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PAPER – SAWDUST COMPOSITES: FABRICATION AND COMPARISON IN TERMS OF HEAT TRANSFER AND STRENGTH PROPERTIES

KOMPOZYTY PAPIEROWO-TROCINOWE: WYTWARZANIE I PORÓWNANIE WŁAŚCIWOŚCI CIEPLNYCH I WYTRZYMAŁOŚCIOWYCH

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Abstract

This study was designed to examine the feasibility of recycling cassava effluent, sawdust, and unused paper products to enhance their utilization for beneficial purpose. Waste newspaper paste (WNP), Waste writing – paper paste (WWP), and Waste carton paper paste (WCP) were prepared and then used separately to similarly fabricate composite panels with Sawdust particle (SDP) proportioned at 0%, 25%, 50%, 75%, and 100% by weight. The binder used was cassava starch slurry prepared from the effluent. Bulk density, water absorption, thermal conductivity, specific heat capacity, thermal diffusivity, nailability, and flexural strength were determined for the developed samples. From the results obtained, the samples were found to be light-weight and their thermal insulation performance improved with increasing proportions of the SDP. Though samples containing the WCP exhibited the best satisfactory performance, it was found that all the studied samples could perform more effectively and efficiently as ceilings compared to some of those reported in the literature. From scientific-economic viewpoint, valorizing the above-mentioned wastes as described in this paper could help to protect the environment and also yield value-added insulation ceilings for enhancement of sustainable building construction especially in tropical areas.

Keywords: Cassava Effluent, Ceiling, Flexural strength, Nailability, Thermal conductivity, Water absorption

Streszczenie

Celem pracy było określenie możliwości recyklingu ścieków z manioku, trocin i odpadowych materiałów papierniczych w celu ich szerszego wykorzystania. Nitki z makulatury gazetowej (WNP), nitki z makulatury z papieru do pisania (WWP) i nitki z makulatury z kartonu (WCP) zostały przygotowane, a następnie użyte osobno do wytworzenia paneli kompozytowych z dodatkiem trocin (SDP) przy udziale masowym 0%, 25%, 50 %, 75% i 100%. Zastosowanym spoiwem była przygotowana z odcieku zawiesina skrobi z manioku. Dla przygotowanych próbek określono gęstość nasypową, nasiąkliwość, przewodność cieplną, ciepło właściwe, dyfuzyjność cieplną, zdolność do wbijania gwoździ i wytrzymałość na zginanie. Na podstawie uzyskanych wyników stwierdzono, że próbki miały małą gęstość objętościową, a ich właściwości termoizolacyjne poprawiały się wraz ze wzrostem udziału trocin (SDP). Chociaż próbki zawierające WCP wykazywały najlepsze właściwości, stwierdzono,

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że z wszystkich badanych próbek można wytworzyć sufity o lepszych właściwościach w porównaniu z podobnymi opisanymi w literaturze. Z naukowo-ekonomicznego punktu widzenia zastosowanie wyżej wymienionych odpadów, jak opisano w tym artykule, może pomóc w ochronie środowiska, a także w uzyskaniu bardziej ciepłochronnych stropów, a co za tym idzie przyczyni się do rozwoju bardziej zrównoważonego budownictwa, zwłaszcza w obszarach tropikalnych.

Słowa kluczowe: ścieki z manioku, strop, wytrzymałość na zginanie, zdolność do przybijania gwoździ, przewodność cieplna, absorpcja wody

1.INTRODUCTION

In recent years, there has been a rapid increase in the engineering applications of hybrid composites. This is because hybridization enables such composites to exhibit versatile properties (like high strength, low weight, ease of manufacturing, and so on) that none of the components possesses. In such undertaking, synthetic fibers are frequently utilized. Nevertheless, some factors including high density, non-biodegradability, non-recyclability and increase in cost [1] raise serious concerns about the use of synthetic fibres as reinforcers for development of hybrid composites for various engineering applications. According to Mahir et al [2], natural fibers have been proven alternative to synthetic fiber in transportation such as automobiles, railway coaches and aerospace, military, building, packaging, consumer products, and construction industries for ceiling paneling, partition boards, etc. Since natural fibers are promising enough to address the mentioned challenges and are also cheaply available and sustainable, there is an urgent need to shift attention to their utilization with the aim of replacing synthetic ones. On the strength of this consideration, recycling natural fiber into hybrid composites could help to improve the economy of a country while becoming a safe technique of managing the wastes in order to ensure sustainable development.

Wastes may be defined as the by-products of human activities regarded to have become useless and as such, remain unwanted and desperately crying for immediate disposal. Sanandiya et al [3] posited that urban residents generate wastes four times greater in quantity than their rural counterparts. These wastes emanate from various sources/sectors and are made up of different kinds of materials. For instance, between 25% and 40% of municipal solid wastes generated worldwide consist of paper and paper products [4]. Also, in wood working sectors, sawdust is constantly produced as waste during wood processing [5] and every 1,000 kilos of wood processed generates almost 40% to more than 52% of sawdust [6]. In Nigeria, about 1.8 million tons of sawdust are produced annually [7]. Not only that, in 2017, Food and Agriculture Organization Statistics (FAOSTAT) showed that among the 100 countries that collectively produced 291,992,646 tons of cassava (*Manihot esculenta*) in the world, Nigeria was the largest producer with capacity of 59,485,947 tons. More so, a moderate growth in production is a recurring trend in subsequent economic years. Processing of cassava into assorted useful items (like garri, flour, fufu, tapioca, etc for consumption) usually generates some solid and liquid wastes, among which the most prominent is the effluent (wastewater). Between 6 tons and 8 tons of cassava tubers supplied daily, 3 m^3 to 6 $m^3$of the effluent could be generated during cassava processing [8].

Findings from some studies have revealed that the aforementioned wastes could be used for certain beneficial purposes. For example, starch derived from waste generated during cassava processing is a promising raw material for preparation of binders that are suitable for use as coating materials [9, 10] and in tablet formulations [11, 12]. Slurry prepared from cassava effluent can be utilized in recycling of periwinkle shells, Clam shells and Oyster shells into disc-shaped compacts for electrical/electronic applications [13-16]. In their study, Okeyinka and Idowu [17] reported that ceiling boards produced from a mixture of waste paper and $CaCO_3$ compare well with asbestos ceilings. Aside that, briquettes [18], wood-plastic composites [19, 20], wood-cement composites [21] and reinforced epoxy composites [22, 23] produced with sawdust exhibit satisfactory performance tendencies.

It has been observed that wastes generation is an intrinsic part of human existence and its rate is a function of growth in urbanization. As noted by Kaza et al [24], the World Bank estimated a drastic increase in the amount of global municipal solid waste generation from today's 2.01 billion tons to 3.40 billion tons by 2050. From a careful consideration of the present situation, there is no doubt that the said wastes volume may continue to accelerate throughout this century. In Nigeria and other developing countries, waste management system is ineffective and so, the prevalent habit of getting rid of the wastes in question is by burning in an open space or indiscriminately discharging them into water ways. These practices are detrimental to environment and public health in diverse ways. For example, diseases can be spread from dumpsites, atmosphere can be polluted with large amount of greenhouse gas and soil productivity can be affected through release of phenol compound into the soil. Since wastes can become eco-toxic if not handled properly, this work focuses on tailoring sawdust with some types of waste paper materials into green hybrid composites using cassava starch slurry (derived from effluent) as binder. In order to determine the suitability of the new materials for engineering applications, their heat transfer and strength properties will be investigated. Interestingly, this paper will be the first to provide scientific information on such attempt so as to address the dearth in the literature of studies on uses of the wastes.

2. EXPERIMENTAL DESIGN

2.1. Materials collection and Description

In this study, cassava effluent, newspapers, writing papers, cartons and sawdust discarded as waste materials were utilized. The cassava effluent was collected from local cassava processing units whereas the sawdust (heterogeneous) was obtained from sawmills. Also, the newspapers, writing papers, and cartons were picked from dumpsites in markets and schools. These materials were sourced in large quantities within Uyo Metropolis, Akwa Ibom State, Nigeria.

2.2. Processing of the materials

The cassava effluent was put in a plastic bucket and allowed to remain undisturbed for 24 hours before the residue (starch) was recovered by decantation. After that, the starch was sun-dried until it became powdery and moisture-free. Also, the waste newspapers, writing papers, and cartons were segregated and then cleaned with brush to ensure that they were free from any accompanying impurities. Each of them was cut into tiny pieces by means of scissors. The pieces obtained in each case were soaked separately in warm water for 24 hours. On removal, the soaked materials were strained to remove excess water from them before they were pound into paste, one at a time, using Agate mortar and pestle. The paste of each material was subjected to continuous sun-drying and weighing until no further reduction in mass was observed. More so, the as-collected sawdust was soaked in water at 24^{o}C for 20 seconds in order to remove sand and other unwanted materials from it. This was followed by complete sun-drying of the sawdust before it was communited. Figure 1 shows the dumpsite as well as dry forms of the processed materials.

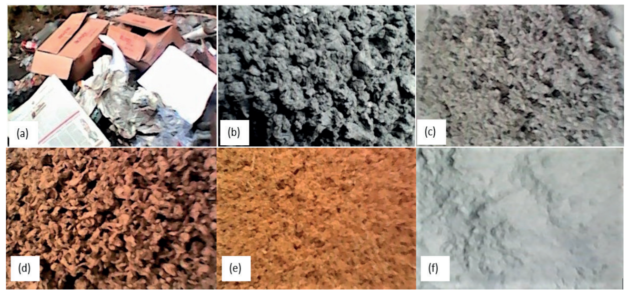

Fig. 1. A dumpsite (a) Waste newspaper paste (b) Waste writing-paper paste (c) Waste carton paste (d) Sawdust particle (e) Cassava starch (f)

2.3. Analysis of the processed materials

For the purpose of evaluating flowability of the as-prepared cassava starch, its Carr's compressibility index was determined as per the standard protocol outlined in [25] and its static angle of repose was measured using fixed funnel method [26]. Sieve analysis was carried out [27] to determine the particle size distribution of the sawdust and the quantity that passed through 2.36 mm openings was utilized in this work. The sieved sawdust and each of the prepared pastes were divided into two portions. In each case, one portion was analyzed for quantification of lignocellulosic components by adopting gravimetric method [28]. Each analysis was performed three times before the mean value and standard error in the results were computed.

2.4. Composites fabrication

The remaining portion of each material was used to fabricate various composites by hand lay-up technique. Each paste was used separately to form composites with various loadings of the sawdust particles. The same loading fractions were applied in all the cases and cassava starch slurry was used as binding agent. This was prepared by continuously stirring and heating a 14% solution of the starch until it became gummy, after which it was allowed to cool completely. Throughout the formulation processes, 1:1 weight ratio of the binder to composite mix was maintained. While the composites meant for flexural strength and nailability tests were cast in a mold measuring 100 mm x 30 mm x 10 mm, those meant for other tests were formed in a circular mold of diameter 110 mm and thickness 9 mm. Compaction was performed by means of a laboratorymade compacting machine maintained at 5 kN for 24 hours. The composites were prepared in triplicates per formulation. Prior to properties investigation, the developed composites were allowed to dry completely in air before they were subjected to the tests intended for them in this study.

2.5. Property tests

2.5.1. Thermal conductivity

This transport property of a material was examined for each of the test samples by using Modified Lee-Charlton's Disc Apparatus Technique as described in details elsewhere [29]. The experimental set-up used consisted of two identical discs (made from nickel, each measuring 110 mm in diameter and having thickness of 10 mm) and a cylindrical aluminum block [30]. In this study, an electric hotplate (Model Lloytron E4102WH) was used as the heat source. The control dial of the hotplate was adjusted to ensure that the temperature of the disc that supplied heat to the sample was maintained at 98°C. Until steady state was reached, temperature monitoring and measurement were done by means of two digital thermometers (Model 305, properly calibrated) each equipped with type-K probe. Temperature – time models were developed using Microsoft Excel Curve Fitting and with coefficient of determination of at least 0.9998. In each case, the rate of cooling was determined by application of differentiation and then used to compute the corresponding value of thermal conductivity in accordance with Fourier's law equation for one-dimensional heat conduction as:

$$k = \left(\frac{M_d C_d x}{A\Delta\theta}\right)\frac{dT}{dt} \tag{1}$$

where: k – thermal conductivity, M_d – mass of the upper disc, C_d – specific heat capacity of the disc, x – of the sample, A – cross-sectional area of the sample, $\Delta\theta$ – temperature difference across the sample's thickness, $\frac{dT}{dt}$ – rate of cooling of the disc.

After that, the circular samples were cut into reasonable sizes and shapes required in other tests for which they were prepared.

2.5.2. Bulk density and Water absorption

For bulk density determination, Modified water displacement method was applied [31] to obtain the bulk volume of each sample. The bulk density, ρ was obtained for each sample by computation using the mass, M and bulk volume, V based on the relation [32, 33]

$$\rho = \frac{M}{V} \tag{2}$$

Regarding water absorption determination, immersion method was used. The masses of the samples were measured before they were completely immersed in cold water. After 4 hours, the samples were removed from the water and allowed to surface-dry before their masses were measured again. The mass of water absorbed in each case was determined as the difference between the mass before and that after the immersion. From the data gathered, the water absorption of each sample was calculated as:

$$WA = \left(\frac{M_a}{M}\right)100\% \tag{3}$$

where: WA – water absorption, M_a – mass of water absorbed.

2.5.3. Specific heat capacity and Thermal diffusivity

In the case of specific heat capacity determination, SEUR'S apparatus [34] was designed and used. Aside each of the samples, accessories for heat exchange were aluminum plate of thickness 8 mm and plywood plate of the same thickness. The masses of the accessories were measured using a digital balance (S. METTLER – 600 g). A square cavity measuring 60 mm x 60 mm was centrally provided inside each half for heat exchange. When thermal balance was established, the amount of heat lost or gained (as the case may be) was determined for each plate as the product of mass, specific heat capacity and change in temperature. With assumption of negligible heat losses to the surroundings, the data obtained were then used to calculate the specific heat capacity of sample thus:

$$c = \frac{(Q-q)}{M\Delta T} \tag{4}$$

where: c – specific heat capacity of the sample, Q – total quantity of heat lost by the aluminum plate during heat exchange, q – total quantity of heat gained by the plywood plate during heat exchange, M – of the sample, ΔT – change in temperature of the sample.

The values of thermal conductivity, bulk density and specific heat capacity obtained for each sample representative were used to compute the corresponding thermal diffusivity, λ as [35-38]:

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

2.5.4. Flexural strength and Nailability

A universal testing machine (Model H10KT) was used for determination of flexural strength based on three-point bending technique as stated in [39]. During each test schedule, a load of 10 kN was applied and a test speed of 1 mm/min was maintained until fracture occurred. At that instant, the maximum load, P applied, span length, L. width, b and thickness, x of the sample were used to compute the flexural strength, according to the relation:

$$\sigma = \frac{3PL}{2bx^2} \tag{6}$$

The samples were then subjected to nailability test in order to assess their ability to withstand nailing. This test was performed by means of a nail gun named Finish Nailer (Model D51257K, manufactured by Dewalt). In the design of this electric hammer, a motor rotates two drive axles and the hammering force is generated by ordinary springs. Each hammering operation was performed slowly and methodically with a 2" – nail fired through the thickness of a sample until either a tiny visible crack was noticed or the nail tip appeared on the opposite side of the sample. In any case the crack was observed, the nailing was discontinued and the nail penetration depth was determined as the difference between the overall length of the nail and the length of the nail's portion remaining. But if the nail penetrated without causing any visible crack, the penetration depth was considered to be the same as thickness of the sample under test. In either case, nailability was obtained using the formula:

$$n_b = \left(\frac{D}{x}\right)100\% \tag{7}$$

where: n_b – nailability, D – penetration depth of the nail.

All the tests/measurements in this work were carried out at (24.0 ±1.0)°C and 53.0% relative humidity. The mean and corresponding standard error values were calculated for each formulation of the developed composite panels.

3. RESULTS AND DISCUSSION

The results of the analysis carried out on the processed material are presented in Table 1. Table 2 shows the results of tests performed on the fabricated samples in order to determine their heat transfer and strength properties.

From Table 1, it can be seen that the WCP contains the highest proportion of cellulose but lowest percentage of lignin compared to the WNP, WWP and SDP. Also, the WNP contains fractions of cellulose and hemicelluloses that are slightly greater than those contained in the WWP. Among the lignocelluloses, cellulose is highly hydrophilic having a very strong hydrogen bonding which enables it to absorb water readily, hemicelluloses acts like a semi-soluble polyelectrolyte and binder whereas lignin is a highly randomized condensed polymer full of chemically resistant cross-links of various types. Thus, the results show that the WNP, WWP, WCP and SDP cannot have the same chemical behavior. From the grading curve illustrated in Figure 2, it can be deciphered that the sawdust particles finer (in diameter) than 0.6 mm are less in quantity than the fine ones. This is a pointer to the fact that many void spaces exist in the developed samples as the SDP loading increases. Since the Carr's compressibility index of value below 15% and static angle of repose value between 31° and 35° generally indicate good flowability [40, 41], it can be averred that the starch utilized in this study has flow characteristics that make it suitable for manufacturing purposes.

Table 1. Particulars of the processed materials

Parameters	Values obtained per material				
	WNP	WWP	WCP	SDP	CST
Lignocellulosic constituents					
Cellulose (%)	43.4 ±0.1	42.8 ±0.2	47.6 ±0.2	41.8 ±0.2	–
Hemicelluloses (%)	27.0 ±0.1	26.7 ±0.1	26.5 ±0.2	26.4 ±0.1	–
Lignin (%)	20.1 ±0.2	20.8 ±0.1	19.7 ±0.2	22.3 ±0.2	–
Flowability					
Carr's compressibility index (%)	–	–	–	–	–
Static angle of repose (°)	–	–	–	–	–

WNP – Waste Newspaper Paste, WWP – Waste Writing-paper Paste, WCP – Waste Carton Paste, SDP – Sawdust Particle, CST – Cassava Starch

Table 2. Results of property tests performed on the test samples

Composite mix	Mix ratio (%)	Measured values per property						
		WA (%)	ρ (kgm^{-3})	k (Wm^{-1}K^{-1})	c (Jkg^{-1}K^{-1})	λ (10^{-7} m^{2}s^{-1})	n_b (%)	σ (N/mm^2)
WNP:SDP	100:0	86.34 ±0.01	390.84 ±1.03	0.0879 ±0.0004	1342.76 ±0.02	1.67 ±0.01	100.0 ±0.0	1.048 ±0.001
	75:25	91.21 ±0.02	352.43 ±1.11	0.0793 ±0.0003	1482.63 ±0.01	1.52 ±0.01	100.0 ±0.0	0.841 ±0.002
	50:50	97.22 ±0.02	316.27 ±1.09	0.0722 ±0.0004	1597.88 ±0.02	1.43 ±0.02	98.8 ±0.2	0.682 ±0.002
	25:75	102.18 ±0.01	280.06 ±1.07	0.0631 ±0.0003	1722.91 ±0.02	1.31 ±0.01	96.4 ±0.2	0.476 ±0.001
	0:100	106.24 ±0.03	245.21 ±1.01	0.0543 ±0.0003	1866.08 ±0.01	1.19 ±0.02	86.7 ±0.1	0.306 ±0.001
WWP:SDP	100:0	85.10 ±0.02	394.77 ±1.08	0.0886 ±0.0005	1339.35 ±0.01	1.68 ±0.01	100.0 ±0.0	1.050 ±0.002
	75:25	89.21 ±0.02	358.18 ±1.05	0.0810 ±0.0003	1482.07 ±0.03	1.53 ±0.02	100.0 ±0.0	0.867 ±0.002
	50:50	94.03 ±0.01	318.06 ±1.12	0.0724 ±0.0002	1581.24 ±0.02	1.44 ±0.02	99.5 ±0.2	0.689 ±0.001
	25:75	100.78 ±0.01	280.91 ±1.10	0.0633 ±0.0003	1710.09 ±0.02	1.32 ±0.01	96.9 ±0.1	0.497 ±0.002
	0:100	106.24 ±0.03	245.21 ±1.01	0.0543 ±0.0003	1866.08 ±0.01	1.19 ±0.02	86.7 ±0.1	0.306 ±0.001
WCP:SDP	100:0	89.73 ±0.02	268.77 ±1.00	0.0742 ±0.0002	1681.84 ±0.01	1.64 ±0.01	100.0 ±0.0	1.151 ±0.001
	75:25	94.27 ±0.01	264.49 ±1.04	0.0686 ±0.0004	1728.99 ±0.01	1.50 ±0.01	100.0 ±0.0	0.943 ±0.001
	50:50	99,48 ±0.01	257.71 ±1.07	0.0646 ±0.0002	1776.36 ±0.03	1.41 ±0.01	100.0 ±0.0	0.736 ±0.002
	25:75	104.33 ±0.02	252.05 ±1.05	0.0595 ±0.0004	1836.42 ±0.02	1.29 ±0.01	98.9 ±0.2	0.527 ±0.002
	0:100	106.24 ±0.03	245.21 ±1.01	0.0543 ±0.0003	1866.08 ±0.01	1.19 ±0.02	86.7 ±0.1	0.306 ±0.001

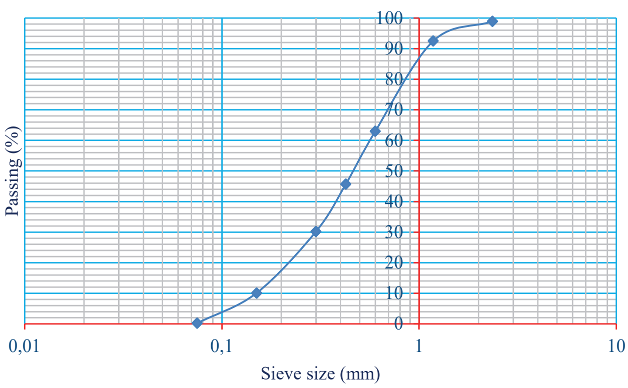

Fig. 2. Grading curve of the processed sawdust

Every porous material that contains lignocellulosic constituents is prone to attack by water during its service life as a partition element or ceiling panel in buildings. It can be seen from Table 2 that water absorption value is the highest in the case of sample developed with 100% content of the SDP, followed orderly by those similarly produced but with the WCP, WNP and WWP. With the use of pastes at 100% level, the sample containing the WNP possesses water absorption capability that is 1.24% greater than its counterpart containing the WWP but 3.39% less when compared to the sample developed with the WCP. This could be understood to be as a result of the differences in the proportions of their lignocelluloses. That is to say, the greater the cellulose content and lower the lignin fraction in a paste, the more affinity the sample developed with it has. Thus, by containing 4.2% and 4.8% cellulose fractions in excess and being deficient by 0.4% and 1.4% in terms of lignin proportions compared to the percentages of such lignocellulosic constituents in the WNP and WWP respectively, the WCP obviously possesses the highest tendency for hydrophilicity. In the case of the sample fabricated with the SDP alone, the porous nature of the fiber plays a major influencing role for its water uptake. Since all the samples are completely dry and porous, the voids in them serve as reservoirs for water accommodation. This insinuates that though cellulose-based materials are naturally hydrophilic, the more porous a material is, the more water it is capable of absorbing under defined conditions. So, due to refractory nature of the SDP, more voids exist in it than in any of the pastes (WNP, WWP and WCP), thus causing the sample fabricated with 100% of it (the SDP) to absorb the highest quantity of water. Consequently, by increasing the SDP content in any of the composite mixes, the water absorption of the resulting sample increases. For instance, utilization of the SDP at 25%, 50% and 75% with the WNP increases water absorption by about 4.87%, 10.88%, and 15.84% respectively. Also, at similar SDP loadings, the samples produced with the WWP show increase in water absorption by about l4.11%, 8.93% and 15.68% respectively. Again, water absorption increases by 4.54%, 9.75% and 14.60% respectively in the case of composites similarly developed but with the WCP as component. However, the sample made using 25% of the SDP with 75% of the WCP has almost the same ability to take up water as the composite fabricated with the SDP and WWP at 50% levels. Although considerable variations are observed in the results of the water absorption test, the use of one-way analysis of variance (ANOVA) at 0.05 reveals that the water absorption values obtained for the samples developed using various proportions of the WNP are not significantly different from those obtained for their counterparts produced with either the WWP or WCP as component. Comparatively, it is found that the water absorption values of the studied samples are less than the minimum value of 121.06% reported by Akinyemi et al [42] for composite boards developed using corn cob and sawdust and also recommended for indoor uses in buildings.

Bulk density expresses how large the mass of a porous material is in relation to the material's bulk volume. In this study, it is found that increase in proportion of the SDP results in decrease in bulk density of the composites notwithstanding the paste (WNP, WWP or WCP) used. Also, the composites made with various percentages of the SDP and WWP have greater bulk density values than their counterparts containing the WNP while those similarly produced but with the WCP has the least bulk density values. Since the fabrication procedures and conditions adopted in this work remained unchanged, this simply indicates that the SDP is the lightest whereas the WWP is the densest and the WWP is denser than the WCP. The lightness of the pastes and fiber is attributable to the interstices/voids in them. Between the samples developed using the WNP as component and those similarly prepared using the WWP, the largest difference in mean bulk density values is 5.75 kgm^{-3} and this is yielded when utilizing the SDP at 25% level. Also, incorporating up to 75% of the SDP leads to the smallest difference (0.85 kgm^{-3}) between their bulk density values. With respect to the bulk density values obtained for the samples containing 100%, 75%, 50% and 25% of the WCP, the bulk density of counterpart samples with the WNP content increases by about 45.42%, 33.25%, 22.72% and 11.11% whereas the increase in the case of samples containing fractions of the WWP at similar levels is about 46.88%, 35.42%, 23.42% and 11.45% respectively. Due to their closeness in bulk density values, it appears that if used in building design, the sample with 25% content of the WNP would contribute the same weight like the one fabricated with the WWP at similar level. Statistically, application of the ANOVA at p <0.05 reveals a significant difference only when comparing the bulk density values obtained for samples that contain the WCP with the values obtained for their counterparts developed with the WNP or WWP. Based on the standard criteria stipulated in [43], it suffices to remark that all the studied samples may be regarded as low-density panels.

In order to characterize a material's ability to allow transfer of heat as a result of temperature difference around it, the knowledge of its thermal conductivity is a necessity. At 100% content level, the sample made with the SDP has the least mean thermal conductivity value whereas the sample developed with the WWP has the highest value of thermal conductivity. Also, the sample containing 100% of the WNP has a higher thermal conductivity than the sample made with the WCP alone. Since thermal conductivity of a porous material depends on the ratio of pore free path for zero-porosity, the observed trend in this case is possible. Meanwhile, the void spaces in the samples are filled with air, which is well-known to be one of the best thermal insulants. Also, the volume of air correlates positively with the extent of interstices/void spaces in the samples. Thus, being that the SDP is the lightest, followed by the WCP, WNP and then WWP, the air volume in them increases in that order and causes decrease in thermal conductivity accordingly. On the whole, utilization of the SDP with any of the pastes enhances reduction in thermal conductivity of the resulting composite samples. For instance, making use of the SDP at 25%, 50% and 75% content levels reduces the mean thermal conductivity value by 28.21% for the sample containing the WNP. Also, a reduction by 28.56% is noticed in the case of sample made with the WWP content while it reduces thermal conductivity by 19.81% for sample developed with the WCP content. On comparison of the samples fabricated with the SDP at 0%, 25%, 50% and 75%, the thermal conductivity values of those containing the WWP are greater by 0.80%, 2.14%, 0.28% and 0.32% respectively than the values obtained for their counterparts produced with fractions of the WNP. When compared to the thermal conductivity values of the samples similarly fabricated with the

WCP as a component, the increase is found to be by 19.41%, 18.08%, 12.07% and 6.39% respectively. This implies that if all the composites are applied under same thermal conditions, those that contain the WCP will exhibit the best insulation performance and their counterparts with the WNP content will likely be effective and efficient for restriction of heat transmission as the ones similarly developed using the WWP. Nevertheless, the samples investigated in this work have thermal conductivity values that are within the recommended range given as 0.023 $Wm^{-1}K^{-1}$ to 2.900 $Wm^{-1}K^{-1}$ [44] for heat-insulating and construction materials. In terms of thermal resistivity (reciprocal of thermal conductivity), it can be inferred that the most thermally-conductive sample in this study has thermal resistivity of 11.29 $W^{-1}mK$ against the value of 0.34 $W^{-1}mK$ that associates with the least suitable heat-insulating material. This gives 96.99% difference, showing that the said sample is far better than the least possible material that could be applied for the purpose of thermal insulation in a system.

For samples developed with the WNP and SDP other than at 0% loading level of either of them, proportioning the materials (WNP and SDP) at 75% and 25% respectively yields a sample with mean specific heat capacity value that gives maximum marginal increment (139.87 $Jkg^{-1}K^{-1}$). In the case of those that contain the WWP and similar SDP loadings, the same is applicable at 25% of the SDP content in which case the maximum marginal increment is found to be 142.72 $JkgK^{-1}$. As for the use of the WCP instead of the WNP or WWP, the marginal change in the mean specific heat capacity (60.06 $Jkg^{-1}K^{-1}$) is maximum when the SDP content is 75%. Between samples containing the WNP and those produced at similar mix ratios using the WWP as a component, the specific heat capacity values are very close and are also less than the values obtained for their counterparts containing fractions of the WCP. This indicates that incorporation of the WCP can improve thermal insulation efficiency over utilization of either the WNP or WWP at similar levels for development of composite panels. Stating differently, specific heat capacity of the composite constituents has significant influence on the thermal insulation performance of the developed samples. As all the samples contain the SDP as reinforcer, it can be asserted that the use of the WCP makes the resulting composites require more energy in order to change the temperature of their unit mass by one Kelvin compared to their counterparts containing either the WNP or WWP. The graphical illustration in Figure 3 depicts that specific heat capacity of the studied samples increases with increasing SDP loadings in all the cases. This is, plausibly, due to the fact that the SDP has the highest specific heat capacity value compared to the WNP, WWP and WCP.

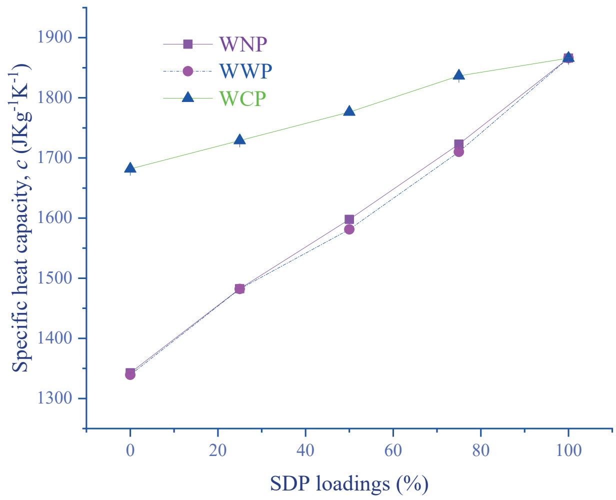

Fig. 3. Variation of specific heat capacity with sawdust proportion

In a situation the samples are photothermally heated during service, high specific heat capacity or bulk density and low thermal conductivity favor low thermal diffusivity in order to prolong thermal equilibrium duration of the thermal environment. By considering this fact based on the support of the empirical relationship expressed as eq. (5) in this work, the implication of the results obtained is that if all the samples fabricated with 25%, 50%, or 75% loadings of the SDP are subjected to the same thermal disturbance, those containing the WCP will enhance the slowest rate of temperature propagation for heat diffusion within them. Because heat-diffusing tendency of the SDP is less than that of the WCP, WWP or WNP, sluggishness in the spread of heat within the samples is observed to improve as the SDP proportion increases. The response of the samples to thermal waves could also be explained in terms of thermal resistance (ratio of thickness to thermal conductivity), keeping in mind that all the samples prepared in this work for investigation of heat transfer properties have the same thickness (9.0 mm). From the obtained results, it can be deduced that at 100% loading level, samples developed using the WNP, WWP, WCP and SDP have mean thermal resistance values of 0.102, 0.102, 0.121 and 0.166 (all in $W^{-1}m^2K$) respectively. This portrays that when exposed to thermal front, the highest opposition to heat transmission would be offered by the sample with 100% content of the SDP while the least resistance to such oscillatory heat flow would be provided by the sample containing 100% of the WNP or WWP. For the studied samples, the highest thermal diffusivity value ($1.68 \cdot 10^{-7}\ m^2s^{-1}$) is 29.54% less than the value of $2.38 \cdot 10^{-7}\ m^2s^{-1}$ reported by Gesa et al [45] for a conventional ceiling panel called Isorel. It therefore means that all the samples examined in this work could perform better than Isorel as far as their application for actualization of thermal management by restriction of heat propagation is a priority.

When joining of the samples to a suitable material by nailing is needed, it is clear from the results of nailability test that sample developed with the SDP at 100% content level cannot withstand such operation. This observation could be argued in the light of refractory nature of the SDP with respect to the concentration of the binder used in fabricating the samples. That is to say, using slurry of cassava starch that is more viscous/gummy than the one utilized in this work could enhance adhesion to ensure successful nailability of a sample made with the SDP alone. Evidence in support of the effect of sawdust nature on nailability of the samples is in the cases involving the use of the paper pastes. Understandably, the WNP, WWP and WCP are known to be less refractory compared to the SDP. As expected, utilizing at least 75% of the WNP or WWP as a component or by using at least 50% of the WCP fraction yields a composite panel that is nailable. Below the afore-stated limits, adhesion effect is reduced with increasing SDP content and consequently weakens the internal bond strength between the constituents in the composite matrix. When decline in the nailability value occurs, the use of the WWP ensures the least difference (0.5%). At 75% level of the SDP incorporation, the use of the WCP produces the smallest difference (1.1%) compared to 3.1% obtained in the case of the WWP and 3.6% due to utilization of the WNP. The refractory nature of the SDP also influences the flexural strength of the samples. As can be seen from Figure 4, the bending stress the samples can withstand before they fracture varies negatively with the SDP proportions. This shows that the pastes utilized in this study are less fragile than the sawdust. Even as it is, the maximum flexural strength ($0.1\ N/mm^2$) reported for Agro-waste composite ceiling boards [46] is found to be 67.32% less than the minimum mean value ($0.306\ N/mm^2$) obtained in this work for the studied samples.

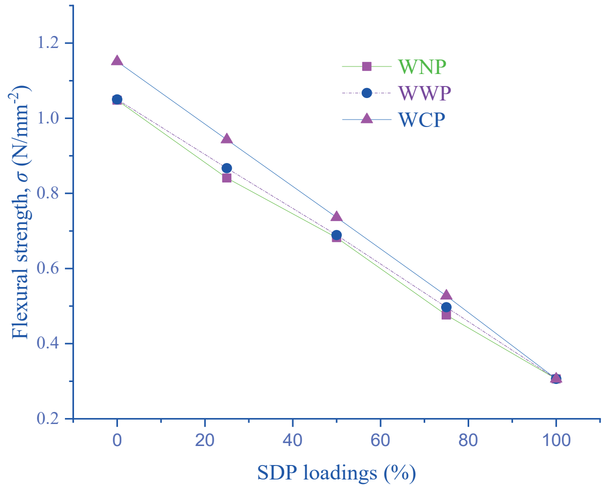

Fig. 4. Variation of flexural strength with sawdust proportion

4. CONCLUSION

From the results of the tests performed on the samples developed in this work, it was found that composites fabricated using sawdust particle (SDP) and waste newspaper paste (WNP) have almost similar property values when compared to their counterparts containing waste writing-paper paste (WWP) as a component. For samples made with either the WNP or WWP content, decline in nailability from 100% was observed when utilizing at least 50% of the SDP in the composite mix whereas in the case involving the WCP, a similar phenomenon occurred when making use of at least 75% of the SDP. All the studied samples showed heat-insulating and strength tendencies that are better than those reported in the literature for some known ceiling panels. However, it was found that composites fabricated with the WCP and SDP contents could exhibit the best performance in terms of thermal insulation, absorption of dead loads and energy saving in buildings. It can therefore be adjudged that cassava effluent, sawdust and waste paper products (such as discarded newspapers, writing papers and cartons) are promising alternative raw materials for production of thermal insulation panels that are suitable for indoor application as ceilings especially in tropical areas. Valorization of the wastes as described in this study is an important step to protect the environment while ensuring availability of economically-sustainable and environmentally-friendly insulation ceilings for building design.

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