Identification of Mechanical and Sound Absorption Properties of Porous Concrete Containing Different Amounts of Palm Oil Clinker

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ABSTRACT

Palm oil clinker (POC) is an industrial waste by-product of the palm oil industry that is usually dumped into landfills. This paper identified the mechanical and sound absorption properties of porous concrete (PC) when different amounts of porous POC aggregates were used. In addition, an ultrasonic pulse velocity (UPV) test was performed to explain the specimen porosity which affected the properties of concrete. POC with a size of 2.36 mm – 6.7 mm was used at 25%, 50%, 75%, and 100% as a substitute for river sand. Compressive strength, density, and UPV decreased as the percentage of POC increased. Replacement of 100% POC reduced the strength by 62%, density by 30%, and UPV by 16% as compared to without POC. A reduction in the UPV value indicated an increase in the porosity of concrete due to the macropores in POC aggregates. The highest improvement of 673% in average sound absorption coefficient for 100% POC as compared to PC which used sand at 250 Hz – 1250 Hz for 75 mm specimen thickness. Compressive strength data showed that specimens with 100% POC exceeded the minimum limit for

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a PC barrier layer. Therefore, 100% POC with 75 mm thickness had the potential to be applied as a barrier component.

Keywords: *Palm Oil Clinker; Porous Mortar; Sound Absorption; Porous Concrete*

Introduction

Porous Concrete (PC) can be used as a sound-absorbing component for a sound barrier structure. A layer of PC with between 50 mm – 100 mm thickness that is combined with a layer of normal concrete with 50 mm – 150 mm thickness, will result in a standard traffic noise barrier [1]. The noise barrier absorbs incident noise that originates from the highway. According to studies, incident noise originates from tyre-road contact which is dominated at 500 Hz – 1250 Hz [2]. According to Kim and Lee [3], noise pollution is dominated by reflected sound from the road at a larger frequency which ranges between 250 Hz and 1250 Hz. Additionally, in urban areas, excessive noise pollution occurs because the roads are surrounded by building surfaces that reflect noise that originates from the roads. Studies showed that building walls tiled with reflective tiles produced high road echoes [4], which caused high disturbance levels in the community.

The porous concrete layer absorbs sound energy mainly due to friction on the pore walls, whereby sound energy is converted into heat energy [5]. For this purpose, an open pore structure with sufficient porosity is required, which can be achieved by a variety of materials [5]-[6]. Waste materials that are used as aggregates in porous concrete reduce landfiling and consumption of coarse aggregates from natural resources. These types of aggregate include recycled aggregates, bottom ash, and slag. Bottom ash is one of the materials that are extensively researched for the production of porous concrete as a sound absorber.

There is another by-product waste derived from the energy production process of the burning of palm oil shells and palm fibers in the palm oil industry, known as Palm Oil Clinker (POC). POC has porous properties, light and flaky [7]-[11]. It is 25% lighter than river sand and 48% lighter than crushed granite [12]. Previously, POC was extensively studied as a substitute for natural aggregates in normal concrete mixes, and the results were suitable for lightweight structures due to their relatively low mechanical properties as compared to ordinary concrete. However, the use of POC in the production of PCs has not been studied yet, especially the mechanical properties and sound absorption properties. Only recently, there was a study on conventional mortar mixes by using POC aggregates of less than 5 mm in size as a substitute for sand, but it produced a very low sound absorption capacity [13].

This paper evaluates PCs made by using different amounts of POC aggregates for the purpose of sound-absorbing materials. This study investigates the influence of POC aggregates on mechanical properties and sound absorption capacity of PC when the replacement rate is 25%, 50%, 75%, and 100% by weight. Along with that, ultrasonic pulse velocity (non-destructive testing) is carried out to describe the porosity of the specimen and its influence on strength sound ability. Test results were analysed and compared with those obtained from previous studies. The effectiveness of POC in PC as well as other PCs manufactured by using other waste aggregates was also evaluated. This study revealed the capabilities of PCs made by using POC in terms of absorption rate.

Design mixes and their relation with mechanical and sound absorption properties

According to previous studies, a mixture is used for PCs for sound insulation, which corresponds to the report of the ACI 522R Committee [14]. Recommended aggregates are those with a size of greater than 5 mm, water to cement (w/c) ratio between 0.27 and 0.34, and cement content between 270 kg/m^3 and 415 kg/m^3 (Table 1). Fine aggregates (FA) are allowed with 0.11% of coarse aggregate (CA) weight. The small amount of FA causes density to decrease as compared to normal concrete so PC is classified as lightweight concrete. It is suggested that lightweight concrete has strength of less than 7 N/mm^2 for insulation purposes [15]. However, previous researchers had set the minimum strength for the sound-absorbing layer to be no less than 2.8 N/mm^2 or 3.1 N/mm^2 [14], [16]-[17]. This minimum strength is required because sound barrier walls are usually designed to support their weight. Therefore, the mix design is determined based on a compressive strength of PC at least 3.1 N/mm^2 and good sound absorption at 200 Hz - 1800 Hz. For PC with normal aggregates, good sound absorption is attained when the porosity is between 15% and 35% [2]. The open pores form connected channels to transmit sound and most effectively convert sound energy into heat energy.

Table 1: Limit of typical PC [14]

Density of cement (c) kg/m^3 and (%)	Percentage of CA	Ratio of C/CA	CA density kg/m^3	Size of CA mm	Ratio of FA /CA	w/c
270 - 415 (18 - 20%)	80 - 82%	1:4 - 4.5	1190 - 1480	>5	0 - 0.11	0.27 - 0.34

According to the study, aggregate size/grading is the main factor that affects sound absorption, whereby a relatively large size results in a large average pore diameter and causes sound energy to be forced and converted into heat energy. Tian [2] found that PC manufactured by using a maximum aggregate size of 9.5 mm resulted in 24% porosity and yielded a relatively high peak Sound Absorption Coefficient (SAC). PC with the same porosity but manufactured using the maximum aggregate size of 13.5 mm experienced a reduction in the peak of SAC. Neithalath [18]-[19] suggested that PC with 20% porosity and contained aggregate sizes of 2.37 mm – 4.95 mm and 4.95 mm – 9.5 mm were able to produce a suitable average pore of 2.17 mm diameter and had the highest connected channel factor and high SAC. Another study by Rodrigues et al. [20] found that more pores were on the PC surface than in the specimen. These surface pores were found to have a strong relation with sound absorption at 200 Hz – 1600 Hz, due to their resonant properties. Researchers also found that high porosity did not necessarily result in good SAC [21].

Recently many research studies utilised porous aggregates, such as Bottom Ash (BA) and Air-Cool Blast Furnace Slag (ACBFS) for replacement of normal aggregates. It was found that the aggregate size was between 1.25 mm and 10 mm with a similar composition as the usual PC mix design produced PC, with good strength and sound absorption properties [22]-[23]. However, higher w/c was required due to the higher water absorption properties of porous aggregates. According to Rios et al. [23], w/c = 0.6 was used for PC that contained ACBFS aggregates to produce higher porosity and better NRC than the normal PC with the same aggregate size. It showed that aggregates with internal pores helped to increase sound absorption because sound waves that enter closed pores produce a longer path and multiple reflections and refraction at the solid-gas interface in closed pores, which in turn produce more sound energy dissipation.

When the design mixture with good strength and sound absorption properties is determined, the sound absorption properties of the PC layer can be changed by changing the thickness in an effort to change the position of the max SAC and its dominant frequency corresponding to the problem of noise pollution from traffic. This is because frequency and thickness have a relation as shown in Equation (1) [3].

$$f_p . l = \frac{(2n-1)c}{4} = Constant \quad (1)$$

where f_p is the frequency at the peak, n is the number of peaks (constant), c is the sound speed of air (fixed for temperature), and l is the thickness of the specimen.

Methodology

Specimens and mix proportions

The POC was obtained in chunks, which were then crushed and sieved by using an ASTM C33 standard sieve [24]. The retained size was sieved 2.36 mm and passed through the 6.7 mm filter to obtain a size between 2.36 mm and 6.7 mm. This size was within the range of porous aggregates for manufacturing PC that yield high sound absorption. Micro-pores existed in the POC structure as shown by SEM analysis (Figures 1(a) i-iii). Due to this, POC has lower density than river sand. The specimens were manufactured by mixing aggregates and cement by using the ratio of 20% of cement and 80% of sand by weight. The sand was replaced by 25%, 50%, 75% and 100% of POC aggregates. Table 2 summarises the percentage of weight of the mixture used. Holcim Top Standard Cement was chosen because it was chemically tested under the blended cement category. According to Bakar et al. [25] this type of cement is produced with less carbon dioxide emissions as compared to normal type cement.

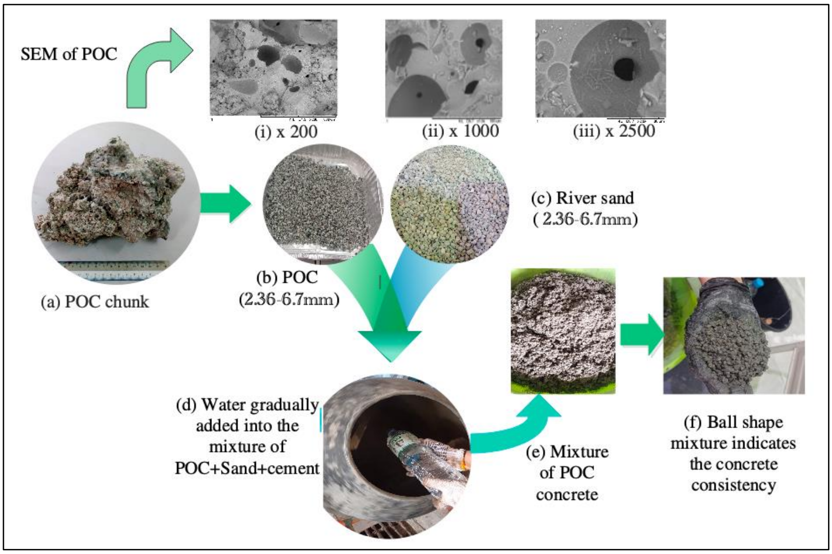


Figure 1: SEM of POC and procedures of mixing of POC concrete

Cement, sand, and POC (CPOC25, CPOC50, and CPOC75) were first mixed for about 2 min - 5 min. Then, water was added gradually to the concrete mixer and turned for 3 min. Sufficient water content was tested by forming the mixture into a ball. To ensure that the water did not flow out from the mixture and collapse, a sheen look must be attained during "ball making", which showed that the pore structure between aggregates was not lost (Figures 1(b)-1(f)). In this stage, the concrete mixture could be put into the mould sample (Table 3) for acoustic, density, and compression. The same steps were repeated for mixing which contained 0% (CPOC0) and 100% POC (CPOC100). Compactions of concrete mixtures in the mould were done lightly to obtain good porosity by using rods. Samples were demoulded after 24 hours and all were cured in the air at room temperature. Tests on these research samples and other comparison samples were made according to the standard method given in Table 3.

Table 2: Specimen mixtures by weight percentage

	CPOC0	**CPOC2**	**CPOC5**	**CPOC7**	**CPOC100**
POC (%)	0	20	40	60	80
River sand (%)	80	60	40	20	0
Cement (%)	20	20	20	20	20
Water/cement (wt%)			0.5		
Size of aggregate			2.36 mm – 6.7 mm		

Experimental details

Compression test

The compressive strength was determined according to ASTM C109/C109M-20b standard. Specimens were clamped in a hydraulic universal testing machine and the loading rate was set to 2 kN/s until the specimens failed (Figure 2(a)).

Table 3: Number of test samples

Testing type	**Compressive strength**	**UPV**	**Density**	**Sound absorption**		
Specimen sizes in mm	100 x 100 x 100	100 x 100 x 100	100 x 100 x 100	100 x 25	100 x 50	100 x 75
CPOC0	3	3	3	3	3	3
CPOC25	3	3	3	3	3	3
CPOC50	3	3	3	3	3	3
CPOC75	3	3	3	3	3	3
CPOC100	3	3	3	3	3	3
Standard	ASTM C109/ C109M-20b [26]	ASTM C597-02 [27]	ASTM C64 2-13 [28]	ASTM C384-04 [29]		

Ultrasonic pulse velocity

Ultrasonic pulse velocity (UPV) was used to relate sample porosity. UPV test has been widely used in civil engineering applications to obtain data about its internal condition, including void persistence. Previous research had related that pulse velocity decreased with porosity [30]-[31]. Measurement was made by transmitting ultrasonic waves through the concrete specimen (Figure 2(b)). The time taken was recorded and the speed of the wave could be calculated by using Equation (2).

$$v = \frac{L}{T} \tag{2}$$

where v is the velocity of pulse (m/s), L is the length of the path (m) and T is effective time (s).

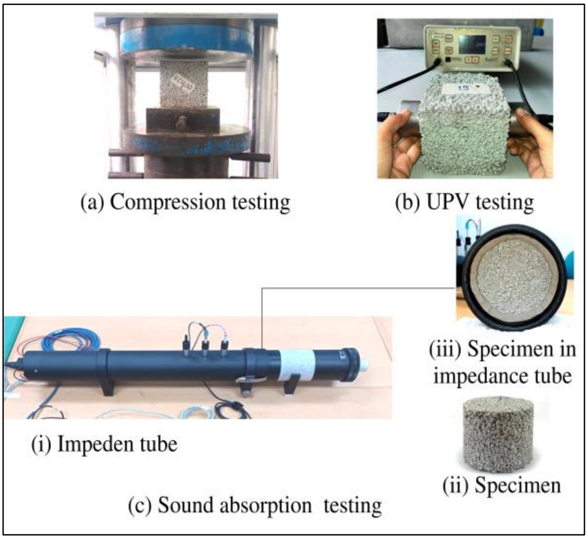


Figure 2: Testing for specimen

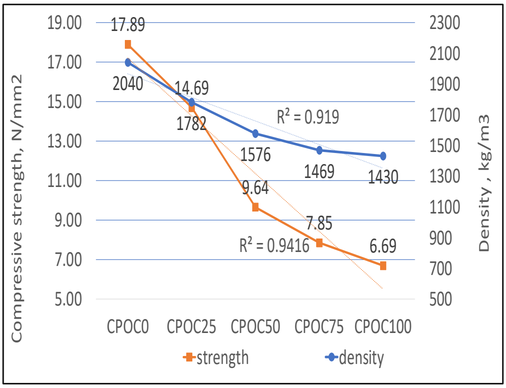
Sound absorption performance

The specimens (Figure 2(c)) were tested using an impedance tube of Type 4206-A with two microphones to obtain SAC at frequencies of up to 1600 Hz. In the impedance tube, the sound source came perpendicular to the noise-incident face of the specimen. Meanwhile, the SAC value could be found through the software provided by Bruel and Kjaer, which was calculated through transfer function analysis. Before the test, calibration was done by testing the material whose absorption value was known. The test was performed at the front and rear surfaces of the specimen as a noise incident face. The Noise Reduction Coefficient (NRC) was determined by averaging the SAC values at 250 Hz, 500 Hz, 1000 Hz, and 1600 Hz, as suggested by [32]. The average SAC value for the 250 Hz–1250 Hz range was obtained as suggested by Kim and Lee [3] in accordance with the reflected traffic noise and for comparison with the previous research.

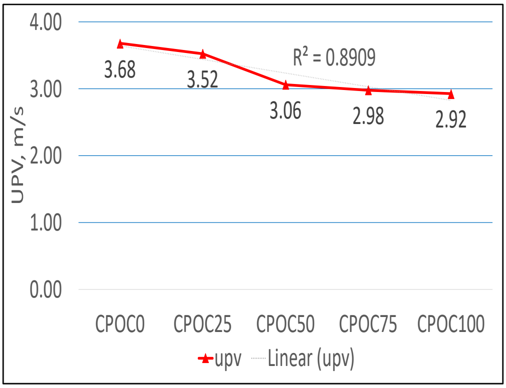
Results and Discussion

Mechanical strength dan UPV

Figure 3 shows the average value for mechanical strength (density and compressive strength) and the UPV values for CPOC0, CPOC25, CPOC50, CPOC75, and CPOC100. Density, strength, and UPV decreased with increasing POC content, with a very strong relation trend evident when analysed by simple regression with an R^2 value of over 0.8. The compressive strengths of CPOC25, CPOC50, CPOC75, and CPOC100 decreased by 17%, 46%, 56%, and 62%, respectively as compared to the compressive strength value without POC content. However, none of these values was below the lowest limit value for compressive strength of 2.8 N/mm^2 [14], [16] or 3.1 N/mm^2 [17]. Noted that only CPOC100 was under the insulating lightweight concrete (<7 N/mm^2). Density was also reduced from 12%, 22%, 27%, and 29% as compared to those without POC. The density of PC decreased with the increment of POC content because POC itself had pores in it, making the concrete lighter. The same situation occurred in ordinary concrete which contained POC, as found by previous researchers [8]. The UPV results further confirmed this fact when the time taken by the wave was longer and ultimately resulted in lower velocities as the POC content increased in the specimen. The UPV velocity decreased by 4%, 16%, 19%, and 22% each for CPOC25, CPOC50, CPOC75, and CPOC100, respectively, from the specimen without POC. These results showed that the specimen had higher porosity with increasing POC replacement.



(a)



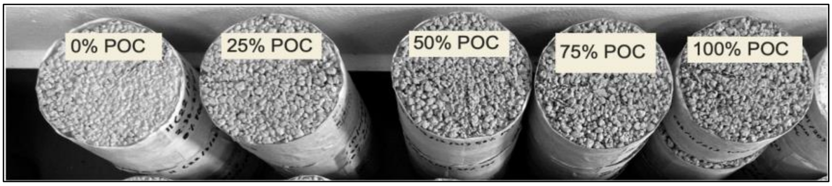
(b)

Figure 3: Effect of POC content; (a) on compressive strength and density, and (b) on UPV

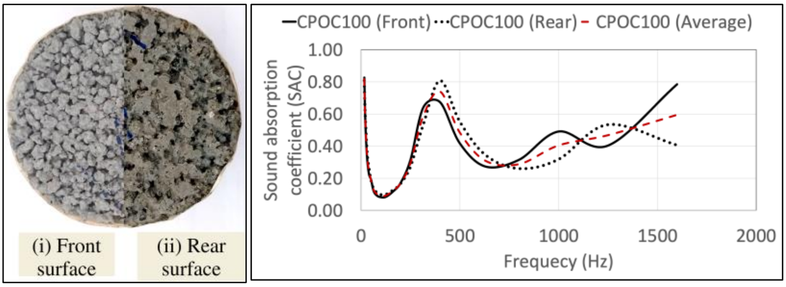
Sound absorption properties of specimens

<u>Effect of POC content</u>

Figure 4(a) shows the surface condition of specimens containing 0% to 100% POC. With the naked eye, each specimen had slightly different front and rear surface conditions. For example, the CPOC100 specimen had a 75 mm thickness (Figure 4(b)). Therefore, there was a slight difference in sound absorption performance when the front and rear faces were used as noise incident faces, especially at a frequency of 1600 Hz (48%) (Figure 4(c)), but the average percentage difference from 16 Hz to 1600 Hz was 5.5%. This was due to the rear surface condition (specimen at the bottom of cylinder), which was likely to contain more pores as the cement flow was higher due to compaction during fabrication. Therefore, it could trap sound waves and result in a higher resonance effect at a frequency of 400 Hz and yield less sound absorption performance at a higher frequency, especially at 1600 Hz.



(a)



(b) (c)

Figure 4: Condition of specimen surface and effect on SAC (h=75 mm); (a) Condition of the front surface of CPO, CPOC25, CPOC50, CPOC75, and CPOC100, (b) comparison of front (left) and rear (right) surface of CPOC100, and (c) disparities of SAC curve obtained from measurement of front and rear face of the specimen

For this reason, the average of SAC value of the rear and front faces was used throughout the study in consideration of the variation of SAC curve disparities between the two faces. The SAC differences between the rear-front incident noise face at frequencies of 250 Hz – 1250 Hz were much lower (3.51%). Therefore, the average SAC value over this frequency range was used for comparison with results from the previous studies.

Figure 5 shows the change in the SAC curve for specimens that contained 25%, 50%, 75%, and 100% POC as compared to the control specimens with thicknesses of 25 mm, 50 mm, and 75 mm. The effect of POC became more dominant when the specimens reached 75 mm thickness. At 75 mm thickness, specimens with 100% POC showed the highest maximum SAC peak value, which was 0.74 at 400 Hz. In addition, all SAC values at frequencies of above 1100 Hz were higher than the other specimens. This indicated that a specimen with 75 mm thickness was able to absorb up to 74% of incident sound energy at 400 Hz and capable of absorbing 40% of incident sound energy at frequencies greater than 1100 Hz. These absorption characteristics were required in order to absorb the dominant sound energy emitted from the highway due to engines and tyre-road noise.

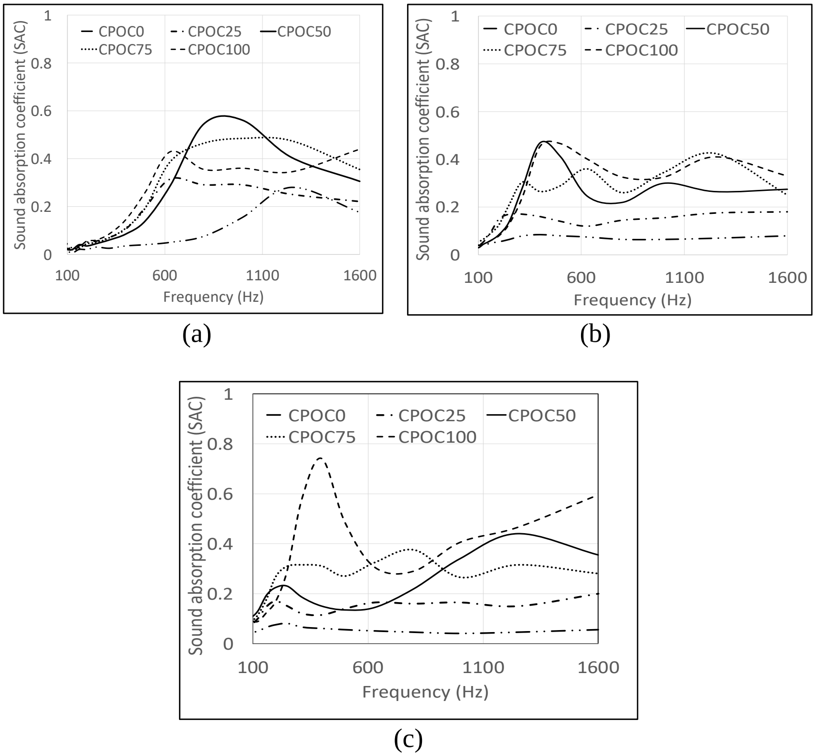
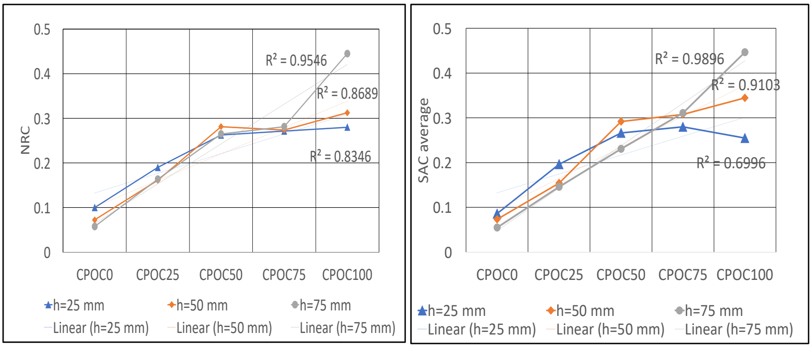


Figure 5: Effect of POC content on SAC; (a) h = 25 mm, (b) h = 50 mm, and (c) h = 75 mm

However, the NRC was significantly increased as the percentage of POC increased ($R^2 > 0.8$) (Figure 6(a)). With that, CPOC100 attained the highest SAC peak and NRC. The reason could be inferred as follows; the wave velocity decreased with increased POC partly due to the macropores in POC, and thus it implied that the POC content had increased the porosity of specimens. When 100 % POC was used, a reduction of 21% in UPV was exhibited as compared to those control specimens. It was observed that CPOC100 with 75 mm thickness revealed an improvement of 711% in the NRC of porous concrete as compared to those with river sand at 250 Hz – 1250 Hz.

However, at 25 mm thickness, the effect of the POC content on SAC was inconsistent at a frequency of 500 Hz and above. The average SAC at frequencies of 250 Hz – 1250 Hz had lower R^2 ($R^2 = 0.69$), showing that the influence of POC content was not as strong as that of specimens at 50 mm and 75 mm thickness (Figure 6(b)). There was an improvement of 673% in the

SAC of porous concrete as compared to those with river sand at 250 Hz – 1250 Hz for 75 mm thickness.

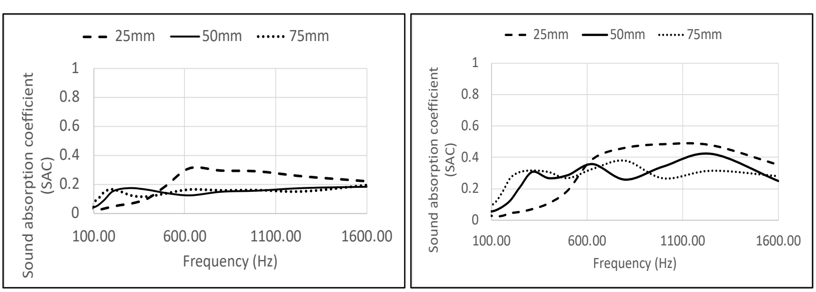


(a) (b)

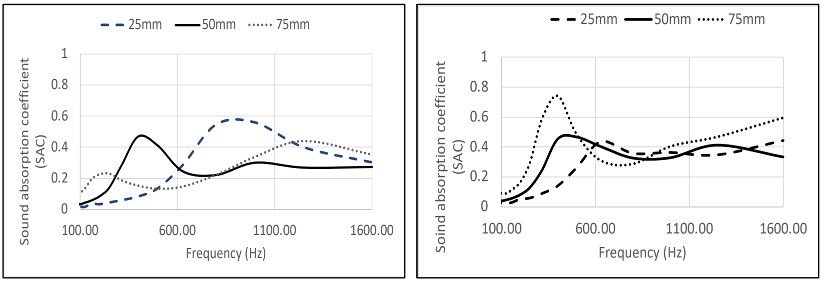
Figure 6: Effect of POC content on (a) NRC and (b) SAC average

Effect of thickness

Figure 7 shows the effect of thickness on SAC performance for each mixture with POC percentages of 25%, 50%, 75% and 100%. In general, an increase in thickness causes the SAC at the dominant frequency (the frequency with the highest SAC) to be shifted from high frequency to low frequency. For 100% POC, 75 mm thickness had an SAC peak at 400 Hz frequency as compared to 50 mm thickness at 375 Hz and 25 mm thickness to the frequency. The same was for 25% and 50% POC as well as for the control specimen. This effect was reversed from the effect caused by increased POC content at 50 mm – 75 mm specimen thickness because the increased POC content caused the SAC at dominant frequency to shift from low to high. Only CPOC75 and CPOC100 were observed to have an increased NRC value with an increase in thickness, due to the existence of higher pores (as in Figure 8). The CPOC100 with 75 mm thickness can be designated as a porous layer for road traffic noise barrier component as peak SAC at the dominant frequency for traffic noise [1].



(a) (b)



(c) (d)

Figure 7: Effect of thickness on SAC average; (a) CPOC25, (b) CPOC50, (c) CPOC75, and (d) CPOC100

The effect of thickness can be explained through the relation between the peak frequency and thickness of the specimen by using Equation (3),

$$f_p . l = \frac{(2n-1)c}{4(3.5)} = Constant \quad (3)$$

This equation is equivalent to the equation obtained from the concept of porous material absorption mechanism [1], [22] from previous researchers.

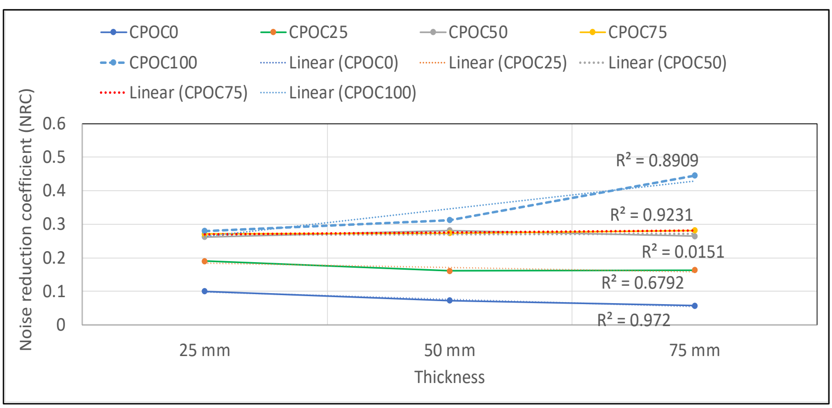


Figure 8: Effect of thickness on NRC

<u>Comparison with previous research studies</u>

Figure 9 shows the comparison of CPOC100 performance of 50 mm and 75 mm thickness and PC fabricated by using porous aggregates such as BA and ACBFS with sizes that ranged between 1.25 mm and 10 mm. The mixture is shown in Table 4. By focusing on the frequency range of 250 Hz – 1250 Hz, which is the reflection from the sound of vehicles on the road and the average SAC at this frequency range. It was found that CPOC with 75 mm thickness had an average SAC comparable to the average SAC performance of BA medium (BAM) PC which contained aggregates of 2.5 mm – 5 mm size with 40 mm thickness. It was even better than the performance of porous concrete which consisted of BA coarse (BAC) PC with an aggregate size of >5 mm and 80 mm thickness.

Moreover, CPOC100 with 75 mm thickness had better SAC than those produced from PC manufactured by using ACBFS medium aggregates of size 1.25 mm – 5 mm (ACBFSM) and coarse size of 5 mm – 10 mm (ACBFSC) with 40 mm thickness. CPOC100 with 75 mm thickness had the same sound absorption performance as PC1, which was made by using a larger normal weight aggregate size that ranged from 4.75 mm – 9.5 mm and 150 mm thickness. CPOC100 with 50 mm thickness had high sound absorption performance as compared to PC2 made by using a normal weight aggregate size of 3 mm – 9 mm with 40 mm thickness. CPOC100 showed that aggregates with pores in them could significantly increase the sound absorption capacity, as seen in [17], [33]-[34] . In addition, the selection of POC aggregate of size 2.36 mm – 6.7 mm delivered good mechanical properties (6.6 N/mm^2), fulfilling the strength limitations for insulation lightweight concrete and PC for sound absorbing layer.

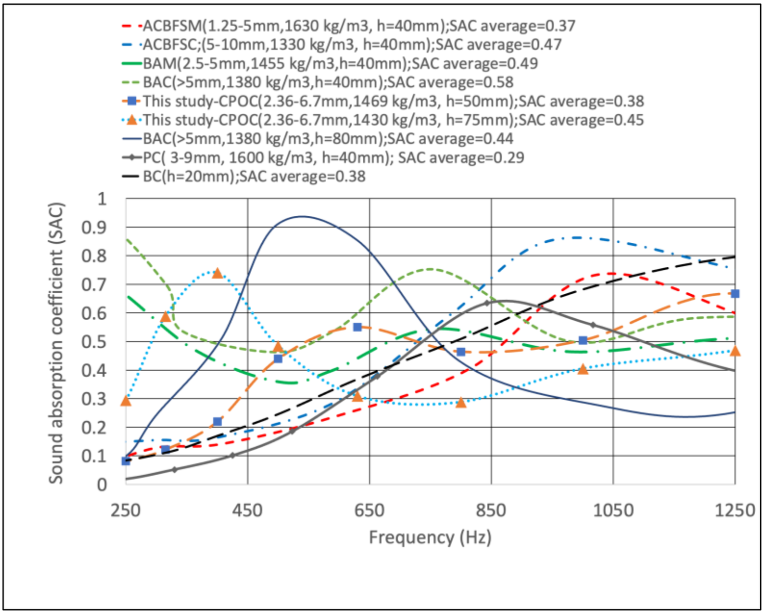


Figure 9: Comparison with previous research

Table 4: Innovative porous concrete

Ref.	Type of agg.	Agg. size mm	Mixtures	H	Density kg/m^3	SAC ave.	f_c
This study	POC	2.36 – 6.7	Cement (20%) POC (80%) w/c=0.5	50 75	1430 1430	0.34 0.45	6.69
[34]	Building Ceramic (BC)	-	BC powder(80%) fly ash (20%) PVA binder Forming agent	20	520	0.38	Max 5.0
[17], [22]	Bottom ash coarse (BAC)	>5	Cement (20%) BAC (80%) Water/solid (9.5)	80	1380	0.44	2.5
[17], [33]	Bottom ash medium (BAM)	2.5 – 5	Cement (20%) BAM (80%) Water/solid (12.5)	40	1455	0.49	4.4
[23]	Air Cooled Bottom Fly Slag Coarse (ACBFSC)	5 – 10	Cement (20%) ACBFSC (80%) W/C O.6	40	1330	0.42	4.9
[23]	Air Cooled Bottom Fly Slag -medium (ACBFSM)	1.25 – 5	Cement (20%) ACBFSM(80%) W/C O.6	40	1630	0.33	6.3
[23]	PC	3 – 9	Cement (20%) NWA (80%) w/c=0.6	40	1600	0.29	4.1

Conclusions

This study evaluated the mechanical and sound absorption properties of porous concrete (PC) when different amounts of porous POC aggregate were used. The main results of this study were as follows:

i. Mixtures with 100% POC reduced the strength by 62%, density by 30%, and UPV by 16% as compared to mixtures without POC. The reduction in UPV with higher POC content indicated an increase in the porosity of concrete due to macropores in the POC aggregate. Due to these micropores, 100% POC concrete also fell under the category of lightweight concretes for insulation.

ii. The higher the POC content the higher the NRC and average SAC. The use of 100% POC with 50 mm thickness resulted in the highest average NRC and SAC values, which exceeded by 0.3 as compared to specimens without POC with NRC and SAC values of less than 0.1. This indicated that the micropores in the POC aggregate helped to increase the sound absorption properties

iii. The higher the thickness and POC content, the higher the NRC and average SAC. There was a tremendous increment of average SAC and NRC when specimens contained 100% POC and 75 mm thickness as compared with specimens without POC (CPOC) with 25 mm thickness.

iv. The selection of POC aggregate with the size of 2.37 mm – 6.7 mm was good enough and had the potential to be used for making the porous layer in a noise barrier. This is due to its sufficient compressive strength and sound absorption properties, which are comparable to those of PC made with other aggregates derived from industrial waste.

Contributions of Authors

The authors confirmed equal contributions in each part of this work. All authors reviewed and approved the final version of this work.

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Conflict of Interests

All authors declared that they have no conflicts of interest

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