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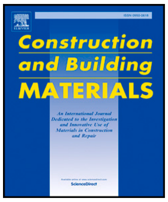

Experimental study on the sound absorption performance of surface-perforated mortar

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ABSTRACT

This study proposes the surface-perforated mortar (SPM) to mitigate railway noise. As one of the most emerging noise problems, railway noise deteriorates the quality of human lives. This paper investigates the sound absorption performance of SPM and it is compared to that of porous concrete which has been adopted as a potential solution for railway noise. The effects of hole size and depth, and surface porosity on the sound absorption performance of SPM is examined using an in-situ sound absorption test and the results explain the sound absorption mechanism of SPM. Based on these understandings, two methods to improve the sound absorption of SPM without strength degradation are proposed: (i) a combination of different depths of the holes and (ii) an application of sound-absorbing filler into the holes. The improvements show the sound absorption performance of the SPMs more than double that of the porous concrete with 25% design porosity.

1. Introduction

Noise is a growing problem in recent days. Based on the World Health Organization/Europe report in 2018, at least 100 million people in the EU suffer from road traffic noise, and in western Europe alone at least 1.6 million healthy years of life are lost by noise [1]. Noise impacts human life in urban area causing cognitive impairment, distraction, stress and sleep disturbance [2–7] as well as wild life in protected area [8]. However, noise pollution issues have rarely been addressed and referred to as '*the ignored pollutant*' [9]. One of the most emerging noise problems among various sources is railway noise because of the increase in demand on the high speed [6,10] and the capacity of the train [4]. Railway noise affects both urban and suburban areas as it is a transportation network between cities [8]. Therefore, controlling railway noise is significantly important.

Porous concrete (also known as pervious concrete) has been studied as one of the feasible solutions to mitigate railway noise. The pores in concrete can absorb fractions of noise caused by train [11–19]. It has been well studied that the porosity of concrete is the main factor contributing to the sound absorption performance of porous concrete because the part of sound energy can be dissipated as the air passes through a large number of pores or apertures [19–23]. However, high porosity yields low strength of porous concrete and it may not be applied to the railway structures. Therefore, the balancing between the sound absorption performance (or the porosity) and the strength of porous concrete becomes an important research subject [24].

The characteristics of pores in porous concrete also affect its sound absorption performance. The sound absorption performance mainly relies on the amount of open pores and its inter connectivity [11,13,14,18,19,25–28]. The closed pores or pores at the bottom do not play a significant role in sound absorption. However, controlling the pore structure such as pore distribution of porous concrete is difficult. Therefore, porous concrete has a disadvantage in terms of sound absorption efficiency.

Surface-perforated mortar (SPM) proposed in this research by adopting an acoustic panel has macro-sized holes only on the mortar surface. The lower layer of SPM is solid mat that could serve as structural member of concrete slab track and the upper layer of SPM plays a role in railway noise absorption similar to non-structural sound-absorbing layers. The strength reduction ratio of SPM to non-perforated mortar can be less than that of porous concrete to non-porous concrete because of the solid mat in lower layer. Therefore, SPM can be more efficient strategy than porous concrete if it absorbs noise more.

Studies on acoustic material have shown the effect of macro-sized holes on sound absorption. The pore system of an acoustic material that has micro and macropores is called by 'double-layer porosity' and the interaction between micro and macropores enhances the sound absorption [29,30]. Although the analytical model and numerical studies resulted in reasonable expectation, the interaction mechanism has not been clearly understood. In fact, the effect of macropore is arguable:

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Table 1
List of SPM specimens.

Name	Surface porosity (%)	Hole properties	
		Diameter (mm)	Height, x (mm)
P30–D15–H(x)	30.6	15	20, 40, 60, 80
P15–D15–H(x)	15.3	15	20, 40, 60, 80
P15–D8–H(x)	14.3	8	20, 40, 60, 80
P7.5–D15–H(x)	8.2	15	20, 40, 60, 80
P7.5–D8–H(x)	8.0	8	20, 40, 60, 80

Table 2
Mix design of the porous concrete (kg/m^3).

Cement	Silica fume	Water	Coarse aggregate[a]	SP[b]
233.7	58.4	73.0	1343.0	2.9

[a] 13–25 mm size.
[b] Superplasticizer.

Atalla concluded that macropore is efficient in low frequency [30] whereas Lenin Babu and Padmanabhan insisted in mid and high frequencies [29]. Furthermore, no studies regarding the effect of macro-sized holes on sound absorption with cementitious materials have been reported. Since mortar has micro-sized pores, SPM might show a synergistic effect between mortar and the macro-size holes. Therefore, the effect of macro-size perforation on the surface of mortar needs to be investigated.

This paper compares the characteristics of SPM and porous concrete in the aspect of the sound absorption performance and the compressive strength. After examining the differences, the sound absorption mechanism of SPM is discussed and the effects of various design parameters of SPM such as hole size and depth, and surface porosity on the sound absorption performances were investigated. Based on the studies, two methods to improve the sound absorption performance of SPM without strength degradation are introduced.

2. Materials and methods

2.1. Surface-perforated mortar (SPM)

A commercial type I cement and natural river sand are used. The water to cement (w/c) ratio of binder was 0.45 and the weight ratio of cement to sand was 1:3. Mortar was mixed following ASTM C305. After mixing, specimens were cast in molds. The cylindrical acrylic rods were used to create holes on the mortar surface. The circular shape of the hole was chosen to prevent surface cracking around the holes. The rods were removed at the initial setting time and the specimens were kept sealed until tested.

The design parameters are surface porosity and diameter and depth of holes. The surface porosity means the ratio of the sum of the hole area to total surface area, and three design surface porosity of 7.5, 15, and 30% were tested. Two different hole sizes of 15 mm and 8 mm are used and the range of depth of the hole is 20–80 mm. The list of specimens is summarized in Table 1.

2.2. Porous concrete

The SPMs were compared to the reference of a porous concrete. The porosity of the porous concrete was designed to be 25% and the actual porosity was measured to be 24.5% using a water absorption test following ASTM C642. The water to binder ratio is 0.25, 20% of cement is replaced with silica fume to increase the binder strength, and a polycarboxylate superplasticizer is applied to adjust flowability of the binder to 170 mm which could generate the uniform pore structure of the concrete. The mix design of the porous concrete is shown in Table 2.

2.3. Sound absorption test

The size of SPM sample used for the sound absorption test is determined as 300 × 300 × 150 mm following the suggestion by Li et al. [27] as shown in Fig. 1 and the array of holes of 15 mm and 8 mm are shown in Fig. 2. After drying specimens in room temperature for 2 days, the sound absorption performance was measured at the center of the top surface using an in-situ sound absorption instrument [11,19]. It should be pointed out that another popular test, the impedance tube system, might not be suitable for current research due to the limited size and shape of the sample. The test provides the sound absorption coefficient (SAC) with respect to sound frequency. The sound absorption performance level is determined in this study by the sound absorption area ratio (SAAR) obtained from Eq. (1) because the SAAR indicates the overall sound absorption performance within the frequency range of material.

$$SAAR = \left(\int_{x_1}^{x2} f(x)\mathrm{d}x\right)/(x_2 - x_1) \tag{1}$$

where $f(x)$ is the SAC at x frequency. Since the in-situ sound absorption instrument can have measurement errors in below 200 Hz, the frequency range chosen for analysis in this study is from 200 (x_1) to 2500 (x_2) Hz [31].

2.4. Compressive strength test

Compressive strength was conducted on the SPM following ASTM C1231 in which SPM specimens were cast in 100 × 100 × 150 mm molds and cured at room temperature for 7 days. The same array of holes in Fig. 2 are used.

3. Results and discussion

3.1. Comparison between SPM and porous concrete

3.1.1. Compressive strength

Table 3 shows the compressive strength test results of porous concrete and SPMs including the solid concrete and the solid mortar specimens made of the same binders of the porous concrete and the SPMs, respectively. Although the compressive strengths of both the porous concrete and the SPMs decrease because of the pores inside, the loss ratio of the porous concrete is much higher than the SPMs; the porous concrete with the design porosity of 25% loses the strength by 69% whereas the SPMs of 8.2–30.6% lose by 31%–40% only.

The first reason of the higher strength loss in the porous concrete is that porous concrete has a higher bulk porosity than the SPMs even with the lower surface porosity because of the solid mat in the lower layer of the SPMs. The second reason is that the amount of the binder of the porous concrete decreases to increase its porosity with the given size of coarse aggregate. Therefore, the material properties of the porous concrete significantly change with a different porosity. In conclusion, the SPM can be more effective than the porous concrete in terms of material strength if the SPM results in better sound absorption than the porous concrete.

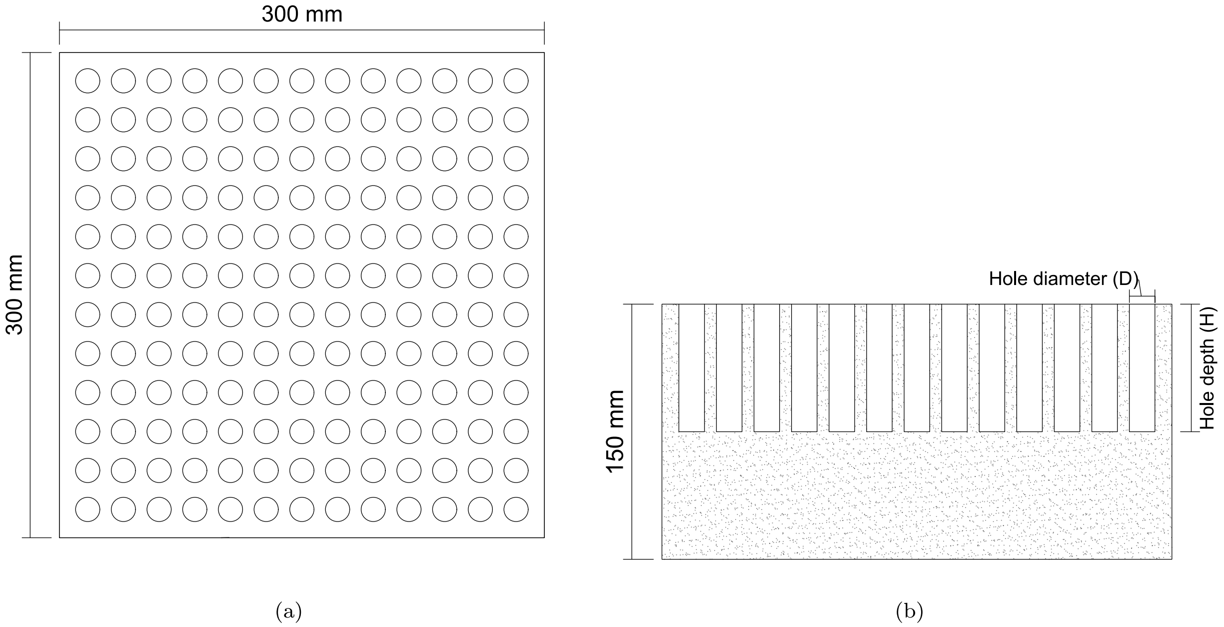


Fig. 1. Drawings of SPM: (a) plan view and (b) side view.

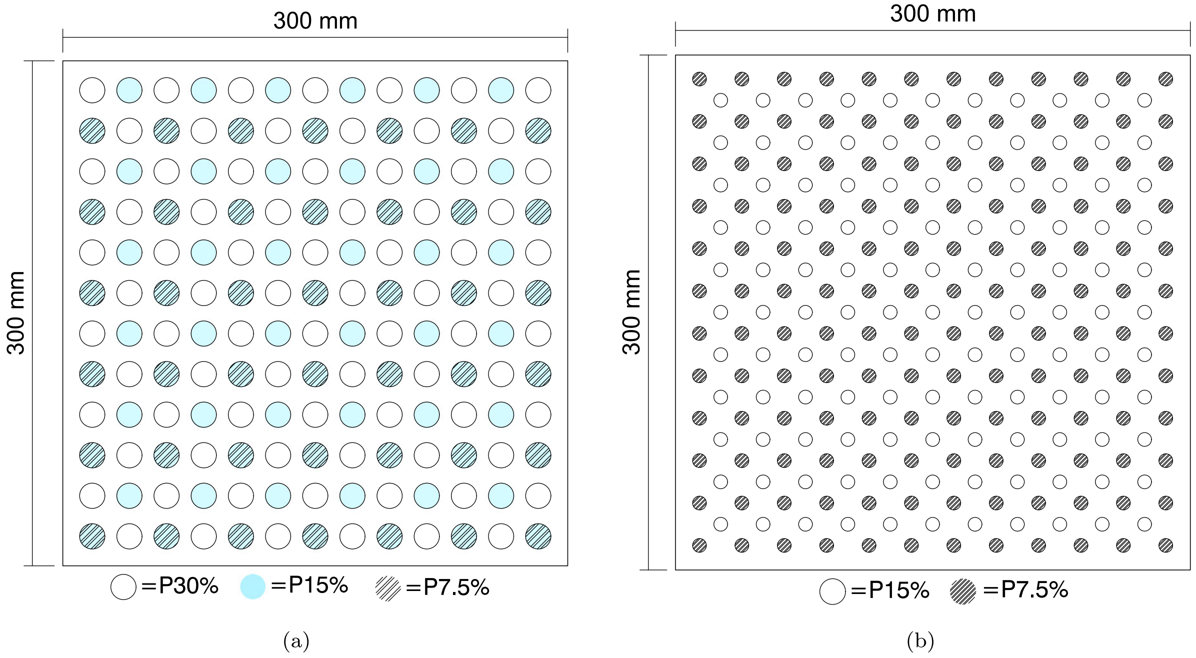


Fig. 2. The array of holes in SPM: (a) 15 mm diameter and (b) 8 mm diameter.

Table 3
The 7 day compressive strength loss of the porous concrete and SPMs.

Category	Specimen	Design porosity		Compressive strength (MPa)	Strength loss (%) [a]
		Surface	Bulk		
Concrete	Solid	0	0	36.4	–
	Porous concrete	25	25	11.4	69
Mortar	Solid	0	0	19.4	–
	P30–D15–H80	30	16	9.9	40
	P15–D15–H80	15	8	11.3	42
	P7.5–D15–H80	7.5	4	13.3	31

[a] The compressive strength loss compared to the solid specimens.

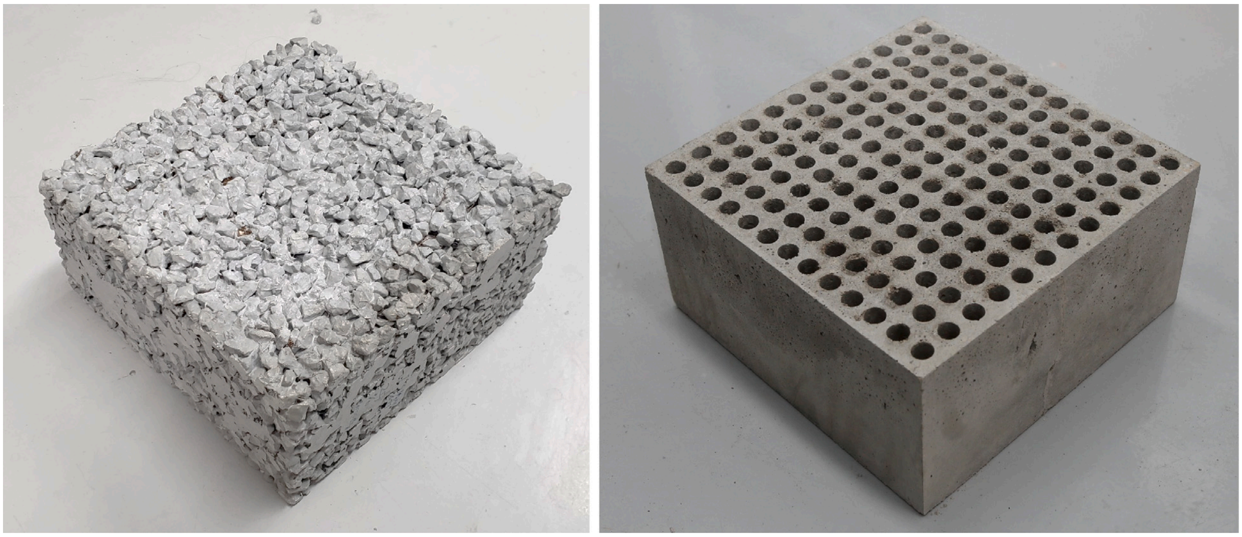

(a) (b)

Fig. 3. Picture of specimens for sound absorption test: (a) porous concrete of 25% design porosity and (b) SPM of P30–D15–H80.

3.1.2. Sound absorption

The sound absorption performance of SPMs is compared with that of the porous concrete. Fig. 3 shows pictures of the porous concrete and the SPM of P30–D15–H80 used for the sound absorption test.

Fig. 4 shows the comparisons of the sound absorption test results between the porous concrete and SPMs of 30%, 15%, and 7.5% surface porosity with D15 and H80. The X-axis is sound frequency and the Y-axis is SAC. In SAC, one and zero stand for the completely absorbed sound and the completely reflected sound, respectively, and a negative value means the amount of sound reflected toward a microphone is greater than those of sound generated by a speaker. The negative values of SAC have been reported in the previous studies [27,32,33] and what causes the negative value of SAC is discussed in more detail in the section of sound absorption mechanism. The SAAR value is shown in the parenthesis next to the specimen name in the figure.

The SAC plots are significantly different between the porous concrete and the SPMs, especially in the frequency below 1600 Hz. In the frequency of 200–900 Hz, the porous concrete has low SACs ranging 0–0.5, and the SPMs have negative SACs and they decrease as the porosity increases. In the frequency of 900–1600 Hz, the SAC of the porous concrete is close to zero, however, the SPMs data shows positive convex curvatures. In the frequency of 1600–2500 Hz, both the porous concrete and the SPMs show positive SACs with similar area. It should be noted that the porous concrete absorbs sound mainly in 1600–2500 Hz, whereas SPM absorbs sound in a wider range from 900 to 2500 Hz.

Even though porous concrete and SPMs have different sound absorption profiles, their SAAR values in the parentheses in Fig. 4 are similar to each other, especially in the case of 7.5% of porosity. Despite the wider positive area in the frequency range of 900–1600 Hz, the negative area in low frequency decreases the SAAR of SPMs, resulted in similar SAAR of the porous concrete. Therefore, it can be concluded based on the experimental findings that the overall sound absorption performance of SPM is similar to that of porous concrete. To improve the sound absorption performance of SPM, the absorption mechanism needs to be understood and is discussed in the following section.

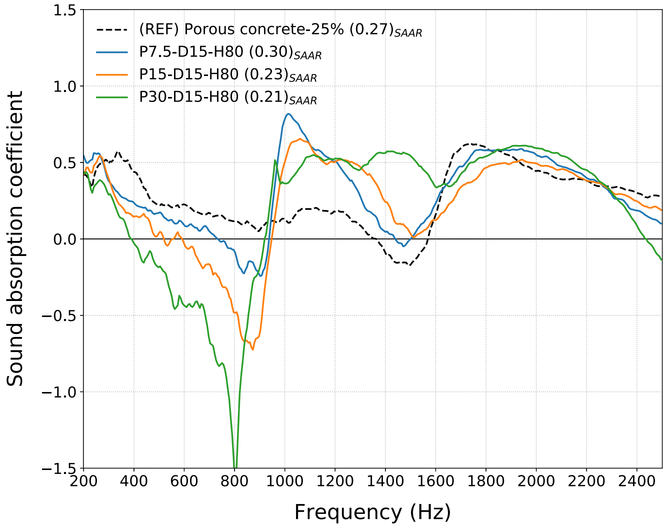


Fig. 4. Sound absorption coefficient of SPMs and the porous concrete.

3.2. Sound absorption mechanism of SPM

3.2.1. Decomposition of SPM sound absorption data

The mortar is known to absorb fraction of sound [34,35]. To examine the significance of the mortar in the sound absorption performance, the sound absorption test was conducted on the solid mortar specimen with the same mix design without a hole on its surface, and the SAC data are compared with the SPMs used in Fig. 4. In Fig. 5(a), the black dash line is the SAC of the solid mortar. The mortar SAC data overlays on the SAC data of SPMs over 1600 Hz. Therefore, it can be inferred that the sound absorption data of SPM can be decomposed into the *mortar* and the *hole*.

The SAC data caused by the holes on the surface of SPM can be obtained by subtracting mortar data from SPM data, and they are shown in Fig. 5(b). The plots are nearly flat on zero over 1600 Hz for all specimens. The SAAR values of the three cases in Fig. 5(b) are almost zero. This implies that the holes in SPM did not play a critical role in sound absorption. It was mortar that contributing to the sound absorption performance of SPM. Therefore, it can be concluded that the holes in SPM do not absorb sound but cause acoustic resonance like a wind musical instrument.

Even though the overall SAAR value by the holes is almost zero, the SAC plots fluctuate crossing the negative and positive areas. This is believed to be a characteristic of sound absorption of the SPM which causes the resonant phenomenon. The sound in the frequency range of 900–1600 Hz goes into the holes and its frequency changes to the resonance frequency which is the peak location of the negative SAC data. Therefore, the sound absorption data shows pseudo-positive SAC data in that frequency range. For example, in the case of the P30–D15–H80, the sound in the frequency range of 900–1600 Hz changes to the resonance frequency of 800 Hz as shown in Fig. 5(b). Finally, the sound of the resonance frequency of each hole results in the negative SAC values. It should be noted again that the sum of the SAC values with respect to the frequency is almost zero, which clearly mean that, overall, the holes in the SPM does not absorb the sound. Also, the results indicate that the energy produced by the speaker barely changes.

3.2.2. Effect of the design parameters of the hole on sound absorption

The effect of the three design parameters of the hole on the sound absorption of SPM is investigated: the hole size, the hole depth, and the surface porosity. Fig. 6 shows the sound absorption test results of SPMs with different hole sizes. For the case of the surface porosity of 15%, the SAC plots and SAAR values of 15 mm and 8 mm diameters are almost identical. Therefore, it can be concluded that the hole size does not play a significant role in the sound absorption. The reason for the ineffectiveness of the hole sizes is possibly that the holes are not large enough to interact with micropores, which absorbs more sound. Previous studies with rockwool and melamine reported that the macropore sizes of around 30–80 mm increases sound absorption [29,30,36]. Therefore, the sound absorption performance of SPM is possibly improved by increasing the hole size.

The sound absorption test results on the SPMs with different hole depths shown in Fig. 7 for the case of the surface porosity of the SPMs is 15%. Figs. 7(a) and 7(b) correspond to the SPMs with 15 mm and 8 mm hole size, respectively. It should be noted that the plots are shifted to the left when the depth of the hole increases. These experimental findings indicate that the resonance frequency depends on the depth of the holes. The frequency of the sound reflected decreases with the increase of the hole depth, which follows the same trend of the theoretical resonance frequency formula [37]. This is another evidence of the acoustic resonance caused by the holes.

It is noted that the deeper the hole is, the wider the area of a positive curve is. However, the SAAR values in Fig. 7 are again close to zero for all specimens. Also, the effect of 20 mm depth of SPMs with both 15 mm and 8 mm hole size on the SAC plot is minimal. Therefore, it can be concluded that the hole depth should be longer than 20 mm to observe the resonance effect by the hole.

The sound absorption test results of the specimens with 15 mm hole size are shown in Fig. 8 and the data are grouped by the hole depth. The height of the negative peak increases when the surface porosity increases. As a result, the SAAR value decreases with higher surface porosity. The lower sound absorption performance with higher porosity of SPM is an opposite tendency to that of porous concrete, which indicates that the resonance effect becomes more severe when the surface porosity is higher. The reason is inferred to be that the smaller space between holes intensifies the resonance. When the porosity of SPM increases, the space between the holes deceases as the holes are distributed equally. The narrower space induces more sound to penetrate adjacent holes through the thinner wall of mortar enveloping each hole, which amplifies the resonance effect. As a result, the sound absorption performance decreases if the surface porosity of SPM increases.

The intensity of the resonance is also affected by the hole depth. The negative peak drops more severely along with the increase of porosity when the hole depth is longer. For example, the negative peak height of SPMs with 80 mm depth in Fig. 8(a) decreases by around 1.2 from 7.5% to 30% porosity while the SPMs with 40 mm depth in Fig. 8(c) exhibits the decrement of around 0.7. Therefore, the total volume of holes is also effective in the resonance intensity. In the case of 20 mm depth, the SAC is not affected by the porosity because the depth is too short as aforementioned.

3.3. Improvement of the sound absorption performance of SPM

The sound absorption mechanism of SPM has been studied and demonstrated through experimental studies in the previous subsection. It was revealed that mortar of SPM absorbs the fractions of sound and the holes on the surface just cause the acoustic resonance. As a result, the SPMs has not been superior to porous concrete in terms of the sound absorption performance. It can be hypothesized that the key factor to improve the sound absorption of SPM is alleviating the resonance effect caused in holes. To address this question, two methods are adopted in this research. The first method is the usage of the combination of different depths and the second method is applying a sound absorbing material as a filler inside holes.

3.3.1. Effect of a combination of different depths of holes

The SPM with 15% porosity and a 15 mm hole size is used to investigate the effect of the combination of two different hole depths. The combination of 40 mm and 80 mm depths is used and the array of holes is shown in Fig. 9, in which total surface porosity is 30.6% and the portion of each hole with the different depth is half, 15.3% surface porosity.

The sound absorption test result is shown in Fig. 10. Fig. 10(a) shows the SAC data of the three SPMs: P30–D15–H80+40, P15–D15–H80, and P15–D15–H40. It should be pointed out that the positive peaks of 15% data of 80 mm and 40 mm virtually remain in the P30–D15–H80+40 as seen from the green line in Fig. 10(a). This phenomenon can be used to absorb specific frequencies of noise. The combination of different depths significantly decreases the resonance effect inside the holes. The negative area of the P30–D15–H80+40 is smaller than that of the P15–D15–H80 and the negative area of the P15–D15–H40 disappears. The positive SAC of the P30–D15–H80 in the frequency range of 900–1400 Hz remains in the SAC of the P30–D15–H80+40 despite the large negative area of the P15–D15–H40 in the same frequency range. As a result, the SAAR of the entire P30–D15–H80+40 is 0.50, which is almost twice higher than that of the reference porous concrete (see Fig. 10(b)).

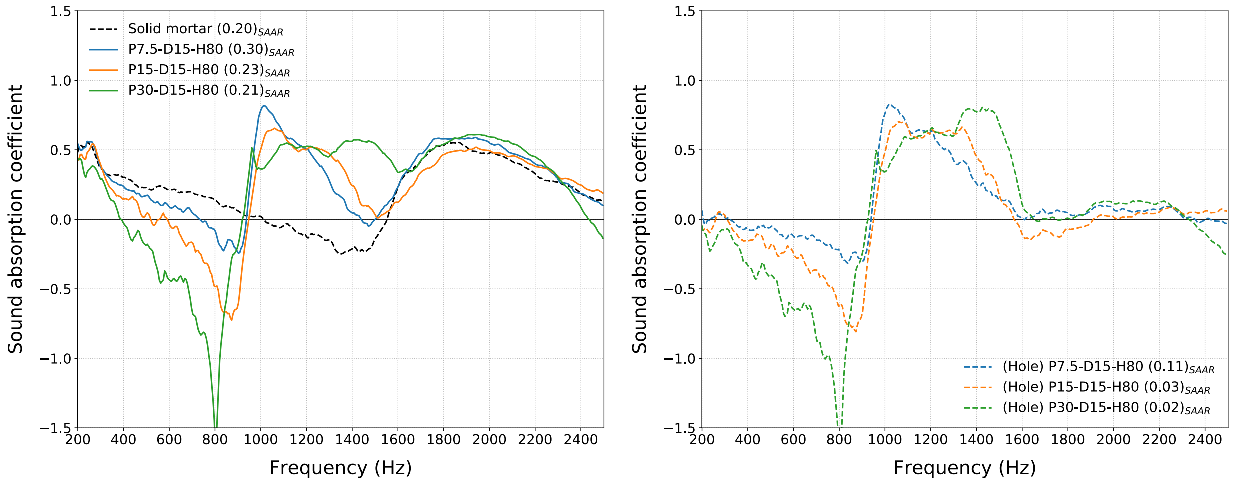
3.3.2. Effect of sound-absorbing filler

To investigate the effectiveness of sound-absorbing filler inside the holes of SPM, the holes of SPM were filled with natural river sand of which particle size is 1.18 mm. The pores in the sand are expected to dissipate part of the sound energy by the same mechanism of pores in porous concrete. The SPM of P30–D15–H80 specimen was used and half of the holes were filled. The sound absorption test result is shown in Fig. 11.

Sand inside the holes of SPM significantly increases the sound absorption. It not only decreases the negative area in the range of 400–900 Hz but also enhances the sound absorption in the wide frequency range of 900–2500 Hz. It is obvious that the sand not only prevents the resonance but also absorbs sound. The sand composed of holes or cavities seems to absorb the sound come into the holes in the same principle of porous concrete. The pores formed by a single particle size of the sand allow the sound to penetrate inside, and the sound is dissipated by the friction between air and the surface of the particles. The SAAR value of the SPM with sand is more than two times higher than that of the reference porous concrete.

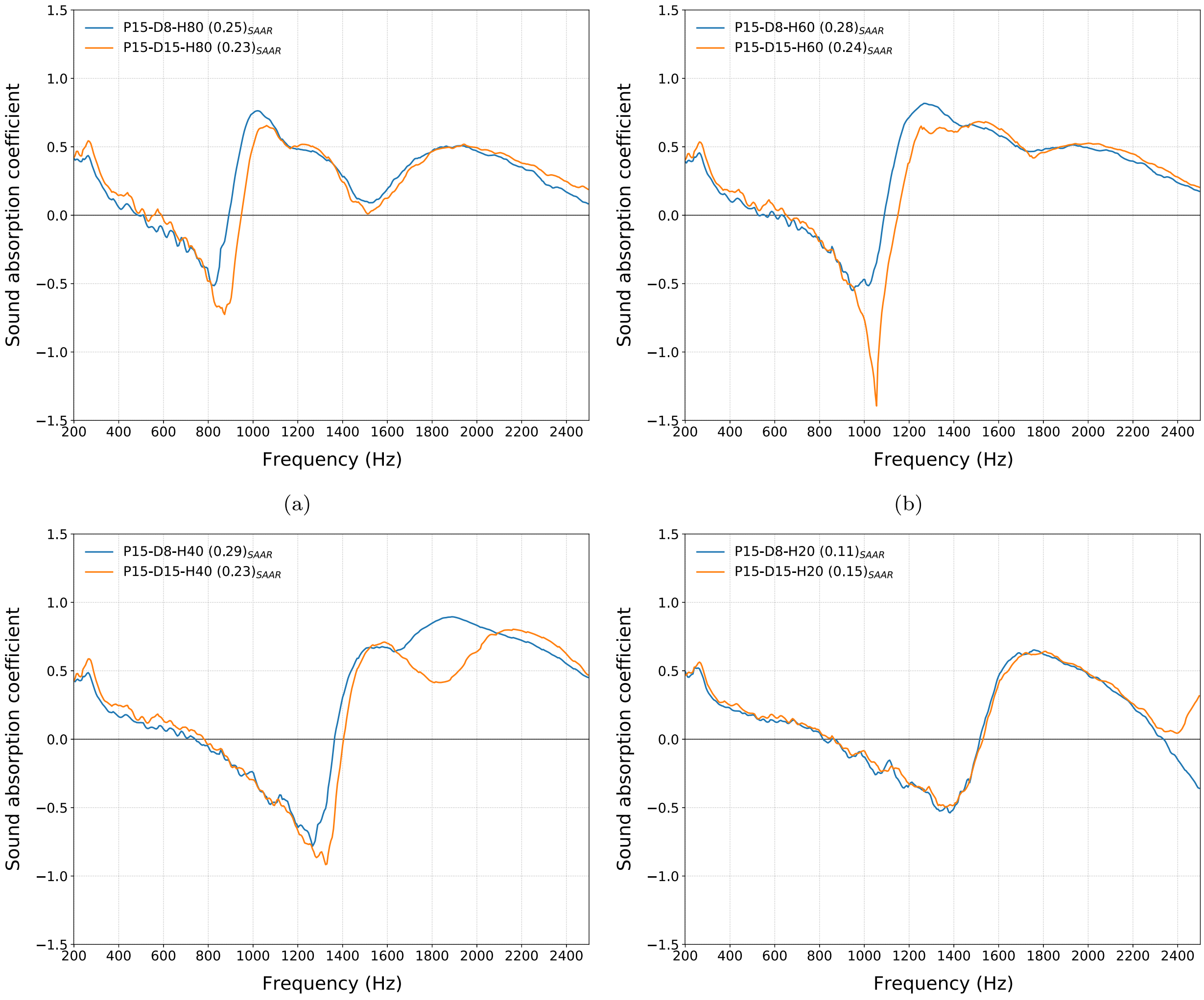
4. Conclusion

This paper proposed SPM as one of the possible solution to reduce railway noise. SPM consists of two layers: the upper layer that has the macro-sized holes and the lower layer that is solid mortar. Based on the hypothesis that the holes on the SPM surface possibly play a role in sound absorption, the sound absorption performance of SPM was investigated using an in-situ sound absorption instrument. The experimental studies on the SPMs with different surface porosity, diameter of



(a) (b)

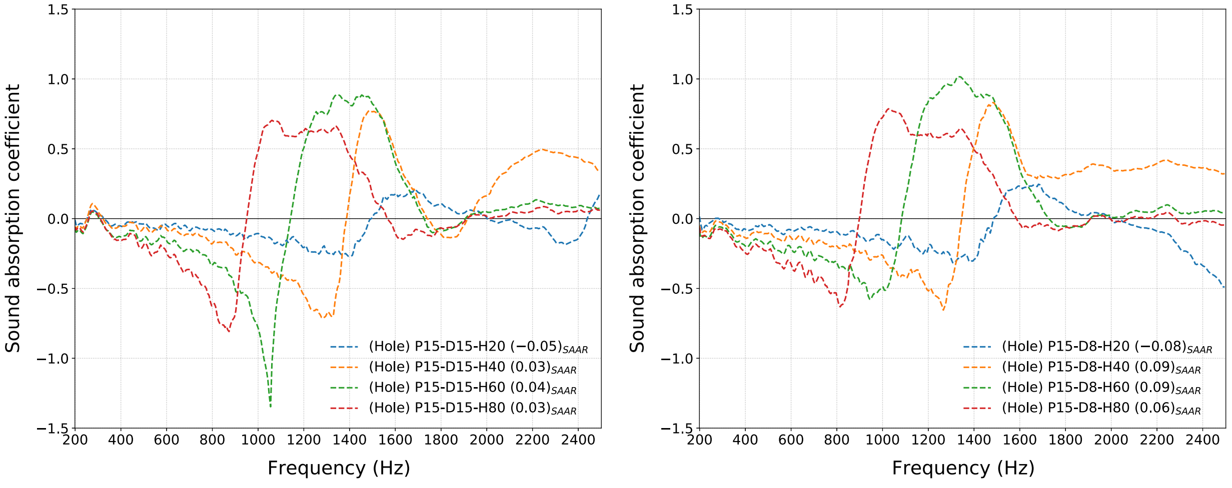
Fig. 5. Decomposition of the SPM sound absorption test results: (a) SACs by the solid mortar and the SPMs; and (b) SACs by the hole of the SPMs obtained by subtracting the SAC of the solid mortar from the SAC of the SPMs.



(a) (b)

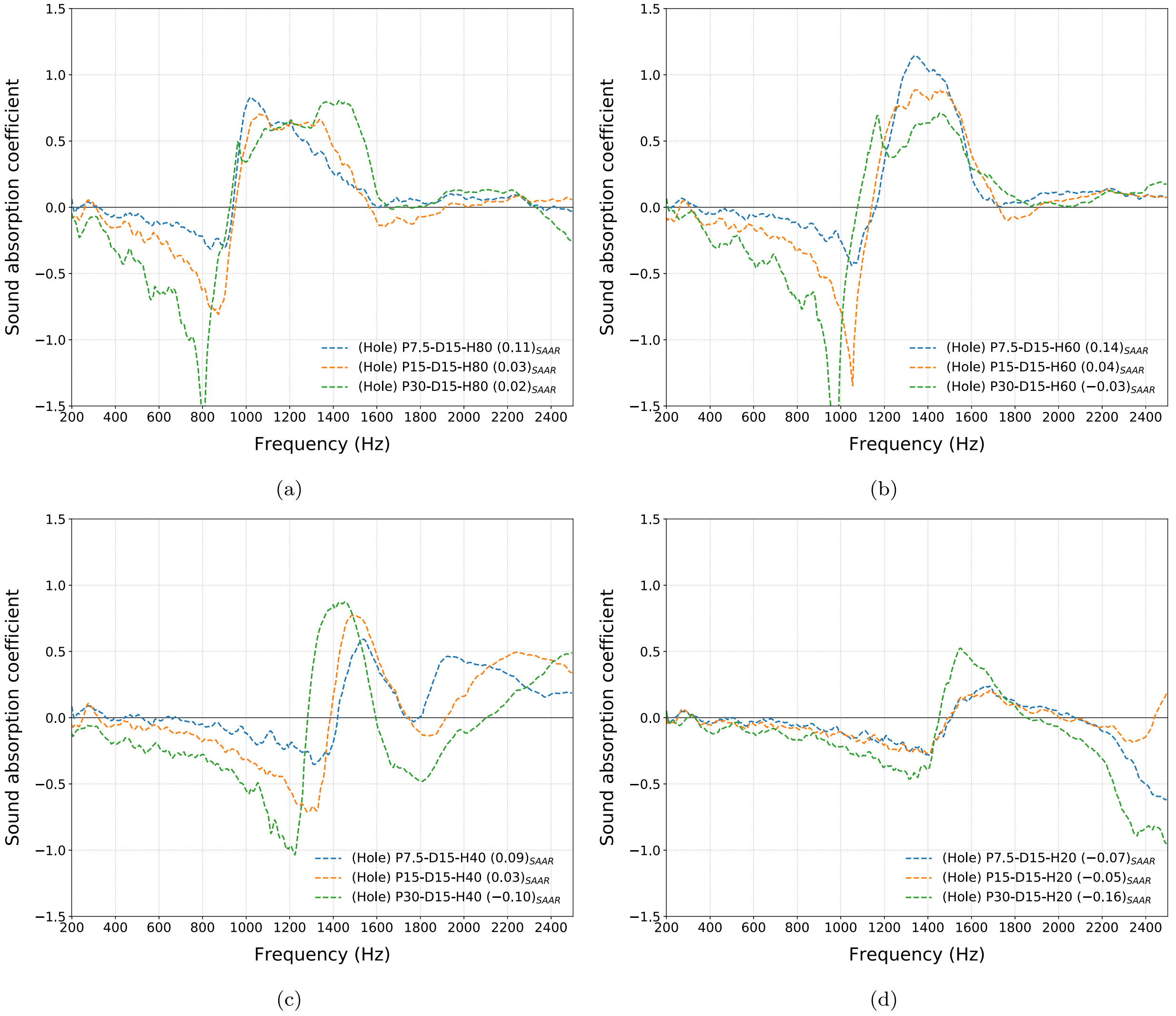
(c) (d)

Fig. 6. Effect of the hole diameter on the sound absorption performance of SPM with 15% porosity: (a) 80 mm depth, (b) 60 mm depth, (c) 40 mm depth, and (d) 20 mm depth.



(a) (b)

Fig. 7. Effect of the hole depth on the sound absorption performance with 15% porosity: (a) SAC of the holes with 15 mm size and (b) SAC of the hole with 8 mm size [Note: The SACs by the hole of the SPMs obtained by subtracting the SAC of the solid mortar from the SAC of the SPMs].



(a) (b)

(c) (d)

Fig. 8. Effect of the porosity on the sound absorption performance of SPM with 15 mm hole size: (a) 80 mm depth, (b) 60 mm depth, (c) 40 mm depth, and (d) 20 mm depth [Note: The SACs by the hole of the SPMs obtained by subtracting the SAC of the solid mortar from the SAC of the SPMs].

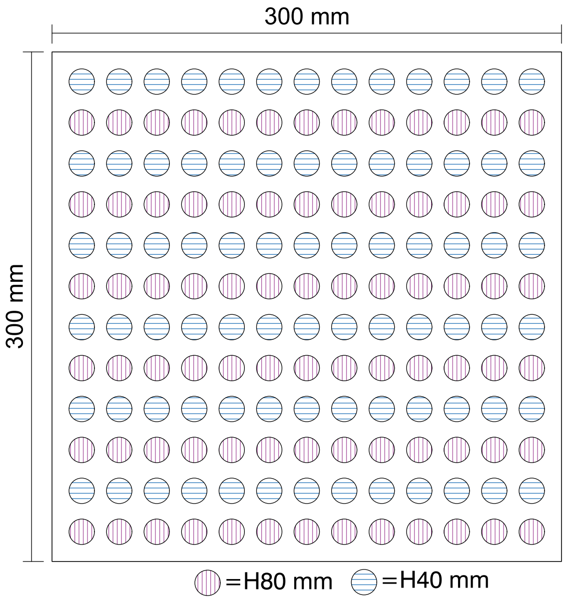
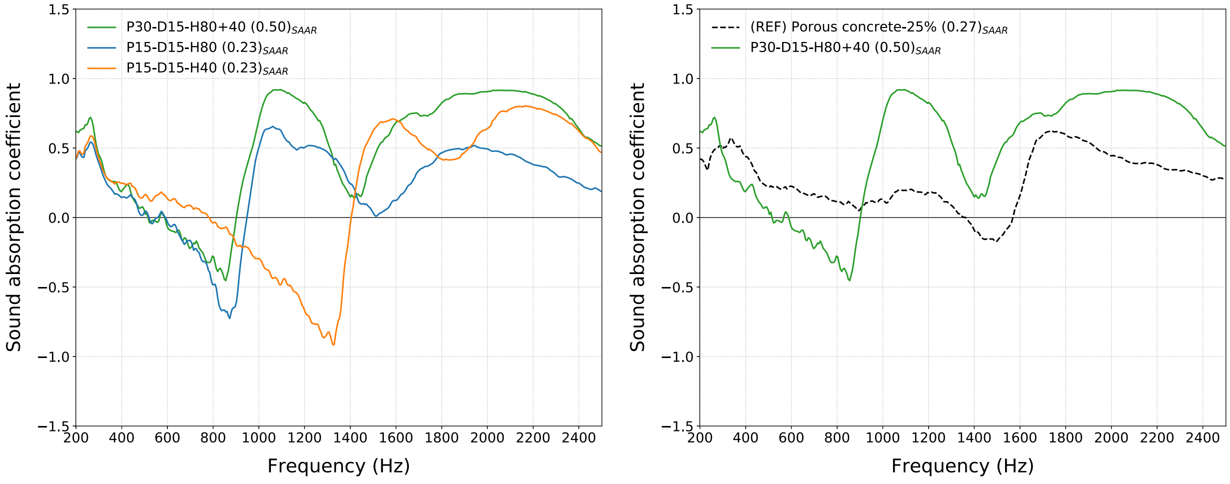


Fig. 9. The array of the holes in the SPM of P30–D15–H80+40 (30% porosity; 15 mm diameter of the hole; and 80 mm and 40 mm depths of the hole).

hole, and depth of hole provided the clue of how SPM absorbs sound. The porous concrete of 25% design porosity was adopted as a reference specimen to compare the sound absorption performance with SPM. The observations and findings of this study can be summarized as follows:

1. The sound absorption mechanism of SPM can be explained by dividing into the mortar part and the hole part. The mortar absorbs sound only in a high-frequency range, whereas the hole does not absorb but causes resonance. The resonance effect resulted in pseudo positive SAC in the mid-frequency range and negative SAC in the low-frequency range. However, overall SAAR values by the hole were almost zero.
2. Through experimental studies on the effect of SPM design parameter, it is demonstrated that (i) the hole size ranging from 8 to 15 mm does not influence sound absorption of SPM, (ii) the resonance frequency depends on the depth of the hole, and (iii) higher surface porosity of SPM amplifies the resonance phenomenon.
3. To improve the sound absorption performance of SPM, this paper introduced two methods: combining different hole depths and filling sound-absorbing material in holes. The first method prevents the resonance inside holes and the second method absorbs more sound without strength deterioration. The usage of the combination of different depths of the hole can be applied to absorb the sound in the targeted frequency ranges. The additional sound-absorbing material in holes dissipates the sound penetrated inside by the friction between air and the surface of the micro-sized pores. It was demonstrated that the sound absorption performance of the SPMs improved by adopting the filling method is more than double that of porous concrete with 25% design porosity.
4. SPM can be more efficient system than porous concrete in the aspects of the sound absorption as well as the compressive strength. It has been demonstrated that the sound absorption performance of SPM can be higher than that of porous concrete even with the lower bulk porosity. Because of the solid mat in the lower layer of SPM, the compressive strength loss ratio of SPM is lower than that of porous concrete when both have the same surface porosity. Furthermore, the sound absorption performance of SPM can be improved without degrading the compressive strength when sound-absorbing material applied. Therefore, SPM would be a feasible alternative solution to reduce railway noise.

Based on this study, SPM is expected to be applied to the railway concrete slab to reduce railway noise. Some future works are needed to improve the sound absorption performance of SPM: (i) study on the synergistic effect between macropores (SPM structure) and micropores in mortar to eliminate negative SAC for all frequencies similar to other acoustic materials but based on cement materials, (ii) optimization of the hole design parameters, (iii) the method to increase the SAC in low-frequency, (iv) the sound absorption expectation model for SPM, (v) additional sound absorption test using international standard methods such as the reverberation room method to compare the sound absorption performance of the SPM with other materials [38], and (vi) development of theoretical models to explain extraordinary acoustic phenomena of the SPM made of cement-based materials.



(a)

(b)

Fig. 10. Effect of the combination of two different depths on the sound absorption performance of SPM: (a) SAC data comparison between the combination of different depths and single depths (b) SAC data comparison between the reference porous concrete and the SPM with the combination of different depths.

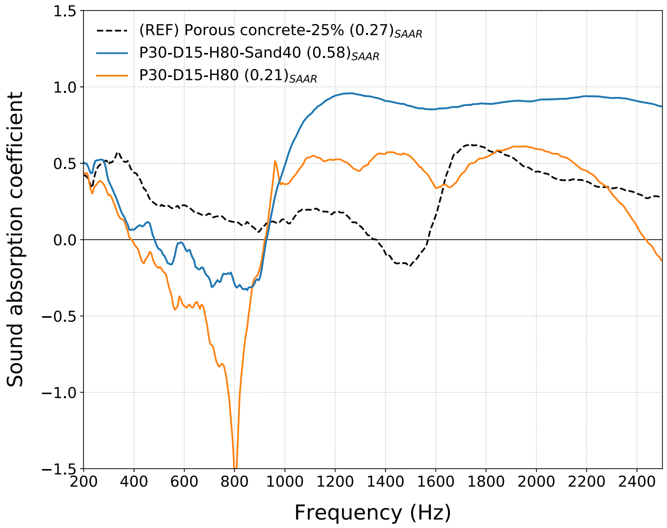


Fig. 11. Effect of filler on the sound absorption performance of SPM.

CRediT authorship contribution statement

Sungwoo Park: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Kebede Alemayehu Moges:** Validation, Formal analysis, Writing - review & editing, Visualization, Data curation, Investigation. **Sukhoon Pyo:** Conceptualization, Writing - review & editing, Supervision, Project administration, Funding acquisition.

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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