(RESEARCH ARTICLE)

Thermophysical properties plaster of Paris ceilings reinforced with oil palm mesocarp fiber for building design

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Abstract

This research focused on how to solve disposal problem associated with oil palm mesocarp fiber by using it to modify plaster of Paris (POP) ceiling. Untreated oil palm mesocarp fiber (UOPMF) and treated oil palm mesocarp fiber (TOPMF) were separately utilized at various weight fractions to fabricate ceiling samples with the POP. The samples were developed in triplicates, dried completely and then tested for their thermophysical propertiess. Samples with varied thicknesses were also prepared for investigation of heat flow time. The results showed changes in mean values of water absorption (12.22 – 25.75) %, bulk density (1.768 – 1.407) 10^3 kgm^{-3}, thermal conductivity (0.2245 – 0.1465) Wm^{-1}K^{-1}, specific heat capacity (1.498 – 1.825) 10^3 Jkg^{-1}K^{-1}, thermal diffusivity (8.477 – 5.705) 10^{-8} m^{2}s^{-1}, and solar radiation absorptivity (20.71 – 25.25) m^{-1} as the fraction of the UOPMF increased from 0 % to 40 %. In the case of utilizing the TOPMF, the respective changes were found to be (12.22 – 31.33) %, (1.768 – 1.477) kgm^{-3}, (0.2245 – 0.1627) Wm^{-1}K^{-1}, (1.498 – 1.789) 10^3 Jkg^{-1}K^{-1}, (8.477 – 6.164) 10^{-8} m^{2}s^{-1}, and (20.71 – 24.20) m^{-1}. Heat flow time related positively with the thickness of the samples. Though it was revealed that all the samples could perform better than conventional ceilings like asbestos and polyvinyl chloride, the UOPMF exhibited a greater potential than the TOPMF for improving thermal insulation performance of the samples. Hence, recycling the mesocarp fiber in the described manner could ensure availability of cost-effective and more thermally-efficient POP ceilings for building design.

Keywords: Bulk density; Ceiling; Thermal conductivity; Thermal efficiency; Water absorption; Waste

1. Introduction

Plantation is a leading agriculture sector closely related to economic development. In supporting the purpose of plantation development, the type of commodity crop plays a critical role. One crop of interest in this consideration is oil palm (Elaeis guineensis). It belongs to Arecaceae palm family in Plantae kingdom of Arecales order [1]. In West Africa, oil palm grows freely in the southern latitudes of Sierra Leone, Togo, Ghana, Nigeria, Benin, Cameroon, and Angola [2]. Oil palm is grown across other parts of the world including Malaysia, Indonesia, Thailand, and Papua New Guinea [3, 4]. Cultivation of the crop has expanded across the West and Central Africa and parts of America [5, 6] and this is driven to a large extent by a higher return rates on investment compared with other uses of land [7]. Consequently, income of rural communities is enhanced, poverty is tackled, and socio-economic development of frequent marginal areas on forest frontiers is supported.

Oil palm has some economic importance and relevance. Its leaf ribs and fiber are used in building and rope making respectively [8]. For making panel products, the trunk is a good candidate [9]. The crop serves as a valuable source of timber/fuel (for cooking as derived from its dead palm) and pleasant/intoxicating wine [2]. Palm kernel oil is a raw material for manufacturing of non-food products like detergents, soaps, toiletries, cosmetics, and candles while palm oil

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is utilized in food products such as shortenings, cooking oil, and margarine [10]. More vegetable oil per unit of land can be derived from oil palm compared to any other crop and this advantage makes the oil to be commonly used for direct consumption by humans and as biofuel as well as ingredient in many processed foods, pharmaceuticals, and other industrial products [11] As of 2018, oil palm area increased to more than 20 million hectares from less than 5 million hectares noticed in 1980 [12].This mostly occurred in Indonesia and Malaysia to the extent that they jointly accounted for almost 85 % of the internationally traded palm oil [13].

Palm oil extraction usually leads to generation of large amounts of mesocarp (palm-pressed) fiber as waste. About 15,700 tons of the fiber could be generated from every 100,000 tons of oil palm fresh fruit bunch processed to extract oil [14]. The fiber can be used as boiler fuel for production of electricity and processing of steam for power needs in palm oil mills [15 – 17], mulching medium and fiber source for composites used in furniture and mattress manufacturing [18], and growing Media for Banana Tissue Culture Seedling [19]. Not only that, it is useful in the preparation of bio-oil [20], and for the production of biogas [21], acetoin [22], and biocomposite whereby it is used to reinforce polymer materials [23, 24]. Even with that, the fiber is under-utilized. Since ineffective solid waste management systems persist in developing countries [25, 26], the fiber is prevalently disposed of by open burning or indiscriminate dumping which eventually causes significant environmental problems. For the fact that the fiber generation will continue to rise from 21,560,251 tons in 2020 to about 30,732,801 tons in 2030 due to increasing demand of crude palm oil [27], the present situation is of great concern.

The essence of this study, therefore, is to proffer an additional way of enhancing utilization of the waste in order to solve the problem associated with its disposal. Considering the feasibility of ensuring sustainable building constructions through recycling of readily available waste in the light of ceilings function in buildings [28], this research is designed to assess the possibility of improving the performance of plaster of Paris (POP) by reinforcing it with mesocarp fiber of oil palm. The choice of POP in this case is due to numerous advantages it has (except in terms of cost) over other conventional ceiling panels like plywood, polyvinylchloride (PVC), and asbestos [29]. Specifically, untreated and treated oil palm mesocarp fiber will be separately utilized as filler in the POP matrix to develop ceiling samples and investigate their thermophysical properties. Keeping in mind that composite is designed to produce a new material that meets the exact requirements for a particular application [30], it is hoped that findings from this study would greatly benefit researchers, builders, and manufacturers of building materials, etc.

2. Material and method

2.1. Materials

Sodium hydroxide pellets, POP, potable water, and oil palm mesocarp fiber were majorly used in this research. The fibrous part of the oil palm fruit was gathered from a palm oil processing site while the POP was collected from a building construction site. Both materials were obtained in large quantities in Uturu, Abia State, Nigeria.

2.2. Processing of the fiber

The oil palm mesocarp fiber was washed with detergent and water to remove the remaining oil still present. This was necessary to enhance adhesion with the POP matrix. After washing, the fiber was sun-dried and then pulverized with a domestic blending device. The resulting material was divided into two portions, one of which was treated in a fresh solution of sodium hydroxide (NaOH) having concentration of 10 %$\frac{w}{v}$.This alkali treatment was allowed for 7 hours before the fiber was removed from the solution, thoroughly washed using water, and then sun-dried until it became moisture-free. The untreated and treated fiber materials were separately screened and the quantity of each fiber that passed the openings of mesh No. 10 of US sieve was utilized in this research.

2.3. Analysis of the fibers

Chemical composition analysis was performed on the UOPMF and TOPMF to determine the proportions of their lignocellulosic constituents. The method used by Mylsamy and Rajendran [31] was adopted in this case and the constituents examined were cellulose, hemicelluloses, and lignin.

2.4. Samples fabrication

Control sample of the POP was prepared after which the UOPMF was used as filler at various weight proportions to develop composite panels with it by hand lay-up technique. Similar procedure was adopted to prepare other composites but with the TOPMF as filler. Table 1 shows the mix design used. For each formulation, the ratio of water to solid component was 2:5 by weight. The mixture was cast in a mold of diameter 110 mm and thickness 7 mm. Immediately

that was implemented, it was kept under ambient conditions for 10 minutes. On demolding, the developed panel was made to dry completely. In order to assess the influence of thickness on duration of heat flow, other samples were similarly developed in addition but with varied thicknesses such as 5 mm, 9 mm, 12 mm, and 15 mm. In each case, three representative samples were fabricated and also subjected to the intended tests. Figure 1 shows the mixing processes of the untreated and treated forms of the fiber (designated as UOPMF and TOPMF for ease of identification) with the POP powder and water resulting to the developed samples.
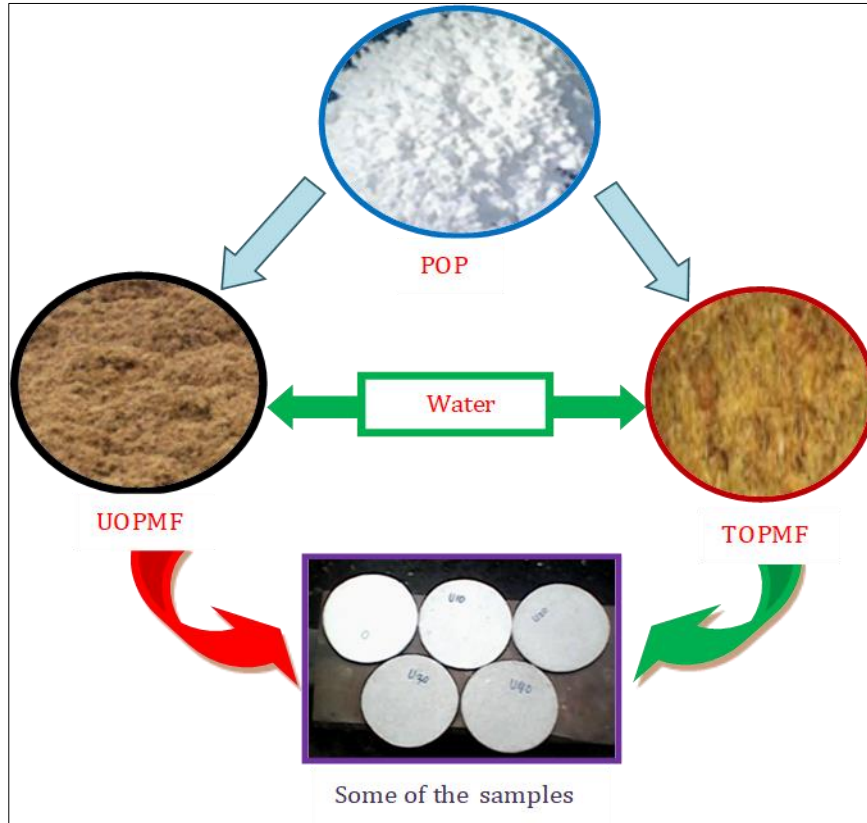

Figure 1 Mixing scheme of the materials

Table 1 Proportioning of the fillers and POP

POP (%)	100.0	90.0	80.0	70.0	60.0
Filler (%)	0.0	10.0	20.0	30.0	40.0

2.5. Properties evaluation

2.5.1. Water absorption and Bulk density

Water absorption was tested to provide information on the extent to which water can be absorbed and retained by the samples. In this research, immersion method was employed for its determination and the mass of each sample was determined by means of a scale balance [32]. The immersion was carried out at 28 °C. After 24 hours, the sample was removed from the water and allowed to surface-dry prior to re-weighing it. Water absorption, WA was computed as [1, 33]

$$WA = \left(\frac{M_w - M_d}{M_d}\right) 100\% \text{...............(1)}$$

where M_d = mass of the sample prior to immersion, and M_w = mass of the sample when surface-dried.

In the case of bulk density test, the bulk volume of each sample was determined by Modified water displacement method [34]. All masses were measured using a digital weighing scale that has resolution of 0.1 g. The data obtained for each sample were applied in line with the conventional density formula to evaluate the bulk density, ρ thus [35, 36]

$$\rho = \frac{M_s}{V} \quad ......(2)$$

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

2.5.2. Thermal conductivity and Specific heat capacity

Modified Lee – Charlton's Disc Apparatus technique was used for determination of thermal conductivity of the samples [37]. The heating processes were executed with the aid of an electric hotplate. During each schedule, the thickness of the sample under test was properly lagged using cotton wool. Also, modeling of cooling rate function was performed by means of Origin software (Version 2019). The data obtained were used to compute thermal conductivity based on the relation [36, 38]

$$k = \left(\frac{Mcx}{A\Delta\theta}\right)\frac{dT}{dt}........(3)$$

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

Specific heat capacity was determined by employing SEUR'S apparatus [39]. In this case, the system consisted of aluminum plate and plywood plate (each of which measured 60 mm x 60 mm x 8 mm) as additional heat exchange accessories to plate of the sample under test. Digital thermometers (Model No. 305, calibrated and equipped with type-K probe) were used to actualize temperature monitoring/measurements. When the system attained thermal balance during heat exchange, the amount, Q_p of heat gained by the plywood plate and the quantity, Q_a of heat lost by the aluminium plate were calculated based on the assumption that energy was conserved. Then the specific heat capacity, C of the sample was calculated thus [1]

$$C = \left(\frac{Q_a - Q_p}{M_s \delta T}\right)............(4)$$

where δT = temperature rise of the sample.

2.5.3. Thermal diffusivity and Solar radiation absorptivity

The values already obtained for bulk density, specific heat capacity, and thermal conductivity of each sample were used to calculate the corresponding thermal diffusivity in accordance with the formula [40 - 43]

$$\lambda = \frac{k}{\rho C} \quad ....(5)$$

where λ = thermal diffusivity.

After that, solar radiation absorptivity, α_r was determined on 24-hour periodic basis using [44]

$$\alpha_r = \sqrt{\left(\frac{\pi}{\lambda T_p}\right)}...........(6)$$

where T_p = periodic time.

2.5.4. Variation of Heat flow time, T_x with thickness

The flow of heat across the thickness of each sample was determined by using the same setup for thermal conductivity assessment but without involvement of the upper disc and lagging material. Meanwhile, the lower disc was heated to the same temperature it attained at steady state and the sample had been allowed to cool completely before it was placed on the disc. Immediately, the probe of the upper thermometer was made to be in contact with the top of the sample and timing of the vertical heat flow commenced. Figure 2 shows features of the setup used in this case. When a

slight change in the temperature was registered by the thermometer by about 0.2 °C, the time was noted and another sample was tested in like manner. All the tests were carried out at (25.0 ± 1.0) °C and the results obtained for the triplicates were averaged for each formulation and tabulated with their standard error value.
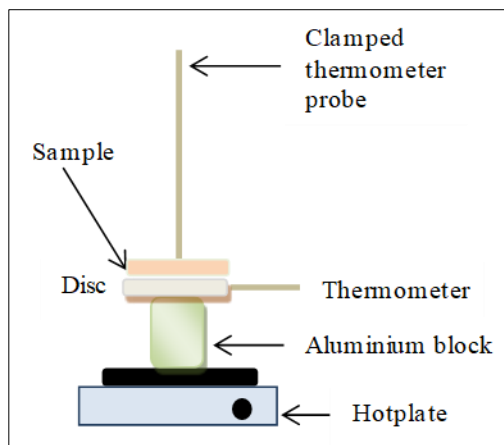

Figure 2 Setup for investigation of sample's thickness influence on heat flow time

3. Results and discussion

Table 2 shows proportions of the chemical constituents in the UOPMF and TOPMF. As seen, cellulose is more in the TOPMF compared to the UOPMF. This may be due to alkalization of the raw fiber using NaOH [29]. The fractions of hemicelluloses and lignin in UOPMF are rather greater by about 28.37 % and 21.01 % respectively than their proportions in the TOPMF. These results simply signify that the UOPMF and TOPMF differ behaviorally from each other.

Table 2 Chemical composition of the fibers

Fiber/Filler materials	Values for five determinations per constituent		
	Cellulose (%)	Hemicellulose (%)	Lignin (%)
UOPMF	42.82 ± 0.91	33.21 ± 0.62	22.63 ± 0.82
TOPMF	92.53 ± 0.62	4.94 ± 0.41	1.62 ± 0.22

Observably, samples with TOPMF content exhibit more affinity for water uptake in comparison with those made using the UOPMF as a component (Table 3). That is to say, higher proportion of cellulose in the TOPMF occasioned by the chemical treatment applied in this study leads to increased hydrophilicity displayed by samples produced with it. This agrees with the observations of Rahman and Khan [45] on alkali treatment of fiber. The trend in water absorption with filler proportion depicts an exponential growth in both cases (Figure 3). Beyond 20 % loading levels, the difference in effect of the alkali treatment on water absorption of the samples gradually becomes more pronounced with the TOPMF enhancing water uptake more than the UOPMF.

Samples produced with the UOPMF have lower bulk densities compared to their counterparts made with the TOPMF. This, as noted in a study by other researchers [46], is possible because the treatment given to the raw fiber leads to densification of the cell wall of the resulting fiber (TOPMF). Consequently, samples developed with the TOPMF become denser than those produced using the UOPMF. At loading fractions of 10 %, 20 %, 30 % and 40 %, the respective difference in mean bulk density values between samples with UOPMF content and those fabricated with TOPMF content is 90.0, 98.0, 91.0, and 70.0 (all in kgm^{-3}). It can be inferred that these differences constitute positive changes by 5.81 %, 6.45 %, 6.12 %, and 4.98 % respectively. Such increments align with the observation reported in the literature that alkali treatment of natural fiber results in slight increase in density [47].

Table 3 Results of tests performed on the samples

| Fibre material	Fraction used (%)	Water absorption, WA (%)	Bulk density, ρ $(10^3 kgm^{-3})$	Thermal conductivity, k $(Wm^{-1}K^{-1})$	Specific heat capacity, C $(10^3 Jkg^{-1}K^{-1})$	Thermal diffusivity, λ $(10^{-8}m^2 s^{-1})$	Solar radiation absorptivity, α_r (m^{-1})
UOPMF	0.0	12.22 ± 0.03	1.768 ± 0.003	0.2245 ± 0.0002	1.498 ± 0.003	8.477 ± 0.066	20.71 ± 0.08
	10.0	13.12 ± 0.09	1.548 ± 0.003	0.2019 ± 0.0001	1.546 ± 0.002	8.436 ± 0.020	20.76 ± 0.02
	20.0	16.49 ± 0.06	1.519 ± 0.002	0.1928 ± 0.0003	1.674 ± 0.002	7.582 ± 0.018	21.90 ± 0.03
	30.0	20.53 ± 0.07	1.488 ± 0.004	0.1736 ± 0.0004	1.722 ± 0.003	6.775 ± 0.027	23.17 ± 0.05
	40.0	25.75 ± 0.05	1.407 ± 0.004	0.1465 ± 0.0004	1.825 ± 0.003	5.705 ± 0.024	25.25 ± 0.05
TOPMF	0.0	12.22 ± 0.03	1.768 ± 0.003	0.2245 ± 0.0002	1.498 ± 0.003	8.477 ± 0.066	20.71 ± 0.08
	10.0	14.07 ± 0.05	1.638 ± 0.004	0.2117 ± 0.0003	1.527 ± 0.003	8.464 ± 0.029	20.73 ± 0.04
	20.0	17.29 ± 0.07	1.617 ± 0.004	0.2048 ± 0.0002	1.627 ± 0.002	7.785 ± 0.023	21.61 ± 0.03
	30.0	25.45 ± 0.05	1.579 ± 0.003	0.1879 ± 0.0002	1.694 ± 0.002	7.025 ± 0.017	22.75 ± 0.03
	40.0	31.33 ± 0.08	1.477 ± 0.003	0.1627 ± 0.0003	1.789 ± 0.003	6.164 ± 0.020	24.20 ± 0.04
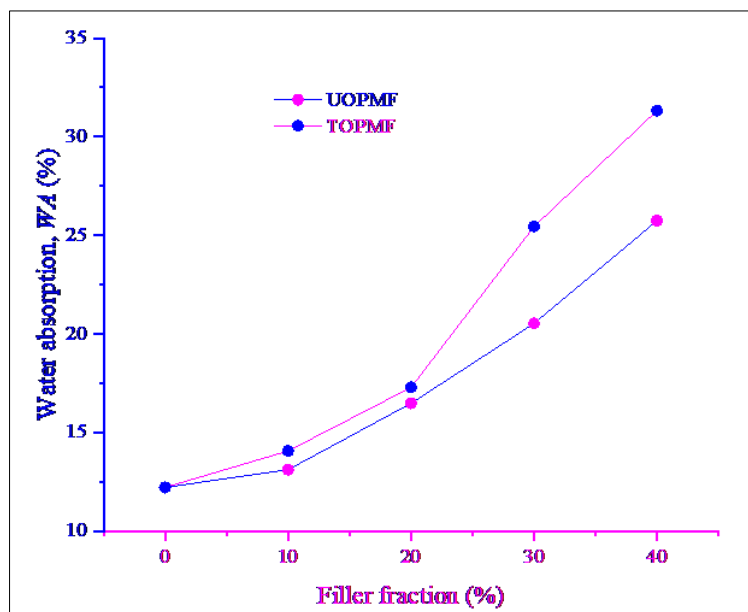
Figure 3 Plots of water absorption against filler fraction in the samples

Regarding heat transmission, samples fabricated with the UOPMF have lower thermal conductivity values than those containing the TOPMF at similar levels. This, plausibly, is due to the fact that many particles of the UOPMF are dusty and tiny and as such, are capable of creating more void spaces in the POP matrix compared to the case of utilizing the TOPMF. Therefore, since the samples were similarly fabricated, those prepared with the UOPMF contain more enclosed dead air spaces than the ones made with the TOPMF. The said spaces are filled with air since the samples are completely dry. Because air is one of the best thermal insulants, samples produced with fractions of the UOPMF have greater ability than their counterparts with TOPMF content for restriction of heat transmission through their thickness. Efficiency in thermal insulation performance between samples that contain the fibers at 10%, 20%, 30%, and 40% levels is about 4.85 %, 6.22 %, 8.24 %, and 11.06 % respectively. Utilization of 20 % UOPMF and 30 % TOPMF yields separate samples that have approximately, the same mean thermal conductivity value (0.19 Wm-1K-1). By implication, these two samples could exhibit comparable ability for heat restriction under same thermal influences if used as ceiling panels.

However, considering the range of thermal conductivity values recommended as 0.023 Wm-1K-1 to 2.900 Wm-1K-1 for building construction materials [48], it means that all the samples could be applied as ceilings in buildings. Figure 4 reveals that thermal conductivity of the samples decreases as the filler content in them increases. This simply means that improvement in thermal insulation is possible by increasing the content of either filler (UOPMF or TOPMF) used to fabricate composite POP ceiling panels as described in this study. The inverse relationships observed are possible because POP has the highest thermal conductivity value, followed by the TOPMF, and then the UOPMF.
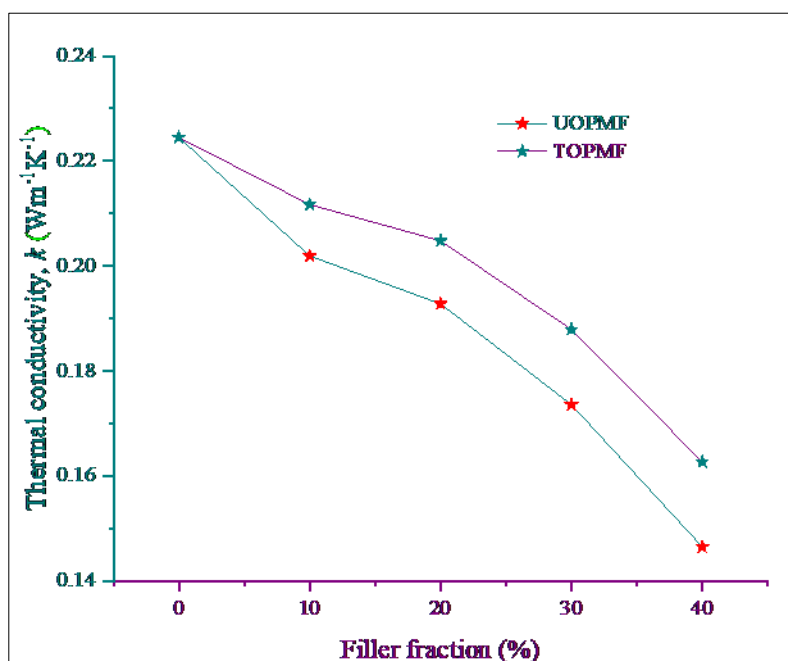

Figure 4 Plots of thermal conductivity against filler fraction in the samples

Specific heat capacity of the resulting samples improves over the control sample as more of either the UOPMF or TOPMF is used with the POP. However, the UOPMF is found to enhance greater improvement than the TOPMF. Numerically, utilizing 10 %, 20 %, 30 %, and 40 % of the UOPMF yield samples with mean specific heat capacity values that are 19.0, 47.0, 28.0, and 36.0 (all in Jkg-1K-1) more than those obtained in the cases with the TOPMF inclusion at similar levels respectively. The respective mean specific heat capacity reported for conventional ceilings like PVC and asbestos are 842.90 Jkg-1K-1 and 1571.09 Jkg-1K-1 [42]. Thus, with respect to the case of PVC, it can be posited that the capacity for heat storage prior to temperature change of a kilogram mass of the samples by one Kelvin is at least 77.72 %. Compared to the asbestos, it is obvious that the samples could perform better only if the filler content in them is at least 20 %. But according to Twidell and Weir [49], asbestos has thermal conductivity of 0.319 Wm-1K-1. This value is greater than any of those obtained for the samples. Based on that, all the samples have preference for selection and application over asbestos.

The decrease in thermal diffusivity with increase in filler proportion, as observed in this research, agrees with the observations from studies conducted by some other researchers [44, 50]. Samples with UOPMF content have lower value of thermal diffusivity than those similarly produced but with fractions of the TOPMF. For instance, utilization of the TOPMF at 10 %, 20 %, 30 %, and 40 % levels causes thermal diffusivity of the developed samples to be greater by

about 0.33 %, 2.68 %, 3.69 %, and 8.05 % respectively compared to their counterparts with the UOPMF content. Comparatively, this implies that if all the samples are photothermally heated under same conditions, heat propagation will happen faster in those that contain the TOPMF.

It is interesting to note that rapid heat propagation leads to a fast rise in temperature and this fact on diffusion of thermal energy within a material is applicable to the samples. This also agrees with the trend in their solar radiation absorptivity. Stating in another way, as the restriction for heat transmission and diffusion is enhanced by increasing the filler content, the tendency of the resulting sample to retain the absorbed solar radiation becomes greater. This submission is supported by the empirical facts expressed in equations (5) and (6) above. However, the UOPMF enables the samples to possess greater ability than those containing the TOPMF for heat retention when subjected to such thermal disturbances. At molecular level of consideration, solar radiation absorptivity plays a major role as far as thermal insulation efficiency is concerned. Though the absorptivities of samples that contain 10 % of the filler are almost alike, the results of heat flow time (Table 4) have substantiated the claim earlier made that the UOPMF enables the samples to be more thermally-efficient compared to the influence exercised by the TOPMF.

Table 4 Heat flow T_x(mins.) per thickness of the samples with respect to fraction of each filler material used

| x (mm)	Control	UOPMF				TOPMF			
	0.0 %	10.0 %	20.0 %	30.0 %	40.0 %	10.0 %	20.0 %	30.0 %	40.0 %
5.0	4.42 ± 0.02	4.98 ± 0.02	5.52 ± 0.01	6.17 ± 0.03	7.53 ± 0.02	4.65 ± 0.03	5.02 ± 0.01	5.71 ± 0.03	6.57 ± 0.02
7.0	9.64 ± 0.03	9.69 ± 0.01	10.78 ± 0.02	12.15 ± 0.04	14.37 ± 0.02	9.66 ± 0.02	10.51 ± 0.02	11.68 ± 0.04	13.32 ± 0.02
9.0	13.98 ± 0.04	17.20 ± 0.02	19.91 ± 0.03	20.93 ± 0.03	26.66 ± 0.01	15.23 ± 0.02	17.39 ± 0.03	19.63 ± 0.03	20.94 ± 0.01
12.0	26.34 ± 0.01	29.53 ± 0.03	33.67 ± 0.01	36.52 ± 0.02	46.09 ± 0.03	27.42 ± 0.03	30.83 ± 0.01	34.46 ± 0.02	40.96 ± 0.03
15.0	43.28 ± 0.02	46.30 ± 0.03	50.48 ± 0.01	57.35 ± 0.02	67.73 ± 0.02	44.96 ± 0.02	48.28 ± 0.01	53.42 ± 0.02	61.48 ± 0.02
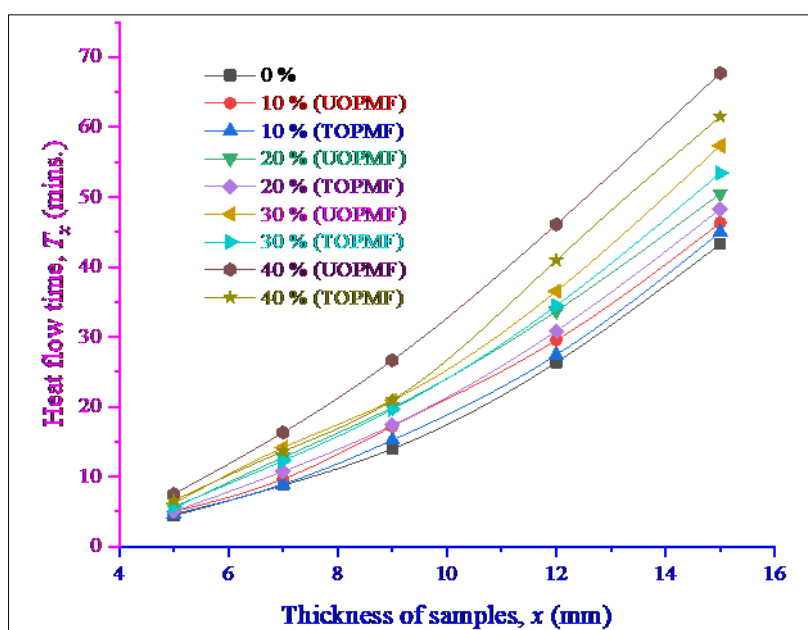
Figure 5 Plots of heat flow time against thickness of the sample

Meanwhile, the time for thermal energy to flow through the thickness of the samples correlates positively with both the thickness of the samples and proportion of the filler in them. It could be averred that samples similarly developed to be 9.0 mm thick but with 30 % UOPMF and 40 % TOPMF would exhibit comparable thermal insulation performance if installed as ceiling in buildings. From figure 5, it is evident that by increasing the filler content to 40 %, the resulting sample is capable of prolonging heat flow time the most and the more significant variation is possible with the use of the UOPMF irrespective of the thicknesses of the samples examined. This is because heat transfer behavior of the samples promotes improved thermal insulation performance as the filler proportion increases in them. In all the cases, the heat flow time relates non-linearly with thickness of the samples.

4. Conclusion

Findings from this study have revealed that it is possible to utilize UOPMF or TOPMF to modify plaster of Paris (POP) ceiling panels. The composite ceilings developed from the process possessed greater ability than the control sample for thermal insulation performances. Also, samples made with the UOPMF could perform better than their counterparts developed using the TOPMF. The samples became more thermally-insulating as the percentage of the filler (UOPMF or TOPMF) increased in them. Not only that, bulk density decreased with increasing filler content. More so, heat flow time correlated positively with filler content and thickness of the samples. With inclusion of the filler, samples developed were found to be better thermal insulation panels than conventional ceilings such as asbestos and PVC. The filler loading could be adjusted to optimize the performance of the samples. Above all, utilization of oil palm mesocarp fiber as described herein could serve as a promising approach for solving its disposal problem while enabling availability of low-cost POP ceilings for thermal insulation in buildings.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare no conflict of interest.

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