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Palm Oil Clinker as Noise Control Materials

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Abstract

Palm oil clinker (POC) is a waste from the production process of palm oil, a hard and porous materials. Many studies have focused on the effect of POC use on strength while this study discusses the ability of POC in concrete to absorb sound and its relationship with concrete properties. The study was done by replacing natural river sand in stages of 25, 50, 75 and 100 percent in a mixture of 1: 4 (cement: sand). Sound absorption coefficient (SAC), strength and physical properties affect the SAC were measured. Although POC significantly reduced the compressive strength but all specimens poses good strength more than 5 N/mm². An interesting result is that POC reduces interconnected porosity and total porosity when replacement is 100% but increases interconnected and total porosity when replacement is between 50 and 75%. SAC at 315 Hz was found has good relationship with percentage of POC and density. It is obtained that POC 50% yield good strength and sufficient SAC that can address the middle frequency range problem, thus can be further suggested to be used for masonry block application for noise control materials.

Keywords: Palm oil clinker, mortar, sound absorption, sustainable concrete, sound absorber

1. Introduction

Oil palm (*Elaeis guineensis* Jacq.) is one of the world's most efficient and versatile crop in the world. It is cultivated in continents of Asia, Africa and South America. In Asia, Malaysia, Indonesia and Thailand produced 91% of total palm oil worldwide [1]. In Malaysia, oil palm is planted on 5.45 million hectares, Indonesia 11.95 million hectares, while Thailand 820,000 hectare in 2020 [2]. 1 hectare oil palm plantation annually produces about 55 ton of dry matter in the form of fibrous biomass while yielding 5.5 ton of oil [3]. These include shells and fibres (**Figure 1**) [4]. Shells and fibres of palm oil are burned together in mills as fuel for firing the furnace of the mill to heat up the boiler, thus producing more waste materials, such as palm oil clinker (POC) and palm oil fuel ash (POFA) (see **Figure 2**) [1, 5]. About 1.1 ton of POC per every ton of oil produced were generated [6]. Palm oil Clinker is a large grey chunk that resembles a porous stone with irregular and flaky shape [1, 5].

Figure 3 shows a literature review search in Scopus data base and mapping results using VOSviewer software [7] show most research in relation to palm oil clinker is focused on their usage as aggregate replacement and investigation on their

Figure 1.
Waste from oil production [4].

Figure 2.
POC production [1].

properties and strength for light weight concrete, mortar and sustainable concrete. Some of these research use combined dust POC and fly ash to replace cement and also used for self-compacting mortar [8]. The properties of acoustic concrete containing POC have just been initiated by [9].

POC is widely used as a lightweight aggregate due to its lightweight nature. POC is estimated to be 25% lighter than river sand and 48% lighter than crushed granite stone [10]. Thus, the density of mortar containing 100% POC sand is reduced by 7% compared to that of river sand [11]. The light nature of this POC aggregate is due to the physical properties of POC that contains micro-pores [12]. Due to the porosity of POC, concrete containing POC has lower compressive strength and tensile strength. POC also has an aggregate crushing value (ACV) of between 15 to 30 kN which is considerably lower than the values for the river sand. Therefore, there

Figure 3.
VOSviewer mapping.

were researchers who coated POC to cover the macro pores of POC to slightly increase its compressive strength [12].

In fact, aggregate porosity can be utilised for the development of sound control materials. This has been stated by previous researchers where pores in aggregate is an important feature that influences the sound absorption [13–16]. For example porous-expanded shale aggregate size of 12–19 mm increased the sound absorption value by 6% [14] compared with porous concrete using natural aggregate (lime stone) size 13–19 mm. This is because the extended shale aggregate has a porosity of 14.1% compared to the regular limestone aggregate of only 5.6%. Bottom ash also yield in a 13% increase in sound absorption [15] when replaced limestone aggregate with an aggregate-cement ratio of 20%. While, porous basalt stone with porosity 42% was found increased the porosity of concrete from 18 to 22% and caused an increase of sound absorption [16]. Preliminary studies of the sound absorption properties of concrete containing POC showed an increase in SAC at 1000 Hz [9].

Noise control materials are an important element component in reducing the environmental noise in urban areas such as noise barrier systems to reduce reflection from traffic noise. The reflective sound barrier system produces continuous reflections to create a “canyon” environment where users and the housing community near the road will be disturbed. According to the study, street canyon produces reverberance condition with RT30 between 1.2 to 1.4 s [17] which is a measure of annoyance. Road noise is also dominantly at 900 to 1100 Hz [18] which is in the range of human hearing sensitive between 20 Hz to 4000 Hz. Recently, it was found that middle frequency range between 200 and 630 Hz especially the 315 Hz produced high annoyance to resident, in particular on the elderly people [19].

The best noise control material is one that has porous properties because it can absorb sound and produce less reflection and at the same time avoid the ‘street canyon’ situation. Sound absorption is measured through a sound absorption coefficient (SAC) which indicates that the capability of material absorption between 0 to 1 in which the previous represented perfect reflection while the latter indicates perfect absorption. The nature of good sound absorption is when the value of SAC exceeds 0.35 [20].

The porosity of the aggregate causes an increase in the porosity of the concrete material and according to [16] interconnected porosity has a significant relationship with the sound absorption properties of the concrete. Further, Tie et al. [21] and Gonzalez et al. [22] stated the characteristic sound absorption properties related to

the density of the material. Based on the sound absorption properties by concrete containing POC from a preliminary study by [9], it may be preferable for noise control materials. Therefore, this study aims to further investigate the potential of concrete POC as a noise control materials in alleviating the problem of noise pollution from roads and railways. In this study, further research on two main parameters related to SAC namely porosity and density and their relationship with sound absorption in POC concrete will be discussed further. By using regression analysis of the relationship between SAC, porosity and density can be established. Further, concrete POC mixtures suitable as sound absorbers can be identified.

2. Methodology

2.1 Material

POC sand as well as natural sand were utilised in this study. POC sand was used as replacement of natural sand. Palm oil clinker (POC) sand was obtained by crushing POC chunk obtained from the palm oil processing plants in Johor. The POC sand that passed 2.36 mm sieve according to ASTM C33 [23] was selected. **Figure 4** shows the grading of the POC compared with that of natural river sand. POC sand has a smaller size than the natural sand but both still well graded and can be used for the mixture. This is implying that surface area of PO is higher than that natural sand. In the SEM micrographs experiment, POC sand show craters between 14 μm to 61 μm and micro pores with diameters between 12 μm and 15 μm (**Figure 5**). POC sand has more porosity of 6% compared to natural river sand of only 3%.

2.2 Sample preparation and testing

POC was used as replacement of sand in mixture of 1:4 (one parts of cement to four parts of river sand by weight). The replacements were 25%, 50%, 75% and 100% in four mixtures using volume method. **Table 1** summarises the five mixes used including the reference sample (without replacement). During mixing, cement and fine sand aggregate were first mixed for about two minutes, followed by

Figure 4. Palm oil clinker (a) large chunk of POC (b) fine POC (c) size distribution.

Figure 5.
SEM micrograph.

Mixture	Reference specimen	(25% POC)	(50% rep.)	(75% rep.)	(100% rep.)
Cement	2610	2610	2610	2610	2610
River Sand	8980	6740	4490	2250	0
POC sand	0	2420	4840	7260	9690
Water	1450	1450	1450	1450	1450

Table 1.
Proportion of mixtures.

Figure 6.
Mixing of materials.

another three minutes with water (**Figure 6**). Three 50x50x50 mm cubes specimens from each mix were moulded for density, porosity and compressive strength testing. Also, three 200 mm high cylinders specimens for each mixes were prepared for sound absorption test. Compaction done lightly to obtain good porosity by using the vibrating table. After demoulding of the specimens on the following day, they were all cured in water at room temperature.

The compressive test for all specimens was carried out for the concrete aged 7 and 28 days of moist curing in accordance with ASTM C109/C109M [24]. The porosity test was conducted on 50 mm diameter by 200 mm length cylindrical specimens representing all mixtures in 1st batch. Two types of porosity are measured using volume method; interconnected porosity ϕ_{int} and closed porosity, ϕ_{closed} . Total porosity, ϕ_{total} then calculated by summing interconnected and closed porosity.

The interconnected porosity test was done by applying the water displacement method to measure the accessible pores in concrete specimens i.e. displacing the absorbed water in concrete. Water absorbed into the concrete by interconnected pores can be beneficial information related to pore structure, and sound absorption performance by concrete. Meanwhile, the structure of the concrete pores is very important for strength material. The interconnected porosity is determined by using Eq. (1) [25].

$$\phi_{int} = \left[1 - \frac{w_2 - w_1}{\rho_w v} \right] * 100 \quad (1)$$

where, w_1 : submerged weight of the porous specimen underwater (kg), w_2 weight of dry porous concrete specimen (kg), ρ_w : density of water (kg/mm^3), v : volume of porous concrete specimen (mm^3).

The specimens were totally dried until no further reduction of weight. The closed porosity is determined by using Eq. (2) [25].

$$\phi_{closed} = \left[1 - \frac{w_3 - w_1}{\rho_w v} \right] * 100 - \phi_{int} \quad (2)$$

where, w_3 : totally dried weight of the porous specimen (kg),

where, w : weight of dry porous concrete sample (kg), w_2 : submerged weight of the porous sample underwater (kg), ρ_w : density of water (kg/mm^3), v : volume of porous concrete sample (mm^3).

Figure 7.
Impedance tube set up for measuring specimen's sound absorption coefficient.

Sound absorption coefficient (SAC) or α of specimens were obtained by using impedance tube Type 4206-A, **Figure 7**, which was in accordance with ASTM E1050–98 [26]. SAC was determined using transfer-function method in a two-microphone method by placing the specimen at one end of the tube; involving the decomposition of a broadband stationary random signal into incident sound, P_i and reflected sound, P_r . The transfer function compensates for the possible gain and phase mismatch of the two microphones, then the measurement is repeated by interchanging the two channels. The complex reflection coefficient R is calculated by:

$$R = \left[\frac{H_1 - H_I}{H_R - H_1} \right] e^{j2k(l+s)} \quad (3)$$

Where H_I is the frequency response function; H_1 is the frequency response function associated with the incident component; H_R is the frequency response function associated with the reflected component; j is defined as $\sqrt{-1}$, k is wave number, l is the distance to the first microphone location from the specimen and s is spacing between the microphones.

The normalised surface impedance ratio of specimen, $\left(\frac{z}{\rho c}\right)$ and α can be calculated;

$$\frac{z}{\rho c} = \frac{1 + R}{1 - R} \quad (4)$$

$$\alpha = 1 - |R|^2 \quad (5)$$

z is the surface impedance modulus of specimen which is obtained by calculating the characteristic air impedance ρc . Surface impedance implies the resistance of specimen surface to the sound energy. In this study ρc for temperature 25°C is 409 Rayls. Using this technique specimens' SAC in Eq. (5) were measured, and this was carried out by inserting the specimens in the impedance tubes and measuring the SAC absorption of the whole system.

3. Result and discussions

3.1 Porosity

Porosity is an important parameter in determining the sound absorption properties of materials. **Figure 8** shows the effect of increasing the percentage of POC in mixtures. Interconnected pores, mainly due to capillary pores [27], form channels to the other end surface that allow sound propagation, the same principle for the water penetration. While closed porosity occurs due to; (i) compaction that cause the air trap between the aggregate, (ii) POC pores and (iii) pores caused by hydrated cement. POC sand and natural river sand are covered with cement paste, thus makes closed pores in all specimens are identical. Without replacement, the interconnected porosity of specimen greater than that of 100% replacement of sand. This is also due to higher surface area of POC sand and its rough surface that makes the cement paste stick to the surface and cover micro-pores resulting in a decrease in interconnected pores. For substitution of 25–75% of natural sand results in a linear increasing relationship as shown in **Figure 9**.

The trend of changes of interconnected porosity and total porosity of mixture with POC 25–75% have very good relationship with the increment of POC

Figure 8.
Interconnected and closed porosities variation with the changes of POC percentage.

Figure 9.
Interconnected and closed porosities variation with the changes of POC percentage between 25–75%.

percentage with R^2 of 0.997 and 0.986, respectively. In this study, R^2 can be simplified as very good (>0.9), good (>0.8) [28], substantial (0.75), moderate (0.5), and weak (0.26) [29]. In summary, POC replacement between 50 and 75% increases interconnected and total porosity due to the angular shape and rough texture of POC sand, and the capillary porosity and connectivity of between capillary pores. **Figure 10** shows the irregular pores in both 100% sand and 50% POC replacement in samples. Based on these SEM micrographs, it is expected that the irregular pores for 100% sand has smaller diameters about 0.2 μm while 50% POC replacement with larger diameter of 0.6 μm . Larger pores was also created because of decrease of free water due to C-S-H bond formation and C-H gels crystallisation as surface area of POC is larger than natural sand.

Figure 10.
Morphology of sample 0% POC and 50% POC.

3.2 Sound absorption performance

Performance of SAC on samples tested using impedance tube test is shown in **Figure 11**. In general, all specimen curves have 2 peaks. The first peak is higher with a frequency around 300–400 Hz while the second peak is relatively low at a frequency of 1000 Hz. Anti-resonance occurs at 500 Hz with a SAC less than 0.1. For specimens containing 100% natural sand, the second resonance is somewhat unstable. However with POC replacement, the curves for all three specimens are almost the same. Also, there is no significant change in the SAC curve when the percentage of POC replacement is increased from 25–100%. However, close examination revealed that at 1000 Hz, the SAC curves for all three specimens produced almost identical SACs.

Figure 12 shows the average SAC for each sample containing 0%, 25%, 50%, 75% and 100% POC. Generally, as the % POC increase, the first dominant frequency shifts to a low frequency. It was obtained that the first dominant frequency and second dominant frequency can be described as follows;

$$f_1 = \frac{C}{\beta 4h}; \text{ where } \beta = 1.25\text{--first dominant} \tag{6}$$

$$f_2 = \frac{3C}{\beta 4h} f; \text{ where } \beta = 1.35. \text{ -- second dominant} \tag{7}$$

These findings are in opposite with the previous researches [18, 30–32], that an approximate relationship between the thickness, h , and dominant frequency f , is numerically by $f_1 = \frac{C}{4h}$; and $f_2 = \frac{3C}{4h}$; for first and second dominant frequency, respectively. C is wave velocity in the medium and h is thickness. This is showed that POC had changed the frequency for the 1st and 2nd peak. The maximum 1st peak of SAC occurs at a frequency of 315 Hz, which is good value of SAC of 0.41 to 0.52. The increase due to POC sand is about 5%. 315 Hz is a category of middle frequency range that usually causes problems in the elderly if the sound intensity exceeds the allowable threshold. The source of the noise that causes problems at 315 Hz including road traffic and train noise.

The results show the 2nd peak of maximum SAC occurs at a frequency of 1000 Hz with a good value of SAC of 0.36 when the POC is 50%. At 1000 Hz, POC sand yield in a 30% increase in SAC although POC sand has a porosity of 6% compared to the natural river sand of only 3%. This can be used to reduce the traffic noise from heavy traffic which its dominant frequency is between 800 to 1250 Hz

(i) Without POC

(ii) With 25% POC

(iii) with 50% POC

(iv) With 75% POC

(v) With 100% POC

Figure 11.
Effect of POC percentage on SAC curve.

Figure 12.
Average sound absorption and POC percentage.

Figure 13.
Effect of POC percentage on NRC and 315 Hz.

[18]. Result from this study showed that all specimens have better result of SAC compared to that of mosaic tiles that have a very low SAC in the frequency range of 400 Hz and above of between 0.028 to 0.1 [33]. Overall increase of SAC is between 5 to 30% identical with previous studies using porous aggregate by [14–16].

3.2.1 Relationship between SAC and POC content

The average of SAC coefficient at 250 Hz, 500 Hz, 1000 Hz, 2000 Hz or noise reduction coefficient (NRC) is shown in **Figure 13**. NRC has weak linear relationship with increase of POC percentage with $R^2 = 0.14$ but surprisingly, SAC at 315 Hz has significant relationship with $R^2 = 0.78$, significant at 0.05 with the following expression;

$$\text{SAC at 315 Hz} = -0.523 - 0.098 * \text{POC} \quad (R^2 = 0.761, 0.05) \tag{8}$$

3.2.2 Relationship between porosity and sound absorption coefficient

Figure 14 shows the relationship between interconnected porosity and the first peak, second peak SAC and NRC. All showed that interconnected porosity relatively

Figure 14.
Effect of interconnected porosity on NRC, 315 Hz and 1000 Hz.

Figure 15.
Density of specimens with POC content.

has low relationship with SAC and NRC. This is indicated that interconnected porosity is not the factor influence the sound absorption. This finding is in disagreement with finding of Zhang et al. [16] that interconnected porosity has a significant relationship with the sound absorption properties of the concrete.

3.3 Density

As known, the specific gravity of the POC is lower due to micro-pores, and as a result, the replacement of natural sand with POC decreased the density of the specimens. The densities ranged from 1878 to 2070 kg/m³ for replacement of POC percentage 25 to 100%. It can be seen that POC50–100% fell within the range of light weight concrete (between 900 to 2000 kg/m³) while in previous work by Kanadasan et al. [34] 100% POC still resulted density more than 2000 kg/m³. This could ideally fall under sustainable and energy efficient materials category [35].

Based on the density results, it can be observed that there is a direct relationship between the density and the percentage of POC as the density decreases linearly (Figure 15) as shown by Eq. (9). Such behaviour can be explained by taking into account the light weight properties of fine POC with high pore content [12], which

reduces the mass per unit volume of mortar. It should also be noted that the POC itself is approximately 25% lighter than river sand [10], as mentioned in sect 1.

$$\text{Density} = -240.4 * \text{POC} + 2118.8 \quad (R^2 = 0.994; p = 0.000) \tag{9}$$

Figure 16 shows the relationship between SAC at 315 Hz, 1000 Hz, NRC, and density of specimens containing POC of 0%, 25%, 50%, 75% and 100%. NRC has weak relation with density and this result opposite with findings from Gonzalez et al. [22] and Tzer el al. [21]. On the other hand, density has very good relationship with SAC at frequency 315 Hz with the following;

$$\text{SAC at 315 Hz} = -0.356 + 0.0004 * \text{density} \quad (0.785, 0.045) \tag{10}$$

3.4 Compressive strength

Figure 17 shows the changes of compressive strength for 7 and 28 days. As can be seen, there is constant development of compressive strength within 7 and 28 days. At 28 days, the compressive strength of specimen decreases more

Figure 16.
Relationship between density and SAC.

Figure 17.
Effect of POC percentage on compressive strength.

significant ($p = 0.001$) as the percentage of POC replacement increases. It is noted that all specimens meet the range for compressive strength of 5 N/mm^2 according to Specification for masonry units Part 2: Calcium silicate masonry units [36].

The relationship of compressive strength (f_c) and POC content at 28 days is as follows:

$$f_c = -0.081 * \text{POC} + 17.592 \quad (R^2 = 0.952; p = 0.004) \quad (11)$$

The reduction of compressive strength is due to reduction of density as explain in 3.3. The strength gradually reduced and almost 44% of strength was lost when replacement was 100%. This is due to fine POCs having micro pores in the internal structure have affected the strength capacity leading to a reduction in the strength of the mortar, this is also obtained by Kanadasan et al. [34]. Therefore, the higher the percentage of POC used then the more macro pores and this makes the mixture have even higher strength reduction. Regression analysis on compressive strength is statistically significant ($p = 0.006$) governed by density:

$$f_c = 0.034 * \text{density} - 53.57 \quad (R^2 = 0.938; p = 0.006) \quad (12)$$

Figure 18 shows specimen containing 50% POC failure in compression occurs quicker than specimen with 100% sand river due to porous POC contribute to lower density and lower strength which is in agreement with Eq. (11). Also, since the crushing value of aggregate (ACV) for POC is three times lower than that of ordinary [12, 34], this has given maximum effect of compressive strength compared to mixtures with river sand where the pores in POC allow greater crack spread than conventional aggregate. This type of failure similar with that of previous research [37–39].

3.5 POC concrete as noise control materials

Previous research show that reducing multiple sound reflections from building façades can be reduced by making them sound absorbing [40]. When considering NRC, the highest is given by 50% POC which dominated by SAC at 315 Hz and 1000 Hz of 0.5 and 0.36, respectively. Thus, based on this study the development of noise control materials for application on or as building façade can be based on SAC values exceeding 0.35 especially at 315 Hz and 1000 Hz. This is to address the problem of middle frequency range and dominant noise source from roads is

Figure 18.
Compressive mode of failures of specimens.

Mixture	Cement = 2610 kg/m ³ River sand = 4490 kg/m ³ POC sand = 4840 kg/m ³ Water = 1450 kg/m ³
Compressive strength	13.04 N/mm ²
NRC	0.3
Max SAC	0.5 (315 Hz) 0.4 (1000 Hz)

Table 2.
Noise control material suggestion.

sufficient apart from sufficient strength 5 N/mm². This means that concrete with a POC mixture of 50% replacing natural river sand has the potential to be used as masonry blocks that have sufficient strength and can absorb sound. This can replace application of conventional concrete having a SAC between 0.03 to 0.09 in the range of 400–4000 Hz as building façade [17]. A detailed summary of the properties and mixtures is shown in the **Table 2**.

4. Conclusion

This study focuses on the effect of the use of POC in mortar by substituting river sand by 25%, 50%, 75% and 100% on the sound absorption properties. Two important influences on sound absorption properties namely porosity types and density, and its relation with sound absorption properties have been studied. Compressive strength is also studied to obtain adequate strength. Morphology using SEM was also used to look at the microstructure of POC concrete. The following are the results obtained from this study and the conclusion:

Although POC contains micro-pores however inclusion of 100% POC reduces interconnected porosity and total porosity. The trend vice-versa when POC inclusion is between 50 and 75%. Generally, it is found that interconnected porosity has no relation with sound absorption coefficient (SAC) which contradict with previous research. However, it was found, sound absorption coefficient at 315 Hz has good relation with percentage of POC.

Further, interconnected porosity had no good association with density. Instead percentage of POC inclusion reduced density significantly and has a good linear relationship with sound absorption at 315 Hz. This study also proved that statistically there is no association between average of sound absorption at 250 Hz, 500 Hz, 1000 Hz and 2000 Hz or noise reduction coefficient with density which opposed to the previous research findings.

Finally, POC inclusion reduces compressive strength significantly however all specimens still poses good strength of more than 5 N/mm² fulfilling the specification standard for masonry units. It is suggested that inclusion of 50% POC produces concrete with good sound absorption at 315 Hz and 1000 Hz and may be used for alleviating the problem of noise from trains and roads. Thus, this mixture can be further suggested to be used for masonry block application for noise control materials.

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