Recycling of Waste Cartons and Musanga Cecropioides Heartwood into Composite Panels for Structural Application

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Abstract

In this research, the suitability of composite panels developed from waste carton paste (WCP) and *Musanga cecropioides* heartwood particles (MHP) was assessed for structural applications. Proportions of the MHP adopted were 0, 25, 50, 75, and 100 % by weight of the composite mix. For each formulation, three representative samples were fabricated and also subjected to various tests. The results of the tests showed variations in the mean values of water absorption (8.83 – 30.35 %), thickness swelling (3.72 – 10.84 %), bulk density (342.3 – 461.6 kgm^{-3}), thermal conductivity (0.1166 – 0.1717 $Wm^{-1}K^{-1}$), thermal diffusivity (2.051 – 2.397 x 10^{-7} m^2s^{-1}), and flexural strength (1.388 – 9.636 MPa) as proportion of the MHP decreased from 100 % to 0 %. On the contrary, a positive correlation was observed in the cases of specific heat capacity (1.552 – 1.661 x 10^3 $Jkg^{-1}K^{-1}$) and solar radiation absorptivity (12.32 – 13.32 m^{-1}) with respect to increase in the proportions of the MHP used. Though all the samples exhibited better performance tendencies for thermal insulation compared to conventional ceilings or partition elements used in buildings, it was observed that samples developed with more than 50 % of the MHP could not withstand nailability. Above all, waste cartons and *Musanga cecropioides* heartwood are promising raw materials to be considered for fabrication of low-cost composite thermal insulation panels suitable for application in building designs. This undertaking could also serve as a safe way of managing them as wastes.

Keywords: *Ceiling, Lignocellulosic constituents, Thermal insulation, Wall panelling, Waste.*

1. Introduction

Shelter (house) that is both safe and affordable is a basic thing every human desires to acquire for satisfaction. Incessant rise in the cost of conventional building materials, global warming, and increase in population are among other factors that have been militating against achievement of such feat. Consequently, construction industries and people face issues like cost overrun and lag in time. This, in recent times, warranted conduction of relevant researches with the aim to proffer possible solutions to the emerging problems. Facts established so far from studies conducted in this regard have shown that adoption of low-cost construction is an ideal approach to use in order to overcome the challenges. This approach involves replacement of conventional building materials with alternative ones without sacrificing the quality and strength [1]. Notably, only the alternative materials manufactured from or with wastes could meet the considered criteria and satisfy conditions such as cost-effectiveness and availability. This is because most recyclable wastes are commonly-available and many of them are sustainable but their potentials are yet to be realized.

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Robert et al. [2] defined wastes as items regarded to have no usefulness again and ought to be disposed of immediately. Observably, papers (newspapers, writing papers copier papers, cartons, and so on) are a necessity of civilization thereby warranting no halt in their production and in turn, generation as waste [3]. This makes valorization of waste papers to attract research interest as far as fabrication of sustainable materials for thermally-safe building design is concerned. For instance, some researchers [4] – [9] found that ceilings developed from waste newspapers are inexpensive, environmentally-friendly, and more thermally insulating compared to conventional ones such as asbestos, poly vinyl chloride (PVC), plaster of Paris, etc. Studies also revealed that composites suitable for application as ceilings and in wall panelling can be made with waste cartons [10, 11]. Some reports have shown that ceiling boards prepared from plant-derived wastes like sugarcane leaves [12], sugarcane bagasse [13], coconut leaflets [14], oil palm and raffia frond [15] can enhance thermal comfort satisfactorily in buildings. Composite panels made with Bamboo fibers [16], coconut leaf sheaths [17], carbon fibers [18], wood wastes [19], and Midrib of Coconut Palm Leaves [20] are not left out in this consideration as they possess desirable properties for engineering applications.

Musanga cecropioides (corkwood), commonly called ‘Umbrella tree’ and ‘Igioga’ in English and Yoruba respectively, belongs to tree family known as *Urticaceae*. It is a forest tree found in tropical Africa (from Sierra Leone south to Angola and east to Uganda) and is characterized by soft branched trunk crowned by compound leaves. Depending on the soil conditions, the tree can grow to a height of at least 10 m within a short time. Some benefits can be derived from the tree. For instance, its bark has efficacy to cure cough when eaten with cola nut [21]. The tree can be used for production of flotation devices (such as rafts and toys), match sticks, pulp, and xylophone. Its heartwood is a potential thermal insulator for refrigerators, coolers, and food flask [22]. Aqueous extract from this tree contains active analgesic, anti-hypertensive, and spaspogenic ingredients for administration on rodents [23].

It has been observed that *Musanga cecropioides* heartwood and waste cartons are produced in large quantities and the dearth of scientific information on their economic benefits has resulted to their under-utilization. Nowadays, solid waste management system is very ineffective in developing and less-developed countries [24]. Also, considering the fact that population and urbanization grow exponentially, waste generation is certainly inevitable since it is an intrinsic part of human existence [25]. It was asserted in a study [26] that if the present situation persists, the quantity of global municipal solid waste generation will drastically increase from today’s 2.01 billion tons to 3.40 billion tons by 2050 as estimated by World Bank. Unfortunately, disposal of the wastes in question is prevalently done by open burning or indiscriminate landfilling and either practice poses substantial adverse effects on both the environment and public health. Hence, this research is designed to assess the feasibility of recycling waste cartons and *Musanga cecropioides* heartwood for beneficial purposes. Composites developed from them will be examined in terms of thermophysical and mechanical properties in order to determine their suitability for structural applications.

2. Experimental Processes

2.1. Materials description and collection

Cartons, *Musangace cropioides* heartwood, and epoxy resin with its hardener (K7001) were the maim materials used in this research. The cartons were picked from dumpsites whereas the *Musanga cecropioides* heartwood was collected from timber dealers. Both materials were obtained in large quantities as waste materials. The resin was obtained from a building materials shop and its bending strength and deformation were (110 – 130) MPa and (5 – 7) % respectively. All the materials were sourced within Mkpat Enin Local Government Area, Akwa Ibom State, Nigeria.

2.2. Processing and Analysis of the materials

Surfaces of the waste cartons were cleaned with shoe brush to remove any dirts from them. After that, they were cut into smaller pieces with the aid of scissors. The pieces were soaked in warm water for 24 h after which they were removed from it, lightly squeezed (to get rid of excess water from them), and then pounded into paste using Agate mortar and pestle. The paste was subjected to continuous sun-drying and weighing until there was no further reduction in its mass. Also, the *Musanga cecropioides* heartwood was pulverized and then screened using a standard US sieve. The quantity that passed 2 mm – sieve openings were used. The waste carton paste and *Musanga cecropioides* heartwood particles obtained were coded WCP and MHP respectively. Each processed material was divided into two portions. One portion in each case was used for chemical composition analysis following the Technical Association of Pulp and Paper Industry (TAPPI) Standards T-203 and T-222 as adopted by Robert et al. [11].

2.3. Composites fabrication

The remaining portion of each material was used to fabricate samples by hand lay-up technique. In this research, the proportions of MHP utilized were 0, 25, 50, 75, and 100 % by weight of the composite mix. Also, the epoxy resin was thoroughly mixed with its hardener in 1:1 ratio by weight and then applied as binder. In each case, the ratio of binder to composite mix was 0.8 by weight. A circular mold of thickness 7 mm measuring 110 mm in diameter was used to form samples meant for investigation of thermophysical properties. Those fabricated for determination of mechanical properties were formed in a mold of dimensions 150 mm x 120 mm x 14 mm. After casting, compaction was performed by means of a laboratory- made compacting machine maintained at 5 kN for 10 h before the samples were demolded and subjected to continuous sun-drying and weighing until their masses remained unchanged. For each formulation, the samples were prepared in triplicates. Figure 1 summarizes samples preparation processes.

Figure 1. Samples preparation processes (a) Waste cartons (b) *Musanga cecropioides* tree (c) WCP (d) MHP.

2.4. Properties evaluation

2.4.1. Water absorption, Thickness swelling, and Bulk density

Water absorption test was performed by immersion method. Each sample was weighed before it was immersed in water initially at 26° C. After 24 h, the soaked material was removed and surface-dried before being re-weighed. The mass of water absorbed was determined and water absorption, WA was calculated as [14].

$$WA = \left(\frac{M_{a-M_i}}{M_i}\right) 100\ \% \quad (1)$$

where M_a = mass of the sample after immersion in the water, and M_i = mass of the sample before immersion in the water.

In the case of thickness swelling, the thickness of the sample was measured before and after the immersion. This was carried out by means of digital callipers (0 – 150 mm) and the data obtained were used to compute the corresponding thickness swelling, T_s [11].

$$T_s = \left(\frac{T_i - T_0}{T_0}\right) 100\% \quad (2)$$

where T_0 = thickness of the sample before immersion, and T_i = thickness of the sample after immersion in the water.

With the aid of a digital balance (S. METTLER – 600g), the mass of each sample was measured. Also, their respective bulk volumes were determined by Modified water displacement method. This method is based on Archimedes' Principle with slight modifications. It involves sealing of the sample with paraffin wax and finding the difference between the volume of the sealed sample and that of the sealant used for the coating as detailed elsewhere [27]. Using the data obtained, the bulk density, ρ was evaluated thus [2, 12].

$$\rho = \frac{M}{V} \quad (3)$$

where V = bulk volume.

2.4.2. Thermal conductivity and Specific heat capacity

By employing Modified Lee – Charlton's Disc Apparatus technique as described in details elsewhere [28], thermal conductivity of each sample was determined. In this research, an electric hotplate (Model E4102WH, Lloytron) was used as heat source. Sample's thickness was properly lagged using cotton wool. Origin software (Version 2019) was used for modelling of each cooling rate function. Using the data obtained, the thermal conductivity value was computed based on Fourier's law equation for one-dimensional heat conduction as

$$k = \left(\frac{M_d C_d x}{A\Delta\theta}\right)\frac{dT}{dt} \quad (4)$$

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

For determination of specific heat capacity, SEUR'S apparatus was employed [29]. Aluminium plate and plywood plate (each measuring 60 mm x 60 mm x 8 mm) were used as heat exchange accessories. Actualization of temperature monitoring/ measurement was by means of three digital thermometers (Model No. 305, calibrated and equipped with type-K probe). When the system attained thermal equilibrium during heat exchange, the quantity, Q_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 in accordance with the following relation

$$C = \left(\frac{Q_a - Q_p}{M\Delta T}\right) \quad (5)$$

where ΔT = temperature rise of the sample.

2.4.3. Thermal diffusivity and solar radiation absorptivity

The values of bulk density, specific heat capacity, and thermal conductivity obtained for each sample were applied to compute the thermal diffusivity based on the formula [3, 12].

$$\lambda = \frac{k}{\rho C} \tag{6}$$

where λ = thermal diffusivity. After that, solar radiation absorptivity, α was examined by calculation using the equation [30].

$$\alpha = \sqrt{\left(\frac{\pi}{\lambda T_p}\right)} \tag{7}$$

where T_p = periodic time (of 24 h)

2.4.4. Nailability and Flexural strength

For applications in wall panelling, nailability is an important property to be considered. Each sample was subjected to this test by hammering method using a carpenter's hammer and a nail of length 50 mm. Nailing was directed through the thickness of the sample. When either a visible crack or successful nail penetration was observed, the process was discontinued. At that moment, the depth of nail penetration was determined and nailability of the sample was calculated [10].

$$n_b = \left(\frac{h}{x}\right) 100\ \% \tag{8}$$

where n_b = nailability, h = depth of nail penetration into the sample, and x = thickness of the sample. Each sample was tested for flexural strength by three – point bending method according to the standard procedure outlined in [31]. An Electromechanical Universal Testing Machine (WDW – 10) was employed for the task and a test speed of 1 mm/min was adopted. During each test schedule, a sample was placed on the flexure configuration of the machine and loaded at its middle. When it failed flexurally, the maximum value of the applied load, F_{max} was used with the values of width, b and thickness of the sample to calculate the flexural strength, f_s [32].

$$f_s = \frac{3}{2}\left(\frac{F_{max}L}{bx^2}\right) \tag{9}$$

All the samples developed were subjected to their respective tests (as intended in this work) at 25.0 ± 1.0 °C. The results obtained for the triplicates were averaged for each formulation and tabulated with their corresponding standard error value.

3. Results and Discussion

3.1. Proportions of lignocellulosic constituents in the WCP and MHP

Table 1 shows the proportions of various lignocellulosic constituents present in the WCP and MHP used for fabrication of the samples. For the MHP, the cellulose and hemicelluloses fractions are less by 78.65 % and 57.30 % while the lignin proportion is more by 36.46 % compared to the respective percentages in the case of the WCP. This shows that MHP and WCP have different degrees of affinity for water.

Table 1. Chemical composition of the materials.

Material	Proportion of lignocellulosic constituents (%)		
	Cellulose	Hemicelluloses	Lignin
WCP	47.3	26.7	19.2
MHP	10.1	11.4	26.2

WCP = Waste carton paste; MHP = Musanga cecropioides heartwood particles

3.2. Effect of mix design on Water absorption and Thickness swelling of the samples

In Table 2, results of the tests performed on the samples are recorded. The sample made with 100 % WCP has a greater tendency for water absorption than its counterpart containing the MHP. This is possible because the proportion of lignin (a highly hydrophobic constituent) in MHP exceeds the percentage of it in the WCP. The same reason accounts for the sample with 100 % content of the WCP having a greater thickness swelling than the one containing similar proportion of the MHP. Both properties (water absorption and thickness swelling) trend inversely with proportion of the MHP utilized in the composite mixes. This observation resonates with the findings reported by another group of researchers [33] that as water absorption of a material increases, so does its thickness swelling. On the whole, dimensional stability is enhanced by increasing the content of MHP in the composite mix.

Table 2. Results of tests performed on the samples.

Composite mix (%) WCP:MHP	Water absorption WA (%)	Thickness swelling T_s (%)	Bulk density $\rho\ (kgm^{-3}$	Thermal conductivity $k\ (Wm^{-1}K^{-1}$	Specific heat capacity $C\ (10^3 Jkg^{-}$	Thermal diffusivity $\lambda\ (10^{-7} m^2 s^{-1})$	Solar radiation absorptivity $\alpha\ (m^{-1})$	Nailability, n_b (%)	Flexural strengt, $f_s\ (MPa)$
0:100	8.83 ± 0.46	3.72 ± 0.41	342.8 ± 0.3	0.1166 ± 0.0004	1.661 ± 0.001	2.051 ± 0.006	13.32 ± 0.04	96.9 ± 0.4	1.388 ± 0.004
25:75	12.50 ± 0.64	4.25 ± 0.73	384.7 ± 0.7	0.1379 ± 0.0001	1.643 ± 0.002	2.182 ± 0.005	12.91 ± 0.03	99.8 ± 0.2	2.968 ± 0.002
50:50	16.38 ± 0.72	5.77 ± 0.56	410.5 ± 0.9	0.1468 ± 0.0002	1.607 ± 0.003	2.225 ± 0.007	12.78 ± 0.04	100.0 ± 0.0	4.929 ± 0.002
75:25	26.63 ± 1.01	8.69 ± 0.35	444.9 ± 1.1	0.1609 ± 0.0002	1.574 ± 0.002	2.298 ± 0.007	12.58 ± 0.04	100.0 ± 0.0	7.089 ± 0.002
100:0	30.35 ± 1.04	10.84 ± 0.28	461.6 ± 1.3	0.1717 ± 0.0003	1.552 ± 0.002	2.379 ± 0.009	12.31 ± 0.05	100.0 ± 0.0	9.636 ± 0.004

Tangjuank and Kumfa [34] obtained 101 % and 12 % as minimum values of water absorption and thickness swelling, respectively, for ceiling tiles fabricated from *Pypyrus* fibers. Comparatively, the maximum mean values of water absorption (30.35 %) and thickness swelling (10.34 %) of the studied samples are lower by about 70.00 % and 9.67 % respectively than the reported values for the said ceiling tiles.

3.3. Effect of mix design on Bulk density and Thermal conductivity of the samples

Since this research was designed to enable the sample have same volume, it can be inferred from the results of bulk density tests that MHP is lighter than WCP and its inclusion creates more voids proportionally. Based on the standard classification for particleboards [35], all the samples in this study may be regarded as medium-density panels. Being that the samples are completely dry and porous as well, the voids in them are filled with air. As a matter of fact, air is a good thermal insulant. Obviously, the more its volume is in a material, the lower thermal conductivity of the material becomes. This simply explains why thermal conductivity is lower in the case of sample containing 100 % of MHP compared to the one with 100 % content of WCP. That notwithstanding, the thermal conductivity values obtained for all the samples fall within the range (0.023 $Wm^{-1}K^{-1}$ to 2.900 $Wm^{-1}K^{-1}$) recommended [36] for heat-insulating and construction materials. It can be observed from Figure 2 that bulk density and thermal conductivity relate inversely with proportion of MHP in the samples. By implication, the tendency of the samples to reduce dead load while at the same time enhancing restriction of heat transmission if applied in buildings can be improved by increasing the proportion of MHP in the composite mix.

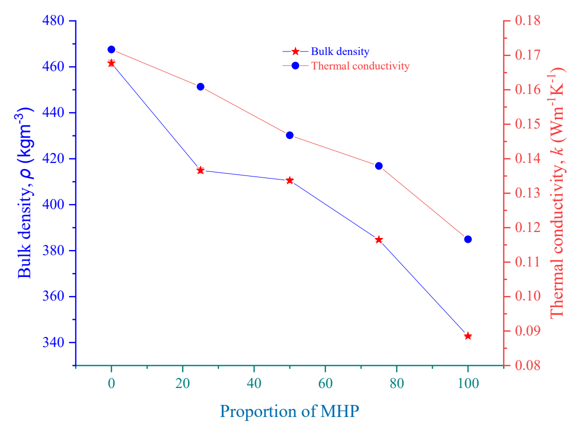

Figure 2. Variations of Bulk density and Thermal conductivity with proportion of the MHP.

3.4. Effect of mix design on specific heat capacity of the samples

The specific heat capacity values of the samples show that a greater heat demand for a unit change in the temperature of a kilogram mass can be ensured by increasing the percentage of MHP utilized to fabricate the samples. It can be deduced from the results that increment in specific heat capacity by 1.42 %, 3.54 %, 5.86 %, and 7.02 % is possible by using of 25 %, 50 %, 75 %, and 100 % of the MHP respectively in the composite formulations. This further substantiates the submission made earlier that utilization of MHP enhances improved thermal insulation efficiency of the samples. George et al. [35] reported specific heat capacities of (1468.80 ± 6.00 $Jkg^{-1}K^{-1}$) for pure plaster of Paris and (842.90 ± 2.96 $Jkg^{-1}K^{-1}$) for asbestos used as conventional ceilings in buildings. By considering such values in the light of heat requirement of the studied samples for temperature change, it is appropriate to assert that the one associated with the least quantity of heat in this research could be 5.75 % more efficient than the plaster of Paris and 84.13 % better compared to the asbestos if applied as a ceiling panel to ensure thermal comfort in buildings.

3.5. Effect of mix design on thermal diffusivity of the samples

Thermal diffusivity generally expresses the rate at which heat flows and propagates temperature within a material. If the samples in this study are applied in buildings, they would be exposed to thermal front during service. It can therefore be inferred from the thermal diffusivity results that, during such moments, ability of the samples to slow heat diffusion would relate positively with proportion of the MHP in them. From molecular point of view, inclusion of MHP promotes lowering of thermal diffusivity which in turn portrays better thermal insulation efficiency. For the composite mix proportions adopted in this research, the largest marginal difference in thermal diffusivity occurs between 75 % and 100 % while the smallest value is observed between 50 % and 75 % contents of the MHP in the samples.

3.6. Effect of mix design on solar radiation absorptivity of the samples

Regarding solar radiation absorptivity, the samples exhibit a greater ability to absorb and retain incident solar radiation as the fractions of MHP inclusion increase. This possibility can be attributed to the fact that since the added proportions of MHP enhance slower heat diffusion for propagation of temperature, they simultaneously retain the absorbed heat more than when the content of WCP is increased. In the instant case, the maximum variation in solar radiation absorptivity of the samples is about 8.20 % due to inclusion of the MHP in them. There is a clear indication from the results that the more thermally-conductive sample is, the lower ability it has to retain the thermal energy absorbed by it when being photothermally heated.

3.2. Effect of mix design on Nailability and Flexural strength of the samples

It is evident from the nailability test results that, for installation as ceiling tiles or partition elements in buildings, only the samples that contain at most 50 % of the MHP can successfully withstand nailing as a technique for joining them to a suitable material. This, plausibly, is due to influence of the MHP nature on internal bonding strength of the samples. Meanwhile, MHP appears to be refractory, a nature that is capable of weakening the ability of the binder to hold its particles together as more fraction of it is incorporated into the composite mix. Okorie et al. [10] observed a similar behavior in the case of tiger nut fiber inclusion in composite mix for development of thermal insulation panel for structural applications. However, 100 % nailability might be actualized for the samples in this case if the binder quantity is increased. Flexural strength is seen to be affected by the same nature of MHP, thereby signifying that WCP forms a stronger internal bond than it. At 0 % and 25 % levels of MHP inclusion, the values of flexural strength compare well with those reported by Nathaniel et al. [8] for composite ceiling panels developed using treated wood dust at 50 % level (9.710 MPa) and 25 % level (6.619 MPa) with waste newspaper paste.

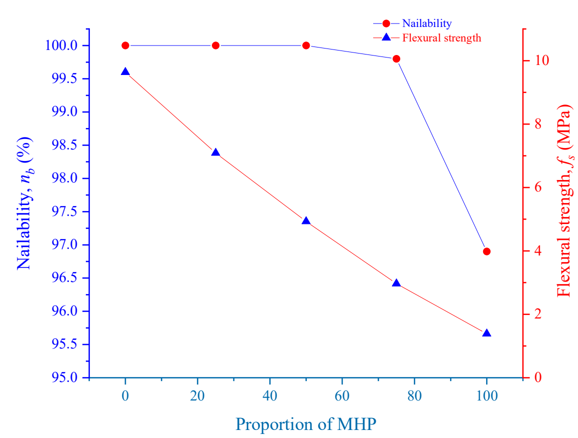

Figure 3. Variations of Nailability and Flexural strength with proportion of the MHP.

Figure 3 illustrates that nailability and flexural strength of the samples exhibit inverse trend with increasing percentages of the MHP used. This portrays that increase in the content of WCP enhances improvement in the sample's ability to withstand nail penetration as well as bending stress. Above all, it appears that while the MHP has the potential for improvement of thermal insulating ability, the WCP can rather improve mechanical properties of the samples.

4. Conclusion

The experimental investigation conducted in this work revealed that composite panels could be successfully fabricated using waste carton paste (WCP) and *Musanga cecropioides* heartwood particles (MHP). Incorporation of more MHP into the composite mix was found to enhance dimensional stability, resistance to attack by water, and lightness of the samples. Also, thermal conductivity of the samples was observed to decrease by 32.05 %, thus indicating improvement in thermal insulation efficiency due to increase in the contents of the MHP. Again, the least proportion of the MHP to be utilized in order to produce the composite with satisfactory nailability and flexural strength was found to be 50 %. In general, all the samples exhibited the tendency to perform better than conventional ceilings or partition elements commonly used in buildings. Hence, recycling waste cartons and *Musanga cecropioides* heartwood as described herein could help to solve their disposal problems while ensuring availability of suitable alternative panels for safe and affordable building constructions.

Competing Interest Statement

The authors declare no known competing financial interests or personal relationships that could have influenced the work reported in this paper.

Data and Materials Accessibility

No additional data or materials were utilized for the research described in the article.

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