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STRUCTURAL THERMAL INSULATING FOAM CONCRETE PROPERTIES FOR FOUNDATION INSULATION

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ABSTRACT: This research aims to study foam concrete density and its correlation with the material thickness, analyzing its impact on the airborne sound reduction index. Several investigations have proven that, in comparison to traditional heavy concrete, the use of lightweight concrete with a density between 900 and 1100 kg/m3 is the most efficient way to soundproof. The study reveals that effective noise protection can be achieved with an 8 cm thickness of the inner partition between rooms in all categories of houses. The research reports that a 10 cm partition thickness is sufficient to attain the required sound reduction index between the bathroom and a room within a single apartment. Additionally, it was found that the required level of soundproofing for walls and partitions between apartments, rooms of apartments, stairwells, halls, corridors, and vestibules varies according to the categories of houses. Specifically, C-category (satisfactory soundproofing) houses require a 12 cm wall thickness, B-category (moderate soundproofing) houses necessitate 14 cm, and A-category (advanced soundproofing) houses demand 16 cm for optimal sound reduction.

Keywords: Non-autoclaved foam concrete, Strength, Thermal conductivity, Airborne sound reduction index.

1. INTRODUCTION

Reducing noise is a pressing challenge in urban environments, as it significantly impacts the quality of life, health, and ecological sustainability of residential, work, and recreational spaces [1]. While modern construction prioritizes cost efficiency, larger living spaces, and convenient transportation access, it often compromises acoustic comfort [2]. This neglect results in inadequate airborne sound reduction index (ASRI) in inter-apartment walls and partitions, ineffective floor structures, and increased structural noise due to monolithic designs. Consequently, many multi-story residential buildings fail to meet acceptable noise level standards, adversely affecting public health and reducing overall living comfort [3,4].

Advances in acoustic materials and noise control strategies emphasize the importance of innovative solutions to enhance sound insulation [5]. Satbayev University (Almaty, Kazakhstan) has developed foam concrete technology to address these issues by manufacturing lightweight panels for non-load-bearing partitions. Current materials used in the construction industry in Kazakhstan, such as split blocks and gas foam blocks, often fall short of modern requirements, as they demand highly skilled labor, fail to provide adequate noise reduction, and do not meet seismic safety standards [6-7]. Thin block-based partitions, in particular, are unable to achieve the required ASRI levels of at least 41 dB for room partitions and 52 dB for inter-apartment walls, as outlined in [8].

Foam concrete panels provide a viable alternative by combining lightweight construction with excellent sound insulation properties. Their use not only addresses acoustic challenges but also aligns with the growing demand for energy-efficient and sustainable building materials. Furthermore, these panels enhance seismic safety, reduce labor costs, and support faster installation, making them a superior choice for contemporary construction practices. An example of ASRI standards for internal enclosing structures is presented in Table 1, further illustrating the need for effective noise reduction measures in residential construction.

Table 1 Normative values of the weighted ASRI for internal enclosing structures R_w

Designation and location of the enclosing structure	R_w, dB
Walls and partitions between apartments, between apartment rooms and stairwells, halls, corridors, lobbies:	
- A-category houses	54
- B-category houses	52
- C-category houses	50
Partitions between rooms, between kitchen and room in an apartment:	
- In A-category buildings	43
- In B- and C-category buildings	41
Partitions between a bathroom and a room in one apartment	47

In Kazakhstan, houses are categorized based on their soundproofing quality into three classes: A for advanced soundproofing, B for moderately soundproofed, and C for satisfactory soundproofing. These categories provide a structured framework for assessing the effectiveness of noise reduction in residential buildings, ensuring that each category meets specific acoustic performance standards. According to [9,10], the Airborne Sound Reduction Index (ASRI) for internal enclosing structures is standardized at 53 dB, irrespective of the building category. This baseline value ensures a minimum acceptable level of sound insulation across all residential spaces, which is particularly critical in urban areas with higher noise levels.

Specialized materials and innovative construction techniques are employed to achieve enhanced soundproofing in higher-category buildings. For instance, foam concrete, recognized for its lightweight and porous structure, effectively absorbs sound waves, while acoustic panels provide additional noise dampening. These materials not only enhance the ASRI but also contribute to thermal insulation, offering dual benefits. The adoption of such advanced solutions aligns with global trends in sustainable construction, where noise control and environmental impact mitigation are key considerations. Similar approaches have been applied to address ecological challenges, as evidenced by studies on waste accumulation and its environmental impact in Kazakhstan [11]. Moreover, the integration of modern soundproofing technologies reflects compliance with evolving noise control regulations, aiming to mitigate urbanization effects and promote well-being.

2. RESEARCH SIGNIFICANCE

This research focuses on investigating foam concrete density and its correlation with material thickness, emphasizing its impact on the airborne sound reduction index. The findings reveal that aerated concrete panels with a density of 1000 kg/m³ are highly effective when used for interior walls. Such panels not only ensure superior sound insulation but also meet fire safety standards, contribute to hygienic indoor conditions, and support practical needs like mounting cabinets, radiators, and other household items. Furthermore, these panels provide a lightweight yet durable construction solution, reducing overall structural loads while enhancing energy efficiency and acoustic comfort in buildings.

3. MATERIALS AND METHODS

The following raw materials were used for the production of foam concrete:

- Portland cement of M500 D0 grade from Heidelberg cement (Bukhtarma Cement Plant in the past);
- Ash component of the ash-slag mixture of Almaty CHP-1;
- Expanded clay sand;
- Additives and a protein-based foaming agent manufactured by Kotloservise LLP.

Tables 2-5 present the physical and mechanical characteristics of the raw materials used.

Table 2 Physical and Mechanical Properties of Portland Cement M500 from Heidelberg Cement Plant

Residue on sieve 008		%	0.8
Normal density		%	28
Setting time	beginning	h-min	2-45
	end	h-min	3-20
Strength at 28 days of curing	flexure	MPa	7.5
	compression	MPa	52.8
Compressive strength after steaming,		MPa	41.1

Table 3 Chemical-Mineralogical Composition of Portland Cement M500 from Heidelbergcement Cement Plant

Oxide content, %					
SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	SO_3
20,85	5.62	4.22	63.52	1.53	2.09
Content of main minerals					
C_3S	C_2S	C_3A	C_4AF		
56.29	16.62	7.28	13.14		

Table 4 Chemical Composition of the Ash Component of the Ash-Slag Mixture of Almaty CHP-1*

Oxide content, %			
Na_2O	MgO	Al_2O_3	SiO_2
0.71	0.40	27.56	61.95
Oxide content, %			
K_2O	CaO	TiO_2	MnO
0.47	1.44	1.12	0.05
p.p.p, %			
3.4			

*Note: *Residue on sieve 008 - 13.5%.*

Table 5 Grain Composition of Expanded Clay Sand*

Sieve size, mm	2.5	1.25	0.63	0.31	0.16	< 0.16
Residue, %	62.0	31.0	6.0	0.8	0.1	0.1

*Note: *Bulk density - 1000 kg/m³*

The following steps were taken -in order- to prepare the foam concrete. Cement, ash, and expanded clay sand were first combined to create a solution combination, which was subsequently combined with foam that had been made separately. To create the foam, an aqueous solution of the foaming agent at a 2.5% concentration was whipped in a 1.5-liter vessel using a stirrer with a perforated paddle. The paddle rotation speed was 1000 rpm. The volume of mixing was prepared at the rate of obtaining 1.15 liters of mixture. Following 28 days of curing at normal temperatures and humidity levels, the 70.7 x 70.7 x 70.7 mm samples were examined using the real standards that apply to cellular concretes, particularly: for average density [12], for moisture content [13], and for compressive strength [14].

The authors' formula was used to manufacture samples of foam concrete panels for acoustic testing in a cassette installation at the experimental base of "Almaty Beton Materialdary" LLP. The article's experimental section outlines the testing procedure used to measure the ASRI of foam concrete panel samples. The panels were made of cellular concrete with an average density of 1000 kg/m^3 in the size of 2800×600×100 mm, which were then cut to obtain slabs in the size of 1200x600x100 mm from which a box-chamber was constructed with the length of the ribs of 1200 mm.

An omnidirectional sound source (dodecahedron AT-001 No. 001 in the set) was put inside a box chamber constructed in the shape of a hollow cube with a rib size of 1.2 m to experimentally determine the ASRI of foam concrete walls that were 10 cm thick and had a material density of 1000 kg/m3. After installation of the AT-001 No. 001 apparatus, the box chamber was sealed completely.

The noise level outside the chamber was recorded using a noise meter PKDU 411000.001RE "Acoustic multifunctional meter Ecofizika" (Fig. 1).

(a) Conducting an experiment

(b) Box chamber

Fig. 1 Preparation of the box with control enclosures for the measurement of the weighted ASRI

The ASRI (R_w) was determined by Eq. (1) recommended in [8]:

$$R_w = 37 \lg m + 55 \lg K - 43 \quad (1)$$

where: m – surface density, kg/m^3; K – a coefficient that considers the relative increase in bending stiffness of enclosures made of lightweight concrete aggregates, porous concretes, etc. compared to structures made of heavy concrete with the same surface density. The value of K for cellular concrete with a density of 1000 kg/m^3 is 1.5, and for a density of 800 kg/m^3 is 1.6. The measured and estimated data was processed in "Signal + 3GRTA" software.

3.1 Quantities Characterizing the Acoustic Properties of Buildings

Impact sound insulation is expressed by two interrelated quantities. These quantities are identified in frequency bands (octave or third-octave bands), from which an assessment of a single number is computed for instance according to [15-16]

$$\boldsymbol{L'_{n,w}}\ ,\ \boldsymbol{L'_{nTw}}\ \boldsymbol{or}\ (\boldsymbol{L'_{nTw}} + \boldsymbol{C}_{\text{l}}) \quad (2)$$

3.2 Normalized Impact Sound Pressure Level (Ln), dB

The following formula determines the impact sound pressure level after accounting for the receiving room's comparable sound absorption area:

$$L_n = L_i + 10lg\frac{A}{A_0} \quad (3)$$

where: L_i -is the average impact sound pressure level in the receiving room, created using a standard tapping machine; A - is the equivalent sound absorption area of the receiving room, m²; A_0- is the standard equivalent sound absorption area (A_0=10 m^2) [15].

* These values are determined in accordance with [15].

3.3 Standardized Actual Sound Pressure Level of Impact Noise

The following formula is used to compute the sound pressure level of impact noise, accounting for indirect sound transmission and matching to the reception room's reverberation duration:

$$L'_{n,} = L_i + 10lg\frac{T}{T_0} \quad (4)$$

where: T - reverberation time of the receiving room, s; T_0 - standard reverberation time (for residential premises is T_0 = 0,5 s);

*These values are determined in accordance with [15].

3.4 Relationship Between Quantities

The relationship between L_{nT} and L_n is determined by the formula:

$$L'_{nT} = L'^{\sim}_{n} - 10lg\frac{0,16V}{A_0T_0} = L'_n - 10lg0,032V \quad (5)$$

where: V - volume of the receiving cheek m3,

Note: These values are determined in accordance with [15].

3.5 Acoustic Characteristics of Building Elements

Building components' acoustic properties serve as the starting point for assessing building characteristics. Third-octave frequency bands are used to calculate these values, as well as octave bands when required. The single-number ratings of the element's characteristics, such as L_{nw} (C_1), ΔL_w $C_{1\Delta}$, or ΔL_{lin} and R_w (C; C_{tr}) can be determined in accordance with [16].

3.6 Normalized Impact Sound Pressure Level (Ln), dB

The following formula determines the impact sound pressure level while accounting for the receiving room's comparable sound absorption area:

$$\boldsymbol{L_n = L_i + 10lg\frac{A}{A_0}} \quad (6)$$

where: L_i -is the average impact sound pressure level in the receiving room, created using a standard tapping machine in accordance with [14], dB; A - is the equivalent sound absorption area of the receiving room, m²; A_0- is the standard equivalent sound absorption area (A_0=10 m^2).

*These values are determined in accordance with [17].

3.7 Reduction of Impact Sound Pressure Level ΔL*dB

The following formula is used to quantify the decrease in impact sound pressure level that results from utilizing the tested floor covering:

$$\boldsymbol{\Delta L = L_{no} - L_n} \quad (7)$$

L_{no} - reduced sound pressure level of impact noise without floor covering, dB; L_n - reduced sound pressure level of impact noise with floor covering, dB.

*These values are determined in accordance with [18].

3.8 Reduction of Impact Sound Pressure Level by Layer DL_d, dB

Reduction of impact sound pressure level by an additional layer on the separating element (floor) from the receiving room side.

*This value is determined in accordance with [18].

3.9 Normalized Flanking Impact Sound Pressure Level $L_{n\,f}$, dB

The following formula is used to determine the average sound pressure level of noise produced in the receiving room by a typical impact machine deployed in various locations within the source room, accounting for the receiving room's equivalent sound absorption area:

$$\boldsymbol{L_{n,f} = L_i + 10lg\frac{A}{A_0}} \quad (8)$$

where: A_0 = 10 m^2.

*Sound transmission is considered only through known secondary elements, for example, a false floor.

*This value is determined in accordance with [19].

*Determination of $L_{n,f}$ of raised floors - according to [20].

3.10 Sound Insulation [of an element] (sound reduction index) R, dB

Ten times the decimal logarithm of the ratio of the sound power W_1 incident on the element under test to the sound power W_2 transmitted through it.

$$\boldsymbol{R = 10lg\frac{w_1}{w_2}} \quad (9)$$

*This value is determined in accordance with [21].

3.11 Sound Reduction Improvement IndexΔR, dB

The difference between the sound insulation of a basic structural element with and without an additional layer (e.g. a suspended ceiling).

3.12 Vibration Reduction Index K_{ij}, dB

The average direction difference in the speed levels through the connection, related to its length and the equivalent absorption length of both elements, if applicable, describes the transmission of vibration power through the connection of elements I and J and is normalized to make it invariant with respect to the dimensions of the elements using the following formula:

$$K_{ij} = \frac{D_{v,ij}+D_{v,ji}}{2} + 10lg\frac{l_{ij}}{\sqrt{a_i a_j}} \quad (10)$$

where: $D_{v,ij}$ - is the difference in the speed levels in the junction of elements / and j when element / is excited, dB; $D_{v,ji}$ - is the difference in the speed levels in the junction of elements / and / when element j is excited, dB; l_{ij} - is the length of the junction of elements / and y, m; a_j - is the equivalent absorption length of element; a_j - is the equivalent absorption length of element j, m.

*The equivalent absorption length is calculated using the formula:

$$a = \frac{2{,}2\pi^2 S}{C_0 T_s}\sqrt{\frac{f_{ref}}{f}} \quad (11)$$

where: T_s - is the structural reverberation time of the element i or j, sec; S -is the area of the element I or j, m^2; f - is the geometric mean frequency, Hz; f_{ref} - is the reference frequency equal to 1000 Hz; c_0 is the speed of sound in air, m/s.

* The equivalent absorption length of an element is the conventional total length of the absorbing edge of an element, assuming that its critical frequency is 1000 Hz, providing losses equal to the real total losses of the element under consideration in a given situation.

*The value of K_{ij} is determined in accordance with [19].

Additional data for calculations are:
- surface density of the element, kg/m^2;
- element type;
- material;
- connection type.

The computed ASRIs were validated by comparing their values to reference values and defining adverse deviations according to [9].

4. RESULTS AND DISCUSSION

The ASRI calculated by the equation recommended in the [8], depending on the density of the concrete at various material thicknesses, is presented in Fig. 2 and Table 6. The information obtained suggests that using lightweight concrete with a density of 900–1100 kg/m3 is more effective than using heavy concrete. This is consistent with a paper that discussed the environment where sound waves propagate [22].

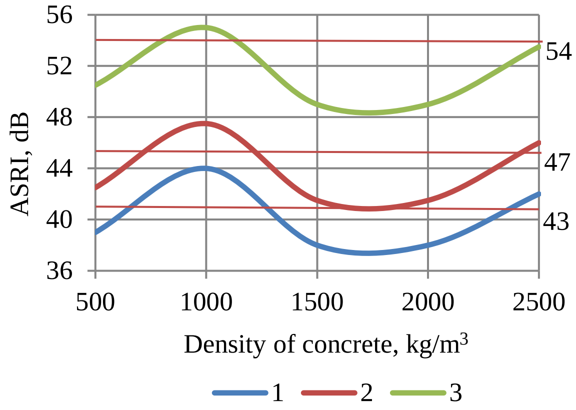

Fig. 2 Dependence of ASRI on concrete density: 1 – 80 mm; 2 – 100 mm; 3 – 140 mm

Table 6 Effect of the thickness of foam concrete with 1000 kg/m^3 density on the ASRI

Thickness of reference structure, cm	8	10	12	14	16
ASRI, dB	43.9	47.5	50.4	53.2	55.1

Estimates show that employing D1000-graded foam concrete, which has a density of 1000 kg/m3, is an effective way to produce panels for interior walls and partitions. Internal room walls in all types of homes have an effective ASRI of 8 cm, whereas the necessary ASRI between a bathroom and a room within an apartment is reached with a thickness of 10 cm.

Wall thicknesses of 12 cm for C-category homes, 14 cm for B-category homes, and 16 cm for A-category homes achieve the necessary degree of soundproofing for walls and partitions between flats, rooms, stairwells, hallways, corridors, and vestibules [23].

The wall thickness needed to achieve the requisite soundproofing is significantly higher when utilizing autoclaved aerated concrete blocks, which are often used in Kazakhstan (see Table 7). However, it is difficult to determine with certainty whether sound reduction requirements are fulfilled in our country while building homes.

Table 7 Effect of the thickness of aerated concrete with 500 kg/m^3 density on the ASRI

Thickness of reference structure, cm	8	10	12	14	16	20	21
ASRI, dB	39.2	42.8	45.5	48.2	50.3	53.9	54.7

Based on the requirements established for internal wall concrete panels, we have developed a composition of constructional-thermal insulation non-autoclaved foam concrete with 1000 kg/m^3 density, compressive strength class of B7.5, and a thermal conductivity coefficient of 0.21 W/(m·°C) [24,25]. The Kazakhstani KazKer LLC, situated in Otar village, Almaty area, produces fine crushed stone sand, which is used as a fine filler. Since construction firms only employ crushed stone gravel with a 5–20 mm fraction to create sound-reducing layers in the flooring of home buildings, the sand is regarded as a by-product at the factory [26]. Crushed stone gravel is no longer used as a lightweight filler in the manufacturing of thermal insulation concretes because of its higher density and resulting thermal conductivity [27,28].

The necessity to accomplish the B5 compressive strength class of foam concrete with 1000 kg/m3 density, which was not possible with sands from dune, river, or screens from rock crushing, explains the usage of ceramsite sand.

We utilized the following raw materials to create 1 m^3 of non-autoclaved foam concrete graded D1000: Portland cement M500 grade – 310 kg, crushed stone sand – 0.49 m^3, ash component of the slag mixture – 90 kg, additives – 7.3 kg, protein foam former – 0.6 liters.

According to an analysis of international building practices, panels must be made to fit the room's proportions, usually measuring no more than 600 mm in width and the room's height in length, in order to be installed using craneless panels. These panels are interconnected using a "tongue-and-groove" system.

Currently, Kazakhstan implements [25] to produce non-autoclaved cellular concretes, with average densities classified by the following grades:

- Thermal insulation – D200, D250, D300, D350, D400, D450, D500;
- Structural-thermal insulation – D500, D600, D700, D800, D900;
- Structural – D800, D900, D1000.

By 28-day age compressive strength, concretes are classified by strength classes (Clause 5.5):

- Thermal insulation – B0.5; B0.75; B1; B1.5;
- Structural-thermal insulation – B1; B1.5; B2; B2.5; B3.5; B5; B7.5; B10;
- Structural – B7.5; B10; B12.5.

According to the data analysis, foam concrete functions as a structural concrete class when its density reaches 1000 kg/m³, with a minimum class for compressive strength of B7.5 (9.83 MPa). This aligns with findings in [29-31], where advanced modeling methods were used to predict compressive strength based on varying material compositions and densities.

The results of tests on sound pressure level (SPL) measurement in the acoustic test room (TR) and box chamber (BC), and ASRI estimation processed in "Signal + 3GRTA" software are presented in Tables 8-14.

Table 8 SPL in TR at mid-geometric frequencies of 1/3-octave bands

Frequency, Hz	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
SPL, dB	35.4	26.9	24.3	22.3	22.0	21.3	20.1	19.7	20.2	20.5	19.6	17.7	15.2	14.1	13.3	12.5

Table 9 SPL in BC and TR at mid-geometric frequencies of 1/3-octave bands for microphone No. 1

Frequency, Hz	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
SPL in BC, dB	58.9	71.0	83.8	88.8	94.5	92.9	91.5	85.1	85.9	82.4	80.5	80.4	85.1	82.2	77.2	76.5
SPL in TR, dB	38.9	46.9	52.6	58.6	59.2	59.0	56.9	51.6	50.5	45.8	44.1	38.2	41.0	38.6	32.3	27.1

Table 10 SPL in BC and TR at mid-geometric frequencies of 1/3-octave bands for microphone No. 2

Frequency, Hz	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
SPL in BC, dB	58.9	71.0	83.8	88.8	94.5	92.9	91.5	85.1	85.9	82.4	80.5	80.4	85.1	82.2	77.2	76.5
SPL in TR, dB	38.9	51.1	51.0	57.7	63.4	58.1	58.7	53.2	52.0	48.0	45.0	41.0	42.8	39.8	34.2	32.3

Table 11 ASRI of enclosure structure in BC (wall panel made of D1000 foam concrete) for microphone No. 1

Frequency, Hz	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
ASRI, dB	23.8	31.5	38.6	37.6	42.7	41.3	42.0	41.0	42.8	44.0	43.8	49.6	51.6	51.1	52.3	56.9
Reference values, dB	33.0	36.0	39.0	42.0	45.0	48.0	51.0	52.0	53.0	54.0	55.0	56.0	56.0	56.0	56.0	56.0
Unfavorable deviations, dB	3.2	0.0	0.0	0.0	0.0	0.7	3.0	5.0	4.2	4.0	5.2	0.4	0.0	0.0	0.0	0.0

Table 12 ASRI of enclosure structure in BC (wall panel made of D1000 foam concrete) for microphone No. 2

Frequency, Hz	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
ASRI, dB	27.4	27.3	40.1	38.5	38.5	42.2	40.2	39.4	41.3	41.9	42.9	46.8	49.8	49.9	50.4	51.6
Reference values, dB	33.0	36.0	39.0	42.0	45.0	48.0	51.0	52.0	53.0	54.0	55.0	56.0	56.0	56.0	56.0	56.0
Unfavorable deviations, dB	0.0	1.7	0.0	0.0	0.0	0.0	3.8	5.6	4.7	5.1	5.1	2.2	0.0	0.0	0.0	0.0

Table 13 Averaged SPL in BC and TR at mid-geometric frequencies of 1/3-octave bands for microphone No. 2

Frequency, Hz	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
Averaged SPL in BC, dB	58.9	71.0	83.8	88.8	94.5	92.9	91.5	85.1.	85.9	82.4	80.5	80.4	85.1	82.2	77.2	76.5
Averaged SPL in TR, dB	41.0	49.5	51.9	58.2	61.8	58.6	57.9	52.4	51.3	47.0	44.6	39.8	42.0	39.2	33.4	30.4

Table 14 Average ASRI of enclosure structure in BC (wall panel made of D1000 foam concrete)

Frequency, Hz	100	125	160	200	250	315	400	500	630	800	1000	1250	1600	2000	2500	3150
ASRI, dB	25.3	28.9	39.3	38.0	40.1	41.8	41.0	40.1	42.0	42.8	43.3	48.0	50.6	50.4	51.3	53.5
Reference values, dB	33.0	36.0	39.0	42.0	45.0	48.0	51.0	52.0	53.0	54.0	55.0	56.0	56.0	56.0	56.0	56.0
Unfavorable deviations, dB	1.7	0.0	0.0	0.0	0.0	0.7	3.0	5.0	4.2	4.0	5.2	0.4	0.0	0.0	0.0	0.0

The ASRI for 1000 kg/m³ density cellular concrete walls with a 100 mm thickness ranges between 45 and 46 dB, meeting the specifications for highly comfortable living conditions [4,31].

5. CONCLUSION

In conclusion, the effectiveness of aerated concrete panels with a density of 1000 kg/m³ for internal partitions is confirmed by experimental findings. The D1000 grade of cellular concrete offers a balance of strength and sound-reducing qualities. Additionally, it ensures fire safety, healthy indoor conditions, and supports wall-mounted fixtures like cabinets and radiators. When the box chamber and production area were separated by D1000 panels, the airborne sound reduction index measured 45–46 dB, meeting the standards for highly comfortable living conditions.

6. ACKNOWLEDGMENT

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