Journal of Physics: Conference Series

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To cite this article: N S Galip *et al* 2024 *J. Phys.: Conf. Ser.* **2721** 012012

Sound Absorption Properties of Porous Concrete Layers for Noise Barrier

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Abstract. The porous concrete layer is an open pore material placed on the noise incident face of a sound barrier structure on the road. Pore characteristics such as diameter, area and distribution are the main characteristics of porous concrete different from conventional concrete and play a dominant role in sound absorption properties. Factors affecting the pore structure of typical porous concrete have been discussed. The effects of macroscopic properties on sound absorption properties such as maximum sound absorption coefficient (SAC max), noise reduction and noise average were reviewed. The porous concrete containing other types of aggregate such as recycle, waste material, and lightweight in porous concrete innovation were discussed. Consequently, the effect of thickness, two layers and multiple layers of porous concrete to improve sound absorption at low frequencies. Finally, the guidances were proposed for the mixture composition for producing porous layer for good sound absorbing properties.
Keywords: *Palm oil clinker, porous mortar, sound absorption, porous concrete, noise barrier*

1. Introduction
The porous concrete (PC) layer is an open pore material placed on the noise incident face of a sound barrier structure. Apart from natural aggregate, aggregate recycle or by-product has been proposed for manufacturing the porous layer[1]–[5]. Porous layer would be suitable as base material in acoustic barriers as its compressive strength is lower than structural concretes (nonporous) employed in civil uses[6]. Thus, researchers have also used layered PC of various porosities to improve sound absorption properties[2], [5], [7], [8]. Commercial concrete barriers usually consist of a combination of two layers: one made of PC with a thickness between 50-100 mm to absorb noise, and a hard backing layer of non-PC also 50-150 mm that has a high transmission loss index. The materials are classified according to EN 11654 standard traffic noise barriers[9].

The main factors affecting the sound absorption properties of PC are: porosity[1], [10], specimen thickness[3], [5], [7], [8], [11], and multilayer structure[2], [3], [8], [11]. However, porosity is said to be the main factor that has been extensively researched in relation with pore characteristics such as the diameter and distribution of pores[10], [12], [13], pore interconnectivity[14] and pore tortuosity[2] and sound absorption properties. Aggregate size or aggregate grading[2], [10], [13], cement and w/c [4], [15]–[17], are factors that affect pores properties and eventually change the sound absorption properties of PC. In addition, the selection of PC for the layer of the noise barrier component is a compression strength exceeding 2.8 N/mm^2 [18]or 3.1 N/mm^2[6].

The study began with a search for previous research using bibliometric analysis and measurement of sound absorption coefficient (SAC) of PC in relation to published works. The review works carried out on the sound ability of typical PC and the usage of waste material/recycle known as innovated PC. Factors influencing the SAC such as pore size, pore connectivity and tortuosity were discussed. Next, the effect of thickness and two layers of PC to improve the sound absorption performance of the materials. Finally, a review discussion on the sound barrier performance consists of multiple layers of PC and sound insulating layers to improve sound absorption at low frequencies.

2. Previous research on PC and method of measurement of sound absorption properties

A bibliometric analysis using a mechanistic approach [19] to evaluate research was conducted through the Scopus database using the title, abstract and keywords of articles in the subject of porous concrete. A data search was conducted in September 2023 using the query string provided in Scopus. For example, a search for research articles containing the title and keywords "acoustic-absorbing" OR "porous* concrete" OR "pervious* concrete" OR "highway* noise". In addition, google scholar search engine was also used for the same titles and keywords. The oldest publication date obtained is 1973 and the most recent one is from September 2023. From this search, 119 articles and book chapters were found. From this list 28 were selected as they have criteria that are very important for the discussion in this paper such that; a complete mix of design, acoustic properties, porosity greater or equal than 15% and compressive strength values.

The intended acoustic properties include the SAC curve at a certain frequency range, maximum SAC (SAC max) and its related frequency, average SAC (SAA) for 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz, and noise reduction coefficient (NRC) or average SAC data at 250 Hz, 500 Hz, 1000 Hz and 2000 Hz. In addition, some researchers suggest that SAC for each frequency band less than 0.35 is considered relatively low [20]. Researchers also suggest SAA greater than 0.20 is called a sound-absorbing material, and for more than 0.56 is an efficient sound-absorbing material [21] while NRC above 0.45 [22], [23] is relatively good sound absorber. Figure 1 shows the SAC for 100 Hz – 5000 Hz of the two layers porous concrete atop hard backing layer for the purpose of development of noise barrier researched by Arenas and single layer porous concrete by [2]where the intended acoustic properties can be obtained.

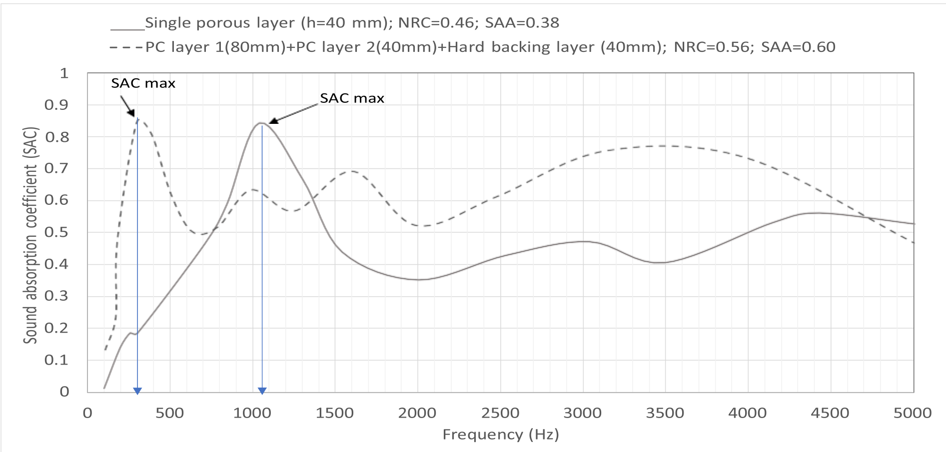


Figure 1. Sound absorption properties

In order to obtain such sound absorption properties, the selected papers have used either impedance tube (IT) or reverberation room (RR) methods. Many researchers use the IT method in figure 2(a) as it requires a small sample. For measuring frequencies < 1600 Hz, a large tube of 100 mm diameter and for exceeding 2000 Hz, a small sample of 30 mm is used. Figure 1a shows a Type 4206-A impedance tube with two microphones, which is according to ASTM E1050-98[24]. IT using 2, 3 and 4 microphones, with the difference explained in [21], assuming that the sound comes perpendicular to the surface of the specimen. For the measurement of sound properties using a RR, a slab-shaped specimen is used in figure

2(b). The test is performed with sound incident waves coming from various directions, causing measurements using RR to be more accurate as it represents real conditions.

(a) Impedence tube [25] (b) Reverberation room[26]

Figure 2. Equipment for measuring specimen's sound absorption coefficient

3. SAC capability review

3.1 Typical PC layer

In general, typical PC for sound absorption is made of ordinary Portland cement, coarse aggregate (size>5 mm), some fine aggregate and water. The design of the PC mix can be determined simply by setting the target porosity and sufficient strength. Target porosity is usually in the range of 15-35% while strength > 2.8 N/mm^2. The researchers used the same mix design as pervious concrete with 1 part cement to 4 parts coarse aggregate as suggested in ACI 522[18]. However, the developed porous layer concrete shows diversity in the selection of aggregate size range and water to cement ratio(w/c) or water to solid (w/s) (table 1). This causes a difference in sound absorption performance as well as density and strength for layer concrete (table 1& figure 3) which is partly caused by open porosity exceeding 20%. Sound absorption is usually associated with the loss of energy produced by the friction of sound waves in the channel created by pores.

Table 1. Composition of typical porous concrete using normal weight aggregate, acoustic properties and strength

Ref.	Specimen codes	Size of agg. mm	Mix design	Open Porosity	NRC	Testing method	Thick. h-mm	Density kg/m^3	Comp N/mm^2
[27]	PC1	2.36-4.75	w/c=0.3 cement=22% Agg.78%	22.56	-	-	150	-	-
[27]	PC2	4.75–9.5	w/c=0.3 cement=22% Agg.78%	20.35	0.21	-	150	-	-
[27]	PC3	9.5-13.5	w/c=0.3 cement=22% Agg.78%*	19.3	-		150		-
[2]	PC4	5-10	w/c=0.6 cement=20% Agg.80%	43.76**	0.46	IT	40	1600±75	5.9±0.4
[25]	PC5	6.3 & 0-4	w/c=0.32 cement=340 kg/m^3	23	0.09	IT	100	-	14

Journal of Physics: Conference Series **2721** (2024) 012012 doi:10.1088/1742-6596/2721/1/012012

			Agg.-=1314 kg/m^3(6.3mm) Agg. =139 kg/m^3 (0-4mm)						
[6]	PC6	3-10	w/c=0.3 cement=20% Agg.80%	26	0.27	IT	40	1727	4.1
[26]	PC7, PC8& PC9	4.75, 9.5, 13.5	w/c=0.32 cement=340 kg/m^3 Agg.=1460 kg/m^3	24	0.39,0.39, 0.29	IT	200	-	-
[14]	PC10	8–13	w/c=0.2 cement=22% Agg.78%	38.2	0.68	IT	100	1611	3.1
[4]	PC11	5–13	w/c=0.25 cement=253 kg/m^3 Agg.=1480	30	0.45	RR	100	-	13.5
[16]	PC12	4.75–9.5	w/c=0.3 cement=323 kg/m3 Agg.=1487 kg/m^3	29.6	0.38	IT	150	1860	14.2
[6]	PC13	2-12	w/c=0.6 cement=20% Agg.=80%	23±0.2	0.25	IT	40	1700± 70	3.10± 0.33
[3]	PC14	3-9	w/S=9% cement=20% Agg.=80%	23	0.27	IT	40	1730	3.4
Limit [18]		>5	w/c=0.27-0.34 cement=18-22% Agg.80-82%	>15%	-	-	-	-	>2.8

*-additive=2 kg/m^3; ** total porosity

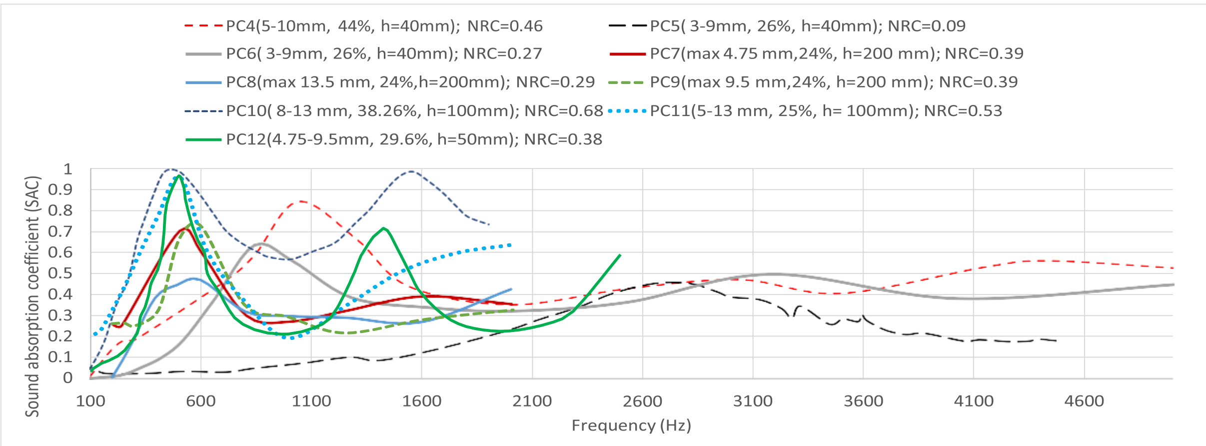


Figure 3. SAC of typical PC with different mixtures (extracted from the original source using WebPlotDigitizer 4.5 [21])

Researchers have 3 views: First, when porosity increases, the sound absorption performance of PC increases [2], [7], [10]. Therefore, materials with low open void ratios usually have low SAC at different frequencies. Second; The sound absorption performance of PC shows a trend that it first increases and then decreases with increasing porosity [4]. Third; there is no strong relationship between SAC max and porosity because it depends on effective porosity characterized by diameter, pore distribution [10], and pore connectivity [14] as well as pore tortuosity[2]. Pores can be seen on the PC surface, consisting of disconnected pores (closed) and interconnected pores (open/effective pores) (figure 4). Inside the concrete, open pores that connect from the upper surface to the lower surface, forming curvy channels. This channel that carries sound energy then forces it to expand and contract to convert heat energy. A small channel produces a narrow groove known as the throat[28]. The ratio of the length of the curve channel to the original length is known as tortuosity with a value >1. The ratio of total pores (closed pores and connected pores) to total volume is called total porosity.

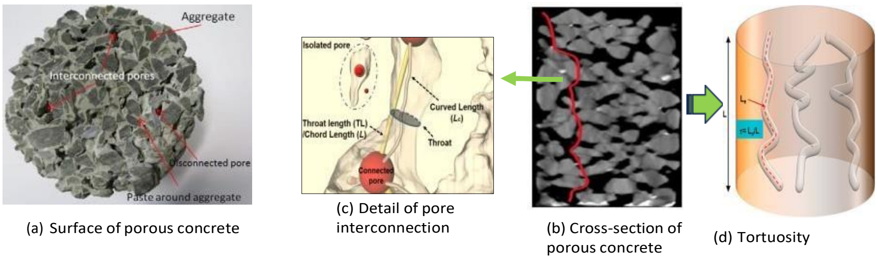


Figure 4. Pores details in porous concrete[28]–[30]

3.2 Innovative PC layer

3.2.1 Waste materials. The use of waste materials reduces deposits in landfills, reduces the use of coarse aggregates from natural resources and develops porous concrete that allows to eliminate environmental noise problems. Therefore, recycled aggregates, bottom ash, slag, oil palm shell (OPS) and mollusk shells are among the materials, which can be used to produce lightweight PC (density less than 2000 kg/m3) (figure 5 & table 2). BA and ACBFS aggregates have micropores in their structure. The researchers used the same mix design as for normal PC, which is 1 part cement to 4 parts of aggregate as in the table. PC BAC and PC BAM are made from bottom ash made from coarse aggregate (>5mm) and medium (2.5mm<dp< 5mm), respectively. Likewise, PC CWM with ceramic aggregate less than 5mm in size. For the PC SC, two different particle size distributions, smaller than 2 mm (PC SCF) and between 2 and 7 mm were used (PC SCT). The water/solid ratio used in the manufacture of PC BA and PC CW however PC ACBFS and PC SC, using w/c=0.6, is higher than the w/c of normal porous PC as suggested by ACR. The high porosity and NRC for PC BA and PC ACBFS prove that aggregates with pores in them can significantly increase the sound absorption capacity (figure 6). PC SC with sizes between 2 and 7 mm shows a 40% increase in weighted acoustic absorption coefficient compared to porous[6]. It is noted that all innovated PCs produce good mechanical properties with the selected aggregate size.

(a) Air Cooled Bottom Fly Slag - medium (ACBFSM)
(b) Air Cooled Bottom Fly Slag Coarse (ACBFSC
(c) Ceramic waste medium (CWM)
(d) Ceramic waste coarse (CWC)

Figure 5. Innovative PC specimen[2], [3], [9]

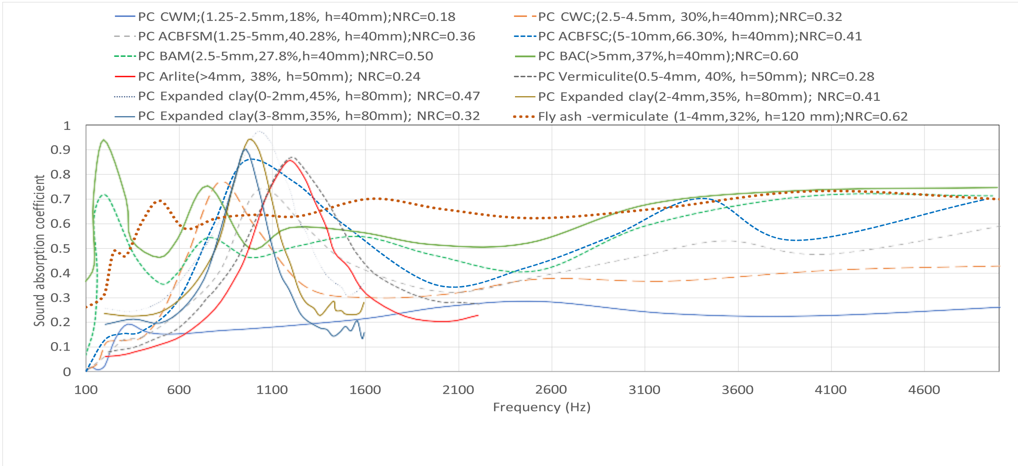
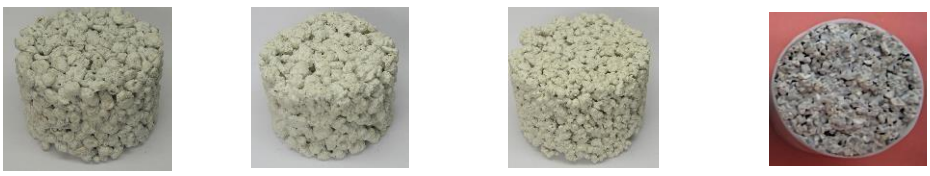


Figure 6. SAC of innovated PC with different aggregate types and mixtures (extracted from the original source using WebPlotDigitizer 4.5 [21])

3.2.2 Lightweight Aggregate. The use of lightweight aggregate, such as expanded clay [31], arlite[32] and vermiculite[9], [32] outside the aggregate composition is recommended by ASTM C33 and ACI 522R-10 due to its porous, water absorbent and light properties (figure 7 & table 2). PCs produced with expanded clay (PC EC), arlite (PC AR) and vermiculite (PC VER) have similar trends of SAC curve (figure 6). The curve has a low SAC at frequencies less than 500 Hz. Expended clay with a smaller size (0-2 mm) has high porosity and provides a relatively broad sound absorption curve when compared to that produced with larger grain size aggregates (3-8 mm). In addition, aggregates of larger size such as 3-8 mm show a significant decrease in NRC, probably due to a larger channel path, and thus a lower viscous heat loss that occurs during the sound propagation process, but there is no relevant study yet with pore sizes conducted by researchers on PC containing expanded clay. In addition, the use of vermiculite with a size less than 1.14 mm [9] and fibers in PC VER using fly ash binder increases the porosity of PC (figure 7d). The open pore size is relatively small (between 2 and 4 mm) with a total porosity of 40% compared to normal PC (with coarse aggregate between (5-10 mm) with a total porosity of 43% but has a larger main pore size than 8.5 mm [8] Vermiculite has exfoliating properties that allow it to retain small air particles that absorb sound and reduce the reverberation time in various frequencies, to increase the amount of absorption even when the open porosity is low.



(a)Arlite PC (>4mm) (b)Vermiculite (>1mm) (c) Vermiculite (0.5-4mm) (d) Vermiculite

Figure 7. Innovative PC specimen[2], [3], [9]

Table 2. Innovative porous concrete (IPC)

Ref.	Type of agg.	Spe. code	Agg. Size Mm/spec density	Mixtures	H mm	Open Porosity %/density kg/m^3	SA properties	f_c N/mm^2	Test method	Comparison with typical PC in Table 1
[17]	Recycle agg. RA	PC RA	4.75-9.0	Cement (18%) RA (82%) W/C (0.3) C/RA=0.2	-	32.8/1739	Max SAC=0.98 at 490 Hz SAA=0.38	12.10	IT	NRC similar with those PC12
[33]	Oil palm shell (OPS)	PC OPS	2-10 (OPS) & 5-10 (NWA)	w/c=0.35 cement=340 kg/m^3 NWA=1095kg/m^3 OPS=118 kg/m^3	100	15	Max SAC=0.85 at 1000 Hz NRC=0.38	3.91	IT	NRC similar with those PC4
[6]	Mussel & Scallop	PC MS1	2-7	Cement (20%) Mussel (40%) Scallop(40%) W/C (0.6)	40	23.9± 0.3/ 1617 ± 61	Max SAC=0.79 at 1000 Hz NRC=0.38	4.38 ± 0.05	IT	NRC higher than those PC13 Pore size:540 µm-1 mm. 23
[6]	Mussel & Scallop	PC MS2	<2	Cement (20%) Mussel (40%) Scallop(40%) W/C (0.6)	40	18.5± 0.05/1907± 74	Max SAC=0.2 at 1000 Hz NRC=0.15	8.77 ± 0.10	IT	NRC less than those PC13
[7], [8]	Bottom ash coarse (BAC)	PC BAC	>5	Cement (20%) BAC (80%) Water/solid (9.5)	40	37 /1380	Max SAC=0.87 at 1250 Hz NRC=0.31	2.5	IT	NRC higher than those PC6
[8], [11]	Bottom ash medium (BAM)	PC BAM	2.5-5	Cement (20%) BAM (80%) Water/solid (12.5%)	40	27.8/1455	Max SAC=0.71 at 200 Hz NRC=0.31	4.4	IT	

[3]	Ceramic waste coarse (CWC)	PC CMC	2.5-4.5	Cement (20%) CWC (80%) Water/solid (25%)	40	30/ 1180	Max SAC=0.75 at 800 Hz NRC=0.32	2.9	IT	NRC higher than PC6
[3]	Ceramic waste medium (CWM)	PC CWM	1.25-2.5	Cement (20%) CWM (80%) Water/solid= 28%	40	18/ 1230	SAC< 0.2 (<1250 Hz) NRC=0.18	3.5	IT	NRC Less than those PC6
[2]	Air Cooled Bottom Fly Slag Coarse (ACBFSC)	PC AC BFSC	5- 10	Cement (20%) ACBFSC (80%) W/C O.6	40	66.30*/ 1330±52	Max SAC=0.85 at 1000 Hz NRC=0.41	4.9+ 0.3	IT	NRC Higher than PC4
[2]	Air Cooled Bottom Fly Slag - medium (ACBFSM)	PC AC BFSM	1.25-5	Cement (20%) ACBFSM (80%) W/C O.6	40	40.28*/ 1630±79	Max SAC=0.85 at 1000 Hz NRC=0.36	6.3+ 0.4	IT	NRC less than those PC4 and similar with those of PCMS1
[31]	Expanded Clay	PC EC	0–2, 2–4, 3-8	Cement(43.96%) Agg.(37.36%) Water (18.68%)	80	45, 35, 34	Max SAC=0.92, 0.88,0.91 NRC=0.47,0.41,0.32	-	IT	NRC higher than those PC4 for EC agg. 0-2 mm
[9]	Vermiculite	PC VER	1-4	Fly ash (60% wt) Cement (25%) Vermiculite (12.5%) Fiber (0.5%) Water/solid (0.5%)	120	32.0/886.9	SAC 0.2 <200 Hz SAC0.7 at 4000 Hz (RR) NRC=0.62	2.5	IT	NRC higher than those PC4
[32]	Arlite	PC AR	>4	Arlite (50%) Cement (33%)	50	38	Max SAC=0.85		IT	NRC similar with those PC6

				Water (17%)			NRC=0.24	
	Vermiculite	PC VER1	>1	Vermiculite (12%) Cement (49%) Water (39%)	50	37	Max SAC=0.84, NRC=0.26	IT
			0.5-4	Vermiculite (11%) Cement (56%) Water (33%)	50	40	Max SAC=0.86, NRC=0.28	IT

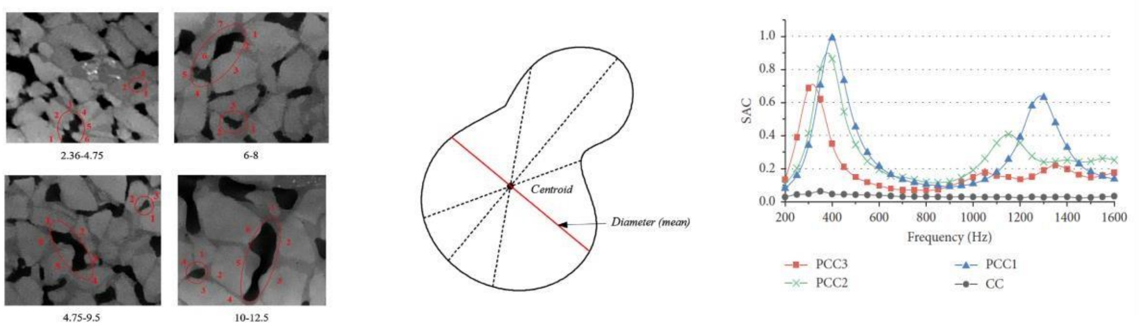
** total porosity

4. Factors affecting the sound absorption properties

4.1 Pore characteristics

Pore characteristics such as pore radius, pore diameter and also pore distribution are determined by aggregate size/grading, cement content, and water cement ratio (w/c).

4.1.1 Size and aggregate grading. The relationship between the aggregate size in the PC mix and the average pore diameter and acoustic properties can be seen from Neithalath's[13] study (table 3). Neithalath's findings related to aggregate size and pore diameter seem to be the same as Fan Yu's[34] findings, with almost the same porosity (21%). Fang yu measured the size of the pores measured through the method of 2D CT images by considering the size of the pores as an ellipse and measuring the average diameter (figure 8) while Neithalath used analytical images. It was found that the average pore diameter is positively correlated linearly with different aggregate sizes where the larger the aggregate size the less the average pore diameter. The findings of Fan Yu & Neithalath can be linked to the findings of Tian[35] that porous concrete layers with a maximum aggregate size of 9.5mm produce highermaximum sound absorption compared to porous concrete layers with a maximum aggregate size of 13.5mm (figure 3). Although Tian[35] specimen has a slightly higher porosity (24%), this situation is similar to the findings from Neithalath. It can be seen that a larger size of 9.5mm results in a large poresize (> 4 mm) causing when the sound waves enter the pores, the sound waves are not forced to be compressed and expanded, to improve the conversion to heat energy and as a result the average SAC becomes low[14], [35].



(a) Pores size in internal PC (b) Elliptical assumption of pores (c) SAC performance

Figure 8. Effect of aggregate size on characteristics of pores (a) & (b) [34] and SAC performance [10]

A study by Song[10] showed that the inclusion of sand in a PC mixture with an aggregate/sand ratio of 0 (PCC1), 0.044 (PCC2)and 0.095(PCC3) reduced the porosity from 24.2%, 20% and 18.3% and changed the average pore radius to 2.026, 2.061 and 1.933 mm, each (Table 3). The existence of small aggregates less than 5mm creates more pores on PC that contains more sand. The frequency of existence of pores with an average radius of 1.933mm is more frequent (0.643) in PCC3 than PCC1 and PCC2 with an average size of 2.026 and 2.061 mm with a frequency of 0.611 and 0.60, respectively. This results in a reduction in average sound absorption at PCC3. Nevertheless, the 1st peak is most optimally produced by PCC1, showing that the larger porosity affects the peak value (figure 7c). It is noted that the pore radius on PCC1 matches Fan Yu's findings for size of 4.75-9.5 mm. A study by Rios[2], shows that when PC (Table 1) is made using 5-10 mm aggregate, it gives an average main pore larger than 6.8 mm (compared to the findings of Fang Yu and Neithalath) because of the porous aggregate and higher w/c (0.6) , with a total PC porosity of 43%, and produces an excellent average noise reduction (0.46). The results of Song's study can be related to the PC produced by Arenas (figure 2) which shows that PC with an aggregate size of 3-10 mm, produces a lower NRC compared to the PC produced by Rios who uses an aggregate size of 5-10 mm. This is partly because with the same porosity, the distribution of small pores becomes more abundant with inclusions >3 mm in size, creating throats in the pore channels and resulting in lower noise reduction NRC0.27. Similarly, the sound absorption properties of ACBFS PC influenced by pore size distribution[2]. Pore size distribution of ACBFSM manufactured from aggregate size less than 5mm yield pores size of 1-5mm, with an average of 3mm with a cumulative total porosity 40.28%. The SAC is higher for ACBFSC manufactured using aggregate size between 5 - 10mm as the average pore diameter yielded is relatively larger (8 mm) and has a cumulative total porosity 66.30% compared to typical PC with same size aggregate and w/c, and with total porosity 43.78% with average pore diameter 6.8mm. PC SC with shell sizes between 2 and 7 mm showed pore sizes between 540 μm-1 mm [6] which is a 52% increase in acoustic absorption coefficient compared to typical porous PC13 with the same w/c and almost the same porosity. The pore size is smaller than the pore size in PC ACBFSM even though the aggregate size range is larger because the aggregate shell is not porous and layered.

Table 3. Effect of aggregate size on average pore diameter and sound absorption properties

Ref.	Agg. type	Size agg.	Agg. (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	w/c	Porosity	D_{av} (mm)	SAC Max	Average SAC	Remark
[13]	NWA	2.36-4.75	100%	-	-	0.33	20.7	2.17	-	-	-
		2.36–4.75 4.75–9.5	75 25	-	-	0.33	20.8	2.69	-	-	-
		2.36–4.75 4.75–9.5	50 50	-	-	0.33	24.7	2.48	-	-	-
		2.36–4.75 4.75–9.5	25 75	-	-	0.33	22.5	3.14	0.81	0.44	100-1000 Hz
		4.75–9.5	100%	-	-	0.33	20.6	3.29	0.56	0.34	
		2.36–4.75 9.5–12.5	50 50	-	-	0.33	19	3.04	-	-	-

		9.5–12.5	100	-	-	0.33	19.3	4.77	0.30	0.25	100-1000 Hz
		4.75–9.5 9.5–12.5	50 50	-	-	0.33	26.4	3.29	-	-	-
[34]	Basalt	2.36–4.75	1703	378	117	0.3	21.03	2.2	-	-	-
		4.75–9.5	1703	378	117	0.3	21.25	3.3	-	-	-
		10–12.5	1703	378	117	0.3	20.78	4.7	-	-	-
		12.5–15	1703	378	117	0.3	21.16	5.5	-	-	-
		10–15	1703	378	117	0.3	20.56	5.3	-	-	-
[10]	NWA PCC1	4.75–9.5	1405	330	90	0.3	24.2	4	0.98	0.3	200-1600 Hz
	PCC2	4.75–9.5 , Sand	1346, 59	330	90	0.3	20.0	4.2	0.88	0.276	
	PCC3	4.75–9.5 , Sand	1283,122	330	90	0.3	18.3	3.8	0.65	0.19	
[2]	ACBFSM	1.25-5	80%	20%	-	0.6	40.0	3.0	0.85	0.37	100-5000 Hz
	ACBFSC	5-10	80%	20%	-	0.6	66.3	8	0.85	0.45	-
	NWA	5-10	80%	20%	-	0.6	43.7	6.8	0.84	0.42-	-

NWA-normal weight aggregate; D_{av}-average pore diameter

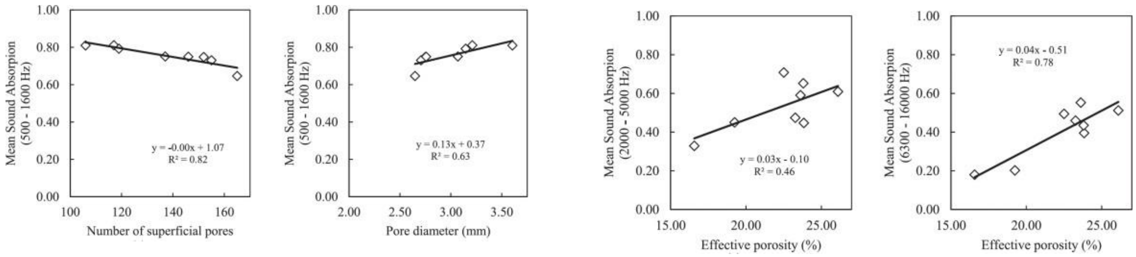
4.1.2 Cement and w/c. The change of cement content C/A (0.27, 0.29, 0.31) and w/c (0.3, 0.32, 0.34) on the change in the SAC of PC specimens containing aggregate pebbles was studied by Rodrigues[12]. Findings show that the variability of cement flow paste, produces a mixture that gives different pore sizes and different pore distribution on the surface of the concrete and inside the concrete, even though the PC specimen has the same amount of porosity (table 4). In general, the presence of pores on the surface is larger and more numerous than internal pores (figure 9a&9b). Generally, the same w/c with higher cement paste give smaller pores. At w/c ratio of 0.34, a reduction in the average SAC occurred because the cement paste filled the surface and internal pores resulted smaller pores (2,65-2.75mm) (figure 8c) which limited the potential of sound absorption. Average SAC and the number of pores on the surface of the sample (figure 10) have a strong relationship compared to the linearity results with internal pores. This shows that the surface pores initially control the sound absorption of PC at lower frequencies (500-1600 Hz) with the larger diameter the higher the SAC. Rodrigues described this material as approaching the characterization of a resonance-type absorbing material.

Table 4. Specimen for determination of effect of cement paste and w/c on sound absorption properties

Mixture code	Coarse aggregate 4.75 -9.5 mm	Fine aggregate 2.36-4.75mm	Cement	Water	C/A	W/C	Open/effective porosity (%)	No of superficial pores	Diameter of superficial pores
M1.1	1208.67	361.03	430.0	130.32	0.27	0.30	23.83	137	3.07
M1.2	1208.67	361.03	461.9	139.97	0.29	0.30	26.10	152	2.75
M1.3	1208.67	361.03	493.7	149.62	0.31	0.30	23.80	155	2.70
M2.1	1208.67	361.03	416.8	134.71	0.27	0.32	22.51	117	3.21
M2.2	1208.67	361.03	447.6	144.69	0.29	0.32	23.61	119	3.14
M2.3	1208.67	361.03	478.5	154.67	0.31	0.32	23.27	106	3.60
M3.1	1208.67	361.03	404.3	138.85	0.27	0.34	31.99	165	2.64
M3.2	1208.67	361.03	434.2	149.13	0.29	0.34	19.24	146	2.75
M3.3	1208.67	361.03	464.2	159.42	0.31	0.34	16.57		

(a) Surface pore distribution of M2.1 (b) Internal pore distribution M2.1 (c) Condition of cement paste filled the surface and internal pores when w/c=0.34

Figure 9. Surface pores, internal pores distribution and effect of cement paste filled that reduced mean SAC[12]



(a) Surface pores (b) Internal pores

Figure 10. Surface pores, internal pores vs mean sound absorption[12]

Further, Park [4]found PC specimens with mixtures shown in table 5, resulted in different porosities, 20%, 25% and 30%. The higher cement content the less the porosity of PC because of high cement causes less pores (table 4) as confirmed by Rodrigues. Opposite with Song's study, the average SAC increased when the porosity reached 25% and then decreased at 30%. Also found that the greater the porosity, the SAC max shifts to a greater frequency. Moreover, the effect of cement flow 80%, 110% and 140% on the SAC of PC fabricated using crushed gravel lager aggregates of size 8–13 mm and 13–19 mm does not show significant changes[36]. It was found by Kim & Lee on PC with cement/aggregate ratio of 0.28 and 0.21, with a fixed w/c of 0.3 and a target void ratio of 0.28. There is a shape change of the surface (figure 11) but not in the change in SAC curve (only a small shift even though the ratio of open voids of PC specimens with 8–13 mm and 13–19 mm aggregates changed from 38.2% to 28.5% and from 38.1% to 29.7% respectively when cement flow increased from 80–140%. This is partly due to the large pores created by these mixtures and low pore connectivity as experienced by Neithalah[14].

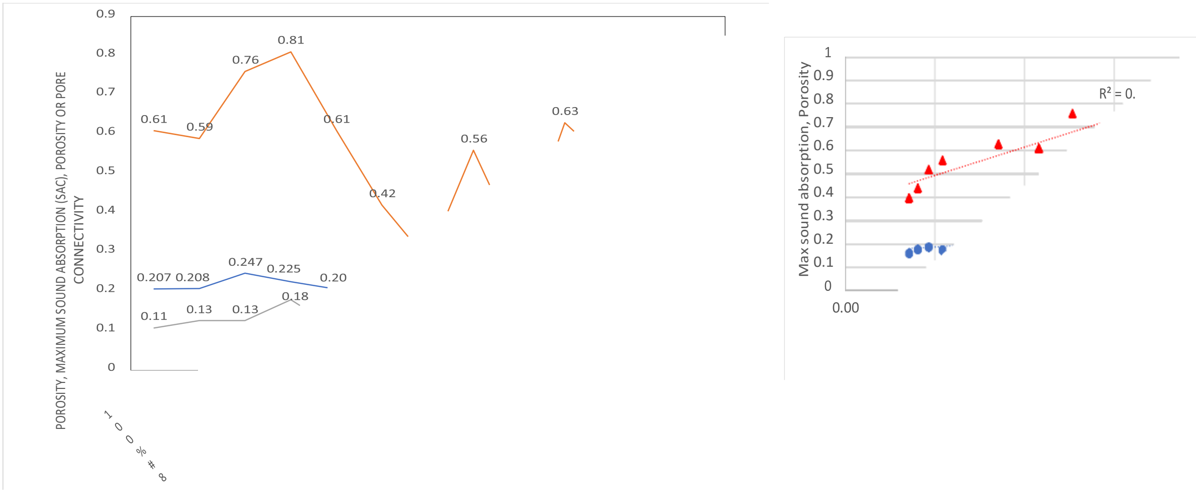
Table 5. Effect cement content on porosity and acoustic properties (extracted from Park [4]

Aggregate A, 5-13 mm	Cement C	Water w	Additive	C/A	Porosity	SAC max	Average SAC 200 Hz to 2000 Hz
1480	430	107	2.47	0.29	20	0.9	0.51
1480	342	85	1.98	0.23	25	0.95	0.55
1480	253	63	1.50	0.17	30	0.95	0.49

Figure 11. Effect of cement flow on surface shapes of PC and sound absorption properties[36]

4.2 Influence of pore connectivity

Findings show that the pore connectivity decreases as the aggregate size increases, thus reducing the maximum SAC. Connectivity does not depend on pores, although high porosity connectivity may be low. This finding was found by Neithelath [14] who evaluated the porosity and porosity connectivity factor for different aggregate size mixtures with w/c =0.33 using electrical impedance spectroscopy (figure 12a). The maximum SAC was found to have a strong relationship with pore connectivity compared to specimen porosity (figure 12b). In addition to higher porosity, the pore connectivity factor also needs to be higher to produce high optimal sound absorption. The connection of the pores of PC prepared with large aggregate (9.5 mm-12.5 mm) or smaller aggregate (eg with the inclusion of sand) leads to a reduction in the connection of pores and a reduction in sound absorption. The latter is due to due to the occurrence of more throat pores[28]. It is believed that aggregate size of (2.36 mm-4.75mm) and (4.75 mm-9.5mm), offer high porosity (20-25%) and high pore connectivity factor (0.11-0.18) thus these sizes plays a major role in the determination of good sound absorption performance.



(a) (b)

Figure 12. Pore connectivity factors: (a)Size of aggregate and porosity, maximum SAC and pore connectivity factor; (b) relationship between pore connectivity and porosity and Max SAC(extracted from [14]

4.3 Influence of pores tortuosity

It is the tortuosity ratio of the channel that has the potential to carry sound energy and absorb it into the material. It depends on factors such as aggregate size and porosity. Researchers associate open porosity with material density as a basis for estimating the tortuosity. Also, researchers relate tortuosity as the inverse of the pores connectivity factor which is associated with aggregate size and porosity. Tortuosity properties mainly affects the SAC of high-frequency behaviour (>2000 Hz), so increasing tortuosity can increase the absorption of sound energy caused by internal friction in the channel, thereby reducing noise at wider frequencies. Figure 13 shows the difference in the effect of tortuosity on the sound absorption curve of ACBFS PC[2] using two different aggregate sizes (Rios). It can be seen that specimens with larger aggregates (5-10 mm) have higher tortuosity and produce higher SAA compared to specimens with smaller aggregate sizes (1.25-5 mm). In comparison between ACSBFC and typical PC, which is with the same size aggregate content (5-10mm), the SAA of ACSBFC is higher because it has a higher SAC value at 3000-4000 Hz compared to typical PC. On the other hand, Paceno et al suggested that very large particles produce great porosity but the material fails to be tortuous, so energy dissipation decreases and therefore the sound absorption coefficient also decreases. Tortuosity values for porous concrete obtained from previous researchers with specific aggregate sizes are shown in the table 6.

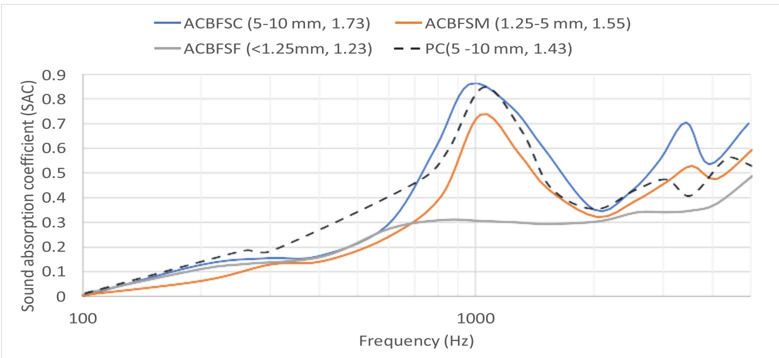


Figure 13. Different Sound absorption performance by PC with different mixtures and tortuosity (extracted from the original source using WebPlotDigitizer 4.5 [21])

Table 6: Tortuosity values for typical PC[28]

Aggregate size, mm	Porosity	Tortuosity
2.36-4.75, 4.75-9.5,9.5-12.5	15.1-30.5	1.282-3.448
1.19, 2.38, 4.75	9.5-29.6	0.943-5.025
5-10,0-5	10-20	1.031-2.174
4.75-9.5,9.5-12.5	17.8-26.5	1.59-2.41

5. Thickness of layers and multilayer PC

The increase in thickness causes the SAC at the dominant frequency (the frequency with the highest SAC) to be moved from high to low frequency levels as the thickness of the sample's changes, although the magnitude of the peak absorption coefficients remained practically uniform. Similar with the effect of cement content increment. This phenomenon can be explained through the relationship between the peak frequencies and the thickness of specimens, which can be expressed by an equation obtained from the concept of the absorbing mechanism of a porous material [5], [7].

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

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.

Figure 14 shows the influence of the thickness on the acoustic properties has been carried out on a CDW-concrete [5]with 40, 80 and 120 mm samples thickness. This fact produces that materials with 120 mmof thickness are appropriated as noise road traffic devices, due to this road noise is produced at low frequencies[8][5]. Researchers have also explored the effect of two-layer structure on the sound absorption properties of PC and recommended the appropriate combination of two-layer structure and thickness[7], [35]. A two-layer sample with a thinner top layer and a thicker bottom layer produced two peak values of the SAC in the tested frequency range. PC two-layer concrete consists of the front part made using lightweight aggregate 4–8 mm (LW1) and the back part made using normal aggregate 8–13 mm (N1) or 13–19 mm (N2) shows that the minimum SAC is more than 0.60 with a frequency range of 400 Hz or higher (figure 15)[15]. These results were consistent regardless of whether the back-mounted specimens were made using 8–13 mm or 13–19 mm aggregate.

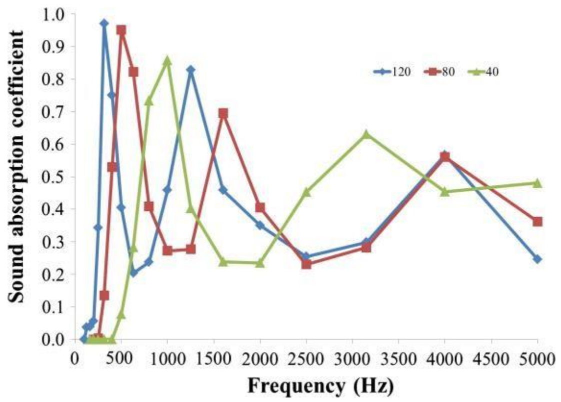


Figure 14. Effect of thickness[5]

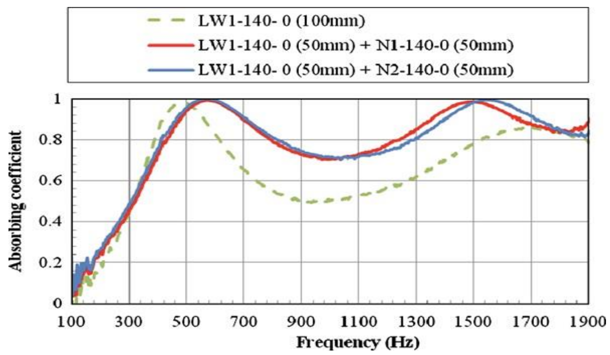


Figure 15. Effect of double layer porous [15]

6. Conclusion

The surface of the PC layer of NB has open porosity that is relatively high and connected to absorb sound well. Typically, it is made using a mixture of normal weight aggregate (>5mm) without or a little fine aggregate and binder but now lightweight aggregate or waste material (innovated PC) is used instead. Based on this review, aggregate size/grading is the main factor that affects porosity characteristics such as diameter, and distribution of pores, connectivity and tortuosity. Based on the review, it can be concluded that the following guide;

i. The composition of a typical PC mixture combining of aggregate size 2.37 mm- 4.75 mm and 4.75 mm- 9.5 mm was found to have good acoustic properties with a high SAC. It demonstrated high porosity with sufficient pore diameter, and high connectivity factor that can force sound energy to be absorbed by the pore's wall. The pores on the PC surface were found to have a strong relationship with sound absorption at 200-1600 Hz, due to their resonant properties.

ii. The composition of a typical PC mixture consists of a large aggregate size >9.5 mm despite having high porosity and characteristic pores with a larger average diameter (>4.72 mm) but the interconnectivity between the pores is low and produces low sound absorption properties. The inclusion of small size (sand) in aggregate size > 5mm also produces PC with smaller pores and low pore connectivity causing a reduction in sound absorption.

iii. The composition of the PC mixture consists of porous aggregates such as lightweight aggregate or waste materials made using diversified aggregates size than typical PC (between aggregate size 1.25-10mm) with composition similar with PC. Porous aggregate >5mm, produced PC with higher porosity, higher tortuosity and subsequently having a better NRC than typical PC with the same aggregate size indicating internal pores aggregate helps sound absorption but requires higher w/c.

iv. The sound absorption properties of the PC layer can be changed by changing the thickness or/and combining two porous layers in an effort to amend the position of max SAC and its dominant frequency corresponding to the problem of noise pollution from traffic.

Acknowledgement

The research was financially supported by the UTM Encouragement Research grant with references R.J130000.7711.4J625, Q.J130000.3822.31J15 and Q.J130000.3851.20J81, which received assistance from the Research Management Centre at Universiti Teknologi Malaysia. The assistance provided by these entities is greatly acknowledged and valued.

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