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Acoustic absorption modeling of porous concrete considering the gradation and shape of aggregates and void ratio

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ABSTRACT

The results of acoustic absorption modeling of porous concrete considering the gradation and shape of aggregates and void ratio are presented. To model the void texture of porous concrete, the multi-layered micro-perforated rigid panel model considering air gaps [1,2] is adopted. The parameters used in this acoustic absorption modeling are determined by a geometrical and experimental approach considering the gradation and shape of aggregates and void ratio. The predicted acoustic absorption spectra are compared with experimental results to verify the proposed acoustic absorption modeling approach. Finally, a parametric study is conducted to investigate the influence of design factors on the acoustic absorption properties of porous concrete.

1. Introduction

Porous concrete is a rigid acoustic absorbing material containing large voids (pores) that have been intentionally fabricated for acoustic absorption or permeation [3]. Although cellular concrete is also an acoustic absorbing material, porous concrete is a more widely applicable material owing to its excellent mechanical properties and durability compared to cellular concrete [3]. The noise energy that propagates in interconnected voids of porous concrete is dissipated via conversion to heat as a result of refraction and interference occurring inside the void texture [4].

Numerous researchers have investigated noise abatement characteristics of porous concrete and their applications in civil engineering fields [5–9]. Porous concrete is applied for sound barriers or pavements to absorb traffic (tire) noise and reduce sound wave reflection. In terms of acoustic engineering, porous concrete can be considered as a rigid frame porous medium [10]. Theoretically, the sound absorption properties of a rigid frame porous medium is mainly influenced by its void texture and thus the main focus of modeling is to determine the generalized void texture [11].

Since porous sound absorbing materials, such as polyurethane, fabrics, formed metal, etc., have irregular inner texture (structure), most sound propagation models for these materials have been developed using a phenomenological approach [12].

In classical (phenomenological) models, the acoustic parameters (e.g., flow resistivity, tortuosity) were measured and then applied into a certain sound propagation equation. Attenborough [13] developed models for acoustic absorption properties of granular materials with this approach. In addition, Attenborough [14] predicted the acoustic impedance of grass-covered ground by introducing the concept of 'a grain shape factor'. Johnson et al. [15] derived a fundamental acoustic model for rigid porous media. Stinson and Champoux [16] reported a theoretical model, appropriate for materials containing pores of uniform cross section that correctly predicts the low- and high-frequency behavior. Allard [12]

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proposed a generalized concept of acoustic parameters considering the geometry of microscopic frame structure. Horoshenkov and Swift [17] developed a model for the prediction of the acoustic properties of porous granular media with some assumed pore geometry and pore size distribution. It should be noted that measurement of acoustic parameters and/or solving complicated equations are generally required for the aforementioned models.

Considering tolerant errors of acoustic absorption spectra, models with high complexity are less applicable to civil engineering fields, including porous concrete as a sound absorber. The simple and easy model without considering the acoustic parameters, thus, is more preferred for civil engineering applications. For example, Neithalath et al. [10] applied 'aperture and pore model' for porous concrete in conjunction with the geometrical simplification method proposed by Lu et al. [18]. The aperture and pore model is based on the theory of a micro-perforated panel absorber, proposed by Maa [19], where air cavities with uniform shapes (same diameter and depth) are considered. The acoustic impedance of porous concrete was derived simply by measuring the dimension of inner texture (not by measuring the acoustic parameters) in their model [10].

On the other hand, design factors, such as the target void ratio (TVR), gradation and shape of aggregates that is derived by subtracting the volume ratio of cement paste from the void content of aggregates, affect the void texture of porous concrete [11,20–23]. Upon this background, acoustic absorption modeling of porous concrete that considers the aforementioned design factors is proposed in the present study. This study also focuses on the geometrical simplification method considering the design factors to develop a model capable of modeling the porous concrete having irregular inner texture. This modeling concept originates from the 'perforated panel model' and the aforementioned 'aperture and pore model' where acoustic absorption occurs due to viscous losses and thermo-elastic damping during the propagation of sound waves through air cavities in the medium [24,25]. The multi-layered micro-perforated rigid panel model considering air gaps [1,2] is adopted to model the void texture of porous concrete. The parameters used in the acoustic absorption modeling are systematically determined by a geometrical and experimental approach considering the void ratio, gradation and shape of aggregates. The predicted acoustic absorption spectra are compared with experimental data to verify the proposed model. Finally, a parametric study is conducted to investigate the influence of design factors on the acoustic absorption properties of porous concrete.

The main concern of the present study is the absorption characteristics of porous concrete in case the vertical incidence acoustic wave has occurred. Many other types of noise, including the rolling noise of vehicles or impact noise with high sound pressure considering random incidence acoustic waves, also need to be considered when designing porous concrete used as an acoustic wall. However, this issue is beyond the scope of the present work, nevertheless, it should be subject of future work for developing more versatile acoustic absorption models for porous concrete.

2. Acoustic absorption modeling

2.1. Model description

Porous concrete can be considered as a stacked assemblage of sphere-shaped aggregates as shown in Fig. 1. The arrangement of aggregates naturally forms a uniform lattice. This lattice consists of perforated panels formed by the aggregates layer and air gaps between panels. The arrangement of aggregates may affect the thickness of an air gap. The 'multi-layered perforated panel model' incorporating air gaps (Fig. 2), proposed by Kang and Fuchs [1], is adopted in this study to model the void texture of porous concrete.

This model is usually used for the acoustic absorption modeling of regular shaped perforated materials, such as the multi-layered perforated membrane and acoustic perforated panel. However, Wang and Lu [25] reported that this acoustic absorption modeling approach could also be used for the acoustic absorption modeling of irregular shaped porous materials such as formed metals. As shown in the figure, perforated panels are stacked following the direction of sound wave propagation, the bottom of the model is assumed as a rigid wall that reflects sound waves perfectly, and numerous cylindrical apertures that model air cavities are included in the perforated panels. The diameters of apertures, thicknesses of air gaps and panels, and perforated area ratio (perforated ratio) are assumed to be uniform in this study for simplicity.

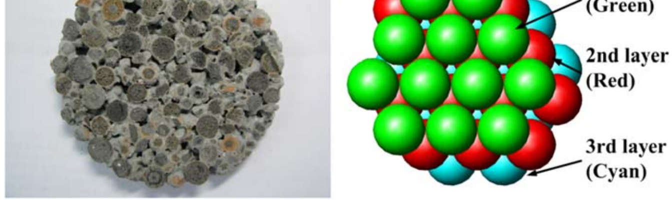

Fig. 1. (a) A typical cross section of porous concrete; (b) the scheme of stacked aggregates (packed lattice).

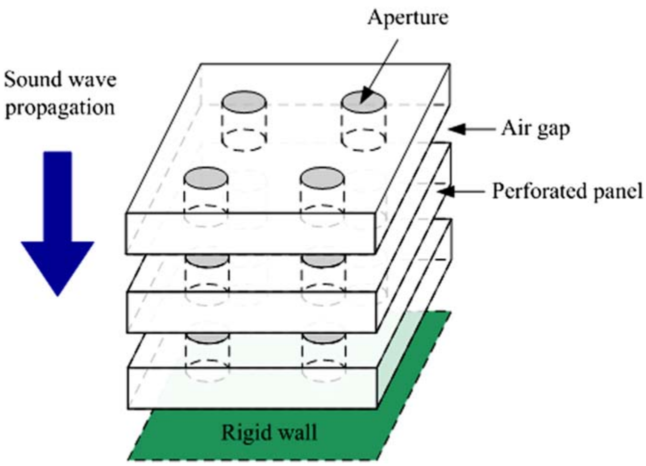

Fig. 2. Multi-layered perforated panel model for porous concrete (cf. [1]).

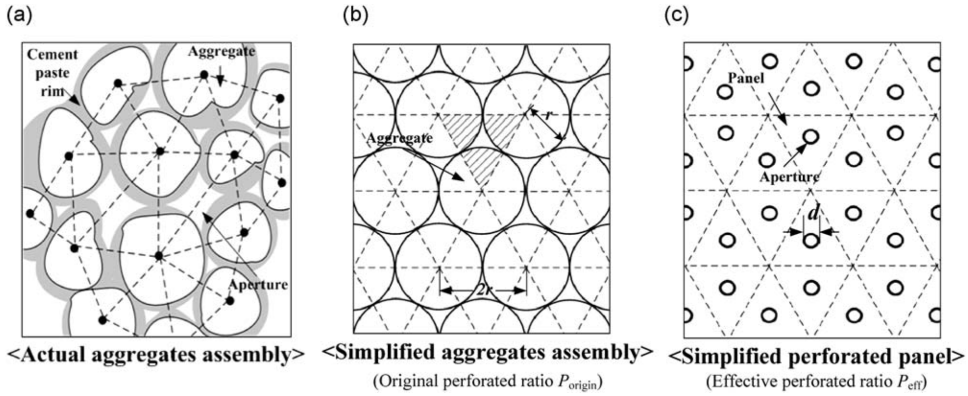

Fig. 3. Schematics to determine the diameter of apertures and effective perforated ratio.

2.2. Parameters used in acoustic absorption modeling

The parameters used in the acoustic absorption modeling include the diameter of apertures (d), effective perforated ratio (P_{eff}), thicknesses of panels (t_{panel}) and air gaps (t_{air}). These parameters are related with the gradation and shape of aggregates and target void ratio. The sagging of cement paste is not considered in this study.

Schematics to determine the diameter of apertures and effective perforated ratio are illustrated in Fig. 3. As shown in Fig. 3(a), aggregates are covered by thin cement paste rims and adhere to neighboring aggregates. Apertures are formed among the assembly of aggregates. The shape of apertures can be determined by the gradation and shape of aggregates and thickness of cement rims which are related to the target void ratio.

It is difficult to define the relation between the cement binder and void ratio in porous concrete because of water absorption on the surface of aggregate, total surface area, shape of aggregates, micropores generated in the cement binder, and sagging of cement binder. Instead of a rigorous model considering the amount of cement binder or thickness of cement rims, a simple two-step transformation process is proposed in this study to determine the diameter of apertures (t_{air}) and effective perforated ratio (P_{eff}), which is the function of target void ratio affecting cement binder contents, and gradation and shape of aggregate, for simplicity.

First, the actual aggregates assembly (Fig. 3(a)) is transformed to the simplified aggregates assembly (Fig. 3(b)), where the radius of aggregates (r) is assumed to be the average gradation of aggregates and an aggregate is assembled with surrounding six aggregates forming a hexagonal arrangement (Step I). The original perforated ratio (P_{origin}) in Fig. 3(b) can be defined as

$$P_{\text{origin}} = \frac{\text{(Area of a triangle)} - \text{(Area of three hatched sectors)}}{\text{(Area of a triangle)}} = \frac{\left(\sqrt{3}r^2 - \dfrac{\pi}{2}r^2\right)}{\sqrt{3}r^2} \simeq 9.31 \text{ percent} \tag{1}$$

Note that the original perforated ratio defined in Eq. (1) is independent of the gradation and shape of aggregates, and the simplified aggregates assembly model cannot consider the shape of apertures and thickness of cement rims. A modified perforated ratio, so called effective perforated ratio (P_{eff}), is thus newly suggested in this acoustic absorption modeling.

The simplified aggregates assembly is further transformed to the simplified perforated panel as shown in Figs. 3(b) and (c) to incorporate the effects of gradation of aggregates and target void ratio into the acoustic absorption modeling (Step II). As the original perforated ratio (P_{origin}) can be considered as a reference for determining the effective perforated ratio (P_{eff}), P_{eff} is suggested to be related with P_{origin} as

$$P_{\text{eff}} = mP_{\text{origin}} \tag{2}$$

where the detail of determination of the parameter m can be found in Section 2.3.

Marolf et al. [11] reported that the diameter of apertures (or pore diameter) is related with the gradation of aggregates. The diameter of apertures (d) is accordingly assumed to be a function of the average gradation of aggregates as

$$d = d_1 r + d_2 \tag{3}$$

where the detail of determination of the parameters d_1 and d_2 can also be found in Section 2.3.

The thicknesses of perforated panels and air gaps are mainly affected by the gradation and shape of aggregates. Schematics to determine the thicknesses of perforated panels and air gaps are shown in Fig. 4. The layer composed of aggregates as shown in Fig. 1(b) can be stacked as presented in Fig. 4. The thickness of the panel (t_{panel}) is determined as the height between the top position of 1st layer (painted by cyan) and the bottom position of 3rd layer (painted by green) as shown in Fig. 4(a). Even though the lattice is changed, the thickness of the panel is fixed. The height between the center of 1st layer and 2nd layer is $2\sqrt{6}r/3$, so that the thickness of the panels (t_{panel}) in Figs. 4(a) and (b) is given by

$$t_{\text{panel}} = 2\left(\frac{2\sqrt{6}}{3} - 1\right) r \simeq 1.266r \tag{4}$$

As shown in Fig. 4(a), the thickness of air gaps of packed lattice is the height between the bottom position of 2nd layer and top position of 1st layer. Also, the thickness of air gaps of rhombic lattice is twice thicker than that of packed lattice, as illustrated in Fig. 4(b). Thus, the thickness of air gaps (t_{air}), which is related with the shape of aggregates (the κ value) and the thickness of the panels, can be expressed as

$$t_{\text{air}} = \kappa\left(r - \frac{t}{2}\right) \simeq 0.367\kappa r \tag{5}$$

where κ=1.0 in the case of a packed lattice and κ=2.0 in the case of a rhombic lattice. Since the ellipsoid-shaped normal aggregates is generally less compacted than sphere-shaped aggregates (κ=1.0), κ=1.1 in the case of ellipsoid-shaped normal aggregates.

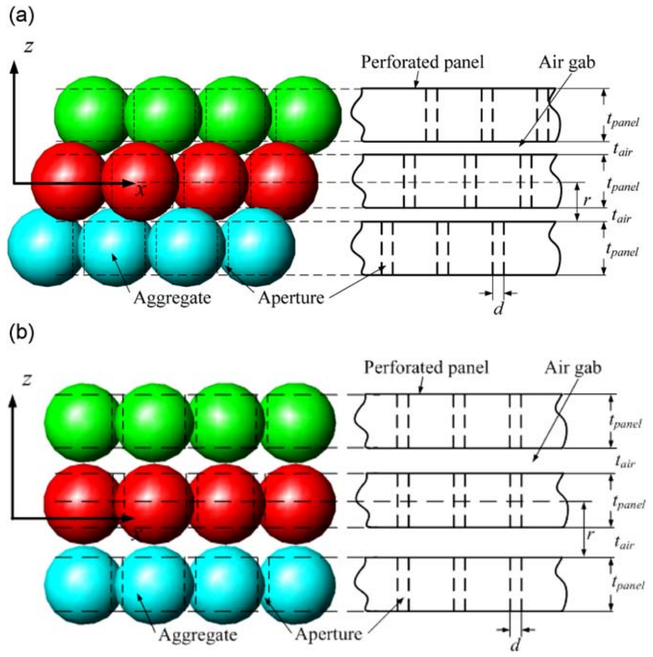

Fig. 4. Schematic to determine the thicknesses of perforated panels and air gaps: (a) packed lattice; (b) rhombic lattice.

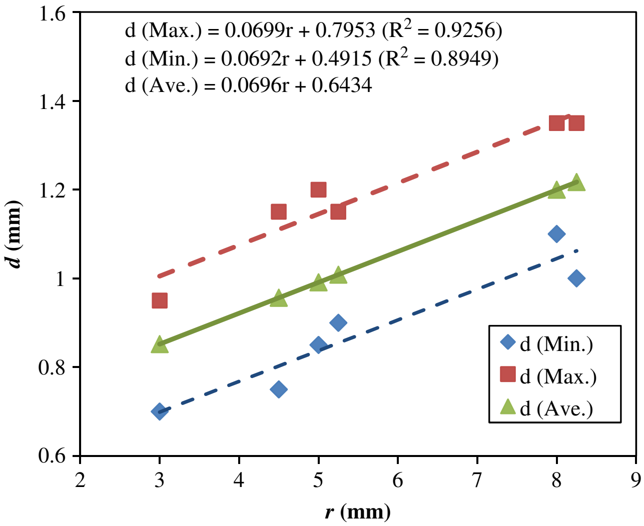

Fig. 5. Relationship between the average gradation of aggregates r and the diameter of apertures d determined by a fitting process.

2.3. *Determination of aperture diameter and effective perforated ratio*

A comparison study between the measured and calculated acoustic absorption spectra is carried out to establish guidelines for the determination of the diameter of apertures (d) and effective perforated ratio (P_{eff}). Experimental data [20–22] considering various thicknesses of specimens, gradations and shapes of aggregates and target void ratios are compared with the present calculation. All values of the diameter of apertures and effective perforated ratio used in Section 3 follow these guidelines.

The diameter of apertures is determined through a fitting process in accordance with the maximum absorption coefficient at the first peak because the diameter of apertures is mainly affected by the maximum absorption coefficient. The acceptable gap between calculated and measured data of acoustic absorption coefficient is determined to be in the range of ± 0.1. Fig. 5 shows the predicted relationship between the average gradation of aggregates and diameter of apertures. Accordingly, the parameters d_1 and d_2 in Eq. (2) can be determined as

$$d = 0.070r + 0.643 \tag{6}$$

Note that Eq. (6) can be used to determine the diameter of apertures of both specimens with irregular ellipsoidal and spherical aggregates.

Fig. 6 shows the relationship between the target void ratio and the factor m which is related with the effective perforated ratio P_{eff}. Alternatively, the factor m can be determined through a fitting process in accordance with the peak frequency. An exponential function is adopted in this study to determine the parameter m since the error of a linear function is higher than that of an exponential function. The acceptable gap between calculated and measured data of peak frequency is determined to be in the range of ± 100 Hz for different thicknesses of specimens. The factor m is given by

$$m = 0.106\mathrm{e}^{0.084\,V_{\mathrm{target}}} \pm 0.121 \tag{7}$$

where V_{target} denotes the target void ratio in percentage. Note that Eq. (7) can be used irrespective to the gradation and shape of aggregates. The value of factor m determined from Eq. (7) is used for all the calculated acoustic absorption spectra in this study.

The porous concrete is applied as a sound absorber (e.g., sound barrier) used for reducing the reflected traffic noise [26]. Since the maximum absorption coefficients and the peak frequencies of the same specimen may have tolerant errors around ± 0.1 and ± 100 Hz, respectively [20], the tolerant errors of acoustic absorption spectra of porous concrete within these ranges are assumed to be negligible in this study.

2.4. *Electro-acoustic analogy*

The acoustic absorption spectra of a material can be determined by its acoustic impedance. The acoustic impedance of a multi-layered perforated panel model is derived from the electro-acoustic analogy proposed by Zwikker and Kosten [27] and Zhu and Huang [2], shown in Fig. 7. In the figure, R_a and M_a denote the specific acoustic resistance (the real component of the acoustic impedance of apertures) and reactance (the imaginary component of the acoustic impedance of apertures) of a perforated panel, respectively [1,10]; and $Z(t_{\mathrm{air}})$ signifies the impedance of an air gap between two panels or between a

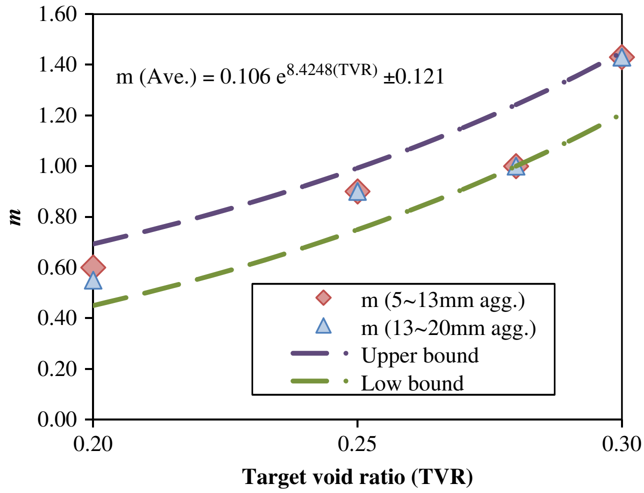

Fig. 6. Relationship between the target void ratio and the factor m determined by a fitting process.

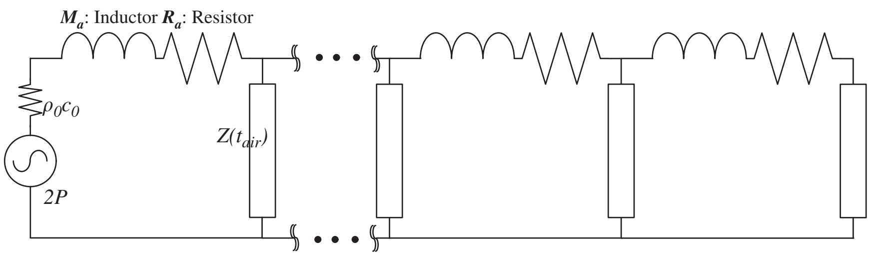

Fig. 7. Electro-acoustic model redrawn from Maa [19].

panel and the rigid wall [10]. Since thermal effects on the acoustic wavenumber is very small in the case of rigid framed porous materials [28], they are neglected in the acoustic absorption modeling. Further details on the electro-acoustic analogy can be found in Maa [19] and Zhu and Huang [2].

Prior to calculation of the impedance of the simplified perforated pane model, the impedance of apertures and air gaps need to be defined. The impedance of apertures is defined as [19].

$$Z_a = j\omega\rho_0 t_{\text{panel}}\left[1-\frac{2}{\sqrt{-j}\beta}\frac{J_1(\sqrt{-j}\beta)}{J_0(\sqrt{-j}\beta})\right]^{-1} \tag{8}$$

where $j=\sqrt{-1}$; ρ_0 and ω are the density of air (1.20 kg/m^3) and the angular frequency of a sound wave, respectively; J_0 and J_1 are cylindrical Bessel functions; and $\beta = d/2\sqrt{\omega\rho_0/\eta}$ in which the dynamic viscosity of air η=1.79 $\times$ 10^{-5} kg/(m s) is the acoustic Reynolds number that refers to a non-dimensional parameter for the quotient of the stresses caused separately by sound pressure and viscosity [19].

In the case of large diameter apertures or high-frequency (such that $\beta > 10$), Eq. (8) can be simplified as [19]

$$Z_a \simeq \frac{8\eta t_{\text{panel}}\beta}{\sqrt{2}d^2} + j\left(\omega\rho_0 t_{\text{panel}} + \frac{8\eta t_{\text{panel}}\beta}{\sqrt{2}d^2}\right) \tag{9}$$

In the case of intermediate range of β ($1<\beta<10$), Eq. (8) can be simplified as [19]

$$Z_a \simeq \frac{32\eta t_{\text{panel}}}{d^2}\sqrt{1+\frac{\beta^2}{32}} + j\omega\rho_0 t_{\text{panel}}\left(1+\frac{1}{\sqrt{9+\dfrac{\beta^2}{2}}}\right) \tag{10}$$

Since the diameter of apertures used in this study is ranged from 0.8 to 1.2 mm, the corresponding β value varies from 0 to 17 in a frequency range of 0–2000 Hz. In fact, Eq. (10) is commonly used by many researchers even when $\beta > 10$ [10,19,25]. The end effect also needs to be considered in the modeling of the acoustic impedance of apertures [18,19].

The acoustic impedance of apertures considering the end effect is given by [18,19]

$$Z_a = R_a + jM_a \tag{11}$$

with

$$R_a = \frac{32\eta t_{\text{panel}}}{d^2}\left(\sqrt{1+\frac{\beta^2}{32}} + \sqrt{\frac{\beta d}{4t_{\text{panel}}}}\right) \tag{12}$$

$$M_a = \omega\rho_0 t_{\text{panel}}\left(1 + \frac{1}{\sqrt{9+\frac{\beta^2}{2}}} + 0.85\frac{d}{t_{\text{panel}}}\right) \tag{13}$$

From Eq. (11), the impedance of a perforated panel z_a reads

$$z_a = \frac{Z_a}{P_{\text{eff}}} \tag{14}$$

The impedance of an air gap between two panels in the case of $\omega t_{\text{air}}/c_0 \ll 1$ is defined as [19]

$$Z(t_{air}) = -j\rho_0 c_0 \cot\left(\frac{\omega t_{\text{air}}}{c_0}\right) \simeq -j\frac{\rho_0 c_0^2}{\omega t_{\text{air}}} \tag{15}$$

where c_0 is the speed of sound in air (c_0=340 m/s).

The impedance of a unit layer Z_1 consisting of a panel and an air gap can be expressed as [19]

$$Z_1 = z_a + Z(t_{\text{air}}) \tag{16}$$

Accordingly, in the case of a series of n stacked layers, the impedance of the system can be calculated as [18]

$$Z_n = z_a + \frac{Z_{n-1}Z(t_{\text{air}})}{Z_{n-1} + Z(t_{\text{air}})} \tag{17}$$

Finally, the acoustic absorption coefficient α of a multi-layered panel system can be expressed as [18]

$$\alpha = \frac{4R/\rho_0 c_0}{(1+R/\rho_0 c_0)^2 + (M/\rho_0 c_0)^2} \tag{18}$$

where R and M are the real and imaginary components of Eq. (17), respectively.

3. Experimental comparison

3.1. Overview

A comparison between the calculated and (experimentally) measured acoustic absorption spectra of porous concrete is made in this section to verify the proposed acoustic absorption modeling approach. For verifying the appropriateness of the present modeling with respect to the gradation and shape of aggregates, a set of measurement data from our preceding work [20] are used. Porous concrete specimens in our preceding work [20] were cast using two different types of single sized aggregates: (1) normal crushed aggregates of 8–13 and 13–19 mm and (2) lightweight aggregates (expanded shale) of 4–8, 8–12 and 12–19 mm. The normal crushed aggregates shaped irregular ellipsoids, while the lightweight aggregates shaped spheres as shown in Fig. 1 of Kim and Lee [20]. The target void ratio of the specimens was fixed to be 28 percent, and the acoustic absorption coefficients of the specimens with various thicknesses (30, 50, 70, and 100 mm) were measured using an impedance tube in accordance with the ISO 10534-2 specification (''Determination of sound absorption coefficient and impedance in impedance tubes—Part 2: Transfer-function method'') [20]. Further details on the specimen preparation can be found in Kim and Lee [20].

For verifying the appropriateness of the present modeling with respect to the target void ratio, the measurement data by Park et al. [21] and Kim [22] are used. Porous concrete specimens in their experiments were cast using single sized normal crushed aggregates of 5–13 mm. The target void ratios of the specimens in their experiments were 20, 25 and 30 percent, and the acoustic absorption coefficients of the specimens were measured using an impedance tube following the KS F 2814-1 specification which is equivalent to the ISO 10534-2 specification ([21]; Kim, [22]. Further details on the specimen preparation can be found in Park et al. [21] and Kim [22].

3.2. Preliminary experimental comparison

In general, porous concrete (or formed metals) specimens are wrapped with a viscoelastic film or a viscoelastic thin layer during the measurement of the acoustic absorption coefficient using an impedance tube in order to prevent

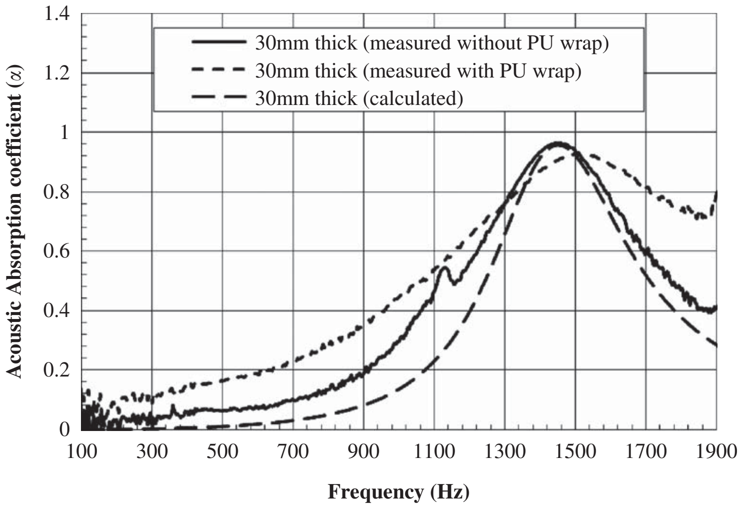

Fig. 8. Comparison of calculated and measured [20] acoustic absorption spectra (r=5.25 mm, d=1.01 mm, κ=1.1, m=1.00).

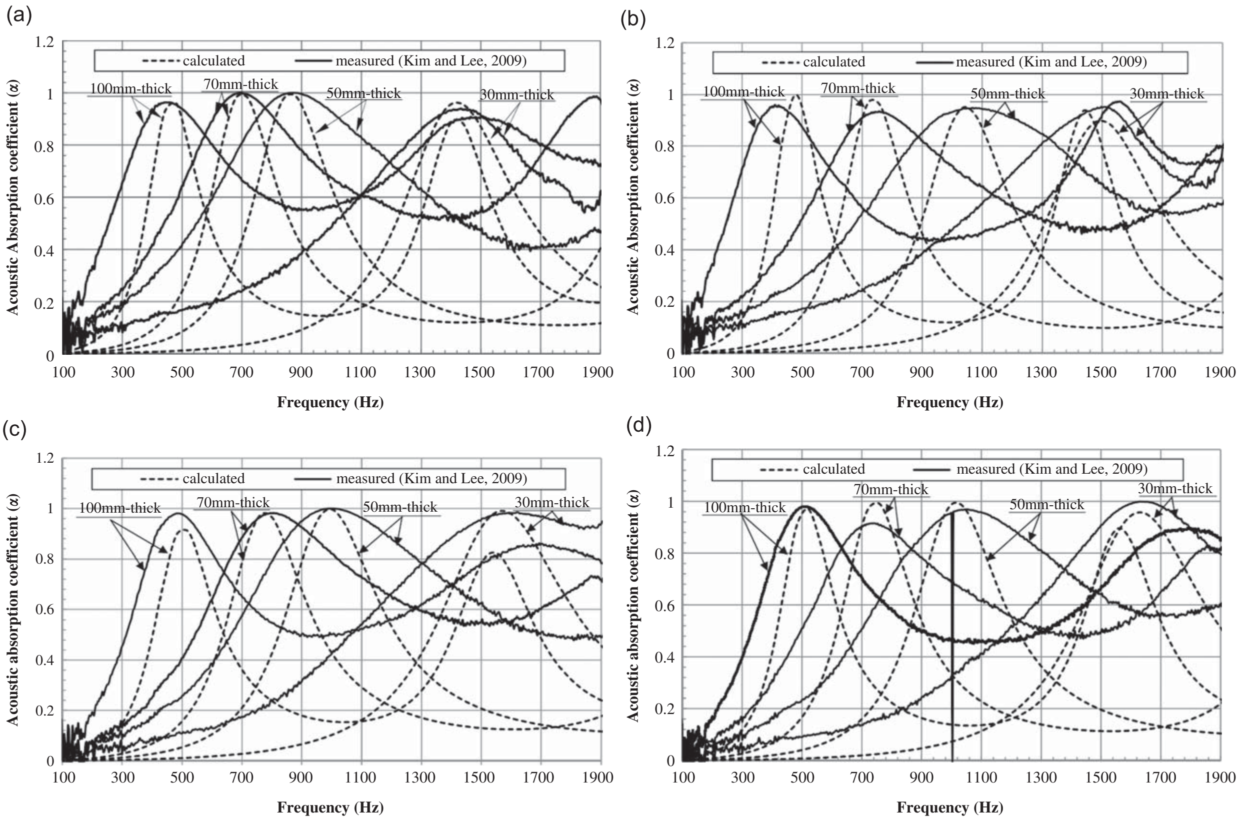

Fig. 9. Comparison of calculated and measured [20] acoustic absorption spectra: (a) r=5.25 mm, d=1.01 mm, κ=1.1, m=1.00; (b) r=8 mm, d=1.20 mm, κ=1.1, m=1.00; (c) r=3 mm, d=0.85 mm, κ=1.0, m=1.00; (d) r=5 mm, d=0.99 mm, κ=1.0, m=1.00.

scratching of the inner wall of the tube [20]. It has been noted in the literature that this may affect the measurement results of the acoustic absorption properties of materials while specimens are wrapped [20]. A preliminary experimental comparison is made to investigate the influence of the wrap on the acoustic absorption by comparing the calculated acoustic absorption spectra with the experimentally obtained acoustic absorption spectra of specimens with and without a polyurethane wrap reported by Kim and Lee [20]. As shown in Fig. 8, the calculated peak frequency and maximum absorption coefficient are shown to be nearly the same as the measured peak frequencies and maximum absorption coefficients of the specimens with and without the wrap. Since only the maximum acoustic absorption coefficient and peak frequency are needed in acoustic absorption modeling of a resonant acoustic absorber (e.g., porous concrete), the influence of the wrap on the specimens on the acoustic absorption is ignored in the present modeling.

3.3. Experimental comparison with respect to the effect of aggregate gradation and shape

Figs. 9(a)–(d) show a comparison between the calculated and measured [20] acoustic absorption coefficients of specimens with various thicknesses (30, 50, 70, and 100 mm) and various gradation of aggregates. The measured acoustic absorption coefficients of specimens made of normal crushed aggregates (irregular ellipsoid-shaped, κ=1.1) and lightweight aggregates (sphere-shaped, κ=1.0) are also compared with the calculated values in Figs. 9(a)–(d). In order to investigate the effect of gradation of aggregates, various *r* values are used. The diameter of apertures d is determined in accordance with *r* value as explained in Section 2.3.

As shown in Figs. 9(a)–(d), the calculated and measured maximum absorption coefficients at the first peak and the corresponding peak frequencies of all the specimens show a good agreement each other. A good agreement between the calculated and measured maximum acoustic absorption coefficients at the second peak is observed with only the 100 mm-thick specimen. Overall, the first peak frequency is shown to decrease as the thickness of specimen increases, which corresponds to the findings from Neithalath et al. [10].

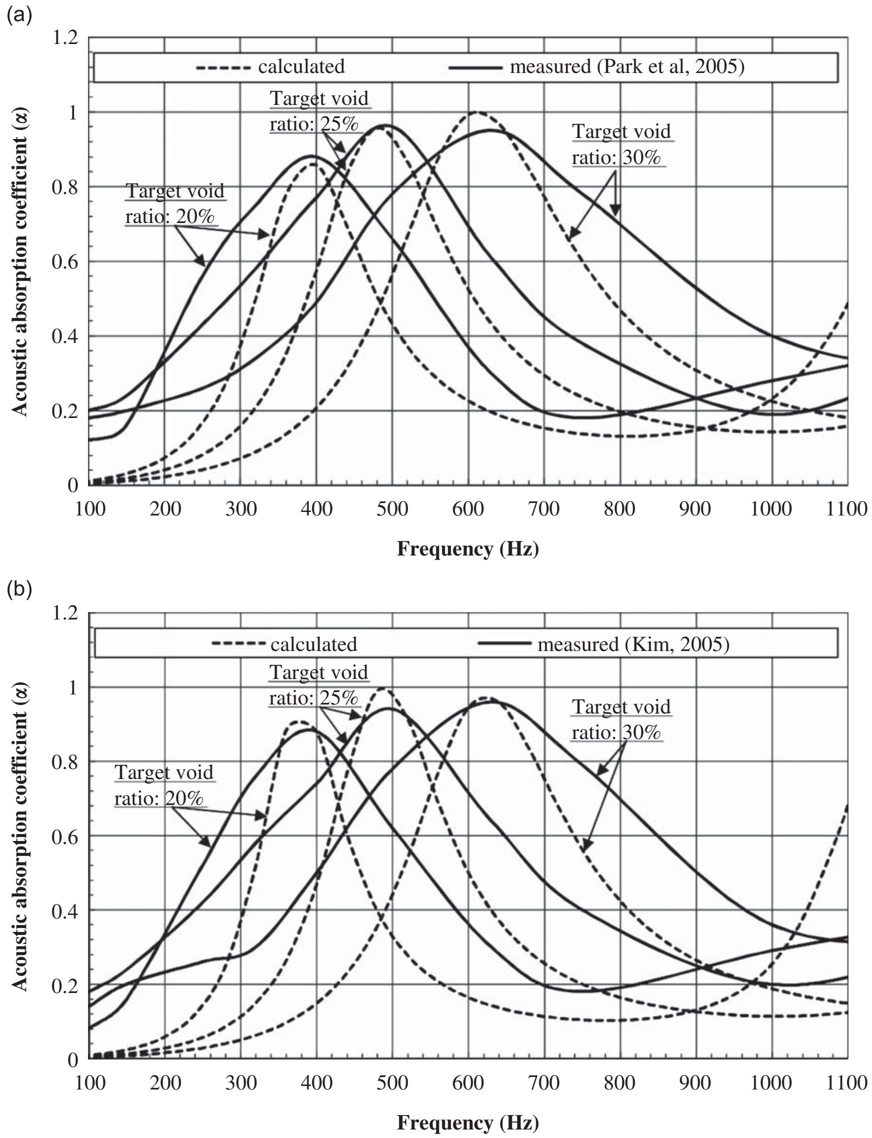

Fig. 10. Comparison of calculated and measured [21,22] acoustic absorption spectra: (a) r=4.5 mm, d=0.96 mm, κ=1.1, thickness of specimen: 100 mm; (b) r=8.25 mm, d=1.22 mm, κ=1.1, thickness of specimen: 100 mm.

It is also noted that the difference between the calculated and measured absorption coefficient and peak frequency increases as the gradation of aggregates increases, despite the target void ratio of the specimens remains the same. The detailed mechanism corresponding to this phenomenon is explained in our preceding work [20].

3.4. Experimental comparison with respect to effect of target void ratio

Figs. 10(a) and (b) show a comparison between the calculated and measured [21,22] acoustic absorption coefficients of specimens with various target void ratios. Only the value of the parameter m, which is related with the effective perforated ratio, is varied in order to investigate the effect of the target void ratio on the acoustic absorption.

The calculated acoustic absorption spectra of specimens made of aggregates of 5–13 mm and 13–20 mm shows a good agreement with the experimental data [21,22] over the entire frequency range at the maximum absorption coefficients and the peak frequencies. The calculated and measured maximum absorption coefficients and the peak frequencies of the 100 mm-thick specimen show a good agreement each other.

4. Parametric study

4.1. Aggregate gradation sensitivity to the acoustic absorption spectra

In this subsection, aggregate gradation sensitivity to the acoustic absorption spectra is studied. The target void ratio is fixed as 28 percent (m=1.0, P_{eff}=9.31 percent), and only irregular ellipsoid-shaped, normal crushed aggregates (κ=1.1) are considered in this subsection.

As shown in Fig. 11, the acoustic absorption spectra are not sensitive to the variation of aggregate gradation. This phenomenon can also be found from the experimental observation of Park et al. [21], Kim [22], and Kim and Lee (2005). It is shown from Figs. 11 and 12 that the gradation of aggregates mainly affects the maximum acoustic absorption coefficient, but does not substantially influence the peak frequency. Both the first and second maximum absorption coefficients gradually reach 1.0 and thereafter decrease as the gradation of aggregates increases. It can be concluded that aggregates of around 10–20 mm would be the most effective for the fabrication of porous concrete with high acoustic absorption properties. However, the accuracy of the current acoustic absorption modeling decreases when using aggregates with large gradation or blended with other size aggregates.

4.2. Target void ratio sensitivity to the acoustic absorption spectra

In this subsection, target void ratio sensitivity to the acoustic absorption spectra is investigated. Only irregular ellipsoid-shaped aggregates of 4–8 mm (κ=1.1, r=3) are considered in this subsection.

When the target void ratio is higher than 35 percent, the absolute volume ratio of normal aggregates is around 50–60 percent and the amount of cement paste in specimens is around 5–15 percent. The strength of the specimens becomes way low due to an insufficient amount of cement paste (binder). When the target void ratio is lower than 10 percent, the acoustic absorption properties of specimen decreases due to the sagging of the cement paste and increase of the closed void ratio. From this rheological viewpoint, porous concrete with a target void ratio less than the critical void ratio is not

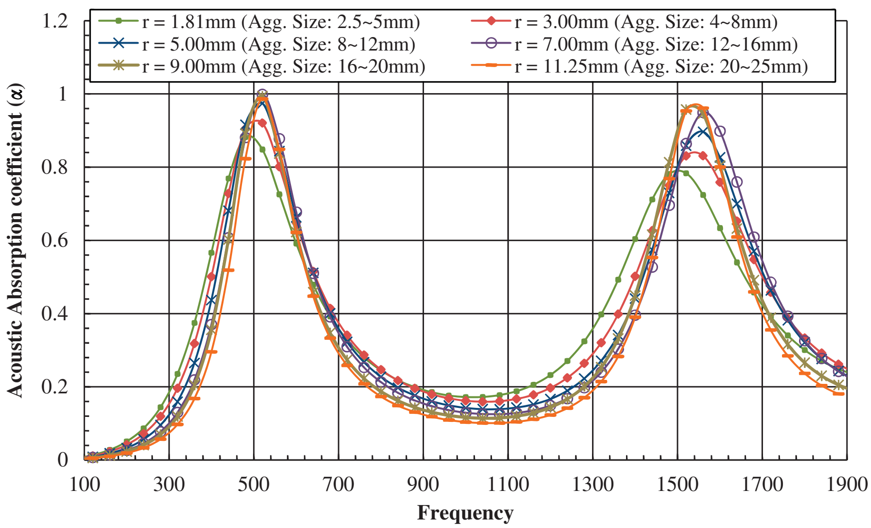

Fig. 11. Calculated acoustic absorption spectra considering variation of aggregates size (κ=1.1, m=1.00).

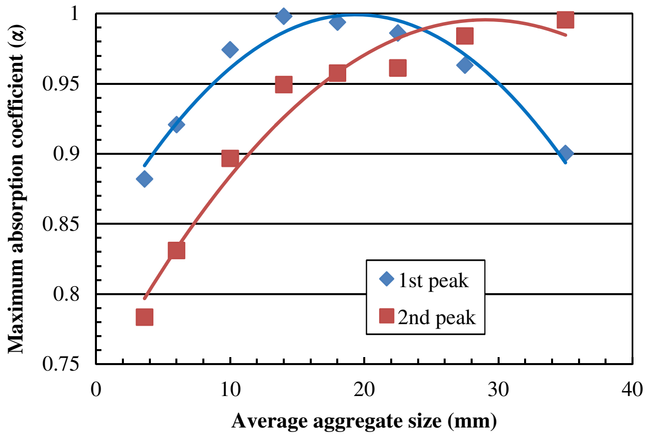

Fig. 12. Variation of the maximum absorption coefficients as a function of the average aggregate size (κ=1.1, m=1.00).

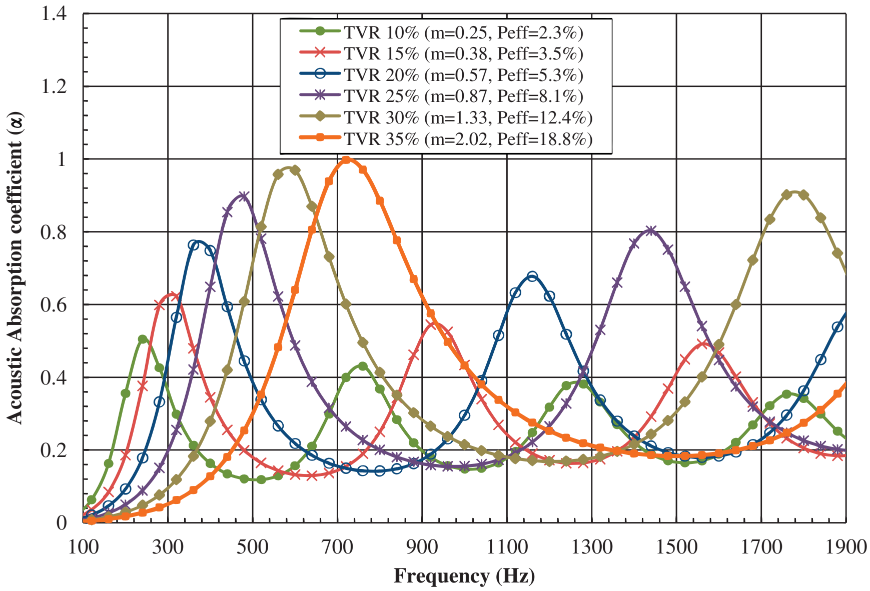

Fig. 13. Calculated acoustic absorption spectra considering variation of target void ratio (r=3 mm, d=0.85 mm, κ=1.1).

expected to provide desired acoustic absorption properties. The critical void ratio of the funicular first range (limit line of existence of interconnected voids) is 8.89 percent in the case of a rhombic lattice [23].

As shown in Fig. 13, the acoustic absorption spectra are shown to be affected by the target void ratio. As the target void ratio increases, the maximum acoustic absorption coefficient and peak frequency decrease increase. This tendency is more clearly seen at the second peak than at the first peak.

Fig. 14 shows the variation of the maximum (peak) acoustic absorption coefficient as a function of the target void ratio. It is seen from the figure that the value of the maximum acoustic absorption coefficient increases as the target void ratio increases, and the acoustic maximum absorption coefficient reaches 1.0 as the target void ratio exceeds 30 percent.

Fig. 15 shows the variation of the peak frequency as a function of the target void ratio. The second peak frequencies are shown to be more dramatically increased as the target void ratio increases. It can be concluded that the target void ratio is an important design factor affecting the acoustic absorption characteristics of porous concrete.

4.3. Sensitivity of air gaps to the absorption spectra

In this subsection, sensitivity of air gaps between perforated panels to the absorption spectra is studied. As shown in Fig. 16, the acoustic absorption spectra are not significantly affected by the value of κ, which is related with the thickness of

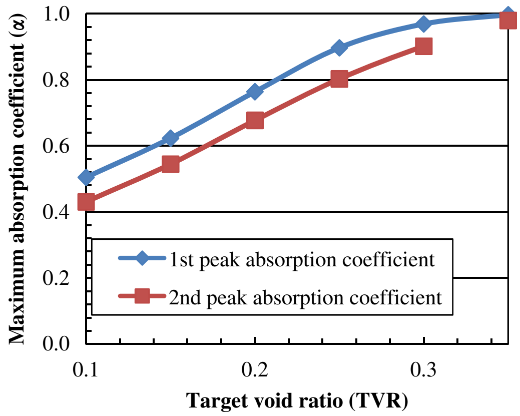

Fig. 14. Variation of the maximum absorption coefficients as a function of the target void ratio (r=3 mm, d=0.85 mm, κ=1.1).

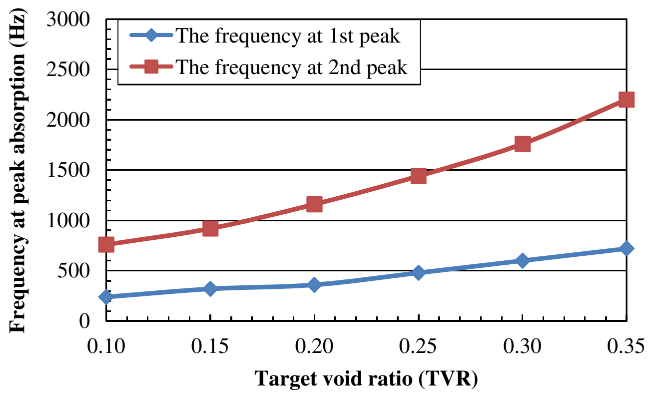

Fig. 15. Variation of peak frequencies as a function of the target void ratio (r=3 mm, d=0.85 mm, κ=1.1).

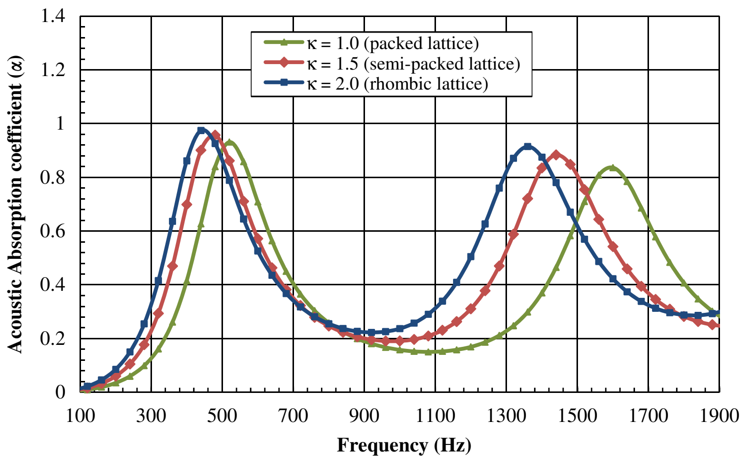

Fig. 16. Calculated acoustic absorption spectra considering the thickness of the air gap between two perforated panels (r=3 mm, d=0.85 mm, m=1.00).

air gaps. When κ increases from 1.0 to 2.0, the increase in maximum acoustic absorption coefficient is less than 0.10 at both the first and second peaks. Since the shape of aggregates is generally an ellipsoid (not rod-like) and porous concrete specimens are in general well compacted, κ of 1.0–1.1 would be reasonable to be used in acoustic absorption modeling of porous concrete.

5. Concluding remarks

The results of a series of acoustic absorption modeling of porous concrete have been presented. The modeling takes into consideration design factors such as the gradation and shape of aggregates and void ratio. To model the void texture of porous concrete, the multi-layered micro-perforated rigid panel model considering air gaps [1,2] is adopted. The parameters used in the acoustic absorption modeling are determined by a geometrical and experimental approach considering the gradation and shape of aggregates and target void ratio. The predicted acoustic absorption spectra are compared with experimental results to verify the proposed acoustic absorption modeling approach. Finally, a parametric study is conducted to investigate the influence of design factors on the acoustic absorption properties of porous concrete. The following conclusions have been drawn.

(1) Overall, the calculated acoustic absorption spectra show a good agreement with experimental data reported by a number of researchers.
(2) The gradation of aggregates mainly affects the maximum acoustic absorption coefficient, but does not substantially influence the peak frequency. Both the first and second maximum absorption coefficients gradually reach 1.0 and thereafter decrease as the gradation of the aggregate increases.
(3) Aggregates of around 10–20 mm would be the most effective for the fabrication of porous concrete with high acoustic absorption properties. However, the accuracy of the current acoustic absorption modeling decreases when using aggregates with large gradation or blended with other size aggregates.
(4) As the target void ratio increases, the maximum acoustic absorption coefficient and the peak frequency increase. This tendency is more clearly seen at the second peak than at the first peak. The value of the maximum acoustic absorption coefficient increases as the target void ratio increases, and the acoustic maximum absorption coefficient reaches 1.0 when the target void ratio exceeds 30 percent. The first peak frequencies are shown to be more dramatically increased as the target void ratio increases. Accordingly, the target void ratio is as an important design factor affecting the acoustic absorption characteristics of porous concrete.
(5) The acoustic absorption properties are hardly affected by the aggregate shape when porous concrete is well compacted.

Further research will be conducted along the line of this research in the future to accelerate the introduction of porous concrete (or macro-void materials) to civil infrastructures requiring excellent acoustic absorption characteristics. Such research may include (1) the optimization of key design parameters of multi-layered porous concrete structures used for acoustic absorption by means of experiments and statistical analyses, and (2) acoustic absorption modeling of porous concrete consideration sagging in cement paste.

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