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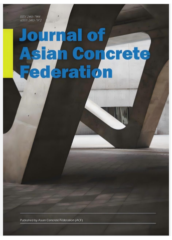

Fundamental Experiments on Evaluating the Sound Absorption Coefficient of Porous Concrete

Keigo Matsuo[a,*], Kei-ichi Imamoto[a], Yutong Li[a], Chizuru Kiyohara[a], Aoqier Erideng[b], Akio Tanaka[c]

[a] Faculty of Engineering, Department of Architecture, Tokyo University of Science, 1-3 Kagurazaka, Sinjuku-ku, Tokyo, 162-8601, Japan
[b] Faculty of Science and Technology, Department of Architecture, Shizuoka Institute of Science and Technology, 2200-2 Toyosawa, Fukuroi City, Shizuoka Prefecture, 437-8555, Japan
[c] Faculty of Architecture, Department of Architecture, Nippon Institute of Technology, 4-1 Gakuen-dai, Miyashiro-machi, Minami-Saitama-gun, Saitama Prefecture, 345-8501, Japan

ABSTRACT

This study examined the sound absorption performance of porous concrete used as an exterior wall cladding material, focusing on four factors: porosity, particle size of aggregate, surface texture, and moisture content. In addition, the influence of measurement techniques was investigated by comparing sound absorption coefficients obtained using the oblique incidence method with those measured by the diffuse incidence method specified in JIS A 1409 (reverberation room method).The oblique incidence method is a simple laboratory-scale technique that does not require a large reverberation room or specialized facilities and uses only limited measuring equipment. Although the sound absorption coefficients obtained by this method were lower than those measured by the diffuse incidence method, the results were stable, particularly in the high-frequency range above 2500 Hz. Therefore, the oblique incidence method is considered suitable for comparative evaluation of material and mix design parameters. The results showed that increasing porosity led to higher sound absorption coefficients at frequencies above 3000 Hz. In contrast, the particle size of aggregate had no clear effect on sound absorption. Furthermore, the sound absorption coefficients tended to be higher in wet conditions than in dry conditions.

Keywords: Porous concrete, sound absorbing performance, reverberation room method sound absorption coefficient, oblique incidence sound absorption coefficient

1. Introduction

Soundproofing (sound insulation and sound absorption coefficient) is extremely important in the living environment of buildings. Therefore, sound-absorbing materials are widely used to improve the acoustic environment of buildings. Porous concrete (hereinafter referred to as POC) is a porous concrete with sound absorption coefficient properties, and one of its characteristics is that its sound absorption coefficient properties vary depending on its porosity. Previous studies [1] have shown that the sound absorption coefficient of POC peaks at approximately 1000 Hz, suggesting that POC could be used as a high-performance sound-absorbing material for exterior cladding in frequency bands such as voiced vowels and traffic noise.

This paper proposes a simplified method for measuring the sound absorption coefficient of POC over a wider frequency region than in previous studies [1], without requiring reverberation rooms or acoustic tubes, and without dependence on the test specimen size. The accuracy and simplicity of the proposed measurement method were evaluated using commercially available porous materials with known sound absorption coefficients. Subsequently, based on the oblique incidence sound absorption coefficient method proposed in prior research [2], the influences of POC porosity, particle size of aggregate, surface texture, and water content on the sound absorption coefficient were measured and discussed.

2. Experimental Methods

2.1 Experimental Factors and Levels

Table 1 shows the factors and levels used in this experiment. First, to investigate the influence of different measurement methods on the sound absorption coefficient measurements, comparisons were made using both the

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* Corresponding author: Keigo Matsuo (4121093keigo@gmail.com)

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reverberation room method and oblique incidence sound absorption method. In this experiment, the porosity of POC was set to 15%, 25%, and 35%, while the particle size of aggregate was set to 2.5-5 mm (Grade.7 crushed stone), 5-13 mm (Grade 6 crushed stone), and 13-20 mm (Grade.5 crushed stone). These aggregate gradations were determined with reference to previous studies on medium-grained porous concrete [3], and the influence of aggregate gradation on the sound absorption characteristics was examined. In this investigation, the 5–13 mm range, which is most commonly used in practical porous pavement concrete in Japan, was adopted as the standard condition. Additionally, following previous research [1], a void ratio of 25% was set as the standard, and to investigate the effect of the void ratio on the sound absorption characteristics, it was varied stepwise within a range of ±10%. The differences between dry and wet conditions were also measured. Additionally, to investigate the influence of the specimen surface texture on the sound absorption coefficient evaluation, measurements were performed on both the cast and formwork bottom surfaces.

Table 1 The factors and levels used in this experiment

Factor	Level
Porosity（%）	15，25，35
Particle size of aggregate	13-20 (Grade.5 crushed stone) 5-13 (Grade.6 crushed stone) 2.5-5 (Grade.7 crushed stone)
Surface	Cast surface Formwork bottom surface
Water content	Dry condition Wet condition

2.2 Materials

Table 2 shows the materials used in POC and their physical properties. The water-cement ratio (W/C) for the POC was established at 30%, with the design porosity set at 15%, 25%, and 35%. Ordinary Portland cement (OPC) was used as the cement, while Grade5 crushed stone (G5), Grade.6 crushed stone (G6), and Grade.7 crushed stone (G7) were employed as aggregates. Furthermore, a high-performance AE water-reducing agent was incorporated to enhance the workability of cement paste. For the test specimens used to assess the influences of the measurement method and measurement surface described in Section 2.3, G6 crushed stone (CS) was used, and the design porosity was fixed at 15%.

2.3 Test specimen preparation method and test specimens

The mixing method for POC was performed using a forced single-shaft pan mixer (100 L capacity). The coarse aggregate and cement were placed in the mixer and mixed for 30 s. After confirming that the coarse aggregate and cement were thoroughly mixed, water and admixtures were added, and mixing was completed after 60 s. Each test specimens were prepared into rectangular steel molds (10 × 10 × 40 cm^3) using a two-layer casting method, and the casting mass per specimen was calculated in advance to achieve the appropriate porosity. Compaction was performed using a tamping rod with each layer tamped individually, followed by surface finishing with a trowel. Test specimens were prepared to investigate the influences of porosity and particle size of aggregate (Photo 1; Table 1). Additionally, to examine the influences of measurement methods and measurement surfaces, rectangular prism test specimens (50×50×5 cm^3) with different dimensions were also prepared (Photo 2(a)). Furthermore, to examine the influences of measurement methods on different sound-absorbing materials, commercially available porous material test specimens (50×50×5 cm^3, off-the-shelf products) were also used (Photo 2 (b)). Additionally, for sound absorption coefficient measurements, test specimens with a smooth surface and 0% porosity (OC) were prepared for measurements on a reference that perfectly reflected the surface. The normal moisture condition for measurement was defined as the dry condition. Specimens (10 × 10 × 40 cm^3) were conditioned by placing them in a laboratory maintained at a temperature of 20 ° C and a relative humidity of 60%.

To investigate the influence of moisture conditions on the sound absorption rate of POC, measurements were conducted on wetted specimens. The wet specimen was removed from the water and drained until it stopped dripping. Then, any excess water on the surface of the specimen was wiped off with a cloth, after which the mass of the specimen was measured, and the surface moisture content was measured using a surface moisture meter.

2.4 Test Methods

2.4.1 Oblique Incidence Sound Absorption Coefficient Measurement

The oblique incidence sound absorption coefficient was measured based on the method presented in a previous study [2]. The measurements setup is shown in Figures 1 and 2. A Class 1 condenser microphone was used, and a Bluetooth speaker with a signal-to-noise ratio (SNR) of 80 dB and a frequency response up to 20 kHz was used. First, using a custom Time-Stretched Pulse (TSP) signal that continuously swept the frequency of a sine wave from a high value to a low value over a short period of time, the power spectrum of the reference perfectly reflecting surface (test specimen with 0% porosity, OC) was measured, followed by POC measurement. Subsequently, the measured sound data, acoustic power spectrum calculation, and sound absorption coefficient calculation were performed using Google Colaboratory. In accordance with prior research [4], we conducted a FFT analysis utilizing Python (version 3.12.12) within the Google Colaboratory environment. This platform facilitates stable and reproducible FFT-based frequency analysis without necessitating a specialized computing setup. In preprocessing, an inverse TSP filter was applied to the measured signal

Table 2 Mix proportion of brick specimens used in the study

Type		Symbol	Ouality
Binder	Ordinary Portland cement	OPC	Density: 3.16g/cm^3 Specific surface area: 3340 cm^2/g
Coarse aggregate	Grade.6 crushed stone (5-13 mm)	CS	Absolute dry density: 2.63g/ cm^3 Water absorption rate: 0.61% Solid content: 60.8%
		G6	Absolute dry density: 2.63g/ cm^3 Water absorption rate: 1.82% Solid content: 59.4%
	Grade.5 crushed stone (13-20 mm)	G5	Absolute dry density: 2.66g/ cm^3 Water absorption rate: 1.35% Solid content: 59.2%
	Grade.7 crushed stone (2.5-5 mm)	G7	Absolute dry density: 2.58g/ cm^3 Water absorption rate: 1.93% Solid content: 56.7%
Admixture	High-Performance AE Water-Reducing Agent (Class I)	Ad	Polycarboxylic acid compounds Lignin sulfonate

to obtain the impulse response, and environmental noise correction was performed. To calculating the acoustic power spectrum, a Hanning window was applied to the impulse response to reduce interference between frequency components, FFT and one-third octave band smoothing to extract the acoustic power spectrum. In this study, the results obtained using the oblique incidence method were comparatively evaluated against the sound absorption coefficients measured by the reverberation room method in accordance with JIS A 1409, with particular focus on frequency-dependent behavior. Based on this comparison, subsequent analyses were limited to frequencies of 2500 Hz or higher, where the influence of environmental noise was minimal and higher measurement precision could be achieved. The sound absorption coefficient was calculated using Equations (1) and (2) as follows: The power spectra of the environmental noise, TSP sound source, and measured sounds before and after correction (OC (red) and POC (blue)) are shown in Figure 3.

Acoustic power spectrum
=10exp(Sound pressure level(dB)/10) (1)

Sound absorption coefficient =1-
(Power spectrum of the test specimen/
Power spectrum of the reference reflector) (2)

2.4.2 Reverberation room method sound absorption coefficient measurement

For comparison with the simplified measurement method proposed in this paper, we measured the sound absorption coefficient using the reverberation room method (referencing JIS A 1409). Previous studies[5] have reported that when specimens are placed exclusively on the floor, the sound absorption coefficient remains nearly constant regardless of the area at low frequencies but increases as the specimen area decreases at higher frequencies. In this study, four test specimens (each 500 × 500 mm, total surface area of 1.0 m^2) were concentrated in the center of the reverberation room without gaps. To prevent lateral sound absorption coefficient, 2 mm-thick aluminum frames were adhered to the sides of the specimens, and sealing material was applied to the gaps between the frames and specimens to ensure airtight contact.

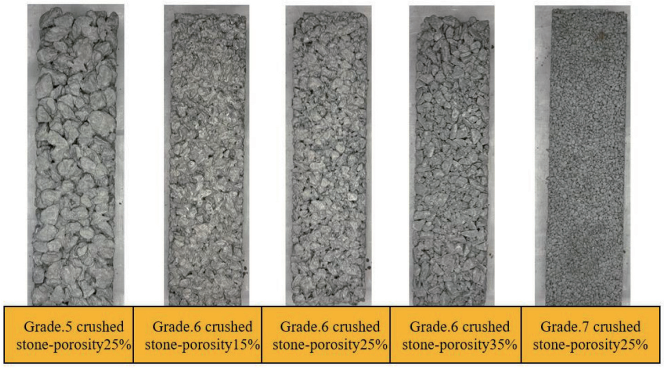
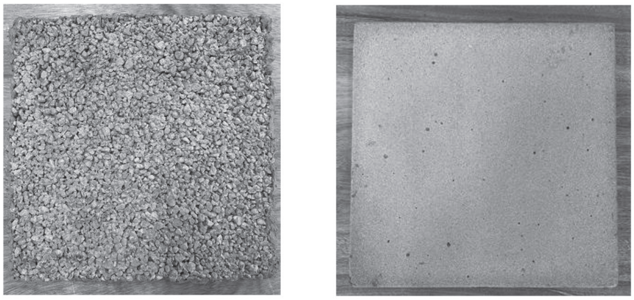


Photo.1 Surface texture of test specimen (10×10×40cm^3)

3. Experimental Results and Discussions

3.1 Measurement Accuracy of the Oblique Incidence Sound Absorption Method

Figure 4 shows the sound absorption coefficient measurement results for commercially available porous materials using this measurement method. The figure indicates that the sound absorption coefficients of commercially available porous materials were highest in the following order: reverberation room method (surface area 10m^2) > reverberation room method (surface area 1m^2) > oblique incidence sound absorption method (anechoic room) > oblique incidence sound absorption method (laboratory). Note that the reverberation room method (10m^2) results were based on tests conducted in accordance with the reverberation room sound absorption coefficient (JIS A 1409). The sound absorption coefficient measured using the reverberation room method with a 1m^2 test specimen exceeded 1.0 at frequencies above 1000 Hz, consistent with the trend reported in previous studies [5], confirming a higher sound absorption coefficient than the results from the JIS-compliant reverberation room method (10m^2 surface area). The test area used in the reverberation room method was approximately one-tenth of the test area specified in the reverberation room method sound absorption coefficient (JIS A 1409), this suggests that the area influenced the measurement results. The differences between the measured sound absorption coefficients and the reference values obtained using the reverberation room method (JIS A 1409) were evaluated with a focus on frequency-dependent behavior. As a result, although some differences in absolute values were observed, no significant discrepancy was found in the high-frequency region. With this method, measurements conducted in an anechoic room showed sound absorption coefficients comparable to those of the reverberation room method (10 m^2 surface area) in the 1000–2500 Hz frequency region. In contrast, measurements conducted in the laboratory showed sound absorption coefficients 0.2–0.4 lower than the product data. Furthermore, at frequencies above 2500 Hz, the coefficients were equivalent to the sound absorption coefficient rates obtained using the reverberation room method (surface area of 10 m^2).



(a) Grade.6 crushed stone(CS) porosity 25%

(b) Comercially available porous material test specime

Photo.2 Surface texture of test specimen （50×50×5cm3）

In the laboratory, it was confirmed that environmental noise, ambient noise, and reflections from walls and ceilings affected the measured sound. Since environmental noise mainly consists of low frequencies, its impact on the measurement sound is minimal in the high-frequency region, and the results closely resemble those obtained in an anechoic room. Conversely, in the low-frequency region, the influence of environmental noise was significant, resulting in lower measured sound absorption coefficients than those obtained in the anechoic room. A future task for laboratory measurements is to eliminate the influence of environmental noise in the low-frequency region and bring the measured sound absorption coefficient closer to the product data. However, for the high-frequency region above 2500 Hz, this measurement method is considered capable of yielding values close to those obtained using the JIS-compliant reverberation room method. Furthermore, based on the results of these measurements, subsequent measurements will be limited to frequencies of 2500 Hz or higher for analysis because these offer higher precision.

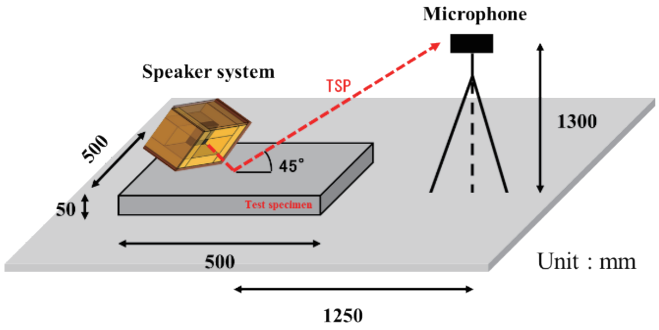


Figure.1 Schematic diagram of oblique incidence sound absorption coefficient measurement

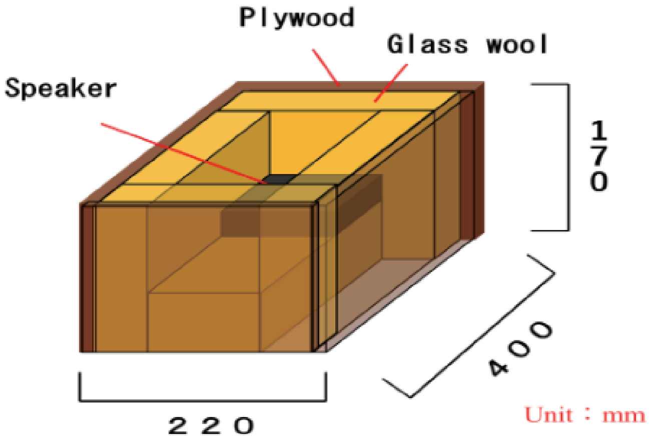
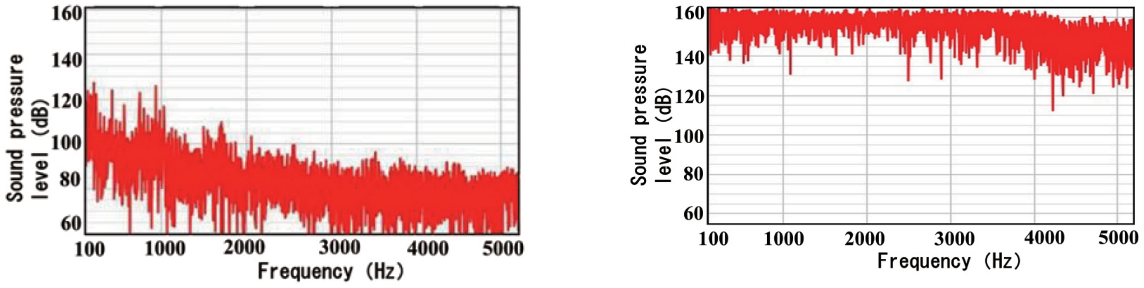


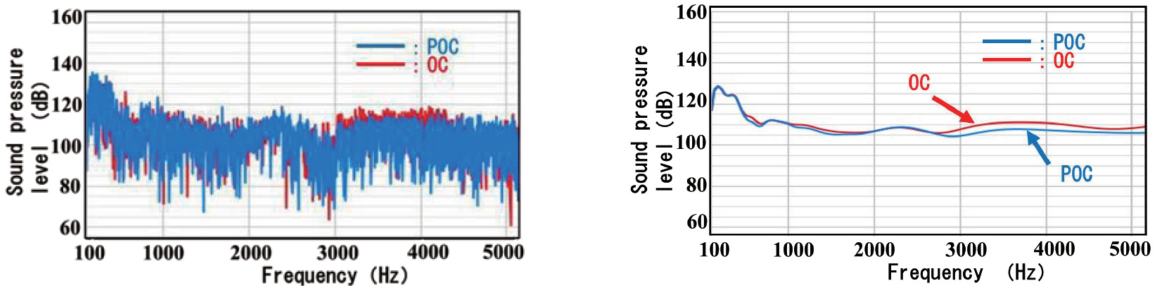
Figure.2 Schematic diagram of the speaker system

3.2 Influence of Porosity on the Oblique Incidence Sound Absorption Coefficient of POC

Figure 5 shows the sound absorption coefficient measurement results for POC using Grade.6 crushed stone, categorized by porosity. At frequencies of 3150 Hz or higher, the sound absorption coefficient measurements stabilized. It was confirmed that the highest sound absorption coefficients were achieved in the order of 15%, 25%, and 35%. This is attributed to the increased volume of interconnected voids, which allows greater sound energy dissipation. In the high-frequency region, a positive correlation was observed between porosity and sound absorption coefficient.



(a) Environmental noise (b) TSP sound source



(c) Measured sounds before correction (d) Measured sounds after correction

Figure.3 Sound pressure level

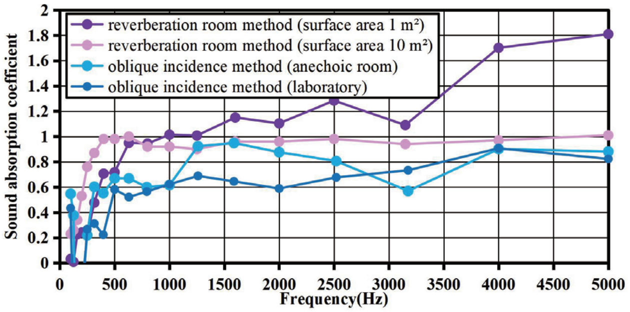


Figure.4 The sound absorption coefficient measurement results for commercially available porous materials using this measurement method

3.3 Influence of particle size of aggregate

Figure 6 shows the sound absorption coefficient results measured for POC with a design porosity of 25%, categorized by particle size of aggregate. As shown in the figure, no significant difference in the sound absorption coefficient was observed across the high-frequency region, indicating that the influence of particle size of aggregate on sound absorbing performance is minimal. Although the target frequency ranges differ from those of the present study, Refs. [6,7] reported noticeable differences in sound absorption coefficients depending on aggregate particle size, suggesting that sound absorption performance may be influenced by aggregate particle size. Based on these findings, further investigations involving finer classifications of aggregate particle size and measurements under different porosity conditions are required to clarify the overall trend.

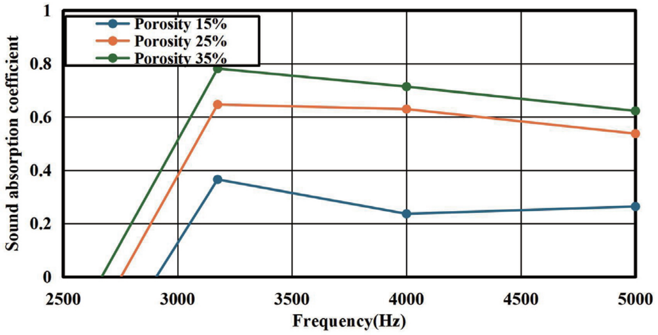


Figure.5 The sound absorption coefficient measurement results by porosity

3.4 Influence of Measurement Surface

Figure 7 shows the measurement results for the differences in the measurement surfaces of the same specimen. As shown in the figure, the sound absorption coefficient at the cast surface was greater than that at the formwork bottom surface in the high-frequency region above 3150 Hz. This is attributed to differences in surface pore structure, as shown in Photo 3, even for the same test specimen, the surface textures differ between the casting surface and the formwork bottom surface owing to paste flow during casting. Furthermore, as shown in Photo 3, the formwork bottom surface of the specimen has almost no voids, whereas the cast surface has numerous voids. Thus, it was confirmed that the sound absorption coefficient of the POC measured using this method was affected by the porosity of the surface layer. In the present study, the surface pore structure was evaluated qualitatively through visual observations, and no quantitative assessment of surface porosity was conducted. For future research, image-based surface porosity evaluation methods, which have been previously applied to porous concrete in previous studies [8], will be employed to quantitatively investigate the relationship between surface porosity and sound absorption coefficient.

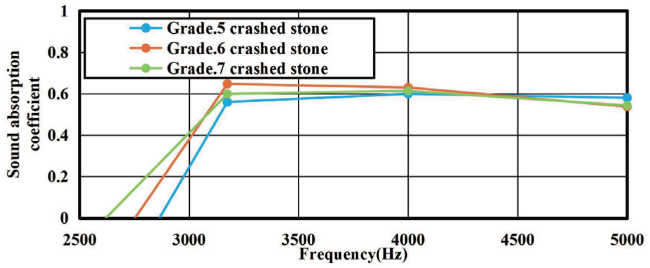


Figure.6 The sound absorption coefficient measurement results by particle size of aggregate3.4 Influence of Measurement Surface

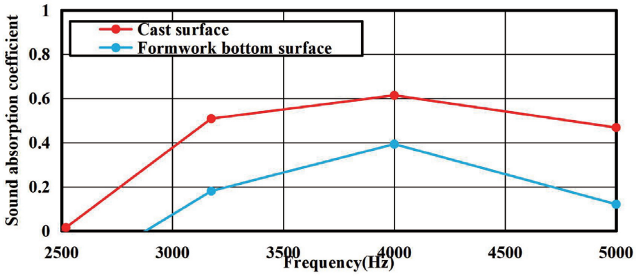


Figure.7 The measurement results for the differences in the measurement surfaces of the same specimen

(a) Cast surface (b) Formwork bottom surface

Photo.3 Surface textures

3.5 Influence of Water Content on the Oblique Incidence Sound Absorption Coefficient of POC

Figure 8 presents the measurement results of the mass and surface moisture contents for each specimen. According to these results, the surface moisture content of the wet specimens was approximately 2–3 times higher than that of the dry specimens, regardless of the differences in porosity.

As shown in the figure9, although the sound absorption coefficients vary depending on the porosity, they were higher in the wet condition than in the dry conditions, indicating an enhancement of sound absorbing performance.

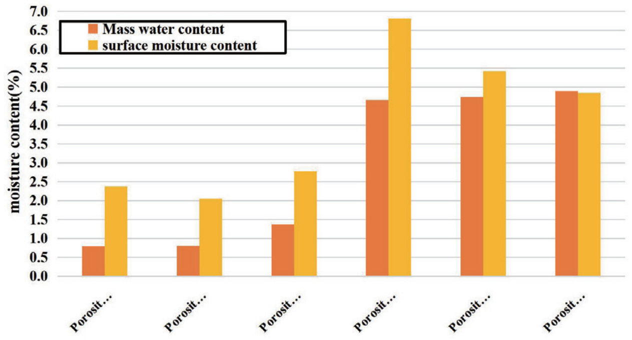


Figure.8 The measurement results of the mass and surface moisture contents

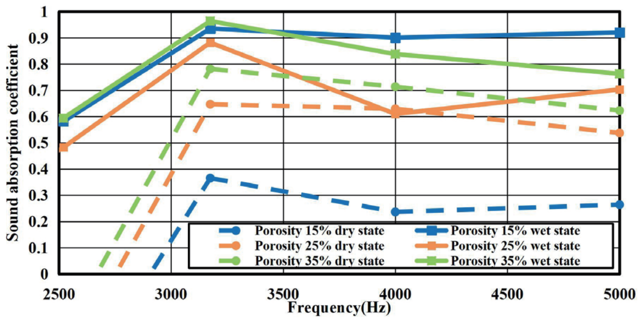


Figure.9 The sound absorption coefficient for each porosity

Figure 9 shows the sound absorption ratio for each porosity condition. The results of this experiment showed that the wet specimens demonstrated sound absorption ratios equal to or higher than those of the dry specimens. This is because most pores in porous concrete are continuous, preventing water from accumulating in the voids; thus, a decrease in sound absorption due to moisture is less likely. Furthermore, the sound absorption performance of porous materials is closely related to acoustic parameters such as porosity, airflow resistivity, tortuosity, viscous characteristic length, and thermal characteristic length [10,11]. An increase in moisture content may alter these acoustic impedance–related parameters, for example by enhancing viscous and thermal dissipation, which may result in the increase in sound absorption coefficients and the shift of absorption peak frequencies observed in this study.

Nevertheless, since an increase in the sound absorption coefficient under wet conditions was observed in this study, it is suggested that porous concrete used as an exterior cladding material is not significantly degraded in terms of sound absorption performance by exposure to moisture.

4. Summary

The findings obtained in this study are summarized below.

(1) The oblique incidence sound absorption method yields lower values than those obtained by the reverberation room

method in accordance with JIS A 1409 (specimen area = 10 m^2), it was suggested that it enables stable measurement of sound absorption coefficient, particularly in the high-frequency region. This suggests that this simplified method can be used to relatively compare and evaluate the influences of different materials and mix designs on sound absorption coefficient.

(2) In the high-frequency region, the higher the porosity of POC, the higher the sound absorption coefficient.

(3) No difference in the sound absorption coefficient was observed based on the particle size of aggregate of POC.

(4) When measuring POC sound absorption coefficient using this method, the voids on the measurement surface significantly affect the sound absorption coefficient.

(5) The sound absorption coefficient of POC increases when wet compared to when dry, suggesting its potential use as an exterior material with improved sound absorption coefficient during rainy weather.

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