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Thermo physical and mechanical properties plaster of Paris ceilings modified with oil palm mesocarp fiber for application in buildings

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Abstract

The essence of this study is to assess the feasibility of improving the properties of the plaster of Paris (POP) ceiling by modifying it with oil palm mesocarp fibre (OPMF) in order to solve the disposal problem of the latter. Various weight proportions of the OPMF were used to replace the POP during the fabrication of the samples. All the samples were dried completely and then tested. The results showed that as the filler (OPMF) inclusion in the POP matrix increased from 0% to 40%, the change in mean values of water absorption, bulk density, thermal conductivity, specific heat capacity, thermal diffusivity, heat flow time, flakiness, and flexural strength (12.22 – 25.75) %, (1.768 – 1.407) 10^3 kgm^{-3}, (0.2245 – 0.1465) $Wm^{-1}K^{-1}$, (1.498 – 1.825) 10^3 $Jkg^{-1}K^{-1}$, (8.477 – 5.705) 10^{-8} m^2s^{-1}, (9.64 – 14.37) mins., (0.65 – 2.08) %, and (3.02 – 1.38) N/mm^2 respectively. It was found generally that the inclusion of the OPMF into the POP matrix could yield composite ceilings with enhanced/better thermal insulation capability for use in buildings. This, if implemented, could help to solve the disposal problem associated with waste while ensuring sustainable construction of thermally-safe and inexpensive buildings.

Keywords: Bulk density; Flakiness; Flexural strength; Heat flow time; Thermal insulation

1 Introduction

A ceiling is one of the materials required for installation to ensure thermal insulation in commercial, residential, and institutional buildings. All over the world, the need for such structures is in high demand. Generally, a ceiling is a finished surface that conceals the underside of a building roof structure [1]. In recent times, the valorisation of waste materials to ceiling panels has gained unprecedented research interest. For instance, ceilings developed using sugarcane leaves [2], coconut leaflets [3], breadfruit seed coats [4], and cassava stalks [5] have been found to perform satisfactorily in buildings. Also, studies have revealed that composite panels produced from a newspaper with coconut husk [6], sugarcane bagasse [7], rattan particles [8], rice husk [9], and pineapple leaf fibre [10], etc possess desirable properties for use as ceilings in buildings. Again, ceilings produced from carton papers and tiger nut fibre [11], untreated and treated coconut husks [12], banana fibres and sawdust [13] were found to exhibit desirable performance tendencies though that varied with respect to the mix ratio of the composite components adopted. Ihueze et al [14] observed that one advantage of composite material is its ability to be designed with desirable characteristics suiting an intended purpose.

In situations nailing of the said panels is suspected to cause either significant damage during their installation or bring about an excessive rise in building construction cost, resorting to plaster of Paris (POP) is an option for consideration. This conventional ceiling is preferable because it poses no significant health risk, has resistance to heat, and shows no easy susceptibility to water from a leaked roof unlike in the case of using asbestos, polyvinyl chloride, and plywood

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respectively [15]. Unfortunately, emphasis on increased access to sufficient, safe, and inexpensive housing for the world's poorest people in slums by the year 2030 as provided in Goal II of the United Nations (UN) 2030 Agenda for Sustainable Development [16] appears to yield no result due to incessant rise in the cost of POP which has contributed a great deal to bane in sustainable housing development in developing countries [15]. So far, few studies reported on how to minimize the cost of applying POP ceiling some of which focused on its modification with rice husk ash [17], groundnut seed coat and waste newspaper paste [18], rattan [19], and wood dust and waste paper ash [15] utilized as fillers. findings from these studies have shown that recyclable solid wastes differ in their potential, thus warranting the quest for utilization of other such wastes.

This research is designed to modify POP ceilings with oil palm mesocarp fibre for application in buildings. The mesocarp fibre is a typical biomass generated during palm oil extraction. Its use as boiler fuel [20 – 22], mulching medium [23] as well as for production of biogas [24] and acetoin [25] have been reported. Even at that, a vast amount of waste is generated and this could ensure sustainability in its applications. Unfortunately, it is majorly under-utilized, a situation that warrants its disposal by open burning or indiscriminate dumping thereby causing serious problems to the environment and public health [26]. Loh [27] noted that palm oil mills in Malaysia generate a total of 7.72 million tons of fibre yearly. As averred by Rizal et al [28], processing every 100,000 tons of oil palm fruit for oil could generate 15,700 tons of fibre. Based on their findings, Hambali and Rivai [29] remarked that due to increasing demand for crude palm oil would cause a continuous rise in fibre generation from 21,560,251 tons in 2020 to about 30,732,801 tons in 2030. This agrees with the assertion of Robert et al [30] solid waste volume may continue to accelerate throughout this century as ineffective solid waste management systems persist in Nigeria and other developing countries. Specifically, the thermophysical and mechanical properties of the new products will be evaluated to determine their suitability in building design.

2 Material and methods

2.1 Materials collection and description

Potable water (from borehole), POP powder (from a building construction site), oil palm mesocarp fibre (from a palm oil mill), and detergent were utilized as major materials in this work. The materials were sourced in large quantities within Uturu, Abia State, Nigeria.

2.2 Processing and Analysis of the Fibre

In order to remove any remaining oil and enhance adhesion with the POP matrix, the fibre was washed with detergent and then water. After that, it was sun-dried until it became moisture-free. The dried material was pulverized by means of a local pepper grinder. This was followed by screening and the quantity of it that passed through a standard sieve having 2-mm openings was coded OPMF. Gradation of the OPMF was performed by sieve analysis [31]. Also, a reasonable quantity of it was analyzed for chemical composition [32].

2.3 Preparation of samples

The OPMF was utilized as filler at various weight replacement levels with the POP to produce ceiling samples. In each case, three representative samples were developed per formulation and the water-to-composite mix ratio was maintained at 2:5 by weight. Figure 1 illustrates the sequence of the processes involved. Those meant for assessment of thermophysical properties were formed in circular molds measuring 110 mm in diameter and 7 mm in thickness whereas the ones prepared for investigation of mechanical properties were formed in molds of dimensions 160 mm x 120 mm x 14 mm. The cast mixtures were kept for 10 minutes under ambient conditions and then after, subjected to continuous sun-drying and weighing until there was further reduction in the mass of each of them. All the fabricated samples were tested as intended for them in this research.

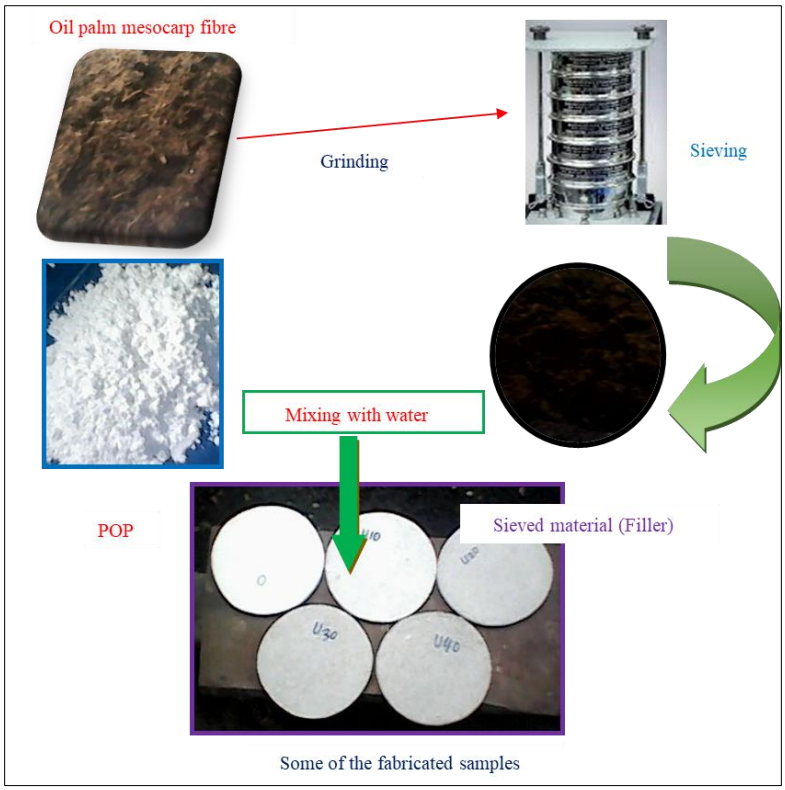

Figure 1 Pictorial illustration of the samples' fabrication processes

2.4 Tests implementation

2.4.1 Water absorption

This test was necessary in order to gain an insight into the ability of the samples to absorb and retain water in the case of leakage from the roof of a building. The method of immersion was employed for its determination in this work [31]. Each sample was weighed before being immersed in water (initially at 28 ^{o}C). After 24 hours, the samples were removed from the water, allowed to surface-dry, and weighed separately again. Water absorption was calculated using the formula [18, 33]

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

Where WA = water absorption of the sample, M_d = mass of the sample prior to immersion, and M_w = mass of the sample after immersion.

2.4.2 Bulk density

For this test, the Modified water displacement method proposed by Robert et al [34] was applied to determine the bulk volume of each sample. The sealant used was wax and each sample was weighed by means of a digital scale having resolution of 0.1 g. Bulk volume was obtained as the difference between the volume of a sealed sample and that of the sealant on it. Based on the data obtained for each sample, bulk density ρ was computed thus [7, 12]

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

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

2.4.3 Thermal conductivity

This test was implemented with the aid of Modified Lee – Charlton's Disc Apparatus technique [35]. During each testing process, an electric hotplate was employed as heat source and the thickness of the sample under test was lagged using cotton wool. Aluminium block (cylindrical in shape) was used to separate the lower disc from the heating element of

the hotplate [36]. For the purpose of modeling cooling rate function, Origin software (Version 2019) was used. The data obtained were applied to calculate thermal conductivity, k according to the relation [12]

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

Where 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, $\Delta\theta$ = temperature difference between the sample's surfaces, and $\frac{dT}{dt}$ = rate of cooling of the disc.

2.4.4 Specific heat capacity

SEUR'S apparatus was used for this test [37]. The measurement system in this case consisted of plywood plate (brown) and aluminium plate as additional heat exchange accessories to plate of the sample under test. Each plate measured 60 mm x 60 mm x 8 mm. By means of three digital thermometers (Model No. 305, calibrated and equipped with type-K probe), temperatures monitoring/measurement was actualized. When thermal balance was attained 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 on assumption that energy was conserved in the system. The specific heat capacity, C of the sample was then determined by calculation using the formula [33]

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

Where δT = rise in temperature of the sample.

2.4.5 Thermal diffusivity and Heat flow time

Using the values of bulk density, specific heat capacity, and thermal conductivity already obtained for each sample, thermal diffusivity was determined as [11, 38 – 40]

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

Where λ = thermal diffusivity.

For measurement of heat flow time across the thickness of the sample, the setup earlier used for thermal conductivity test was employed with some modifications to ensure that the upper disc and lagging material were not applied as shown in figure 2. The lower disc was heat to the same temperature it attained at steady state. A sample that had cooled completely was placed on the disc and immediately, another thermometer was clamped ensuring that its probe tip made a firm contact with the upper surface of the sample. Timing of the process was done by means of a digital stopwatch. When the temperature reading given by the thermometer increased by about 0.2 ^{o}C with respect to the value registered at the commencement of the heating process, the time shown on the stopwatch was noted as the required heat flow time, T_x.

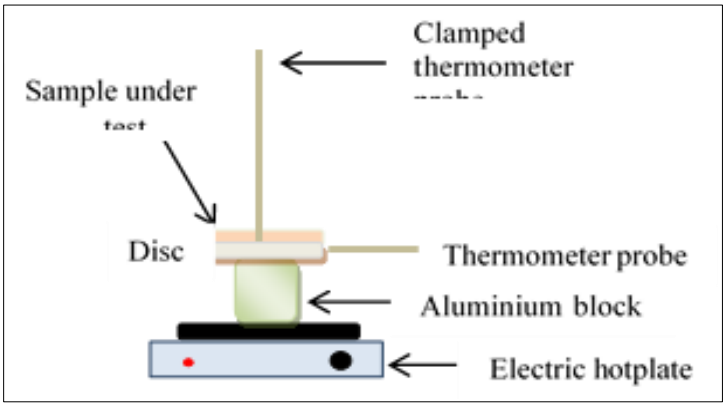

Figure 2 The view of the setup for investigation of the sample's thickness influence on heat flow time

2.4.6 Flakiness

Since the test samples under consideration might undergo wear during their application and service life as building materials, an investigation of their flakiness was deemed necessary. In doing so, the initial mass of each sample was measured after which a 1.0 kg weight was attached to the top of a hard shoe brush to ensure application of uniform pressure during the test. Then the brush was rubbed against both cross-sectional surfaces of each sample until 100 strokes of forward and backward movements were made. The flaked samples were weighed and a decrease in the mass, ΔM of each of them was determined. Their flakiness, F_n was calculated as [41]

$$F_n = \left(\frac{\Delta M}{\mathrm{M_i}}\right) 100\% \text{ .....6}$$

where M_i= mass of the sample before being flaked.

2.4.7 Flexural strength

A flexural strength test was conducted on the samples by using a three-point bending method in line with the standard procedure as stated in [42] and with the aid of an Electromechanical Universal Testing Machine (WDW – 10). During each test schedule, a sample was suspended as a single beam supported at two points and also loaded gradually in its middle. When it fractured, the process was discontinued immediately. The value of the load, P applied at that instant was used alongside the width, b and thickness of the sample to obtain the flexural strength [11, 43]

$$f_s = \frac{3PL}{2bx^2} \text{.....7}$$

All the tests were conducted at (25.0 ± 1.0) ^{o}C. The results obtained for the triplicates were averaged per formulation and tabulated with their corresponding standard error value.

3 Results and discussion

Table 1 shows the loose density and chemical constituents of the OPMF used as filler in this study. the loose density value of the filler indicates that it is light-weight. As can be seen, the proportion of cellulose is the highest followed by that of hemicelluloses and then lignin. Since cellulose is highly hydrophilic, it signifies that the filler has a strong affinity for water uptake. From figure 3, it can be deciphered that the filler particles vary in size. This implies that inclusion of the filler in the POP matrix can create pores spaces of assorted areas.

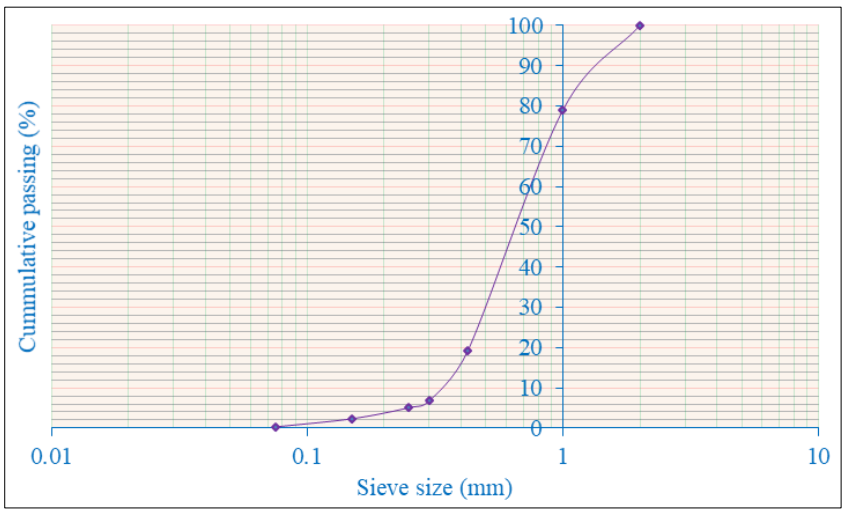

Figure 3 Grading curve of the OPMF

Table 1 Characteristics of the filler (OPMF)

Parameters	**Values for five determinations**
Loose density (kgm^{-3})	356.8 ± 0.4
Chemical constituents	
Cellulose (%)	42.8 ± 0.9
Hemicellulose (%)	33.2 ± 0.6
Lignin (%)	22.6 ± 0.8

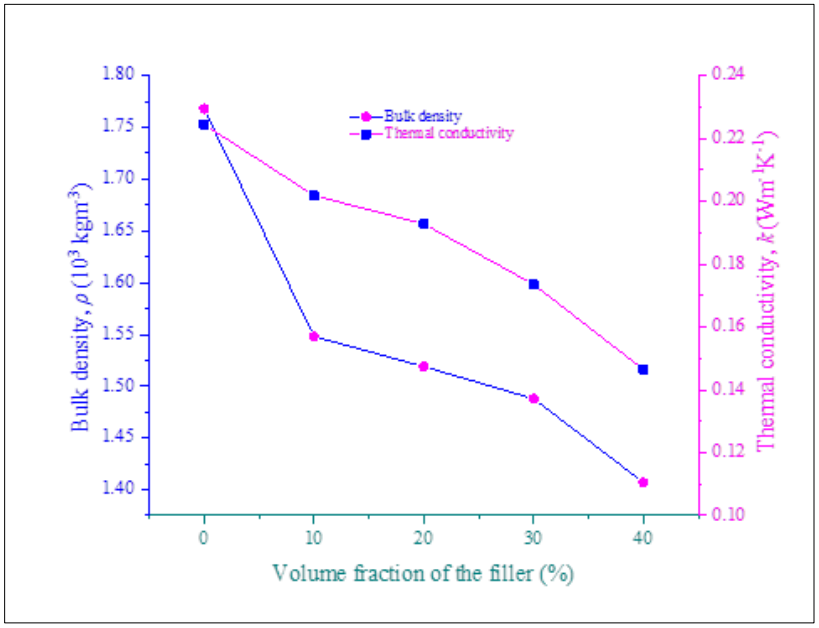

Figure 4 Plots of bulk density and thermal conductivity against filler proportion

Table 2 Thermophysical and mechanical properties of the samples

Filler fraction (%)	$\boldsymbol{WA}$ (%)	$\boldsymbol{\rho}$ $(\boldsymbol{10^3 kgm^{-3}})$	$\boldsymbol{k}$ $(\boldsymbol{Wm^{-1}K^{-1}})$	$\boldsymbol{C}$ $(\boldsymbol{10^3 Jkg^{-1}K^{-1}})$	$\boldsymbol{\lambda}$ $(\boldsymbol{10^{-8} m^2 s^{-1}})$	$\boldsymbol{T_x}$ $(\boldsymbol{Mins.})$	$\boldsymbol{F_n}$ (%)	$\boldsymbol{f_s}$ $(\boldsymbol{N/mm^2})$
0.0	12.22 ± 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	3.02 ± 0.02
10.0	13.12 ± 0.09	1.548 ± 0.003	0.2019 ± 0.0001	1.546 ± 0.002	8.436 ± 0.020	9.69 ± 0.01	0.88 ± 0.03	2.89 ± 0.02
20.0	16.49 ± 0.06	1.519 ± 0.002	0.1928 ± 0.0003	1.674 ± 0.002	7.582 ± 0.018	10.78 ± 0.02	1.24 ± 0.05	1.98 ± 0.02
30.0	20.53 ± 0.07	1.488 ± 0.004	0.1736 ± 0.0004	1.722 ± 0.003	6.775 ± 0.027	12.15 ± 0.04	1.86 ± 0.04	1.57 ± 0.04
40.0	25.75 ± 0.05	1.407 ± 0.004	0.1465 ± 0.0004	1.825 ± 0.003	5.705 ± 0.024	14.37 ± 0.02	2.08 ± 0.04	1.38 ± 0.03

The results of thermophysical and mechanical tests carried out on the samples are presented in Table 2. Water absorption of the samples increases as the proportion of the filler increases. This may be attributed to the fact that the filler is dominated by cellulose. As such, when he samples get in contact with water, their hydrophilicity becomes more pronounced as the fraction of the filler increases. A similar tendency was observed by Umoren et al [44] by utilizing Lagenaria breviflora rinds particle as filler to fabricate composite POP ceiling panels.

By utilizing 10%, 20%, 30% and 40% of the filler, the mean bulk density value of the resulting sample differs from that of pure POP by 220.0, 249.0, 280.0, and 361.0 (all in kgm-3) respectively. The observed tendency is desirable for building design because there would be a reduction in the dead load of the building. This means that the filler application as a POP modifier has beneficial effects. Apart from enhancing the lightness of the composite ceiling formed, it can be seen as well that it improves the thermal conductivity of the products. Adepitan et al [45] reported thermal conductivity values of 0.4197 Wm-1K-1 and 1.6499 Wm-1K-1 for conventional ceilings like hardboard and polyvinyl chloride (PVC) respectively. Comparatively, it can be posited that all the samples are capable of ensuring thermal comfort better than the named ceilings if applied in buildings.

Figure 4 reveals that the bulk density and thermal conductivity of the samples vary inversely with the proportion of the filler. Perhaps, this is due to the fact that the filler is lighter than the POP powder used. Also, its inclusion reduces the cohesiveness of the POP matrix by creating pores which are occupied by air only since the samples are completely dry.

Consequently, the air volume increases in direct proportion to the filler content. Because air is a poor heat conductor, the ability of the samples to restrict heat transmission, therefore, increases with an increase in the percentage of the filler used.

Improvement in specific heat capacity is observed as the filler proportion increases. By increasing the filler content from 0 % to 40 %, the amount of heat the samples can store before the temperature of their unit mass changes by one Kelvin progressively increases from 1498 J to 1825 J. Robert et al [15] reported specific heat capacity of about 1540 Jkg-1K-1 for POP modified with 18.3 % of waste paper ash. For a composite ceiling developed using 25 % of waste newspaper paste (WNP) with 75 % of sawdust particles (SDP), a specific heat capacity of 1722.91 Jkg-1K-1 has been reported [30]. Comparatively, these two values are almost similar to those obtained in this study by utilizing the filler at 10 % and 30 % levels. The implication is that the samples can exhibit the same performance tendency as the ash-modified POP ceiling as well as the composite WNP-SDP ceiling if subjected to the same conditions of application.

The decrease in thermal diffusivity with the filler content of the samples can be explained in terms of specific heat capacity. Since thermal diffusivity expresses the rate of heat spread for temperature propagation within a material, it is certain that the change in temperature of the samples is delayed as specific heat capacity increases. Consequently, heat diffusion within the sample is slowed down. All these occur by increasing the filler proportion used. A lower thermal diffusivity is an indicator of an improvement in thermal insulation because, in such cases, the propagation of thermal energy is restricted more. The least thermal diffusivity value obtained in this work is about 59.1 % less than the mean value of (1.394 x 10-7 m2s-1) found by Ekpenyong et al [46] for composite boards prepared from groundnut shells.

The results of heat flow time lend credence to the thermal insulation performance of the samples. It correlates positively with the filler proportion in the samples, thereby supporting the fact that a reduction in thermal conductivity with an increase in specific heat capacity lowers the thermal diffusion rate within the samples. In turn, it increases the time heat takes to flow across the thickness of the samples. The marginal changes in heat flow time (0.05, 4.09, 1.37, and 2.22 mins.) as the filler content increases in steps of 10 % from 0 % to 40 % in the samples simply indicates a non-linear relationship.

Regarding flakiness, the inclusion of the filler influences how flaky the samples could be in the course of their application in buildings. Except in the case of utilizing 40 % of the filler, the flakiness values obtained for the samples are less than 2.0 % which Berge [47] reported for asbestos ceiling. The meaning of this observation is that, if the samples are subjected to abrasion under same conditions in service, they would appear more durable compared to the asbestos. Plausibly, both the flakiness and flexural strength depend on the existing bonding strength between the filler and POP matrix. Figure 5 illustrates how flakiness and flexural strength of the samples trend with the filler proportion. It could be understood that as more of the filler is introduced into the pure POP, the cohesiveness of POP powder and interlocking strength of the resulting sample are reduced. This eventually weakens the bond between the two materials thereby increasing the flaky concentration but decreasing the strength of the samples to withstand bending stress.

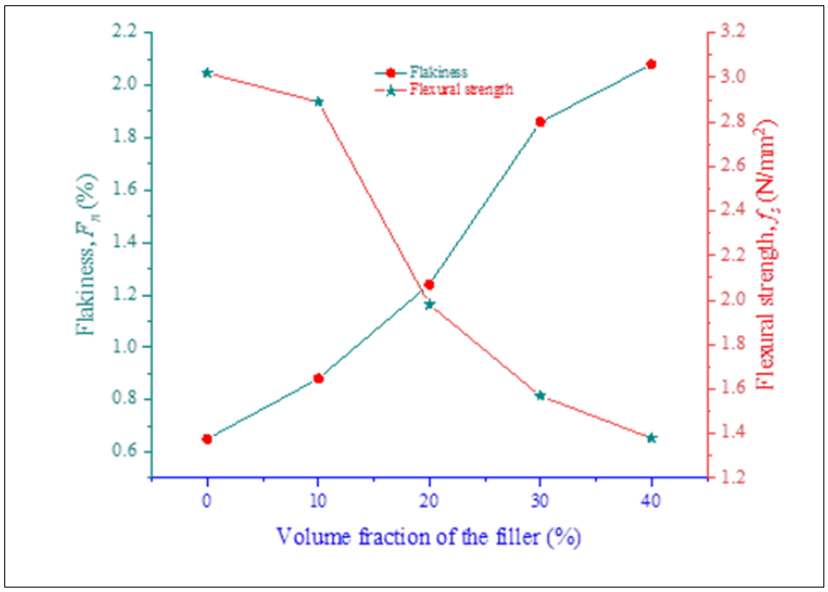

Figure 5 Plots of flakiness and flexural strength against filler proportion

4 Conclusion

Findings from this study have revealed that it is possible to use oil palm mesocarp fibre (OPMF) as filler for modification of plaster of Paris (POP) ceiling. The inclusion of 10 % to 40 % of the filler increased water absorption and lightness of the samples by 13.53 % and 20.4 % respectively. Improvement was observed in thermal insulation based on thermal conductivity, specific heat capacity, thermal diffusivity, and heat flow time of the samples. Though utilization of the filler brought about a decline in resistance to flakiness and a reduction in flexural strength, the samples developed with it exhibited satisfactory tendencies for use in buildings in order to ensure thermal comfort. Hence, recycling of the OPMF could serve as a safe route for handling its disposal problem while also ensuring the availability of inexpensive ceilings for thermal insulation in buildings.

Compliance with ethical standards

Acknowledgments

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Disclosure of conflict of interest

The authors declared no conflict of interest

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