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Influence of oil palm mesocarp fiber on physical properties of fabricated plaster of paris ceilings

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HIGHLIGHTS

- The effect of chemical modification of oil palm mesocarp fiber is considered.
- The effect of the sample's thickness on heat flow time is investigated.
- The properties of the POP composites depend on the proportion of the fiber.

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ABSTRACT

This study was designed to investigate how some important physical properties of Plaster of Paris (POP) ceilings are affected by the utilization of untreated oil palm mesocarp fiber (UOPMF) and treated oil palm mesocarp fiber (TOPMF) as a modifier. Both fibers were utilized separately at various weight proportions (0, 10, 20, 30, and 40%) to fabricate the ceiling samples. The samples were dried completely and then tested for water absorption, porosity, bulk density, thermal conductivity, specific heat capacity, thermal diffusivity, heat flow time, and flakiness. All the samples could improve thermal insulation performance better than conventional ceilings like asbestos and polyvinyl chloride (PVC). However, the UOPMF enhanced a greater potential than the TOPMF over the control sample. Loading up to 30% of the fiber was optimum for a good blend, considering the resistance to wear offered by the samples.

1. Introduction

A ceiling is widely applied in building construction to conceal the underside of a roof structure for beautification and thermal insulation. These aspects of satisfaction desired by humans are challenging nowadays due to the continued rise in the price of building materials and extreme temperatures caused by climate change. Consequently, a dimension has been created for researchers to explore modifying existing products to make high-performing thermal insulation materials available for building construction purposes [1]. By giving thought to this development, Esmaeilkahaian et al. [2] posited that structure protection relies significantly on thermal barrier coating. This present situation is worrisome as Goal II of the United Nations Agenda for Sustainable Development emphasizes increased access to safe, sufficient, and low-cost housing for the world's poorest people living in slums by 2030 [3].

In this regard, modifications of the plaster of Paris (POP) ceiling have sparked attention due to its unique advantages and desirable characteristics over other commonly used conventional ceilings such as plywood, polyvinyl chloride (PVC), and asbestos [4]. Interestingly, the valorization of waste materials is promising for enhancing sustainable and inexpensive housing development and mitigating problems associated with their disposal, especially in developing and less-developed nations [5 – 9]. Findings from the research have revealed that significant improvements in the thermal insulation efficiency of POP ceilings are feasible by reinforcing the POP matrix with rice husk ash [10], cigarette butts [11], groundnut seed coat, and waste newspaper paste [12]. Other recyclable waste items that can yield satisfactory results if utilized as filler to improve the performance of POP ceilings include Lagenaria breviforaRind filled [13], wool fibers [14], and wood shavings [15].

This study investigates how using oil palm mesocarp fiber as a matrix modifier influences some important properties of fabricated POP ceilings. Rizal et al. [16] noted that about 15,700 tons of fiber could be generated from every 100,000 tons of oil palm fresh fruit bunch processed to extract oil. The mesocarp fiber is used for the manufacturing of mattresses and furniture [17], preparation of bio-oil [18], and reinforcement of polymer materials [19]. However, the fiber remains majorly under-

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utilized and, as such, is currently disposed of by open burning. This practice is of great concern as it constitutes a serious environmental and health hazard. Specifically, untreated and treated forms of the fiber will be considered in this study since pre-treatment can help to address certain drawbacks associated with a material [20].

2. Materials and methods

2.1 Materials processing

The oil palm mesocarp fiber was washed with the detergent and then rinsed thoroughly with water to remove dust and oil present in it. After washing, the fiber was sun-dried to constant weight and pulverized using a grinding machine. The resulting material was divided into two portions. One portion of it was treated with a freshly prepared 10%$\frac{w}{v}$solution of NaOH. This treatment lasted for 7 hours, after which the fiber was removed from the solution and washed using water before sufficiently drying in air. The untreated and treated fibers were separately screened. In each case, the quantity that passed through mesh No. 10 of the US sieve was utilized in this research. Figure 1 shows the untreated and treated forms of the fiber (designated as UOPMF and TOPMF, respectively, for ease of identification).

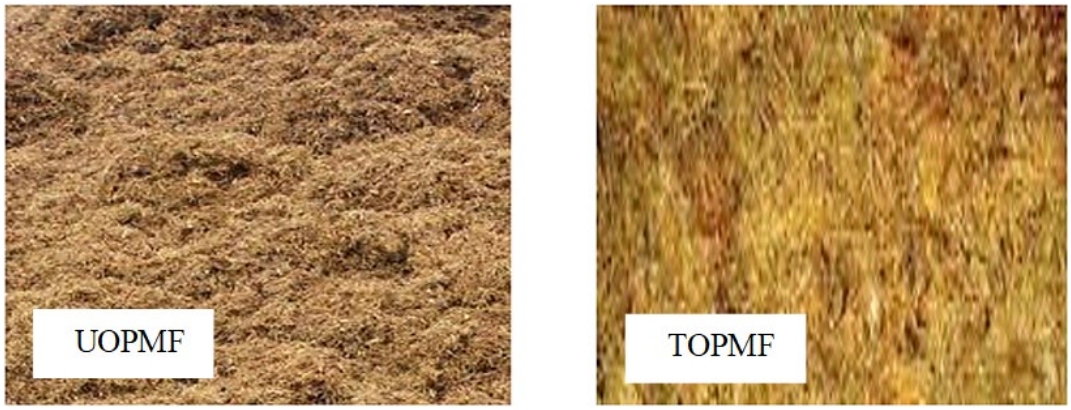

Figure 1: Appearances of the untreated fiber (UOPMF) treated fiber (TOPMF)

2.2 Preparation of the samples

The control sample of the POP panel was prepared using the hand lay-up technique. After that, the UOPMF was used as filler at various weight proportions to develop composite panels with the POP powder. Other composites were similarly fabricated using the TOPMF as filler. Table 1 shows the constitution of the filler and POP composites mix used in this work. For each constitution, the ratio of the water-to-solid components was 2:5 by weight. The mixture was cast in a mold measuring 110 mm in diameter with a thickness of 7 mm. It was immediately kept under ambient conditions for 10 minutes. On demolding, the sample was subjected to continuous sun-drying and weighing until no further reduction in its weight was observed. Three representative samples were prepared and subjected to the intended tests in each case.

Table 1: Constitution of the filler and POP composites

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

2.3 Testing of the samples

In this research, water absorption of the samples was assessed by immersion method [9]. Soaking of the samples lasted 24 hours before they were removed from the water and air-dried before re-weighing them. The water absorption, WA was computed using the Equation 1 [12,21]:

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

where M_d represents the mass of the sample before immersion and M_w represents the mass of the sample after immersion.

The samples were tested for porosity using the vacuum saturation technique. This involved measurements of the total volume of the sample, the mass of the sample in dry and saturated conditions, and the total volume of the sample occupied by the water. The mass of water in the sample was calculated and then divided by the density of water to obtain the volume filled with water. This represented the pore volume, V_p which was used to obtain the porosity based on Equation 2:

$$\varphi = \left(\frac{V_p}{V_T}\right) 100\ \% \quad (2)$$

whereφ represents porosity and V_T denotes the total volume of the sample.

The bulk volume of each sample was determined using the Modified water displacement method [22]. The mass of each sample was measured using an electronic weighing balance. The data obtained for each sample were applied to compute the bulk density, ρ according to Equation 3 [5]:

$$\rho = \frac{M_s}{V} \tag{3}$$

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

The thermal conductivity of each sample was determined using Modified Lee – Charlton's Disc Apparatus technique as described in detail elsewhere [23]. The data obtained were applied to calculate the thermal conductivity, k based on Equation 4 [24]:

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

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

For the determination of specific heat capacity, SEUR'S apparatus was employed [25]. In this case, the system consisted of an aluminum plate and a plywood plate (each measuring 60 mm x 60 mm x 8 mm) as additional heat exchange accessories to a plate of the sample under test. When the system attained thermal equilibrium during the heat exchange, the quantity, Q_p of heat gained by the plywood plate and the amount, Q_a heat lost by the aluminum plate was calculated based on the assumption that energy was conserved. Then, the specific heat capacity, C of the sample, was determined by calculation using Equation 5 [21]:

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

where δT denotes the temperature rise of the sample

The values of bulk density, specific heat capacity, and thermal conductivity already obtained for each sample were used to calculate the corresponding thermal diffusivity value λ using Equation 6 [26 - 28]:

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

where λ denotes thermal diffusivity.

The samples were allowed to cool completely. After that, the heat flow time across each thickness was determined by employing the same setup used for thermal conductivity assessment but without the involvement of the upper disc and lagging material, as shown in Figure 2.

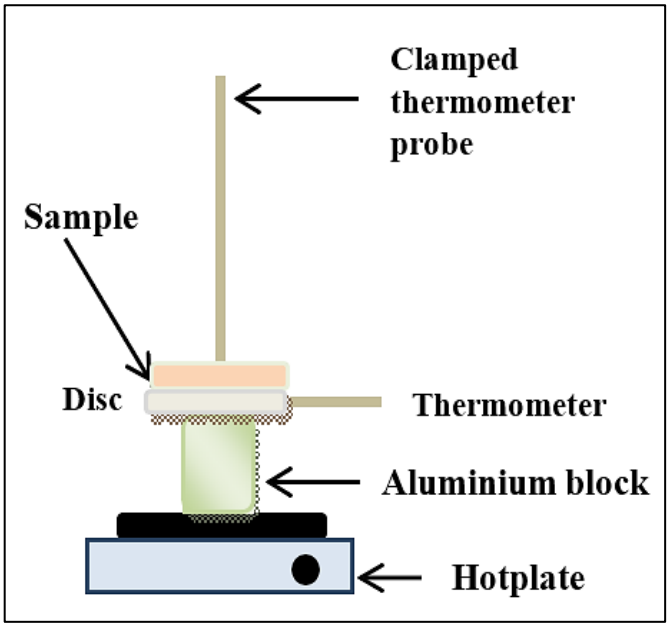

Figure 2: Schematic view of the setup for investigation of the sample's heat flow time

Meanwhile, the lower disc was heated to the same temperature it had attained at a steady state. The sample was placed on the disc, and then the probe of the upper thermometer was made to contact the top of the sample immediately. At that moment, the timing of the vertical heat flow commenced. When the thermometer registered a slight change in the temperature (about 0.2℃), the time was recorded, and other samples were treated similarly.

To determine flakiness, F_n of the samples, the initial mass,M_i of each sample was measured. Subsequently, a hard shoe brush was used to rub against the surfaces of both cross-sections, making 100 forward and backward strokes. Uniform pressure was applied on each sample, using a 1.0 kgweight placed on the brush. The flaked samples were weighed, and a decrease in the mass, ΔM of each of them, was determined. Their flakiness, F_n was calculated using Equation 7 [29]:

$$F_n = \left(\frac{\Delta M}{\mathrm{M_i}}\right) 100\% \tag{7}$$

where M_i= mass of the sample before being flaked

All the tests were carried out at (25.0 ± 1.0) ℃, and the results obtained for the representative samples were averaged per formulation and tabulated with their corresponding standard error value.

3. Results and discussion

3.1 Water absorption

From Table 2, it can be seen that samples fabricated with the UOPMF exhibit less affinity for water uptake in comparison with those made with the TOPMF. This may be attributed to the effect of the alkaline treatment given to the fiber, as observed in some other studies on coir (cocos nucifera) fibers [30]. The treatment causes the TOPMF to become more hydrophilic than the UOPMF. Figure 3 reveals that water absorption of the samples increases exponentially with the proportion of fiber used as filler. Beyond the loading percentage of 20%, a more pronounced effect is observed due to the inclusion of the TOPMF compared to the use of the UOPMF in the POP matrix.

Table 2: Results obtained for the various physical properties of the samples

Filler material	Fraction used (%)	Water absorption,WA (%)	Porosity, φ(%)	Bulk density, $\rho(10^3 kgm^{-3})$	Thermal conductivity, $k\ (Wm^{-1}K^{-1})$	Specific heat capacity, $C\ (10^3 Jkg^{-1}K^{-1})$	Thermal diffusivity, $\lambda\ (10^{-8} m^2 s^{-1})$	Heat flow time, $T_x(Mins.)$	Flakiness,F_n(%)
UOPMF	0.0	12.22 ± 0.03	14.27 ± 0.03	1.768 ± 0.003	0.2245 ± 0.0002	1.498 ± 0.003	8.477 ± 0.066	9.64 ± 0.03	0.65 ± 0.01
	10.0	13.12 ± 0.09	16.88 ± 0.02	1.548 ± 0.003	0.2019 ± 0.0001	1.546 ± 0.002	8.436 ± 0.020	9.69 ± 0.01	0.88 ± 0.03
	20.0	16.49 ± 0.06	19.76 ± 0.03	1.519 ± 0.002	0.1928 ± 0.0003	1.674 ± 0.002	7.582 ± 0.018	10.78 ± 0.02	1.24 ± 0.05
	30.0	20.53 ± 0.07	23.38 ± 0.03	1.488 ± 0.004	0.1736 ± 0.0004	1.722 ± 0.003	6.775 ± 0.027	12.15 ± 0.04	1.86 ± 0.04
	40.0	25.75 ± 0.05	29.99 ± 0.04	1.407 ± 0.004	0.1465 ± 0.0004	1.825 ± 0.003	5.705 ± 0.024	14.37 ± 0.02	2.08 ± 0.04
TOPMF	0.0	12.22 ± 0.03	14.27 ± 0.03	1.768 ± 0.003	0.2245 ± 0.0002	1.498 ± 0.003	8.477 ± 0.066	9.64 ± 0.03	0.65 ± 0.01
	10.0	14.07 ± 0.05	17.89 ± 0.02	1.638 ± 0.004	0.2117 ± 0.0003	1.527 ± 0.003	8.464 ± 0.029	9.66 ± 0.02	0.73 ± 0.02
	20.0	17.29 ± 0.07	22.79 ± 0.03	1.617 ± 0.004	0.2048 ± 0.0002	1.627 ± 0.002	7.785 ± 0.023	10.51 ± 0.02	1.20 ± 0.03
	30.0	25.45 ± 0.05	27.58 ± 0.04	1.579 ± 0.003	0.1879 ± 0.0002	1.694 ± 0.002	7.025 ± 0.017	11.68 ± 0.04	1.67 ± 0.02
	40.0	31.33 ± 0.08	35.36 ± 0.04	1.477 ± 0.003	0.1627 ± 0.0003	1.789 ± 0.003	6.164 ± 0.020	13.32 ± 0.02	1.97 ± 0.03

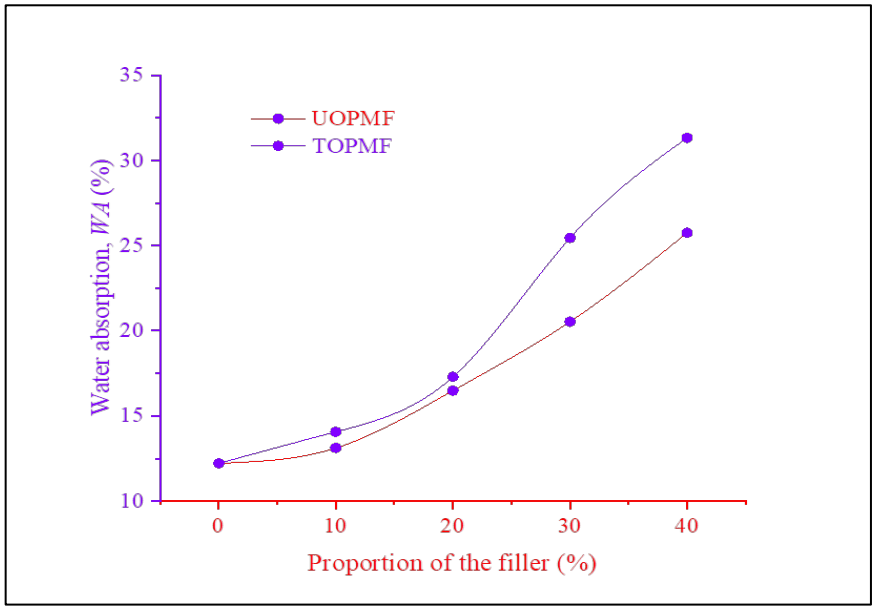

Figure 3: Dependence of water absorption on the filler loadings

3.2 Porosity

The porosity increases with the proportion of the filler. All these indicate that introducing the filler into the POP matrix creates voids filled by air since the samples are completely dry. Samples that contain the UOPMF have greater porosity values than their counterparts made with the TOPMF. This can be attributed to the effect of alkalization of the fiber to obtain the TOPMF. Meanwhile, the TOPMF have rougher surfaces than the UOPMF. Thus, greater interfacial adhesion is ensured at the TOPMF and POP matrix boundaries. This reduces the pore size more than incorporating the UOPMF into a similar matrix. At 20% of UOPMF content, the value obtained is approximately the same (23%) as the result for the sample with 30% content of the TOPMF.

3.3 Bulk density

The bulk density of samples developed with the UOPMF is less dense than in the case of their counterparts made with the TOPMF. It may well be that the treatment of the fiber leads to densification of the resulting fiber's cell wall, similar to the result obtained for coconut husk [6]. It can be deduced from the results that at loading fractions of 10%, 20%, 30% and 40%, the differences in mean bulk density values between samples with the UOPMF content and those fabricated with UOPMF content is 90.0, 98.0, 91.0, and 70.0 (all in kgm^{-3}) respectively. These differences constitute 5.81%, 6.45%, 6.12%, and 4.98 % increments respectively. Such increments agree with the report that alkali treatment of natural fiber results in a slight increase in density, possibly due to cell wall densification after removing some amounts of the lignocellulosic constituents by the treatment [31]. In terms of practical application, using samples fabricated with either fiber as ceilings can help minimize dead load in buildings since it is observed that utilization of the fibers enhances weight reduction of POP ceilings. Nowadays, lightweight materials are more desirable for applications. The use of fiber, as described in this study, can improve the global economy by ensuring the availability of such products at low cost.

3.4 Thermal conductivity

Considering the transmission of heat, samples fabricated with the UOPMF have lower thermal conductivity values than their counterparts containing the TOPMF. This may be because particles of the UOPMF are dusty and are, therefore, capable of creating more void spaces in the POP matrix. Since the samples were similarly prepared, those developed with the TOPMF contain fewer enclosed dead air spaces than the ones fabricated with the UOPMF. This agrees with the findings on porosity, which practically expresses the proportion of air in the samples. It is also noteworthy that since the samples were sufficiently dried, the voids would be occupied by air, enhancing the thermal insulating capabilities of the UOPMF in contrast to the TOPMF.

Utilizing 20% UOPMF and 30% TOPMF yields samples with approximately the same mean thermal conductivity value (0.19 $Wm^{-1}K^{-1}$). By implication, the two samples could exhibit comparable abilities for heat restriction under the same thermal influences if used as ceiling panels. However, considering the range of thermal conductivity values recommended as 0.023 $Wm^{-1}K^{-1}$ to 2.900 $Wm^{-1}K^{-1}$ for heat-insulating and construction materials [32], it can be recommended that all the samples are suitable for use as ceilings in building design. Figure 4 reveals that the thermal conductivity of the samples decreases with increasing proportions of the fillers. This means that improvement in thermal insulation is possible by

increasing the content of either UOPMF or TOPMF used to fabricate composite POP ceiling panels, as described in this study. The inverse relationships observed in this case are possible because POP has a higher thermal conductivity value than

the fibers (TOPMF and UOPMF). That notwithstanding, using either the UOPMF or TOPMF is seen here as a practical approach to creating better thermal comfort for occupants by installing the samples as ceilings in buildings.

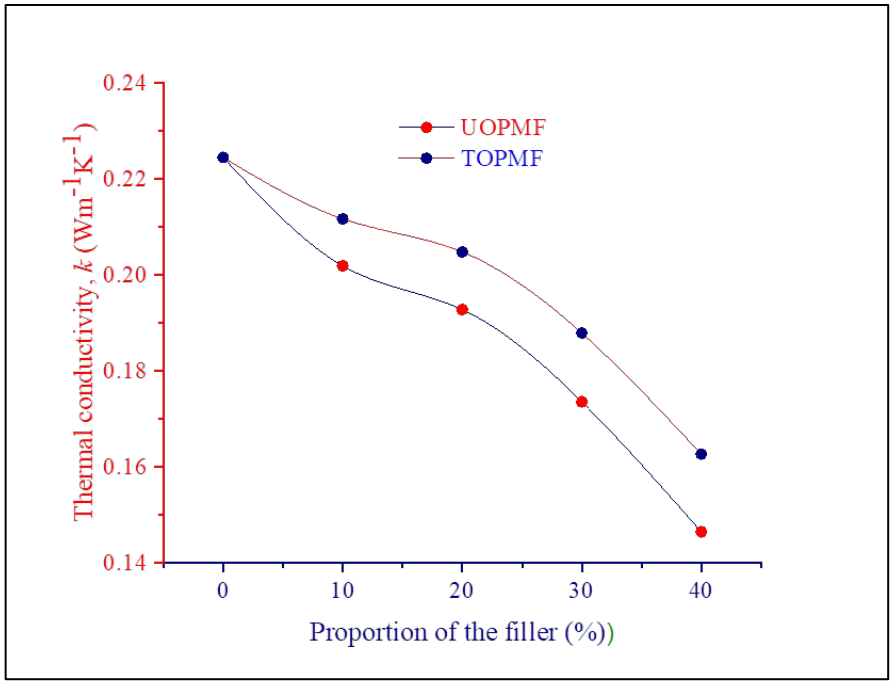

Figure 4: Dependence of thermal conductivity on the filler loadings

3.5 Specific heat capacity

The specific heat capacities of both UOPMF and TOPMF-modified POP increase with increasing filler concentration. However, it is observed that the UOPMF-modified POP shows higher specific heat capacity and is, therefore, a better thermal insulator than the TOPMF-modified POP. 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 $Jkg^{-1}K^{-1}$) more than those obtained in the cases of the POP with TOPMF filler at similar concentration levels respectively. The respective mean specific heat capacities reported for conventional ceilings like PVC and asbestos are 842.90 $Jkg^{-1}K^{-1}$ and 1571.09 $Jkg^{-1}K^{-1}$ [33]. Thus, concerning the case of PVC, it can be posited that the capacity for heat storage before the temperature change of a unit mass of the samples by one Kelvin is at least 77.72%. Compared to asbestos, it is obvious that the samples could perform better only if the filler content in them is at least 20%. This is because the samples that contain less than 20% of the fiber have specific heat capacities that do not exceed the value reported for asbestos. However, it is worthy of note that asbestos has a thermal conductivity value of 0.319 $Wm^{-1}K^{-1}$ [34]. This value is greater than any of those obtained for the samples. In practical terms, asbestos will offer lower resistance to the flow of thermal disturbance during its application. This makes asbestos least attractive for ceiling application in comparison to oil palm mesocarp-modified POP

3.6 Thermal diffusivity

As observed in this research, the decrease in thermal diffusivity with an increase in filler proportion aligns with the results obtained by some other researchers on Lagenaria breviflora rind filled POP ceiling [13] and on sandcrete blocks containing sawdust [35]. Samples with UOPMF content have a lower thermal diffusivity value than those similarly produced but with TOPMF fractions. 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. Thus, if all the samples are photothermally heated under the same conditions, heat propagation will occur faster in those that contain the TOPMF compared to the cases of utilizing the UOPMF as filler to fabricate the composite POP panels.

3.7 Heat flow time

The time for thermal energy to flow through the thickness of the samples correlates positively with the filler's proportion. Though the increase is marginal in some cases, higher values recorded for samples made with the UOPMF are in consonance with the fact that they may contain more air than their counterparts developed with the TOPMF. This, possibly, may be the reason for delays in heat flow as resistance to heat flow becomes stronger. It could be remarked that samples developed with 30% of either fiber could exhibit comparable thermal insulation performance if used as ceiling panels in building design. Figure 5 shows that by increasing the filler content to 40%, the resulting sample can prolong heat flow time the most, and the most significant variation is possible with UOPMF. This is because the heat transfer behavior of the samples promotes improved thermal insulation performance as the filler proportion increases.

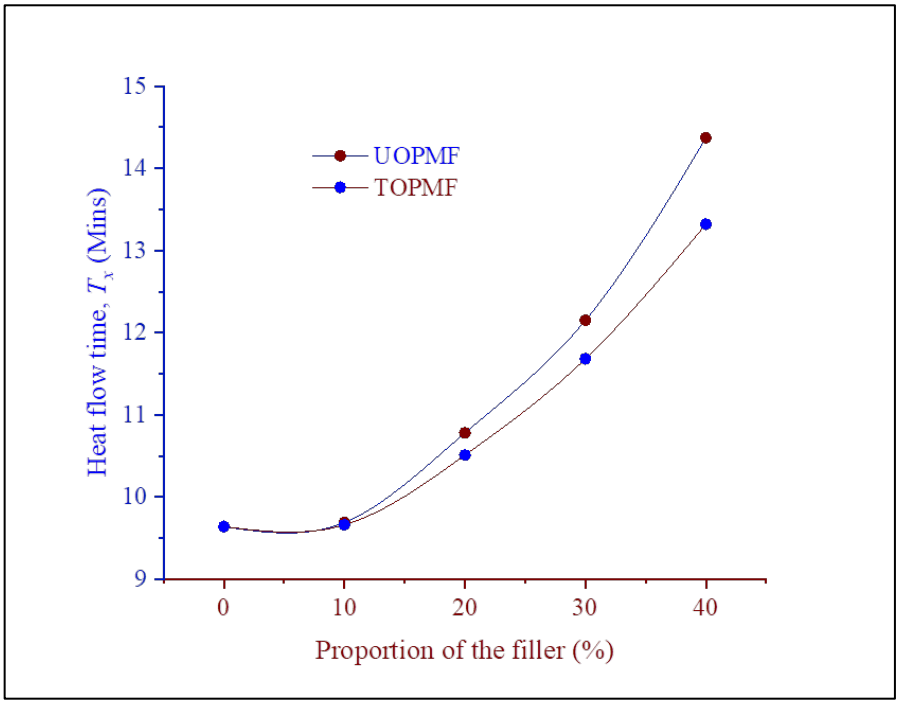

Figure 5: Dependence of heat flow time on the filler loadings

3.8 Flakiness

Inclusion of each kind of fiber influences the resistance to abrasion of the samples. The flakiness values obtained for the samples (except in the case of utilizing up to 40 % of the UOPMF) are less than 2.0%, which Berge [36] reported for asbestos ceiling. This observation means that if the samples are subjected to abrasion under the same conditions in service, they would appear more durable than asbestos. As the loading of the fiber increases, the resistance they offer to wear decreases for both UOPMF and TOPMF, the decrease being more pronounced for TOPMF. This may be because the adhesion of the TOPMF to the POP matrix is greater than in the case of utilizing the UOPMF. Concerning the value obtained for the control sample, utilization of up to 40% of each UOPMF and TOPMF leads to an increase in flakiness by about 1.43% and 1.32%, respectively. However, these differences portray that the effect is insignificant in both cases.

4. Conclusion

This research has shown that it is possible to fabricate plaster of Paris (POP) ceiling panels with UOPMF and TOPMF as fillers. It was also noticed that composite ceilings resulting from including the fibers as filler exhibited improvements in thermal insulation performances over the sample control. Those made with UOPMF could perform better than their counterparts developed using TOPMF. The samples exhibited more thermally insulating capacity as the percentage of the filler (UOPMF or TOPMF) increased in them. Bulk density decreased with increasing filler content. Heat flow time was correlated positively with the filler content. The flakiness due to utilization of up to 40% of the filler was insignificant, though the value was lower with the TOPMF compared to the case of using the UOPMF. With the inclusion of the filler, the samples developed were found to be better thermal insulation panels compared to conventional ceilings made of asbestos and PVC. Also, the filler loading could be adjusted to optimize the thermal and physical performance of the samples. Furthermore, the utilization of oil palm mesocarp fiber, as described herein, could serve as a promising approach for creating wealth from waste and a waste disposal method. The fiber-modified POP described here would create the availability of low-cost POP ceilings for thermal insulation in buildings.

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Author contributions

Conceptualization, A. Anonaba. F. Eze and I. Ndukwe; methodology, A. Anonaba.; software, A. Anonaba.; validation, F.A. and F.N.; formal analysis, A. Anonaba.; investigation, A. Anonaba.; resources, A. Anonaba.; data curation, A. Anonaba.; writing—original draft preparation, A. Anonaba..; writing—review and editing, F. Eze; visualization, F.A.; supervision, F. Eze and F. N.; project administration, F. Eze. All authors have read and agreed to the published version of the manuscript.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

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