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Practical considerations of porosity, strength, and acoustic absorption of structural pervious concrete

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ABSTRACT

This study was conducted to address practical problems in producing structural pervious concrete, such as issues with mix proportioning, paste sagging, porosity, strength, and acoustic absorption. Concrete mixtures with varying aggregate types, target void ratios, and fiber contents were cast in cylindrical and panel-type specimens to determine the compressive strength, porosity, and acoustic absorption coefficient. Porosities of the concrete measured by two methods, i.e., using the volumetric method and computed tomography scanning, were compared to confirm the pore network distribution. A surface impedance method was used to measure the acoustic absorption of the panel samples. Paste with a flow of 170 ± 10 mm containing synthetic fibers prevented sagging successfully even after mechanical vibration. The concrete produced with this paste and having target void ratios of 10–15% possessed adequate connected open pores for acoustic absorption coefficient over 0.5 and structural strength exceeding 20 MPa.

1. Introduction

Pervious concrete, also known as porous concrete or permeable concrete, is a special type of concrete with a porous structure manufactured by mixing cement paste with coarse aggregate, but little or no fine aggregate is added [1]. Pervious concrete has connected pore networks with good water permeability (hydraulic conductivity) and acoustic absorption [2]. The compressive strength of pervious concrete can range from 3 to 30 MPa and is designed by adjusting the mix proportion such that it can also be a suitable structural material for pavements, railways, and structural walls [3,4]. Compared to foamed concrete, which is another type of cement-based porous composite with high volume air bubbles, pervious concrete has higher compressive strength and durability, as the compressive strength of foamed concrete ranges from 1 to 5 MPa [5,6]. Due to the sound absorption performance given by its open pore networks, pervious concrete is also used as a structural wall with soundproofing performance in urban areas or as a concrete block

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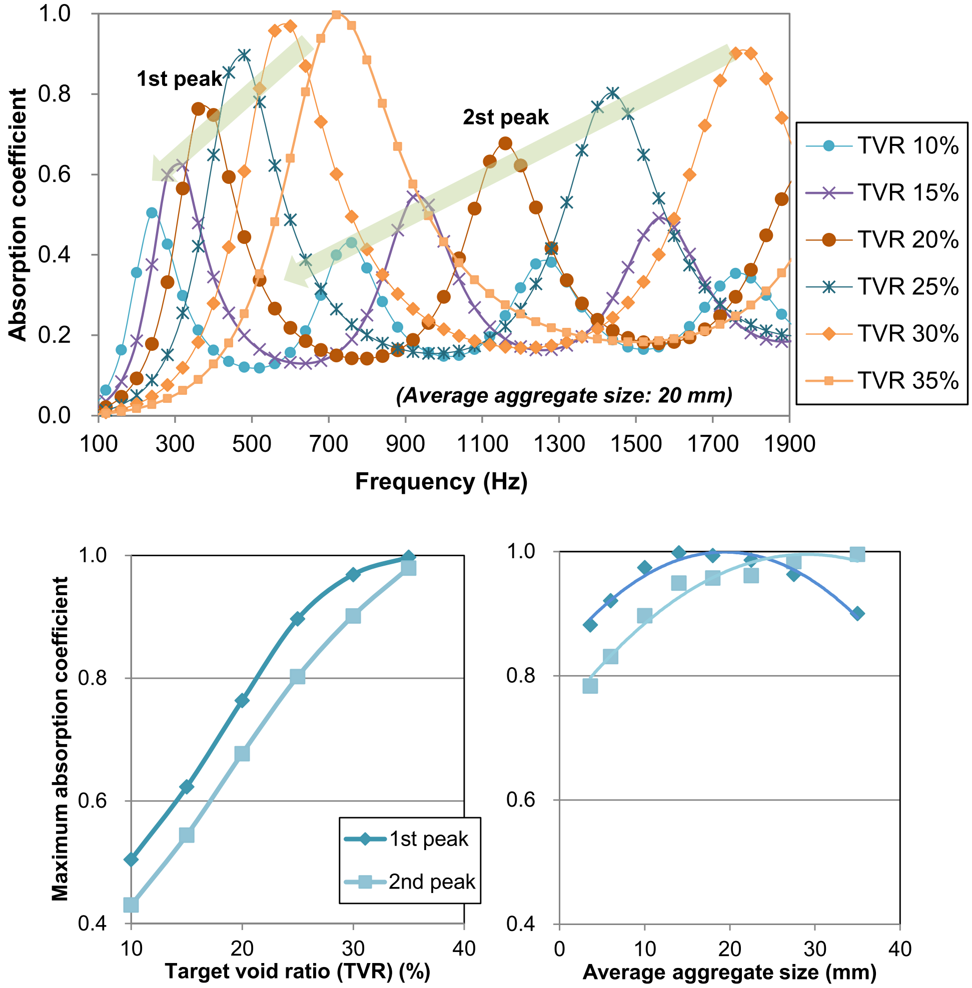


Fig. 1. Simulated acoustic absorption coefficients of pervious concrete: effects of target void ratio (TVR) and aggregate size (for 100 mm thickness) (redrawn from [13]).

river bank protection to improve the urban acoustic environment [7].

The performance of pervious concrete mainly depends on pore structures, such as porosity, i.e., pore volume, pore size, connectivity, and tortuosity [8]. The pore structure of concrete is influenced by various factors, including the aggregate size and shape, cement paste volume, and compaction method [9,10]. As the porosity of concrete increases, the compressive strength decreases, while the acoustic absorption capacity increases; thus, it is challenging to simultaneously satisfy both the strength and acoustic absorption of pervious concrete [11–15]. Therefore, a guideline on mix proportioning is needed to produce concrete with adequate strength and acoustic absorption capacity. Mix proportioning methods for pervious concrete following simple and complex processes have been proposed [16,17]. In our previous study [13], acoustic absorption model of pervious concrete was established, considering mix proportion parameters, such as the aggregate size and paste–aggregate volume ratio. This model can be used for designing the mix proportion of pervious concrete to achieve the target sound absorption coefficient based on the frequency (Fig. 1, from [13]).

Moreover, standards for the fabrication processes of pervious concrete, including mixing, placing, and curing, are required to determine the target performance [4]. The practical fabrication of pervious concrete requires detailed concerns for quality control, compared to that of normal structural concrete [18,19]. Most importantly, the porosity of pervious concrete is challenging to control in practical terms [12]. Pervious concrete with an identical aggregate-to-paste volume ratio may have different porosities, depending on various factors, such as the aggregate shape, compaction method and level, and cement paste flowability [4]. When fresh concrete is overcompacted, the paste may sag downwards, and the porosity and pore connectivity may vary with the direction of gravity [15]. This problem adversely affects the required strength and acoustic absorption of structural pervious concrete [20]. Moreover, because pervious concrete is a resonator-type acoustic absorption material, the acoustic absorption spectra, i.e., the absorption coefficients for various frequency ranges, may fluctuate according to the fabrication method [14,21].

In a recent study [22], it was mentioned that a standard mixture design method to satisfy the target performance of normal pervious concrete including porosity, compressive/flexural strength, and permeability has been established. However, this method was

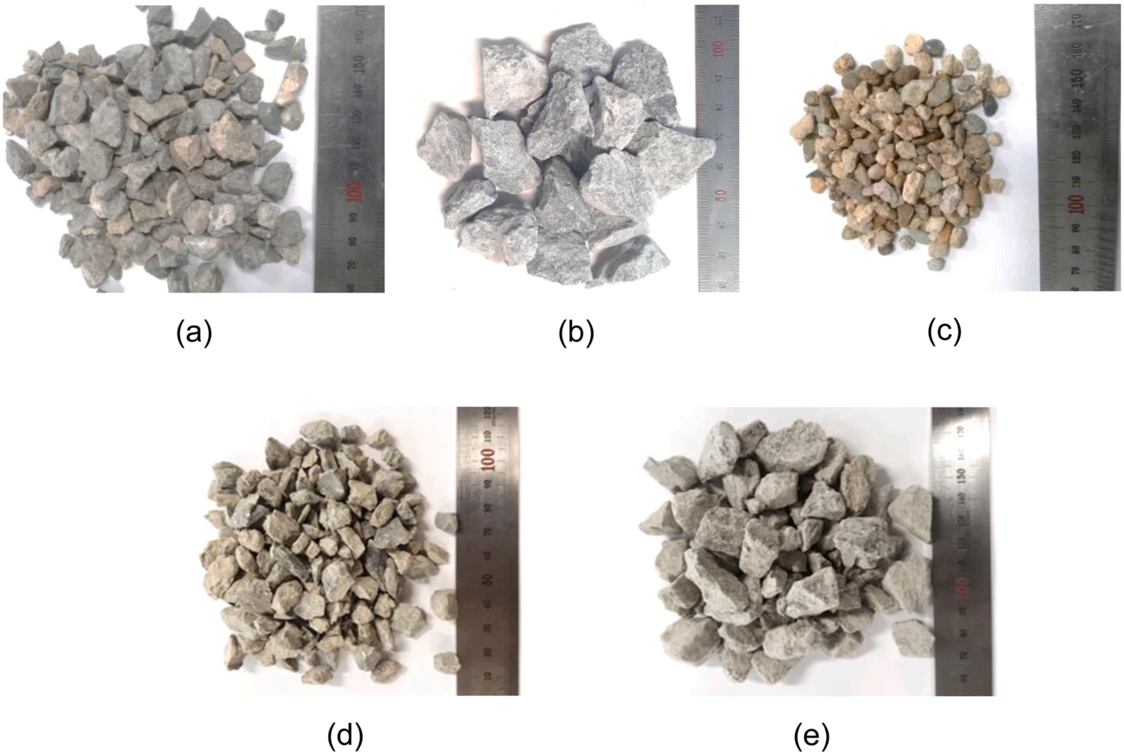


Fig. 2. Shapes and sizes of coarse aggregate particles: a) Type 1 (5–13 mm), b) Type 2 (13–25 mm), c) Type 3 (5–8 mm), d) Type 4 (5–13 mm), and e) Type 5 (13–25 mm).

Table 1
Physical properties of coarse aggregates.

Property	Type 1	Type 2	Type 3	Type 4	Type 5
Type of rock	Granite (crushed)	Granite (crushed)	Sedimentary rock (crushed)	Granite gneiss (crushed)	Granite gneiss (crushed)
Size gradation[a] (sieve range, mm)	5–13	13–25	5–8	5–13	13–25
Specific gravity	2.54	2.70	2.46	2.65	2.55
Water absorption ratio (wt%)	2.60	0.35	10.56	1.54	1.54
Porosity of particles (vol%)	6.78	0.95	29.04	4.14	3.99
Rodded bulk density (kg/m^3)	1390	1560	1414	1390	1457
Absolute volume ratio[b] (%)	56.2	58.2	57.5	52.5	57.1

[a] Gradation ranges “A–B” of the aggregates in this row indicate that 100% of aggregates remained on the A mm sieve and passed through the B mm sieve.
[b] The values were obtained from rod-compacted bulk aggregates.

applicable for normal strength pervious concrete for pavements below strength of 20 MPa, and it is also mentioned that various challenges are still present for high-performance pervious concrete [22]. Although various types of equations, which relate porosity, strength and permeability of pervious concrete, have been applied in mix designs, there have been significant deviations between the designed and actual performances, especially in the case of high-strength mixtures with high cement paste contents [23,24]. Pervious concretes produced with a target of having large porosity and no sagging are typically capable of having a compressive strength of around 10 MPa.

This study was conducted to achieve the practical fabrication of pervious concrete with desirable structural and acoustic absorption properties. Pervious concrete with different aggregate types and paste-to-aggregate ratios was produced. In some specimens, synthetic fibers were added to the mixture to prevent paste sagging. The porosity of the concrete was evaluated using two methods, i.e., the “volumetric method” with water saturation and three-dimensional (3D) “computed tomography (CT) scanning.” The pore structure of the concrete was then evaluated by comparing the results obtained using the two methods. The relationship between the porosity and compressive strength of pervious concrete analyzed in this study was compared with those reported in the literature. Based on the findings, a guideline for the mix proportioning of pervious concrete was proposed, considering the compressive strength and acoustic absorption. The acoustic absorbing performance of a mixture with high compressive strength was evaluated, and the surface condition

Table 2
Chemical composition of binder.

XRF oxide composition		
Oxide	OPC	Silica fume
CaO (C)	59.9	0.3
SiO_2 (S)	18.6	95
Al_2O_3 (A)	4.7	0
Fe_2O_3 (F)	3.1	0.3
MgO	3.7	0.6
Na_2O $+K_2O$	1.6	0
SO_3 ($\overline{S}$)	3.8	0
Cl	0.05	0
Etc.	0.9	1.6
Loss on ignition	3.6	2.2

Table 3
Properties of PVA fibers.

Fiber length (mm)	12–13
Fiber diameter (mm)	0.035–0.040
Aspect ratio	300–350
Nominal strength (MPa)	1600–1700
Elastic modulus (GPa)	42–43
Specific gravity	1.3
Elongation at rupture (%)	5.5–6.5
Weight of surface oil coating (%)	1.2

Table 4
Mix proportions of pervious concrete.

Aggregate type	Target Void (%)	Fiber (wt%/ cement)	P/G (vol%)	Weight composition (kg)				
				Water	Cement	Silica fume	PVA fiber	Aggregate
Type 1 (5–13 mm)	10	0	60	111	555	111	0	1390
	15	0	51	95	473	95	0	1390
	20	0	42	78	391	78	0	1390
	25	0	33	62	309	62	0	1390
	30	0	25	45	226	45	0	1390
Type 2 (13–25 mm)	10	0	55	104	522	104	0	1560
	15	0	46	88	440	88	0	1560
	20	0	37	72	358	72	0	1560
	25	0	29	55	276	55	0	1560
	30	0	20	39	194	39	0	1560
	20	0.5	37	72	358	72	1.8	1560
	20	1.0	37	72	358	72	3.6	1560
	20	1.5	37	72	358	72	5.4	1560
Type 3 (5–8 mm)	5	0.85	65	123	615	123	5.2	1414
	10	0.85	57	107	533	107	4.5	1414
	15	0.85	48	90	451	90	3.8	1414
Type 4 (5–13 mm)	5	0.85	81	139	697	139	5.9	1390
	10	0.85	71	123	615	123	5.2	1390
	15	0.85	62	107	533	107	4.5	1390
Type 5 (13–25 mm)	5	0.85	66	124	622	124	5.3	1457
	10	0.85	58	108	540	108	4.6	1457

Note: The weights of the aggregates listed in this table are identical to the rodded bulk density values in Table 1. Thus, the weight composition provided in this table adopted 1 m^3 of concrete in an ideal case, i.e., the aggregates were compacted to a maximum degree. However, in practice, the cement paste around the aggregate in fresh concrete prevents the complete packing of the aggregates [10].

effect of the specimens on acoustic absorption was assessed. Thus, manufacturing structural pervious concrete based on its sound absorption was considered in practical terms.

2. Specimen and preparation

2.1. Materials

Five different types of crushed stones sold in the local market were used as coarse aggregates. Their particle shapes are depicted in Fig. 2, and their physical properties are listed in Table 1. The aggregates were washed with flowing water and sieved before mixing. The shape factors for the aggregates were not evaluated. However, the absolute volume ratio after rod compaction is known as an indirect indicator of particle shape; for single-sized aggregates, a higher absolute volume ratio indicates a more spherical particle shape [25]. Aggregates passing through a 5 mm sieve, classified as a “coarser part of fine aggregate,” were rejected because it is challenging to form connected pore networks in concrete containing this aggregate size. In addition, for aggregates with particle sizes exceeding 25 mm, the paste may easily sag downward during compaction because of the low specific surface area of the aggregate. Therefore, such aggregates were not used in this study.

Portland cement manufactured according to the Korean Standard (KS F 2567) and ASTM C 150, and silica fume produced according to ASTM C1240, were used as binders. The density and specific surface area of cement were 3.12 and 3100 cm^2/g Blaine, respectively. The 28-day compressive strength of the cement was 42.9 MPa, which was significantly higher than the minimum standard value of 28 MPa (4060 psi) specified in ASTM C 150. The density, specific surface area, and mean particle size of the silica fume were 2.30, 190,000 cm^2/g BET, and 0.30 μm, respectively. The oxide compositions of the cement and silica fume detected through X-ray fluorescence analysis are listed in Table 2. A polycarboxylic acid-based high-range water reducer was used as an additive. In some mixtures, 12 mm long synthetic fibers (polyvinyl alcohol, PVA) were used to minimize the sagging of the fresh paste. The material properties of the fibers are listed in Table 3.

2.2. Mix proportions

The mix proportions of the concrete are listed in Table 4. In this study, the volume proportions of cement paste and aggregates were designed, considering the TVR concept [21]. TVR is defined as follows [26]:

$$\text{TVR} \quad [\%] = 100 - V_a - V_p \tag{1}$$

where V_a and V_p are the theoretical volume proportions of the bulk aggregate and cement paste in pervious concrete (%), respectively. The V_a values for each aggregate type were assumed to be identical to the absolute volume ratios listed in Table 1. For the mix proportioning, the TVR values and aggregate types were determined first, and the V_p values were then calculated using Eq. (1).

The V_p values were used to determine the weights of the materials for the cement paste in a unit volume of concrete. For the cement paste used for all the concrete mixtures, a water-to-cement ratio (w/c) of 0.20 and a silica fume content of 20 wt%/cement were adopted. The mix proportions of pervious concrete used in this study are listed in Table 4. The high-range water reducer content was increased from 0.2 to 0.3 wt%/cement to control the flow diameter of fresh cement paste within a range of 170 ± 10 mm according to ASTM C 230 specifications. In our previous study [15], we found that this flowability range for paste was adequate for forming uniform pore structures in pervious concrete. When the paste flowability was higher than this range, the paste sagged downward, even by hand compaction. However, when the paste flowability was lower, the fresh paste was nonuniformly dispersed with the aggregates and formed “paste balls,” i.e., cement paste lumps (Fig. 7 in [15]).

2.3. Experimental details

In this study, a two-step mixing approach was adopted. The paste was mixed in a 10 L capacity mortar mixer for approximately 5 min. The paste was mixed separately because of the low w/c and high silica fume content before adding aggregates to achieve uniform dispersion. After the flow diameter of the paste was measured, the paste was mixed with aggregates and fibers in a 60 L capacity concrete mixer for 3–5 min. It was ensured that the paste uniformly covered the aggregates before the mixing process was completed. Two mold types of concrete cement were prepared. The first type was cylinder molds, each with a diameter of 100 mm and a height of 200 mm, used to determine the porosity and compressive strength of the specimens. The second type was rectangular molds of 400 mm × 400 mm each, used to evaluate the acoustic absorption performance. Two different heights of specimens were adopted for acoustic absorption, i.e., 50 and 150 mm. A strong motor-in-head type internal vibrator for site construction was used for compacting fresh concrete twice: when the mixtures filled approximately half of the molds and when the molds were filled. The fresh mixtures were compacted until no further consolidation of the mixtures was possible. It should be noted that pervious concrete is generally mixed using a “one-step method,” which involves mixing with all materials simultaneously and applying soft compaction through hand tamping or using a weight roller [4]. Thus, the compaction applied in this study can be considered an extreme case.

The top surface of the cylinder specimens for compressive strength measurement was made flat using residual paste (capping), whereas those for porosity measurement were not capped but only compacted. The top surface of each box specimen was also compacted by placing a metal plate on the surface and hammering the plate to open the surface pores for acoustic absorption. The specimens were initially sealed with a plastic film for 24 h to prevent moisture loss and then demolded and water-cured for 28 days.

The curing temperature was 20 ± 2 °C.

The following equations were used to obtain the porosity using the volumetric method [15]:

$$V_T[\%] = \left[1 - \frac{W_3 - W_1}{V_1\rho_w}\right] \times 100 \tag{2}$$

$$V_{OP}[\%] = \left[1 - \frac{W_2 - W_1}{V_1\rho_w}\right] \times 100 \tag{3}$$

$$V_{CP}[\%] = V_T - V_{OP} \tag{4}$$

where V_T, V_{OP}, and V_{CP} are the volume proportions of the total, opened, and closed pores, also called the total, connected, and disconnected porosities, respectively. W_1, W_2, and W_3 are the weights of the saturated specimen in water, the specimen under the saturated surface-dry condition, and the oven-dried specimen, respectively. V_1 is the apparent volume of specimens determined from a measurement of dimensions using a Vernier caliper, and ρ_w is the density of water [15].

The porosity measurement conducted through 3D CT scanning was only for mixtures containing fibers using a cone-beam computed tomography-CS9300 (Carestream Health Inc., Rochester, NY), and was not conducted for mixtures without fiber, regardless of sagging of cement paste. The voxel size was 0.3 mm, and the detection conditions were a voltage of 90 kVp and a current of 5 mA. A specimen from each mixture was subjected to testing. Through CT scanning, 3D contours of the specimens and axial images were captured. The porosity was calculated by counting the number of pixels of the void portion (darker) and skeleton (brighter) [27]. The porosities of the total cross-sectional diameter (R) and the inner 0.8 R portion were separately calculated to identify the wall effect on the contact surface between the mold and specimen. The wall effect was observed for concrete specimens with a relatively high cement paste-to-aggregate volume ratio [28]. Moreover, the porosity profile along the height direction was obtained through CT scanning. Fig. 3.

The specimens for measuring the compressive strength and porosity were prepared separately. Three or four replicates were used for each measurement. The compressive strengths of the specimens were determined according to ASTM C 39. Only one mixture type, i.e., the specimen containing Type 4 aggregate and TVR 10% (Table 4), was selected to determine the acoustic absorption capacity, considering its porosity and strength. The in situ surface impedance setup, consisting of a set of sensors for sound pressure (P), acoustic particle velocity (U), and loudspeaker (In-situ Absorption, Microflown Technologies, Arnhem, Netherlands), was used to calculate the acoustic absorption coefficients of the specimens. The test procedure and calculation process of the acoustic absorption coefficient are described in [29–31]. The frequency range for the test was 100–3000 Hz, and smoothing with 10-point averaging was applied to eliminate the noise of the acoustic absorption spectra. To evaluate the statistical deviation of the acoustic absorption, two specimens, with sizes much larger than necessary for measuring acoustic absorption, were produced instead of making several numbers of specimens with just the required size; and in these large specimens, the sound absorption coefficient was measured at various locations, i.e., more than 10 different points were measured.

3. Test results and discussion

The experimental results of the porosity and compressive strength tests are listed in Table 5 and plotted in the following sections.

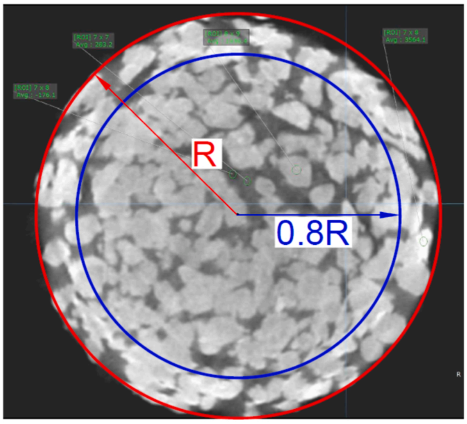
3.1. Porosity and compressive strength

Fig. 4 shows the relationship between V_T and V_{CP} of pervious concrete obtained using the volumetric method with the designed TVR. For mixtures produced with Types 1 and 2 aggregates without fibers, the values of V_T were significantly lower than the corresponding TVR values for the specimens with lower TVR, i.e., lower than 20%. This behavior occurred because of the sagging of cement paste, owing to vibration compaction. The actual photographs of the specimens are shown in Fig. 5. The paste in specimens with lower TVR, i.e., mixtures with a higher volume of cement paste (Table 4), sagged downward; hence, pores could not be formed. The paste did not sag when the specimens were compacted with a compacting rod by hand, while the data on this was not provided in this study. However, hand compaction was a less reliable method for casting pervious concrete with uniformly distributed pores because it should manually control the degree of compaction. For mixtures with higher TVR, i.e., more than 25%, the paste only covered the aggregate surfaces, and no downward flow occurred even after mechanical vibration compaction. In a previous study [15], specimens with TVR higher than 25% had uniform pore structures in the gravity direction when the paste flow was adjusted to 150–200 mm according to ASTM C 230 standards. Therefore, for specimens containing Types 1 and 2 aggregates, the designed TVR and measured V_T were similar within the 10% gap, even when the fibers were not added (red arrow in Fig. 6(a)).

The addition of synthetic fibers is an effective method of preventing paste sagging in pervious concrete with low TVR. For the specimens produced with Types 4 and 5 aggregates containing fibers (Fig. 6(a)), the V_T values were close to the TVR values, indicating that the pores in the specimens were formed as designed. Fig. 6 shows the variations in the porosity and strength of pervious concrete containing Type 2 aggregate with the fiber content. Although the designed TVR was constant, with fibers exceeding 0.5 wt%/cement, the V_T increased, and the compressive strength decreased. However, as mentioned above, the pervious concrete was designed for acoustic absorption, and this high strength of specimens by paste sagging was outside our interest. Fig. 6 shows that when only 0.5 wt %/cement of fiber was added, paste sagging under strong vibration compaction could be prevented (Fig. 5). In addition, the measured

(a)

(b)



(c)

(caption on next page)

Fig. 3. CT scanning of pervious concrete: (a) scanned sample, (b) 3D reconstruction image, and (c) axial image.

V_T was slightly higher (3–5%) than those of specimens without paste sagging, i.e., when fibers were added or when the designed TVR was high (green box in Fig. 4(a)). This behavior could be attributed to several factors, including the incomplete compaction of coarse aggregate due to the pastes between the aggregates and the water absorption by the paste and aggregate. Furthermore, for the specimens containing Type 3 aggregate, which had a very high water absorption (10.6%, Table 1), the V_T values were significantly higher than the TVR values (red box in Fig. 4(a)). As reported in [21], it was difficult to determine whether the pores were generated from aggregates or closed pores in the paste using this volumetric method.

It should be mentioned that the pervious concrete studied in the present work was not limited to being applied as permeable pavement. If it was for a pavement system, the infiltration rate of the concrete according to ASTM C 1701 should be measured [32]. In the case of pervious concrete for the permeable pavement system, the required strength of the pervious concrete is below 15 MPa and the TVR is generally about 20–30% [33]. For this type of concrete, the occurrence of sagging is less because of lower content of cement paste. However, as shown in Fig. 5, sagging might occur in high-strength mixtures with TVR lower than 15%, which requires higher volume of cement paste.

As closed pores cannot contribute to acoustic absorption, lower values of V_{CP} are preferred for the acoustic absorption of pervious concrete. Generally, V_{CP} was 5–8% for most mixtures (Fig. 4(b)), except for the mixtures containing Type 3 aggregate, which exhibited high water absorption. Considering this V_{CP}, the TVR should be higher than 10% to form a connected pore network to improve acoustic absorption. It should be noted that the volumetric method has the following limitations in describing the pore structure of pervious concrete. First, some of the porosity measured using the volumetric method originated from the pores in the aggregate, gel pores, and capillary pores in the paste, which do not influence acoustic absorption or permeability. Second, it is difficult to evaluate the porosity separately according to the location of the specimens.

CT scanning provided further details about the pore structures. The differences between the porosity evaluations using the volumetric method and CT scanning are listed in Table 6. Fig. 7 shows the porosity profile of the specimens detected through CT scanning following the direction of gravity. As the voxel size for the detection was 0.3 mm^3, the pores smaller than this size, including the capillary pores in the cement paste and aggregate pores, were ignored in the calculations. The aggregate and paste sections were not separated because of the lower resolution of the scanning system used in this study. The porosity profile confirmed that the porosity of the specimens fluctuated within a maximum value of 10%, depending on the height, which was not caused by paste sagging. All the specimens subjected to CT scanning contained fibers. In specimens fabricated with Type 3 aggregate, there was no evidence that the porosity decreased in the gravity direction, owing to paste sagging. In specimens containing Types 4 and 5 aggregates, the middle part exhibited a relatively lower porosity than the top and bottom parts. It should be noted that the middle part was mechanically compacted using the vibrator; thus, the pores in this part might have been smaller.

The porosities measured using the volumetric method and CT scanning were compared (Fig. 8). The porosities of the top, middle, and bottom sections of 20 cm high specimens indicated the average values of porosities of the three divided parts of the specimens by height (Fig. 8). First, in mixtures produced with Type 3 aggregate (a porous aggregate), a large deviation between the CT scanning and volumetric method results was observed. The porosity determined through CT scanning was similar to that of TVR and V_{OP} within the deviation range of 2–4%. Moreover, in this mixture, the porosity fluctuation detected through CT scanning according to the height was within 5%. This result indicated that uniform pore structures were formed in the mixtures, and its porosity was similar to that of the design. In specimens produced with Types 4 and 5 aggregates, the difference between the porosity values determined using CT scanning and the volumetric method was within 3–9%. A larger difference in the porosities of these specimens than in Type 3 aggregate specimens, based on the height, was observed (Fig. 7). Moreover, the porosity of the 1 R cross-section was higher than that of the 0.8 R cross-section by approximately 0.5–5% depending on the specimens, which was influenced by the "wall effect." In these "wall parts," the surfaces of the specimens had a higher porosity than the inner parts, which may influence concrete failure.

Based on these experimental results of porosity tests, the following inferences can be drawn. First, fibers should be incorporated in fabricating structural pervious concrete with relatively high cement paste volume to prevent paste sagging and produce uniform pore structures as designed. Second, there may be a difference of 5–10% in pervious concrete porosity, depending on the height or position. Third, the use of relatively small coarse aggregate helps to generate uniform pore structures.

Fig. 9 shows the relationship between the V_T and compressive strength obtained in this study and other relevant studies. The relationship similar to Fig. 9 has already been established in several previous reports, but the process or guideline of mix proportioning based on this relationship has not been presented. The range of V_T vs. compressive strength in this study was similar to the experimental results obtained in previous studies. The compressive strength of the cement paste in this study exceeded 100 MPa and was relatively higher in other studies, as the w/c of cement paste in those studies generally ranged between 0.25 and 0.40, and silica fume was rarely used. Thus, for specimens having lower porosity, such as V_T of 10% or lower, the strength of concrete per V_T obtained in this study was higher than those of other studies. Nevertheless, specimens with V_T values higher than 10% in this study exhibited similar strength per V_T with those of other studies.

The simulation results for the maximum value of the normal-incidence acoustic absorption coefficient corresponding to porosity were plotted, along with the porosity–strength results as a reference. It is known that pervious concrete with V_T lower than 10% is difficult to apply for acoustic absorption, although they may have an ideal pore distribution without paste sagging or porosity fluctuation. Therefore, considering both acoustic absorption and compressive strength, pervious concrete with V_T higher than 10% is applicable in practical terms. Moreover, for the mixtures containing synthetic fibers, the V_T values were close to the TVR values. In other words, pervious concrete possessing the desired strength and acoustic absorption can be designed and fabricated by controlling

Table 5
Experimental results of porosity and compressive strength tests.

Aggregate type	Target Void (%)	Fiber (wt%/cement)	Porosity (vol%)											Compressive strength (MPa)	
			Volumetric methods with water						CT image process						
			VOP		VCP		VT		1 R	0.8 R	Top	Middle	Bottom		
			Ave.	Std.	Ave.	Std.	Ave.	Std.						Ave.	Std.
Type 1	10	0	0.0	0.0	4.4	0.2	4.4	0.2						91.6	15.7
(5–13 mm)	15	0	2.1	2.3	4.0	0.4	6.1	2.7						78.5	10.8
	20	0	4.1	2.6	5.0	0.6	9.1	3.3						53	6.2
	25	0	27.9	6.7	7.0	0.3	34.9	6.3						12.5	2.6
	30	0	28.5	1.6	8.1	0.2	36.5	1.8						8.8	0.9
Type 2	10	0	4.0	0.3	4.3	0.4	8.3	0.7						12.5	4.0
(13–25 mm)	15	0	2.5	2.6	3.8	0.3	6.3	2.6						31.7	17.3
	20	0	0.4	0.6	2.8	0.2	3.1	0.7						69.5	14.2
	25	0	26.5	0.9	4.1	0.4	30.6	0.7						7.5	3.2
	30	0	29.5	1.0	4.3	0.4	33.8	0.6						9.4	0.9
	20	0.5	19.1	2.6	4.5	0.0	23.6	2.6						12.1	1.8
	20	1.0	17.3	1.8	4.7	0.3	22.0	2.1						17.5	7.4
	20	1.5	17.9	1.9	5.2	0.2	23.1	2.1						20.7	1.8
Type 3	5	0.85	11.2	1.7	11.7	0.7	22.9	1.2	6.0	5.2	6.8	4.5	4.4	12.9	4.3
(5–8 mm)	10	0.85	12.7	0.7	12.3	0.2	25.0	0.5	16.7	11.8	10.0	10.0	15.4	9.2	2.6
	15	0.85	20.7	1.7	12.1	0.6	32.8	1.4	18.9	17.9	17.6	18.2	17.7	4.2	1.1
Type 4	5	0.85	10.6	1.1	2.5	0.0	13.1	1.1	–					19.7	3.6
(5–13 mm)	10	0.85	10.8	0.7	2.5	0.6	13.3	1.0	12.1	11.9	16.9	8.8	10.7	25.6	7.4
	15	0.85	15.0	0.8	3.1	0.4	18.1	0.5	15.9	10.7	17.6	8.3	6.3	14.4	5.2
Type 5	5	0.85	7.7	2.5	–	–	–	–	14.6	9.8	14.2	11.8	3.5	14.5	4.3
(13–25 mm)	10	0.85	13.2	2.0	0.0	0.0	13.2	2.0	17.2	14.9	9.8	10.1	24.9	13.9	3.8

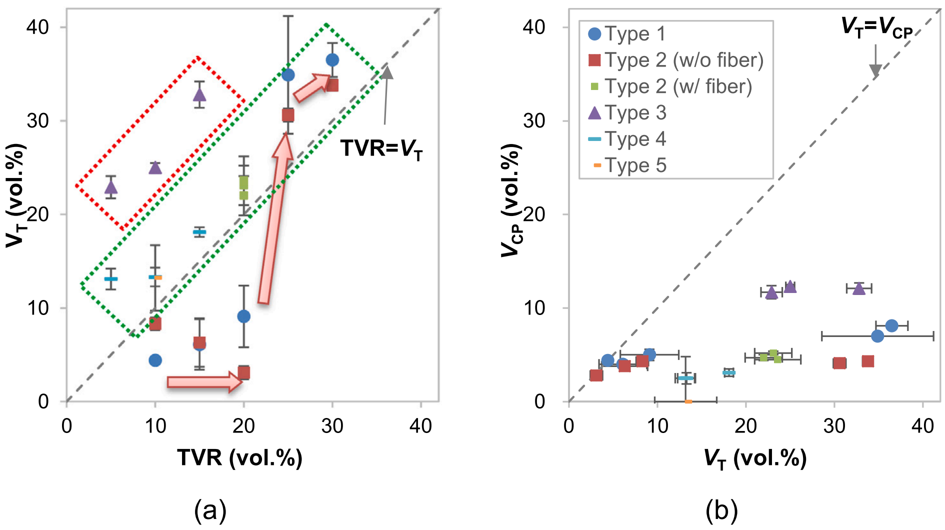


Fig. 4. Porosities of all mixtures measured using volumetric methods: (a) TVR vs V_T and (b) V_T vs V_{CP}.

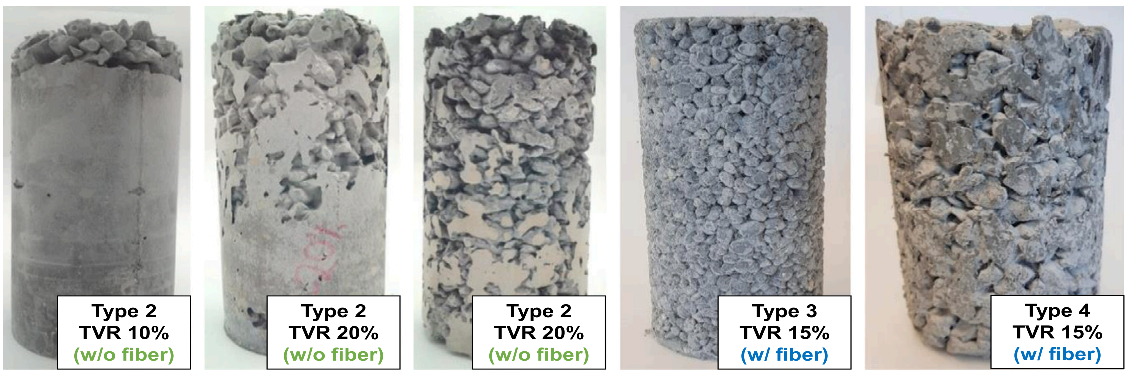


Fig. 5. Shapes of cylindrical specimens with and without fiber.

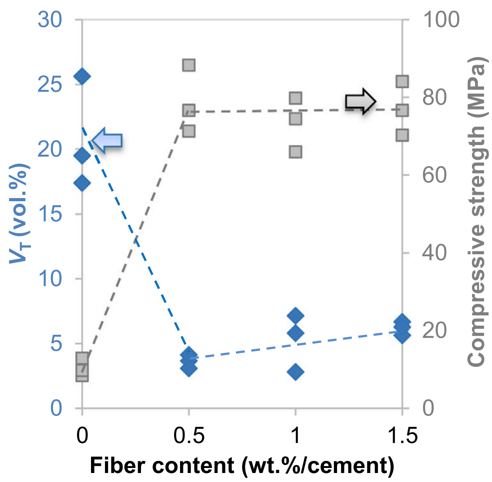


Fig. 6. Fiber content vs. V_T and compressive strength (mixture containing Type 2 aggregate and TVR 20%).

Table 6
Comparison of porosity evaluation using volumetric method and CT scanning.

Feature	Volumetric method	CT scanning
Definition of pore	It is the location where the water can be penetrated.	It is the dark area of the CT scan image detected by X-ray (the non-solid part), which may be varied by the resolution (voxel size).
Measurement range	Only bulk or cut specimen is required.	A location of interest can be selected
Evaluation of pore connectivity	The opened and closed pores are separated through air and oven drying.	Qualitative or semiquantitative evaluation using cumulative 3D images[a] is required.
Analysis of pore size	Impossible	Possible

[a] Further calculation is required for the automatic quantitative evaluation of the connectivity or tortuosity of the pore network (e.g., the Mori–Tanaka approximation) [27].

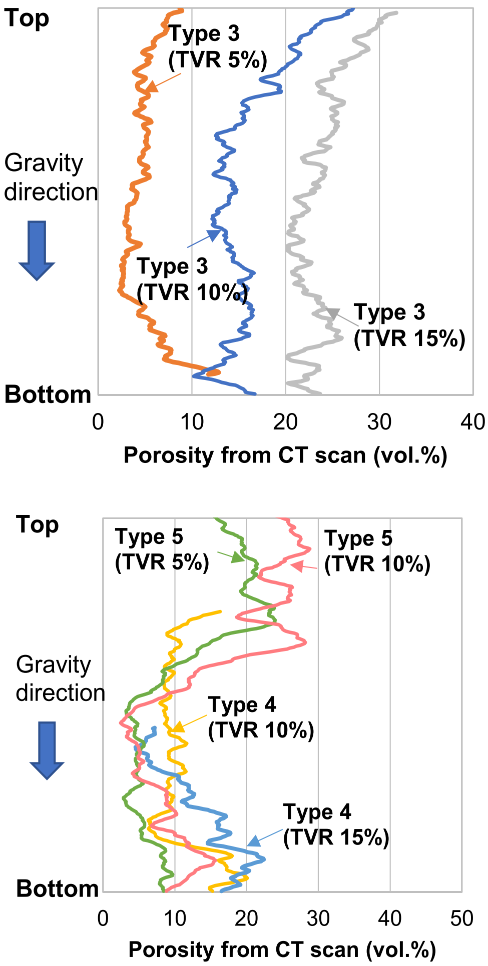


Fig. 7. Porosity profile by height of specimen from CT scan.

the porosity.

From a practical viewpoint, the fluctuations of the characteristics and performance of the concrete should also be considered. The porosity of the pervious concrete may vary even when the mix proportion and fabrication process are controlled. The compressive strength fluctuated probably because of porosity deviation. The deviation in the pervious concrete porosity may be larger than that of conventional structural concrete. The results indicated that the fluctuation in the pervious concrete strength induced by the porosity uncertainty was more significant than that influenced by the paste properties (see the porosity profile by CT scan, Fig. 7). Hence, the determinant approach following an accurate and sensitive process is inadequate to establish a mix proportioning method of obtaining the required compressive strength and acoustic absorption of pervious concrete. A guideline on the relationship between porosity, strength, and acoustic absorption coefficient was established in this study (Table 7). It is more reliable to use this range-based mix proportioning method and follow a suitable fabrication process for obtaining the designed porosity. Based on the findings of this study,

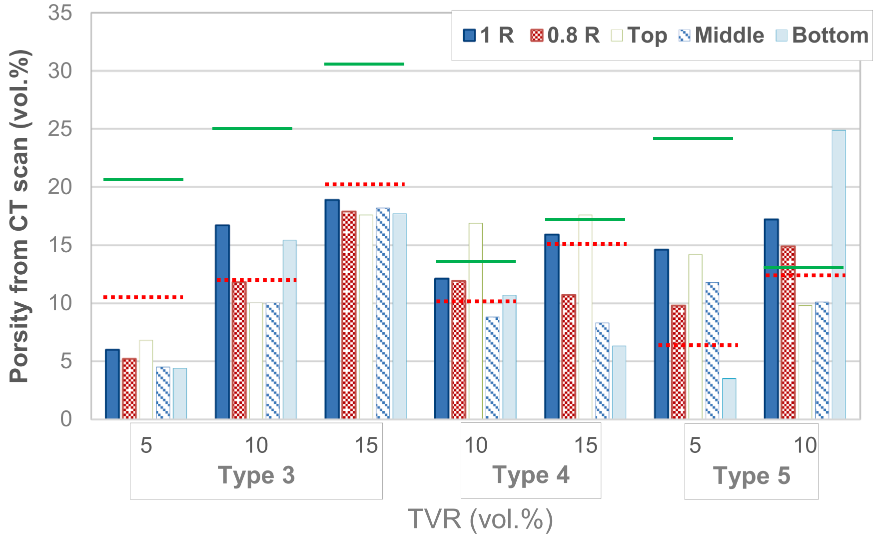


Fig. 8. Porosity of bulk specimens from CT scan (green solid lines: V_T; red dotted lines: V_{OP}. Both parameters were detected using the volumetric method.).

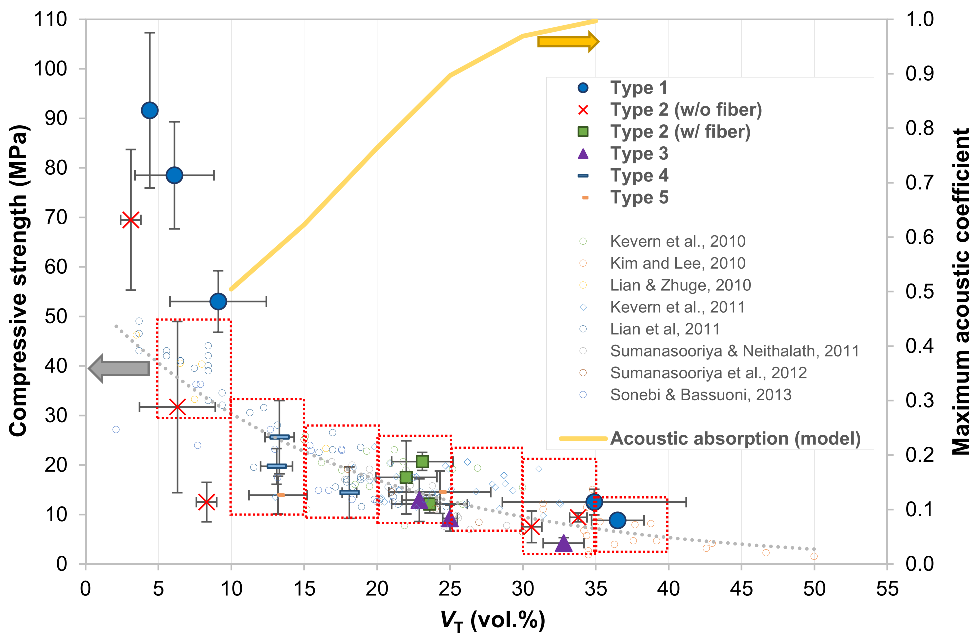


Fig. 9. V_T vs compressive strength of pervious concrete mixtures in this study and other studies [15,19,34–39] (red dot-lined boxes: reliable ranges of compressive strength along with V_T ranges; grey dotted line: regression curves for all data; yellow thick line: maximum normal incident acoustic coefficient of 10–20 mm aggregate concrete from theoretical model in ideal porous structure).

adding synthetic fibers in concrete mixtures and applying adequate vibration may help to achieve the target porosity and compressive strength.

3.2. Acoustic absorption

As mentioned in Section 2.3, only one mixture (Type 4 TVR 10%) was selected for measuring the acoustic absorption spectra. The reasons for this are as follows. First, sagging under mechanical vibration could not be prevented for the mixtures without fibers, i.e., mixtures with the aggregates Types 1–3. Second, in the case of the concrete containing Type 5 aggregate (larger in size than Type 4 aggregate), the compressive strength was relatively lower due to the larger pore size in the concrete. As shown in the results of Table 5, the selected mixture had the compressive strength over 25 MPa and showed no sagging.

Table 7
Guideline ranges of pervious concrete considering TV, compressive strength, and maximum acoustic absorption coefficient (Fig. 9).

V_T (vol%)	Compressive strength (MPa)		Max. acoustic coefficient (model)[a]
	Measured	Eq. (5)	
5–10	31–49	29–40	0.30–0.50
10–15	13–32	22–29	0.50–0.63
15–20	12–27	18–22	0.63–0.75
20–25	12–26	15–18	0.75–0.90
25–30	8–21	11–15	0.90–1.00
30–35	5–15	8–11	1.00
35–40	5–13	6–8	1.00

[a] The maximum coefficients of vertical (normal) incidence acoustic absorption were calculated for the 100 mm specimens. These maximum coefficients were seldom varied according to the depth of the concrete, but the frequency band corresponding to the coefficients may be varied.

Fig. 10 shows the top and bottom sides of a specimen used for the acoustic absorption tests. The surface conditions of the top and bottom sides of the specimens were different. In some areas of the bottom side in the direction of gravity, the pores were closed (the yellow circles in Fig. 10). In contrast, uneven surfaces were formed on the top sides of the samples because of the low flowability of the paste containing fibers. Because of this behavior, the surface condition effect on the acoustic absorption properties of pervious concrete was evaluated. It should be noted that in practice, roller compaction may be applied to these types of concrete, and thus, the top surface can be formed.

Fig. 11 depicts a series of acoustic absorption spectra of pervious concrete specimens. Twenty-five-millimeter bulk aggregates (Type 5) stacked up to a height of 15 cm were also included to compare the absorption performances of pervious concrete. It is well known that bulk gravel can act as a rigid acoustic absorption material. The maximum absorption coefficient was close to 1.0, in a specific frequency band (Fig. 11(a)). In contrast, the measured maximum absorption coefficient of pervious concrete was approximately 0.5. The maximum absorption coefficient for this mix proportion obtained through the modeling in [13] (Table 7) was approximately 0.5–0.6, which was in good agreement with the measured values. Moreover, the deviation of the absorption spectra of specimens with identical mix proportions and fabrication method was large. As mentioned above, the two specimens were prepared for this measurement, and the absorption spectra of both specimens were plotted (Fig. 11(b) using the same color). First, the absorption coefficients in the frequency below 1000 Hz varied within 0.2 for the different specimens with the same mix proportion and height. The maximum absorption coefficient for the uneven top surface was approximately 0.6 in the 500–1000 Hz frequency band, and that for the bottom surface with opened pores was approximately 0.7. The deviation of the absorption coefficients within the frequency range below 1000 Hz for both surfaces was 0–0.2.

However, for the bottom surface with closed pores, the maximum absorption coefficient was 0.4 or lower. In other words, this location did not contribute to acoustic absorption. Moreover, the maximum absorption coefficients for the 5 cm high specimens were higher than those for the 15 cm high specimens. The frequency range corresponding to the maximum absorption coefficient decreased with an increase in the pervious concrete height, and this trend was also expected for the simulation [13]. However, the decrease in the maximum absorption coefficients with increasing height of pervious concrete did not correspond to the simulation trend, as it rarely changed. This behavior indicated that the pores in the thicker specimens could be smaller than those in thinner sections. As evaluated through CT scanning (Fig. 7), there might have been some locations where the porosity was lower than in other locations, indicating that the pore networks for acoustic absorption were closed. The pore connectivity is a critical factor that influences acoustic absorption. In relevant construction specifications and standards such as ACI 522R-10, it is recommended that a hand-held straightedge

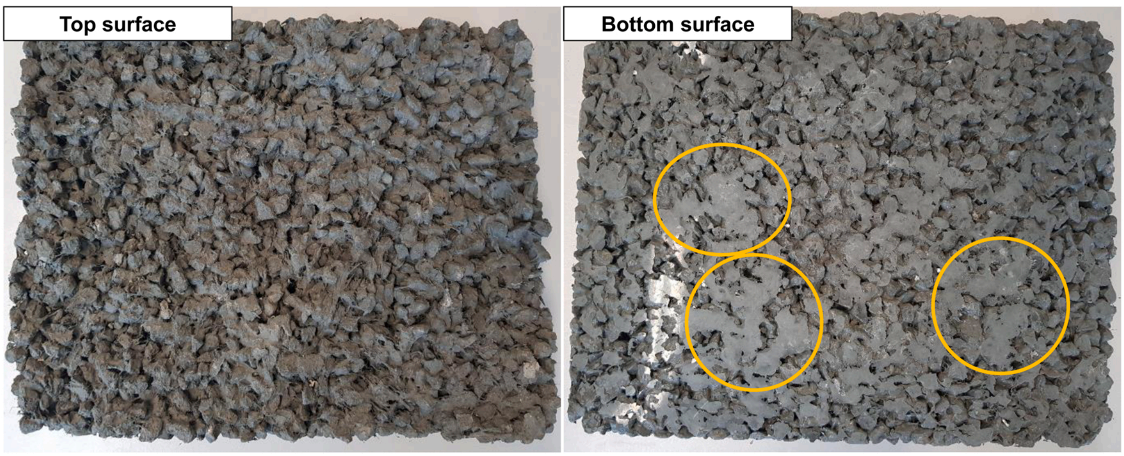


Fig. 10. Top and bottom surfaces of specimens for acoustic absorption measurement.

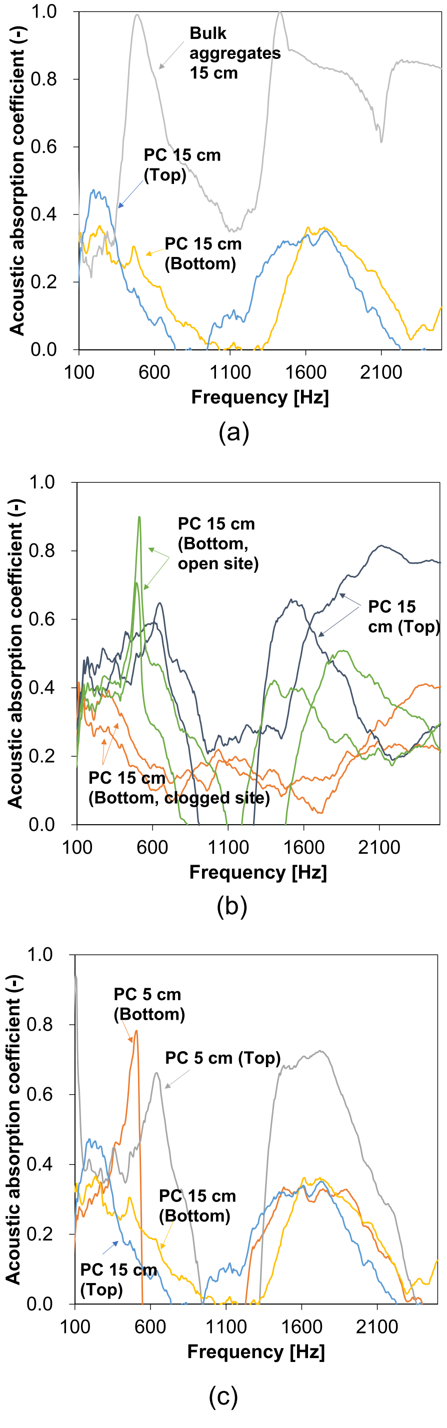


Fig. 11. Variations of acoustic absorption capability with frequency for pervious concrete panels having different thicknesses (PC: pervious concrete) based on (a) bulk aggregate, (b) measurement position, and (c) thickness of specimens.

or vibrating screed should be used to open up pores in pervious concrete pavement. However, this approach is only for securing the water passway, and acoustic absorption is a more delicate property of pervious concrete. Thus, when acoustic absorption is the main property of pervious concrete, it is necessary to establish an adequate fabrication process for achieving uniform porosity.

The absorption coefficients in the frequency range above 1000 Hz, i.e., the secondary peaks, were significantly different, even for specimens produced with the same mix proportion. This is the general behavior for the "resonator-type acoustic absorption material." Therefore, the target frequency band for the acoustic absorption of pervious concrete should be below 1000 Hz.

These results are summarized as follows. Even in the same specimen, the acoustic absorption properties may vary, depending on the surface conditions. This phenomenon becomes more significant when the designed strength of pervious concrete is higher, indicating that the concrete paste volume is also higher. If the wall effect blocks the surface pores, low acoustic absorption of the pervious concrete is expected.

4. Conclusion

This study was aimed to address practical problems faced in the production of structural pervious concrete, such as proper mix proportioning, preventing paste sagging, determining porosity, and obtaining the required strength and acoustic absorption. Pervious concrete mixtures with varying aggregate types, target void ratios, and fiber contents were cast in multiple cylindrical and panel-type specimens to determine the compressive strength, porosity, and acoustic absorption coefficient. Porosity measurements were conducted using the volumetric method and CT scanning. A PU probe was used to measure the acoustic absorption of the panel samples. Based on the experimental results obtained in this study and other studies, a guideline for the mix proportioning of pervious concrete was proposed, considering the compressive strength and acoustic absorption. The main conclusions of this study are as follows:

1. The sagging of cement paste, which was a significant reason for the fluctuation in the properties of pervious concrete, could be controlled by adjusting the fresh paste flow and adding synthetic fibers. The cement paste with a flow of 170 ± 10 mm and the addition of PVA fibers exceeding 0.5 wt%/cement prevented sagging successfully, even after mechanical vibration.
2. The experimental results for pore structures of the pervious concrete through CT scan image processing provided detailed information, such as void distribution to a sample depth and the wall effect on the sample void ratio, which could not be identified using the conventional volumetric method. It was found that the local porosity in the pervious concrete varied over an extensive range.
3. The comparisons between the experimental results obtained in this study and previous studies showed that the cement paste properties did not influence the compressive strength of the concrete as much as the sample porosity. Hence, a nonlinear regression model that predicts the compressive strength of pervious concrete based on porosity data was established. In addition, the large fluctuation of the compressive strength in pervious concrete could induce the porosity fluctuation throughout the sample. The addition of fibers and the application of mechanical vibration were effective in regulating porosity.
4. It was confirmed that the acoustic performance of pervious concrete improves with a larger volume of connected pores, which weakens the compressive strength. A minimum target void ratio of 10% was required to create sufficient open pores for good acoustic absorption and structural compressive strength higher than 20 MPa. Moreover, a sample with a particular porosity could exhibit different acoustic absorption properties, depending on the surface properties. Therefore, the wall effect significantly influences sound absorption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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