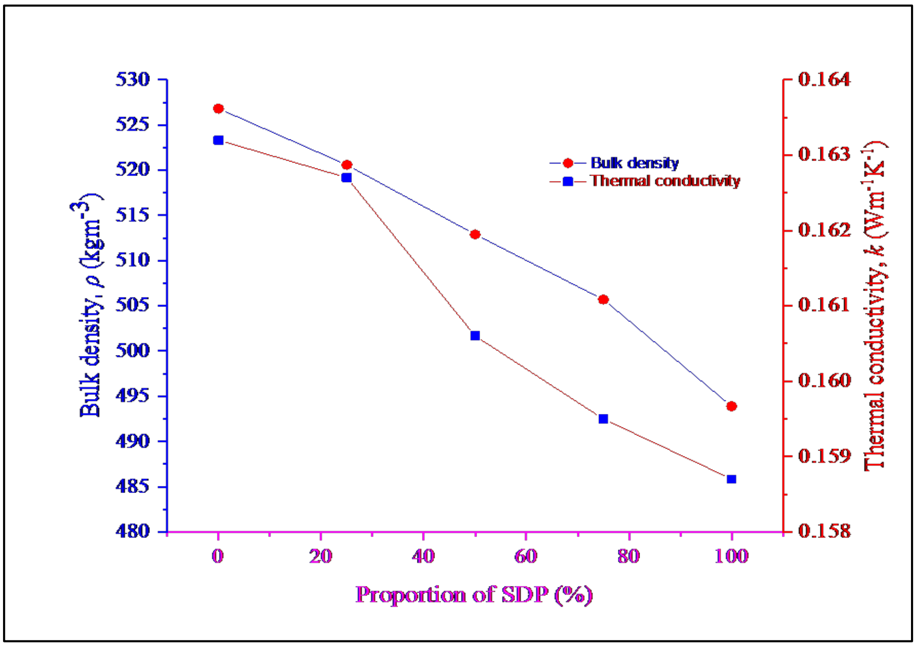

Figure 2: Trends of bulk density and thermal conductivity with proportions of SDP

3.6 Nailability and Flexural Strength Results

Irrespective of the composite mix design adopted in this research, the results of the nailability test reveal that all the samples can be nailed successfully. This suggests that the binder and its concentration (as used) can ensure adequate bonding of the fiber particles. Ekpenyong et al. [55] reported 100 % nailability for composite ceiling/wall partition panels fabricated by utilizing at least 50% of treated groundnut shell particles with untreated groundnut shell particles in the composite mix and cassava starch slurry as a binding agent.

In the case of flexural strength, the values differ depending on the loading levels of the SDP in the developed samples. With 100% content of the GSP, the sample developed exhibits the greatest ability to withstand bending stress. A steady decrease is observed as a proportion of the SDP increases Figure 3. This implies that the GSP and SDP differ in the degree of their effect on the interfacial bonding ability of the binder, as the latter could cause a weakening of the strength of the resulting sample. At a 75% level of SDP utilization, the flexural strength obtained for the samples compares well with the mean flexural strength value of 2.639 MPa reported for clay samples modified with a 10% fraction of Portland Limestone Cement (PLC) for building purposes [65]. Interestingly, all the values of flexural strength obtained in this work exceed the maximum value (0.1 N/mm^2) reported for rice husk-waste paper composite ceiling boards [66], let alone the value of 0.05 N/mm^2 reported by Obam [67] in the case of composite ceilings made from sawdust, paper, and starch.

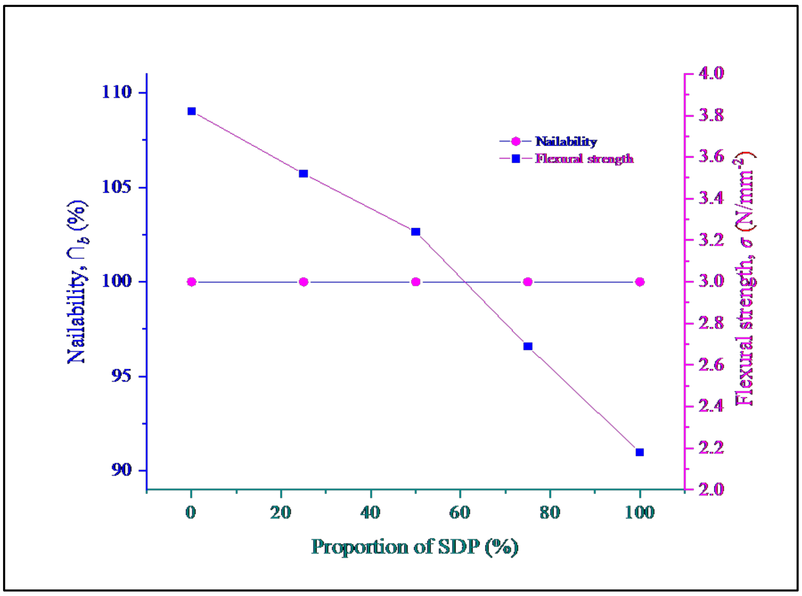

Figure 3: Trends of nailability and flexural strength with proportions of SDP

4. Conclusion

A composite of groundnut shell particles (GSP) and sawdust particles (SDP) based on Topbond as a binder was introduced with five volume proportions (0%, 25%, 50%, 75%, and 100%) of each fiber. Thermophysical and mechanical properties were investigated. It was found that:

1) The thermal insulation capability of the samples improved with increased SDP content while flexural strength trended oppositely, and nailability remained 100%. The sample with 50% content of each fiber tended to balance the investigated properties if used as ceiling or wall partition material.
2) The least mean bulk density value (493.9 kgm-3) was obtained for the sample developed with the SDP at 100% level, and other samples could be regarded as medium-density panels.
3) For application as heat-insulating ceilings in building design, samples can perform better than commonly used conventional ceilings like Isorel and plywood.

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Author contributions

Conceptualization, E. Nathaniel; methodology, G. Umoren.; validation, C. Akaolisa; formal analysis, S. Akpan; investigation, G. Umoren; resources, N. Ekpenyong, N. Ekpenyong and O. Yawo.; data curation, S. Akpan.; writing—original draft preparation, N. Ekpenyong, C. Akaolisa and N. Ekpenyong.; writing—review and editing, N. Ekpenyong, G. Umoren, S. Akpan and O. Yawo.; visualization, C. Akaolisa; supervision, O. Yawo and N. Ekpenyong; project administration, N. Ekpenyong. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data supporting this research's findings are available on request from the corresponding author.

Conflicts of interest

The authors have no financial interests, either directly or indirectly, in the work that is being submitted for publication.

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