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Research Article

Suitability of Composite Panels developed from Waste Paper and Fluted Pumpkin Pod for Structural Application

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Keywords

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Abstract

This research explored the suitability of composite panels fabricated form waste writing-paper paste (WPP) and fluted pumpkin pod particles (FPP) for structural application. The WPP and FPP were utilized at varying proportions (0, 25, 50, 75, and 100%) by weight to fabricate composite panels. The fabricated panels were dried completely and then subjected to various tests aimed at determining their suitability for structural applications. It was noticed that 100% FPP content yielded maximum water absorption (87.21%), thickness swelling (36.85%), specific heat capacity (1464 $Jkg^{-1}K^{-1}$) and minimum bulk density (793.9 kgm^{-3}), thermal conductivity (0.2528 $Wm^{-1}K^{-1}$), thermal diffusivity (2.176 × 10^{-7} m^2s^{-1}), thermal effusivity (542 $Jm^{-2}K^{-1}s^{-1/2}$), nailability (84.4%), flexural strength (1.335 N/mm^2), showing that FPP-rich samples exhibited better thermal insulation. The results revealed that the panels could ensure thermal comfort better than conventional ceilings like Isorel, asbestos, and plaster of Paris. For practical application and service performance, utilization of the FPP at 50 % content level was found to be optimal.

1. Introduction

Recycling of waste items into a useful product is a way of managing them to solve disposal problem while ensuring availability of low-cost materials for certain engineering applications. Wastes are items regarded as no longer useful and are typically disposed of immediately [1]. Of greatest interest is solid waste due to the fact that it is the most frequently occurring of all waste types especially from individuals, industrial, domestic, or agricultural activities [2]. In recent times, development of composites from recyclable waste items has gained significant research interest because such materials may possess the desired properties and provide a feasible solution to the materials selection problem in terms of meeting a particular requirement for an intended application [3]. Also, composites developed from natural fibers have many advantages which include high strength-to-weight ratio and non-toxicity and as such, are better than those made using synthetic fibers [4]. This resonates with the observations of a group of researchers [5] that natural fiber polymeric composites are increasingly used to develop more sustainable, resistant, and lighter materials with good specific properties and performance over a wide range of applications. Several recent studies have equally reported that recyclability of wastes can result in new and desirable products [6 - 11], thus pointing to the efficacy of innovations introduction into manufacturing processes [12 - 15].

Waste paper is a typical recyclable material for development of new value-added products and utilizing it offers additional advantage in terms of availability and sustainability [20}. Reports from studies involving recycling of waste papers/paper products have shown that composite boards developed with waste newspapers [16 – 20], cartons [21, 22], and copier papers [23, 24] can perform satisfactorily in their various aspects of applications. It is noteworthy that ever since paper was created (c.3700–3200 BC), it has become an essential part of human life [25]. As papers are a necessity of civilization, there is no halt in their production and in turn, generation as waste [26]. The global paper market research source "World Paper Markets up to 2030" has similarly reported that world paper production will grow to 482 million tons in 2030, resulting in a further increase of waste generation [27]. These facts indicate that waste papers are under-utilized, highlighting the need to explore additional methods for their valorization. Coupled with the fact that each kind of waste paper has a different type of fiber [28] and this factor influences the quality of the recycled paper [17], this necessity is utmost.

In agriculture, fluted pumpkin (*Telfaria occidentalis*) is a tropical perennial cucurbit grown as a leaf vegetable and for its edible seeds. It is called Ugu in Igbo and Yoruba, and Nkong in Ibibio/Efik native dialect [29]. Its fruits take 5 months to mature and may weigh 2 kg to 10 kg depending on the size. The pod together with pulp constitutes about 64 % of the whole fruit weight. Several nutritional/medicinal values have been reported of the leaves and seeds of this fast-growing crop [29 -- 35]. The uses of the seeds for production of bakery products have also been reported [36 – 38]. Unfortunately, research interest has not been focused on the pods even though each fluted pumpkin stand produces fruits in large quantities such that they could enhance sustainable production if the pods are found promising for use as raw material for certain useful purposes. Consequently, the pods are usually discarded when the seeds are removed.

The essence of this research is to examine the possibility of utilizing waste writing papers and fluted pumpkin pods for development of composite panels and also determine the suitability of the products for structural applications. To the best of the authors' knowledge, this paper will be the first to provide scientific information on such an attempt. It has been observed that an enormous amount of writing papers generated as waste is under-used. Due to persistence of ineffective solid waste management systems in developing and less-developed countries [39 - 42], such paper materials and fluted pumpkin pods are usually disposed of by open burning or indiscriminate dumping into the environment. Either

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disposal practice promotes health hazard in diverse ways. In the light of incessant rise in prices of structural materials, this prompts the need to channel the said wastes for economic benefits and salvaging of the environment to ensure improved public health. Physical, thermal, and mechanical properties of the developed panels will be evaluated to gain insight into their possible performances so as to ascertain their specific usefulness. It is hoped that findings from this study would be of immense benefit to researchers, environmentalists, and building industries.

2. Materials and Methods

2.1. Materials

The main materials utilized in this study were topbond as well as writing papers and fluted pumpkin pods discarded as waste items. The papers were picked from dumpsites in some markets and educational institutions. The pumpkin pods were gathered immediately after harvesting from farms. The topbond, a general-purpose white glue manufactured by PURECHEM limited, was obtained from a building materials shop. Each of the materials was gathered in large quantity within Uyo, Akwa Ibom State, Nigeria. Topbond has greater strength than starch and is cheaply available.

2.2. Processing of the materials

The surfaces of the papers and pods were cleaned with brush to remove any accompanying dirt. After that, the papers were shredded with scissors and then soaked in warm water for 24 hours. When removed from the water, they were squeezed lightly. This was necessary in order to remove excess water from them. Further, the squeezed paper material was mechanically processed into paste using Agate mortar and pestle. The resulting paste was sun-dried completely in air. Also, the pods were allowed to dry completely before they were pulverized. Figure 1 shows the appearances of the waste paper paste (WPP) and fluted pumpkin pod particles (FPP) obtained in this research.

Figure 1. Appearances of the processed waste materials

2.3. Analysis of the WPP and FPP

Gradation of the FPP was performed by sieve analysis [43] to provide an insight into the particles size distribution of the material. This involved shaking the FPP through a series of woven-wire square-mesh sieves arranged in such a way that each sieve has successively smaller openings. The percentage of each aggregate size was measured by weighing the quantity retained per sieve and comparing the weight to the total weight of the aggregate [44]. The quantity that passed standard US sieve with 2- mm openings was utilized in this work. Then, they were divided into two portions of which one in each case was subjected to chemical analysis for determination of lignocellulosic fractions using gravimetric method [40].

2.4. Fabrication of the panels

The WPP was mixed with the FPP at varying weight proportions to prepare the samples by hand lay-up technique. For each formulation, the samples were developed in triplicates. The topbond was used as binder in the ratio of 1:1 by weight of the composite mix. This was necessary due to high refractory tendency of the FPP. Table 1 shows the fibers mix design adopted in this study. Samples fabricated for examination of physical and thermal properties were formed in molds with diameter and thickness of 110 mm and 10 mm respectively while samples developed for determination of mechanical properties were formed in molds measuring 120 mm x 80 mm x 20 mm. Compaction of the mixtures was implemented by means of a laboratory-compacting machine maintained at 5 kN. After 6 hours, the samples were demolded and sun-dried completely before being subjected to the tests intended for them. Adoption of sun-drying helped to prevent denaturing of the samples.

Table 1. Proportioning of the WPP and FPP for the composite formulations

Material used	Proportion (%)				
WPP	0.0	25.0	50.0	75.0	100.0
FPP	100.0	75.0	50.0	25.0	0.0

2.5. Testing of the panel samples

2.5.1. Water absorption

Water absorption and thickness swelling of the samples were tested by immersion method [45]. Prior to complete immersion in water at 28 °C, each sample's mass and thickness were measured using a digital balance (S. METTLER – 600 g with resolution of 0.1 g) and electronic vernier calipers respectively. After 2 hours of soaking, the samples were removed from the water and kept separately on a large wire net for some seconds. Immediately when the excess water on their surfaces disappeared, the mass and thickness of each of them were measured again. The water absorption, WA was computed using the formula [46].

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

where M_f = mass of the sample after immersion, and M_i = mass of the sample before the immersion.

2.5.2. Thickness swelling

Similarly, thickness swelling was determined thus [36]

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

where T_s = thickness swelling, T_i = thickness of the sample before the immersion, and T_f = thickness of the sample after immersion in the water.

2.5.3. Bulk density

The Modified water displacement method [47] was used to determine bulk volume and then obtain the required bulk density of each sample. As applied in several researches including but not limited to [48 – 50], each sample was coated with a known volume of paraffin wax before it was completely immersed in water. The volume of the water displaced was then determined, which was same as the volume of the sealed sample. The difference between the volume of the sealed sample and that of the coating material on it yielded the bulk volume of the sample. The bulk density, ρ of each sample was evaluated based on the relation [51].

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

where M_s = sample's mass, and V = sample's bulk volume.

2.5.4. Thermal conductivity

For determination of thermal conductivity of the samples, Modified Lee – Charlton's Disc Apparatus technique was employed [52]. In the experimental setup, the sample to be tested was inserted between two identical discs. Heat was supplied from electric hotplate at a controlled rate, ensuring that the lower disc reached about 100°C. the temperature of the upper disc was equally monitored until the system attained steady state before the temperature-time data were generated and used to compute the rate of cooling of the disc. From the data obtained, the required thermal conductivity was computed as [53].

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

where k = thermal conductivity, M = mass of the disc used, c = specific heat capacity of the disc, x = thickness of the sample, A = cross-sectional area of the sample, $\Delta\theta$ = difference in temperature between the sample's surfaces, and $\frac{dT}{dt}$ = rate of cooling of the disc.

2.5.5. Specific heat capacity

SEUR'S apparatus was employed to determine the specific heat capacity of each sample [54]. In this case, the measurement system consisted of aluminum plate and plywood plate as additional heat exchange accessories to plate of the sample under test and each of them measured 60 mm × 60 mm × 8 mm. When the system attained thermal equilibrium during heat exchange, the quantity of heat gained by the plywood plate and the amount of heat lost by the aluminum plate were calculated based on assumption that energy was conserved. Then the specific heat capacity of the sample was calculated [50, 55].

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

where C =specific heat capacity of the sample, Q_p = quantity of heat gained by the plywood, Q_a = amount of heat lost by the aluminium plate, and δT = temperature rise of the sample.

2.5.6. Thermal diffusivity and Thermal effusivity

Using the values of bulk density, specific heat capacity, and thermal conductivity already obtained for each sample, the corresponding thermal diffusivity, λ was obtained [56 - 59].

$$\lambda = \frac{k}{\rho C} \quad (6)$$

and thermal effusivity, e was determined for each sample using the formula [45].

$$e = \sqrt{k\rho c} \quad (7)$$

2.5.7. Nailability

More so, a nail gun named Finish Nailer (Model D51257K) was used for the nailability test on the samples [22]. The process was discontinued when a successful penetration or visible crack was observed, and the sample's nailability was then calculated using the formula.

$$n_b = \left(\frac{D}{x}\right) 100\% \quad (8)$$

where, n_b = nailability and D = penetration depth of the nail.

2.5.8. Flexural strength

Flexural strength of the samples was assessed by three-point bending technique [60] employing a universal testing machine (Model H10KT). For each test schedule, a test speed of 1mm/min was applied until flexural failure was observed. At that instant, the necessary data obtained were applied to compute the flexural strength, σ thus

$$\sigma = \frac{3}{2}\left(\frac{Ld}{bx^2}\right) \tag{9}$$

where L = maximum value of load applied when the sample failed flexurally, b = width of the sample under test, and d = length of support span in the flexure assembly of the machine.

For each sample formulation, the mean values of the investigated properties were computed with their corresponding values of standard error.

3. Results and Discussion

From the results presented in Table 2, it is obvious that the cellulose proportion is higher while the lignin fraction is lower in the FPP than WPP. Though the percentages of hemicelluloses in both fibers are approximately the same (26 %), it could be adjudged that the fibers are capable of exhibiting different degrees of affinity for water.

Table 2. Chemical compositions of the WPP and FPP

Lignocellulosic constituents	Proportion (%) Per Material WPP	FPP
Cellulose	42.5 ± 0.2	49.2 ± 0.1
Hemicellulose	25.8 ± 0.1	26.1 ± 0.1
Lignin	18.6 ± 0.1	10.3 ± 0.1

The graphical illustration of particle size distribution for the FPP is illustrated in Figure 2. In this case, the grading curve has a J-shape. As can be seen, the FPP is made up of particles of various sizes. Most FPP particles range between 1-2 mm in diameter, indicating fine gradation suitable for composite reinforcement. With this kind of distribution, it is possible that incorporation of the FPP into the WPP matrix can create more voids/interstices.

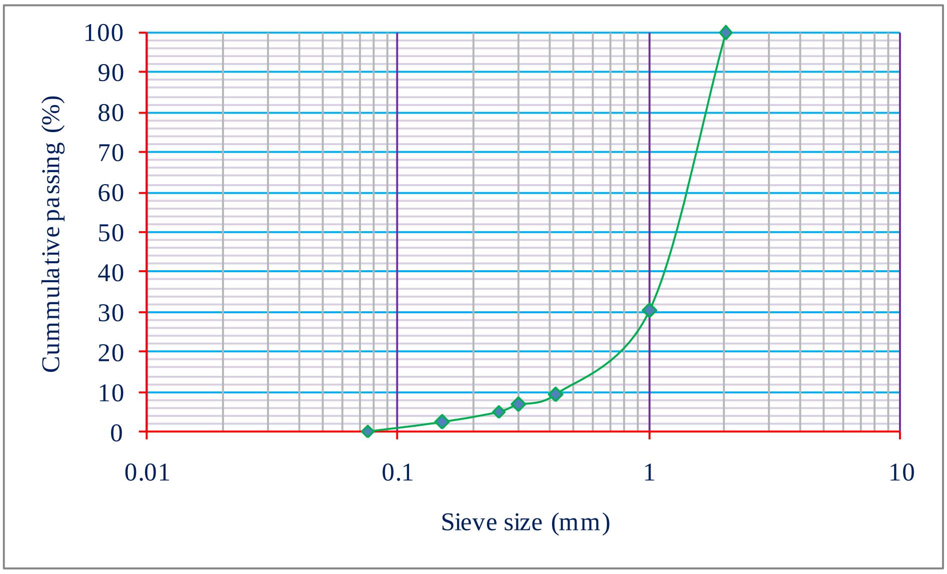

Figure 2. Grading of the FPP

The results presented in Table 3 show that water absorption of the samples made with 100 % WPP is less than that of the counterpart samples containing the FPP. Since cellulose is more hydrophilic than lignin, this may be attributed to the fact that the FPP is richer in cellulose content than the WPP. Consequently, as the proportion of the FPP increases in the samples, the water absorption increases. However, the maximum value of water absorption obtained for the samples is far less than the values (100 % to 154 %) reported [61] for ceiling boards produced from Papyrus fibers. Based on the range of values obtained for the samples in this research, it is obvious that they are suitable for interior applications as ceiling or partition panels in buildings especially in tropical regions.

Generally, water is involved in every form of deterioration of porous solids [62]. The trend in thickness swelling, with respect to increase in proportions of the FPP, is similar to that of water absorption. This observation is supported by the assertion of De Souza et al. (2011) [63] that high thickness swelling is expected from high water absorption. By utilizing 100 % of each fiber, the thickness swelling values of the developed samples differ by about 26.49 %. Since WPP absorbs less water than the FPP, samples made with greater fraction of the WPP would be more dimensionally stable.

The decrease in bulk density with increasing proportions of the FPP simply indicates that the fiber is lighter compared to the WPP. This, perhaps, is due to the fact that it contains tiny particles. The greatest bulk density value in this case (891.6 kgm^{-3}) is lower than the value of 1810 kgm^{-3} reported for asbestos ceiling [64].

By implication, the samples have choice preference over the mentioned conventional ceiling as far as reduction of dead loads in buildings is a thing of concern.

Table 3. Thermophysical and mechanical properties of the samples

Proportion of the FPP (%)	WA (%)	T_s (%)	ρ (kgm^{-3})	k $(Wm^{-1}K^{-1})$	C $(10^3 Jkg^{-1}K^{-1})$	λ $(10^{-7} m^s s^{-1})$	e $(Jm^{-2}K^{-1}s^{-1/2})$	n_b (%)	σ (N/mm^2)
0.0	78.43 ± 0.02	16.36 ± 0.02	891.6 ± 0.3	0.2714 ± 0.0003	1.345 ± 0.002	2.264 ± 0.005	570.5 ± 0.1	100.0 ± 0.0	2.202 ± 0.001
25.0	81.40 ± 0.02	22.77 ± 0.02	865.5 ± 0.4	0.2644 ± 0.0002	1.370 ± 0.002	2.231 ± 0.004	559.9 ± 0.1	100.0 ± 0.0	1.983 ± 0.001
50.0	83.06 ± 0.03	27.52 ± 0.02	846.1 ± 0.2	0.2613 ± 0.0003	1.404 ± 0.002	2.201 ± 0.004	557.2 ± 0.1	100.0 ± 0.0	1.596 ± 0.002
75.0	85.09 ± 0.03	33.03 ± 0.03	814.2 ± 0.4	0.2571 ± 0.0002	1.444 ± 0.003	2.186 ± 0.004	549.8 ± 0.2	96.8 ± 0.2	1.386 ± 0.002
100.0	87.21 ± 0.02	36.85 ± 0.02	793.9 ± 0.2	0.2528 ± 0.0003	1.464 ± 0.002	2.176 ± 0.004	542.0 ± 0.1	84.4 ± 0.3	1.335 ± 0.002

From the results obtained for the samples, the thermal conductivity values lie within the range recommended as 0.023 $Wm^{-1}K^{-1}$ to 2.900 $Wm^{-1}K^{-1}$ for construction materials [65]. By utilizing 50 % of each fiber, the mean thermal conductivity value of the sample compares well with the value (0.2617 $Wm^{-1}K^{-1}$) reported for ceiling made by modifying plaster of Paris (POP) with 10 % of *Lagenaria breviflora* rind particles [58]. However, they can ensure thermal insulation better than conventional ceilings like Isorel, asbestos, and POP which have been reported to have thermal conductivity of 0.4498 $Wm^{-1}K^{-1}$ [66], 0.3190 $Wm^{-1}K^{-1}$ [67], and 0.3171 $Wm^{-1}K^{-1}$ [68] respectively. Figure 3 shows a progressive decline in thermal conductivity as the proportion of FPP increases in the samples. This signifies improved thermal transmission restriction, plausibly, due to higher content of air (since the samples are completely dry and inclusion of the FPP brings about existence of more voids in them).

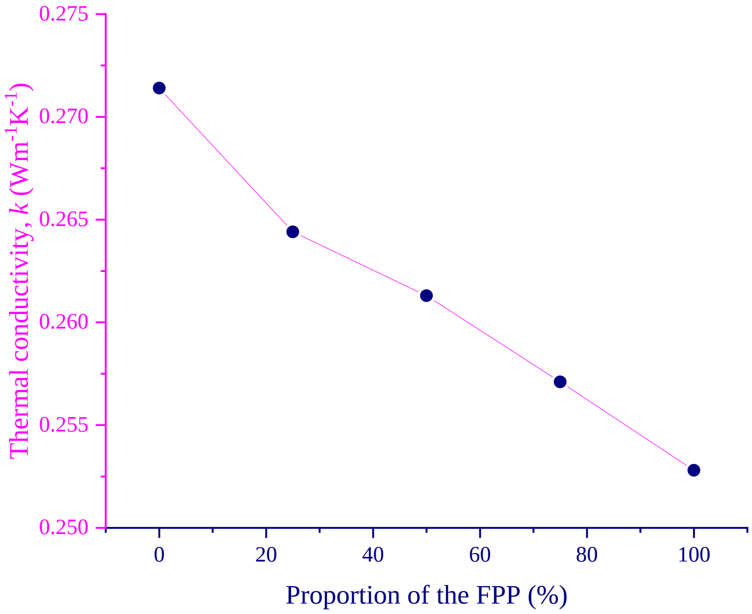

Figure 3. A graph showing the progressive decline in thermal conductivity as the proportion of FPP increases in the samples

The FPP utilization in the composite mixes brings about increase in specific heat capacity. At 25 %, 50 %, and 75 % levels of incorporation of the FPP, the specific heat capacity increases by about 0.025, 0.059, and 0.099 (all in $Jkg^{-1}K^{-1}$) from the value obtained by developing the sample with the WPP at 100 % content level. This indicates that the FPP has a greater potential than the WPP to enhance heat-insulating ability of the samples. As can be deduced to substantiate this remark, the specific heat capacities of the samples are such that the value for sample prepared with the FPP at 100 % content level is 8.85 % higher than the value obtained for its counterpart fabricated with the FPP.

In this case, there is decrease in the value due to increase in the FPP content. Such situation favors the samples and enhances the insulation performance. This is because it reduces the speed at which temperature propagation occurs and in turn, slows the distribution of thermal energy within the sample. The implication of the results is that the FPP is more efficient than the WPP for betterment of thermal insulation performance of the products. Possibly, this is as a result of gradual decrease in thermal conductivity but increase in specific heat capacity with increasing contents of the FPP in the samples.

This thermal transport property expresses the readiness of a material to release heat to the surroundings. By increasing the proportion of the FPP up to 100 %, the thermal effusivity decreases by about 28.5 $Jm^{-2}K^{-1}s^{-1/2}$. This progressive reluctance to release heat is supported by the increased ability to store heat as expressed by specific heat capacity of the samples as a result of increasing the FPP content. Thus, it is appropriate to infer that the sample with greater fraction of the FPP is capable of promoting thermal comfort better if applied as either ceiling or wall partition panel in buildings.

The results of this test reveal that the samples can be installed successfully by nailing only if the proportion of the FPP used to fabricate them is at most 50 %. Perhaps, this optimum content level is dependent on the binder concentration and quantity adopted for fabrication of the samples in this study. Okorie et al. (2020) [21] reported 12.8 % as the optimum percentage utilization of tiger nut with waste carton paste and 10 % cassava starch slurry as binder in 0.8 ratio to the composite mix. But in the case of using epoxy resin to bind waste newspaper paste and sugarcane bagasse particles in the ratio of 4:3, Etuk et al. (2023) [46] observed nailability of 100 % irrespective of the mix design adopted.

The refractory nature of the FPP has a significant influence on the flexural strength of the samples by promoting weakening of the adhesion with the WPP in the resulting composite samples. Consequently, the internal bonding is reduced gradually as the fraction of the FPP increases. In turn, this causes reduction in the flexural strength. It can be seen in Figure 4 that between 25 % and 50 % content of the FPP, the flexural strength decreases by the widest margin. This portrays the greatest susceptibility of the samples to bending stress. It can be inferred that sample with 75 % content of the FPP would resist stress similarly to the sample developed with 100 % FPP if subjected to same conditions in service. Specifically, the results show that as the FPP proportion increases, the bulk density decreases and the flexural strength decreases also. Based on the results of all the tests, it can be adjudged that the studied panels are suitable for non-load-bearing purposes.

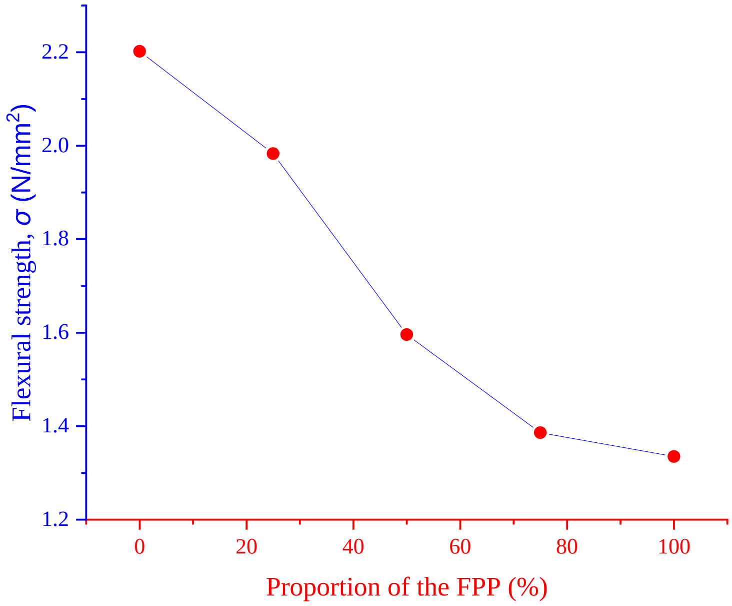

Figure 4. A graph showing the variation of flexural strength with proportion of the FPP in the composite panels

4. Conclusion

The results of the experiments conducted in this research have revealed that recycling of waste paper with fluted pumpkin pods into composite panels is promising and is capable of yielding viable alternative materials for thermal insulation applications. The developed samples exhibited improved thermal insulation efficiencies as the proportion of fluted pumpkin pod particles (FPP) increased. On the contrary, the strength of the panels declined with increase in the content of the FPP. Though all the samples could perform thermal insulation better than conventional ceilings like Isorel, asbestos and plaster of Paris (POP), the optimum content of the FPP for satisfactory utilization of the samples was found to be 50 % beyond which the nailablity started reducing to less than 100%. In all, 50% FPP mix provided the best balance and the panels were found to be suitable as interior ceiling/partition boards. The panels are los-cost and environmentally friendly. By the undertaking described in this research, it would help to minimize adverse effects associated with disposal of the waste materials in question.

The authors declare that there is no conflict of interest. They have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Declaration of Conflict of Interests

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