Mechanical and Acoustic Properties of Ceramsite Sound Absorbing Boards with Gradient Structure

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Abstract
In this work, ceramsite was utilized to fabricate the sound-absorbing boards, in which two types of structure were considered, specifically, single-layer board with homogenous structure and double-layer board with gradient structure. The physical, mechanical and acoustic properties of these prepared ceramsite sound absorbing boards were studied, including the bulk density, compressive strength, flexural strength, softening coefficient, sound absorption coefficient and sound reduction index. The results show that the double-layer board with appropriate mixture design exhibited almost identical bulk density and mechanical strength to the single-layer board. All ceramsite sound absorbing boards had compressive and flexural strengths of more than 3 MPa and 1 MPa, respectively, and also demonstrated good water resistance. In terms of sound absorption and sound insulation properties, the overall performance of the double-layer board with reasonable gradient structure was better than that of the single-layer board. In addition, the physical structure models of ceramsite sound absorbing boards were established to illustrate the variation of mechanical properties and disclose the mechanism of sound absorption and insulation in the material.

Keywords Ceramsite sound absorbing boards · Gradient structure · Mechanical properties · Acoustic properties · Physical structure model

1 Introduction
With the rapid development of modern industry and transportation industry, noise pollution is becoming more and more serious. It has been reported that noise pollution has escalated into a contemporary worldwide problem, which is listed as one of the four major global pollutions, alongside water pollution, air pollution and solid waste pollution [1]. The relevant surveys have suggested that the residents usually exposed to noise pollution could suffer from hearing loss, and under severe cases, their incidence rate of heart attack would be increased greatly [1, 2]. Especially in the human settlements adjacent to highways, urban viaducts and high-speed railways, the impact of noise has emerged as an increasingly significant issue that justifies considerable effort [2]. Therefore, the urgency to take effective measures of sound absorption and insulation to mitigate noise propagation and protect individuals from overexposure is evident.

Porous sound-absorbing materials have been widely used in noise reduction due to their porous porosity structure, particularly in sound absorption. The major function of porous structures was to provide superior sound absorption performance by the friction behavior of the wall of the pores and the viscosity effect of the air in the pores [3, 4]. Generally, porous sound-absorbing materials can be classified into organic fibrous materials, inorganic fibrous materials, foam sound absorption materials, metal sound absorption materials and cement-based sound absorption materials [5, 6]. The fibrous and foam materials had the main disadvantage of poor strength and durability, and the cost of metal sound absorption materials was too expensive nowadays. Thus, several academics [7–10] have investigated cement-based ceramsite sound absorbing materials, attributing their good sound-absorbing capabilities, adjustable mechanical and durability properties, as well as their considerable economic benefits and environmental sustainability. From the characteristics of raw materials, ceramsite is a type of artificial and environmentally friendly aggregate made of clay...
or shale and manufactured by high-temperature calcination. It is featured with a porous internal structure with a honeycomb shape inside [9, 10]. As a result, ceramsite is a light and porous raw material that is very suitable for sound absorption. On the other hand, cement-based ceramsite sound absorbing material is formed by wrapping and bonding ceramsite particles with cement paste. It means that in addition to the pores that existed in the ceramsite itself, numerous voids are formed by the mutual accumulation of ceramsite particles [10]; thereby, the cement-based ceramsite sound absorbing materials exhibit good sound absorption performance. Existing studies by Luan et al. [7] and Wu et al. [10] have reported that the average sound absorption coefficient (arithmetic mean of sound absorption coefficients of six frequencies, i.e., 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz) of the cement-based ceramsite sound absorbing materials was greater than 0.5. Besides, ceramsite sound absorbing material belongs to cement-based material, which can achieve various properties such as strength and durability.

Although many existing studies reveal that ceramsite sound absorbing material has good sound-absorbing performance at high frequency, but its sound-absorbing coefficients at the low and medium frequencies usually lead to unsatisfactory results [11, 12]. Currently, scholars have adopted some measures to improve the sound absorption coefficient at low and medium frequencies, such as increasing the thickness of the material and reserving an air cavity with a certain thickness behind the material [13, 24, 26]. However, increasing the thickness of the material would increase the bulk density and cost of the material. Also, although the method of reserving air cavity behind the material improves sound absorption performance at low and medium frequencies, ceramsite sound absorbing materials still have a narrow sound absorption band [14, 15]. What is more, for field applications, such as acoustic barriers for traffic noise mitigation, the physical and mechanical properties of ceramsite sound absorbing materials should also be investigated to ensure that the materials have sufficient strength and durability to resist the influence of environmental agents [16]. Therefore, it is necessary to conduct relevant studies on the mechanical and acoustic properties of ceramsite sound absorbing boards with gradient structure to give full play to their advantages and broaden their field application in sound absorption and insulation.

Given the above, single-layer and double-layer ceramsite sound absorbing boards were designed and manufactured in this work. The basic physical–mechanical properties and acoustic properties of these developed boards were studied. Based on the test findings, the effect of gradient structure on physical–mechanical properties and acoustic properties was investigated. At last, the corresponding mechanism was discussed by establishing the physical structure model of material. Overall, this research aimed to provide theoretical reference and technical support for preparing gradient-structured ceramsite sound absorbing materials used in field applications.

2 Experimental Programs

2.1 Design and Preparation of Ceramsite Sound Absorbing Boards

Two types of commercial ceramsite were used as the aggregates, including coarse ceramsite and fine ceramsite. The particle ranges of coarse and fine ceramsite were 0–5 mm and 0–3 mm, respectively. The particle size distributions of coarse and fine ceramsite are shown in Fig. 1. The cement paste was used as the binder, which was mainly composed of P·O 42.5 cement and water. In this study, three kinds of mix proportions (i.e., ➀– ➂) were designed for the ceramsite sound absorbing material in consideration of particle gradation of ceramsite and content of cement paste. The details of the mix proportions are presented in Table 1. The mix ➀ adopted all coarse ceramsite as the aggregates, the mix ➁ used half coarse and half fine ceramsite as the aggregates, and the mix ➂ adopted higher content of cement paste on the basis of mix ➁.

Based on the above mix proportions, three types of ceramsite sound absorbing boards were designed. Specifically, specimen A was a single-layer board prepared by the mix ➀, while specimens B and C were double-layer boards prepared by mix ➀ and mix ➁ or ➂. The length and width of sound-absorbing boards were about 975 mm and 495 mm, respectively. The details of the design schemes are pre-
Table 1 Mix proportions of ceramsite sound absorbing materials (kg/m$^3$)

| Mix | Coarse ceramsite | Fine ceramsite | Cement paste |
|-----|------------------|----------------|-------------|
| ➀  | 710              | 0              | 242         |
| ➁  | 355              | 355            | 242         |
| ➂  | 355              | 355            | 805         |

Table 2 Design schemes of ceramsite sound absorbing boards

| Specimens | The thickness of layer X (mm) | The thickness of layer Y (mm) | Total thickness (mm) |
|-----------|------------------------------|------------------------------|----------------------|
| A (single-layer) | 50 (➀) | 0 (❼) | 50 |
| B (double-layer)  | 35 (➀) | 15 (❼) | 50 |
| C (double-layer)  | 35 (➀) | 15 (❼) | 50 |

The ceramsite sound absorbing boards were manufactured by industrial production technology. The raw materials were mixed and stirred according to the corresponding mix proportion, and then, the ceramsite sound absorbing boards were formed by vibratory compaction. The pressure during the vibratory was around 15 kN, and the vibratory compaction was maintained for 2–4 s. Figure 2a and b shows the vibratory compaction equipment and the formed sound-absorbing boards, respectively.

The formed ceramsite sound absorbing boards were covered with plastic films for preventing the evaporation of free water in mixtures and then were stored in a closed room at ambient temperature for curing. After curing for 28 days, experimental tests were carried out to evaluate the performance of the specimen according to the following test methods.

2.2 Test Methods

2.2.1 Physical and Mechanical Properties

The physical and mechanical properties of the specimen, i.e., bulk density, compressive strength, flexural strength and softening coefficient, were tested as per Chinese standards of [17, 18]. Three plate specimens with a dimension of 100 × 100 × 50 mm were used for the measurement of the bulk density of each group; Three plate specimens with a size of 100 × 100 × 50 mm were tested for the compressive strength of each group, and the compressive surface of specimens was 100 × 100 mm; One plate specimen with a size of 250 × 250 × 50 mm was tested for the flexural strength of each group. The flexural strength of the specimen was tested by three-point bending test as per the Chinese standard of [17], in which the force ($F$) was loaded in the two directions on the midspan of the specimen successively. The schematic diagram of the flexural strength test is shown in Fig. 3. The flexural strength in one direction on the midspan of the specimen was calculated via Eq. (1).

$$f_t = \frac{3FL}{2be^2}$$ (1)

where $f_t$ is the flexural strength (MPa); $F$ is the peak load (N); $L$ is the span (mm); and $b$ and $e$ are, respectively, the width and thickness of the section subjected to flexure (mm).

The softening coefficient was used to characterize the water resistance of the specimen, which was the ratio of the compressive strength of the specimen in the water-saturated...
state to that under the dry state. The water-saturated state was achieved by immersing the specimen in water at 20 ± 2°C for 3d. And the test method was following the above-mentioned compressive strength test. It should be noted that all the above specimens for physical and mechanical properties testing were cored from the corresponding sound-absorbing boards, and the average of the multiple test results was taken as the final result.

2.2.2 Acoustic Properties

In this study, the sound absorption coefficients and the sound reduction indexes of the prepared ceramsite sound absorbing boards were tested in the Chinese National Engineering Research Center for Digital Construction and Evaluation of Urban Rail Transit. In the reverberation room, twenty-one pieces of ceramsite sound absorbing boards (the total area of ceramsite sound absorbing boards was about 10.5 m²) were placed in the room floor for sound absorption coefficients measurements, with the layer X facing upwards (as shown in Fig. 4). The acoustic field was diffuse and the angles of incident sound waves were random in the reverberation room, which was closer to the actual conditions during service. Moreover, the sound absorption volume of the boards was calculated from the average reverberation time of each frequency when the boards were placed and not placed via ISO standard [19], so the sound absorption coefficient at each frequency from the reverberation test could be equal to the average coefficient of multiple tests. Thus, the sound absorption coefficients obtained by the reverberation room were reliable to reflect the sound absorption performance of the materials. The sound reduction indexes were measured in a sound insulation test room. The sound insulation test room consisted of two adjacent reverberation rooms, i.e., the sound source room and the sound reception room. In the test hole between the two rooms, four ceramsite sound absorbing boards were installed, with the layer X of ceramsite sound absorbing board toward the sound source room (as shown in Fig. 5).

3 Results and Analyses

3.1 Physical and Mechanical Properties

Figure 6 shows the physical and mechanical properties of ceramsite sound absorbing specimens. Figure 6a shows that the bulk densities of all the specimens were lower than 1000 kg/m³. As an example, the bulk density of specimen B was 860.8 kg/m³, which was about 1/3 times the density of concrete (around 2400 kg/m³). Also, the bulk density of double-layer specimens B and C was greater than that of the single-layer specimen A. Specifically, the bulk density of specimen B was increased by 1.2%, and the bulk density of specimen C was increased by 17.3%, compared with
specimen A. This was attributable to the more compact accumulation of ceramsite in layer Y of specimens B and C due to the mixing of coarse and fine ceramsite, as well as the fact that layer Y of specimen C had large content of cement paste, which had a higher density than ceramsite.

As demonstrated in Fig. 6b, the compressive strengths of all specimens were greater than 3 MPa. The compressive strength of double-layer specimen B was marginally lower than that of single-layer specimen A, while the compressive strengths of specimens A and B was, respectively, decreased by 7.8% and 10.7% compared with specimen C. As shown in Fig. 6c, the flexural strengths of all specimens were greater than 1 MPa. Comparatively, the flexural strength of double-layer specimen C was the highest, which was almost twice that of specimens A and B. This was because that the flexural strength was mainly determined by the tensile strength of bottom portion, and the layer Y of specimen C had higher tensile carrying capacity attributed to the high-content cement paste. Besides, the mechanical strengths of specimens A and B did not differ significantly, with the variation less than 10%.

Figure 6d shows that the softening coefficients of specimens A, B and C were greater than 0.80, indicating that both single-layer and double-layer specimens exhibited good water resistance. Compared with single-layer specimen A, the softening coefficient of specimen B was increased by 5.7% and reached 0.92, while the softening coefficient of specimen C was decreased by 4.8%.

Fig. 6 Physical and mechanical properties of ceramsite sound absorbing specimens
3.2 Acoustic Properties

3.2.1 Sound Absorption Properties

Figure 7 shows the sound absorption coefficients at 100–5000 Hz of specimens A, B and C. It can be observed that with the increase in the frequencies from 100 Hz to around 1000 Hz, the sound absorption coefficients of all specimens were increased gradually. The maximum absorption coefficient of specimen A was at 1000 Hz, while the maximum absorption coefficients of specimens B and C were at 1250 Hz and 1500 Hz, respectively. It indicates that the first peak of sound absorption coefficient was shifted to higher frequency by introducing gradient structure. This was attributed that the use of gradient structure changed the porosity in layer Y of the specimen, thus influencing the resonance frequency of the specimen. After the frequency of the maximum absorption coefficient, the sound absorption coefficient of the specimen exhibited the trend of decreasing first and then increasing.

Moreover, the sound absorption coefficients at 125, 250, 500, 1000 and 2000 Hz of specimen B were higher than that of specimen A. In specific, the sound absorption coefficients at 125 Hz, 250 Hz, 500 Hz, 1000 Hz and 2000 Hz of specimen B were, respectively, increased by 14.3%, 7.7%, 12.5%, 7.4% and 24.6% compared with specimen A. This indicates that employing proper gradient structure could improve the sound absorption performance at 125–2000 Hz. The sound absorption coefficients at 125–1000 Hz of specimen C were lower than those of specimen A, while the absorption coefficients at 2000 Hz of specimen C were higher than those of specimen A. It suggests that the high compactness adopted in the layer Y of specimen C was not conducive to enhancing the sound absorption performance at low and medium frequencies of the specimen, but could improve the sound absorption property at high frequency (2000 Hz). It is worth noting that specimen A exhibited the highest sound absorption coefficient at 4000 Hz, which was followed by specimen B and specimen C. In addition, the comparison between the double-layer specimens B and C shows that the sound absorption coefficients at 125–1000 Hz and 4000 Hz of specimen B were all higher than those of specimen C, while at the frequency of 2000 Hz, the sound absorption coefficient of specimen B was lower than that of specimen C.

The noise reduction coefficient (NRC) and the average sound absorption coefficient (\(\bar{\alpha}\)) were employed to evaluate the overall sound absorption performance of the specimens, as stipulated in the Chinese standard of \([20]\). Thereinto, NRC and \(\bar{\alpha}\) were calculated via Eqs. (2) and (3), respectively.

\[
\text{NRC} = \frac{\alpha_{125} + \alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000}}{4} \\
\bar{\alpha} = \frac{\alpha_{125} + \alpha_{250} + \alpha_{500} + \alpha_{1000} + \alpha_{2000} + \alpha_{4000}}{6}
\]

where \(\alpha_{125}, \alpha_{250}, \alpha_{500}, \alpha_{1000}, \alpha_{2000} \) and \(\alpha_{4000}\) were the sound absorption coefficient at 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz, respectively.

Table 3 shows the NRC and \(\bar{\alpha}\) of specimens A, B and C. It can be found that specimen B had the highest NRC and \(\bar{\alpha}\), indicating that the sound absorption property of double-layer specimen B with reasonable gradient structure was the best. It is worth noting that the NRC of specimen C was higher than that of specimen A, while the \(\bar{\alpha}\) of specimen C was lower than that of specimen A. This was reasonable as that specimen A exhibited a higher sound absorption coefficient at 4000 Hz compared with specimen C, resulting in a higher average sound absorption coefficient (\(\bar{\alpha}\)) for specimen A. In other words, compared to specimen A, specimen C exhibited better sound absorption performance at 250–2000 Hz, but worse sound absorption property at 125–4000 Hz.

3.2.2 Sound Insulation Properties

Figure 8 shows the sound reduction indexes at 100–5000 Hz of specimens A, B and C. It can be observed that the sound reduction indexes at 100–5000 Hz of specimen C were the highest, with the sound reduction index ranging from 10 to 20 dB. The subsequent were specimen B and specimen A,
which had the sound reduction index ranging from 9 to 15 dB and 7 to 14 dB, respectively.

Table 4 gives the average sound reduction index ($\overline{R}$) of specimens A, B and C, which was calculated via Eq. (4).

$$\overline{R} = \frac{R_{125} + R_{250} + R_{500} + R_{1000} + R_{2000} + R_{4000}}{6}$$  \(4\)

where $R_{125}$, $R_{250}$, $R_{500}$, $R_{1000}$, $R_{2000}$ and $R_{4000}$ were the sound reduction index at 125 Hz, 250 Hz, 500 Hz, 1000 Hz, 2000 Hz and 4000 Hz, respectively.

Table 4 shows that the $\overline{R}$ of double-layer specimen was higher than that of single-layer specimen, specifically, the $\overline{R}$ of specimens B and C was increased by 29.4% and 63.6%, respectively, compared with the specimen A. This indicates that the sound insulation properties of double-layer specimens B and C were significantly enhanced by introducing gradient structure compared with single-layer specimen A. Moreover, the $\overline{R}$ of double-layer specimen C was higher than that of double-layer specimen B due to the high-content cement paste adopted in the layer Y of specimen C.

From the above results of sound absorption coefficient and sound reduction index, it can be concluded that specimen B with appropriate gradient structure not only improved the sound absorption properties but also enhanced the sound insulation performance compared with the single-layer specimen A. It suggests that using proper gradient structure had a positive effect on improving the acoustic performance, i.e., sound absorption properties and sound insulation properties, of the ceramsite sound absorbing board. In addition, the average absorption coefficient of specimen C was decreased compared with the specimen B due to the high-content cement paste in the layer Y, which obstructed the entry and consumption of sound waves to some extent. However, it is worth mentioning that the sound insulation property of specimen C was the best among the three groups of specimens A, B and C due to the dense structure of layer Y.

4 Discussions

4.1 Physical Structure Model

Figure 9 gives the cross-sectional view of specimens A, B and C. The results show that the porosity of single-layer specimen A was 80.1%. For double-layer specimens B and C, the porosity of layer X was 80.1%, while the porosity of layer Y was 75.9% and 67.6%, respectively. The existing research has reported that sound absorption coefficients at 100–4000 Hz of cenosphere-reinforced concrete were all below 0.40, and the noise reduction coefficient (NRC) was lower than 0.16 [21]. It indicates that the cenosphere-reinforced concrete with less porosity was a reflective material rather than a sound-absorbing material. In summary, it was the high porosity of the ceramsite porous boards in this work that the sound waves could easily enter the interior of the boards and then be consumed; thus, ceramsite porous boards exhibited better sound absorption performance than concrete.

A good understanding of the relationship between compositions, structures and properties of ceramsite porous boards with gradient structure was important, and the corresponding physical structure model was established according to the cross-sectional view of specimens A, B and C (Fig. 9). The physical structure models of specimens A, B and C are shown in Fig. 10a–c, respectively. The established model was based on the considerations of gradient structure and the assumption that ceramsite particles with different sizes were regular spheres. The accumulation state of ceramites and the process of absorption, reflection and transmission of the acoustic wave in ceramsite porous materials were shown by the model. Thereinto, incident sound energy, reflected sound energy, absorbed sound energy, consumed heat energy and transmitted sound energy were expressed as $E_{in}$, $E_{re}$, $E_{ab}$, $E_{heat}$ and $E_{tr}$, respectively.

For mechanical properties, Fig. 10a shows that the ceramsite sound-absorbing specimen was composed of ceramsite coated with a layer of cement paste, and there was a weak area between ceramsite and cement paste, i.e., interface transition zone (ITZ) [22]. This suggests that the strength of ceramsite porous material was governed by the strength of aggregate phase (the strength of ceramsite itself), the strength
of cement paste and the bond strength between ceramsite and cement paste, which was consistent with the opinion of Ref. [10]. When the number and gradation of ceramsite phase remained constant, the bond strength between ceramsite and cement paste was dependent on the content of cement paste on the surface of ceramsite. In comparison with the layer Y of specimen B, there were more adhesive sites between adjacent ceramsites in the layer Y of specimen C due to the higher content of cement paste adopted. Thus, the strength of layer Y of specimen C was higher, resulting in the overall compressive and flexural strengths of specimen C being higher than those of specimen B. Moreover, the denser structure from the mixture of coarse and fine ceramsite had a positive effect on the specimen’s strength. At the same time, the total surface area of ceramsite was increased through the mixing of coarse and fine ceramsite; thus, the content of cement paste on the surface of ceramsite was reduced when the total content of cement paste remained constant, resulting in a reduction in the specimen’s strength. As a result, the contribution of the above positive and negative effects led to little variation in the strength of layer Y of specimen B compared to specimen A, as well as in the overall compressive and flexural strengths between specimens A and B.

For sound absorption properties, Fig. 10a shows that the incident sound energy entered the interior of single-layer specimen A when the normal incident acoustic wave was propagated to its surface. There were two main ways to absorb sound energy by the material of layer X. One was that in the process of acoustic wave propagation inside layer X, the acoustic wave vibrated the air of micropores or voids in the materials. The other was that acoustic waves rubbed with the pore wall of ceramsite. The above two main ways led to the sound energy being consumed according to the viscosity resistance of air and the friction effect of the wall of the pores [6, 23]. Subsequently, the transmitted sound energy was formed when the acoustic wave passed through the layer X.

Figure 10b shows the physical structure model of the double-layer specimen B. Unlike specimen A which had only one size of pores, specimen B included two sizes of pores due to the two layers with different mixture design. Thus, when the acoustic wave was propagated to the interface between layer X and layer Y, in addition to part of the acoustic wave entering the layer Y, the other part of the acoustic wave was reflected into layer X for another round of consumption. This was attributed that when the sound waves entered the interface of different media, the reflection phenomenon of sound waves would occur due to the different sound resistivity of the media [24, 25]. So, the double-layer specimen B had two different media (layer X and layer Y), leading to multiple reflection and propagation of sound waves [26–28], thus considerably consuming the sound energy. Therefore, specimen B with proper gradient structure exhibited higher sound absorption coefficients at basically all frequencies than those of specimen A. As a result, the double-layer specimen B had
higher noise reduction coefficient and average sound absorption coefficient compared with the single-layer specimen A.

Figure 10c shows the physical structure model of the double-layer specimen C. It can be observed that layer Y of specimen C was denser compared with specimen B because the internal void was filled with high-content cement paste. When the incident sound energy reached the interface of layers X and Y, most of the sound wave was reflected into layer X, and only a small part of the sound energy was consumed due to the lack of pores or voids in layer Y of the specimen C. As a result, specimen C depended primarily on the sound-absorbing material of layer X to achieve sound absorption, resulting in the lowest average sound absorption coefficient among the three groups of specimens A, B and C.

Additionally, for sound insulation properties, specimen A was the single-layer board with a homogenous structure prepared by coarse ceramsite, which meant the overall pore size of specimen A was the largest among the three groups of specimens. Also, the layer Y of specimen B adopted a mixture of coarse ceramsite and fine ceramsite, and the layer
Table 5 Comparisons of the properties of specimens

| Samples      | Density | Strength | Sound absorption properties | Sound insulation properties |
|--------------|---------|----------|----------------------------|----------------------------|
| Specimen A   | Lowest  | Lowest   | Medium                     | Worst                       |
| Specimen B   | Medium  | Medium   | Best                       | Medium                     |
| Specimen C   | Largest | Highest  | Worst                      | Best                       |

Y of specimen C added more cement paste to the mixture of coarse ceramsite and fine ceramsite. So the compactness of layer Y of specimen C was higher than that of specimen B. The sound insulation principle suggested that the denser the material (the smaller the pore size), the better the sound insulation property [29]. Therefore, the value of transmitted sound energy of specimen A \( (E_{tr1}) \) was the largest, which was followed by specimen B \( (E_{tr2}) \) and specimen C \( (E_{tr3}) \). This was consistent with the results of sound insulation properties in this research. It indicates that the sound insulation performance of the double-layer specimen was better than that of the single-layer specimen, and the sound reduction index was enhanced with the increase in the compactness of the layer Y in the double-layer specimen. In conclusion, an appropriate gradient structure adopted in ceramsite sound absorbing boards could play a good dual role in sound absorption and sound insulation.

### 4.2 Comparisons of the Properties of Specimens

According to the investigation of the physical properties, mechanical properties and acoustic properties of the ceramsite sound absorbing boards in this work, the comparisons of the properties of specimens are given in Table 5. It can be found that double-layer specimen B exhibited promising performance in all aspects, and its sound absorption properties were the best. The double-layer specimen C had the highest strength and the best sound insulation performance, but its sound absorption properties was the worst and its density was the largest. For the single-layer specimen A, although it had the lowest density, its strength and sound insulation performance were worst. In summary, each specimen exhibited its own advantages and disadvantages in properties, and thus, we need to adopt the ceramsite sound absorbing boards with appropriate gradient structure according to the requirements in the actual engineering.

### 5 Conclusions

To provide theoretical reference and technical support for preparing gradient-structured ceramsite sound absorbing boards used in field applications, single-layer and double-layer ceramsite sound absorbing boards were designed and manufactured. The mechanical and acoustic properties, including the bulk density, compressive strength, flexural strength, softening coefficient, sound absorption coefficients and sound reduction indexes, of these prepared ceramsite sound absorbing boards were studied. At last, the corresponding mechanism was discussed. Based on the results from this study, the following conclusions can be drawn:

1. The bulk density, compressive strength and flexural strength of double-layer ceramsite sound absorbing board with suitable mix proportion design were almost identical to those of single-layer ceramsite sound absorbing board.
2. The compressive and flexural strengths of ceramsite sound absorbing boards were greater than 3 MPa and 1 MPa, respectively. All ceramsite sound absorbing boards in this work demonstrated good water resistance, with softening coefficients greater than 0.80. Such good strength and durability of ceramsite sound absorbing boards support their field application in future.
3. Introducing proper gradient structure could improve the sound absorption performance at low and medium frequencies of ceramsite sound absorbing boards. The double-layer board B with reasonable gradient structure exhibited better overall sound absorption properties and overall sound insulation performance at 125–4000 Hz compared with the single-layer board A.
4. The sound insulation properties at 125–4000 Hz of double-layer specimens B and C adopted gradient structure were significantly enhanced compared with the single-layer specimen A. What is more, the compactness of layer Y in double-layer board could not be too high; otherwise, it would reduce the sound absorption property at 125–1000 Hz of ceramsite sound absorbing board.
5. The physical structure model successfully illustrated the process of absorption, reflection and transmission of the acoustic wave in the material and explained the variation of mechanical and acoustic properties of ceramsite sound absorbing board.

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Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

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