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Vibro-acoustic testing on impact sound performance of novel floating floor systems with polyurethane cushions

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ABSTRACT

Impact sound transmission in concrete slabs is a persistent challenge in building acoustics, particularly in residential and commercial environments. This study introduces a novel floating floor design utilizing polyurethane cushions of various 3D shapes and sizes to mitigate impact noise. The aim is to improve acoustic performance across a wide frequency spectrum while maintaining flexibility and practicality in installation. Two floating floor configurations — fully-filled and half-filled systems — were experimentally tested on twenty-two specimens under controlled laboratory conditions. Fully-filled systems achieved significant impact sound reductions of up to 6.8 dB, delivering consistent performance in mid to high frequencies and low frequencies when appropriately configured. In contrast, half-filled systems were effective at controlling low-frequency noise but demonstrated limitations at higher frequencies due to resonance sensitivity and variability in configurations. Parametric studies revealed that optimizing polyurethane cushion properties, such as elastic modulus and height, enhanced overall impact sound performance. Additionally, incorporating lightweight concrete layers significantly improved low-frequency insulation. Fully-filled systems consistently outperformed conventional methods, delivering comprehensive and reliable sound insulation. However, half-filled systems require further refinement for broader acoustic applications. This research highlights the critical role of cushion material properties, structural configurations, and multi-layer designs in effective impact sound control, providing a solid foundation for next-generation floating floor systems tailored to advanced acoustic insulation needs.

1. Introduction

Noise exposure has widespread psychological and physiological impacts on human health [1]. Chronic environmental noise, such as traffic or aircraft noise, has been linked to elevated stress levels, increased blood pressure, and heightened secretion of stress hormones like epinephrine and norepinephrine, contributing to cardiovascular diseases [2–5]. Noise levels exceeding 85 dBA have been shown to significantly increase blood pressure, while ambient traffic noise above 60 dBA adversely affects children's cardiovascular health, including elevated heart rate and blood pressure [6,7].

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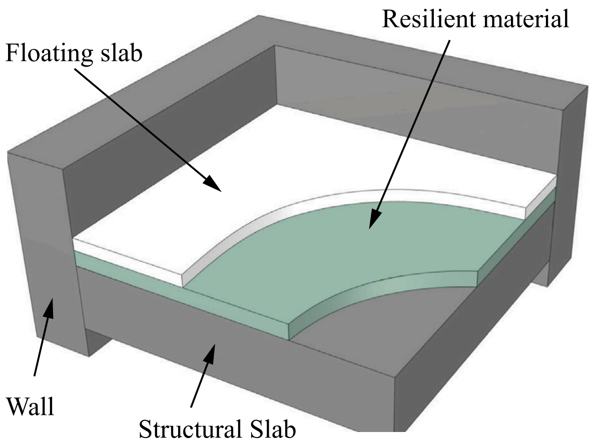


Fig. 1. Typical floating floor system.

In residential settings, noise disrupts mental well-being through annoyance, sleep disturbances, and heightened psychological stress. Footstep noise is a particularly disruptive form of residential noise, impairing sleep quality and mental health [8]. Dissatisfaction with neighbor noise has been associated with mental health risks [9], and floor impact noise has been shown to correlate with physical and mental health complaints [10]. These findings underscore the importance of effective noise management strategies to enhance residential quality of life.

The problem of noise is particularly relevant in densely populated regions like South Korea, where more than half of all residents live in apartments, and in the European Union, where nearly 40% of the population resides in multi-unit dwellings [11]. While these housing solutions are efficient in optimizing land use and providing urban convenience, they also present challenges in managing noise transmission between units.

Floor impact noise — resulting from activities such as walking, furniture movement, and dropped objects — is a major concern in multi-unit residences due to its transmission through structural elements [12,13]. This noise significantly disrupts quality of life and has been linked to adverse health effects, including sleep disturbances and stress [14,15]. Surveys consistently rank floor impact noise among the most disruptive factors in residential environments [16]. In South Korea, increasing complaints about floor impact noise have prompted stricter regulations mandating the replacement of traditional flooring systems with certified noise-insulating alternatives [11,17].

Strategies to mitigate floor impact noise include thicker slabs, sound-absorptive materials, and floating floor systems [18]. Among these, floating floor systems — rigid surfaces decoupled from structural slabs by resilient layers — stand out as effective solutions, particularly for retrofitting existing buildings [11,19]. Fig. 1 illustrates a typical floating floor structure [20]. However, the performance of conventional floating floors is inconsistent at low frequencies, especially in environments with complex structural dynamics or varying room geometries.

Extensive research highlights the importance of resilient layer properties, particularly dynamic stiffness, in determining the effectiveness of floating floors [21,22]. Analytical models have improved the understanding of sound insulation in multilayer systems, capturing critical phenomena such as resonance and air gap effects [23–25]. Sustainable materials, such as recycled rubber and environmentally friendly fibrous layers, have shown potential for acoustic applications [26,27]. Despite these advancements, critical gaps remain in low-frequency impact noise mitigation, inconsistent performance of conventional systems, and the lack of adaptable, modular designs for diverse residential needs [28–30].

This study aims to develop and evaluate a modular floating floor system that addresses the limitations of conventional noise mitigation methods. The system incorporates polyurethane cushions with varied 3D shapes and sizes, arranged in uniform panels, with sound-absorbing materials filling the inter-cushion spaces. Its modular design facilitates tailored configurations for specific acoustic requirements and enables on-site adjustments, offering enhanced flexibility and adaptability across diverse residential environments. A key innovation of this work is its targeted focus on low-frequency noise mitigation, a critical gap in existing solutions. The modular system's adaptability to various building types and acoustic challenges provides a robust and versatile approach to residential noise control, making it a practical solution for improving living environments in multi-unit housing.

Twenty-two specimens were tested under controlled laboratory conditions following KS F 2810-2 standards for heavy-weight impact noise assessment [31]. The acoustic performance of the proposed floating floors was compared to that of a bare concrete slab. This study provides valuable insights into the material properties, structural configurations, and design parameters that influence the effectiveness of floating floor systems, laying the groundwork for advanced noise control solutions in diverse building engineering applications.

Table 1
Layer compositions and thicknesses for the full-filled and the half-filled floating floor specimens.

Type	Name	Layer	Material	Thickness (mm)	Thickness of a panel (mm)
Full-filled floating floor	Type 1a	1	Mortar	40	68
		2	Polypropylene (PP) board	3	
		3	Mineral wool	25	
			Cuboid polyurethane cushion	25	
	Type 1b	1	Mortar	40	110
		2	Lightweight concrete	30	
		3	Polypropylene (PP) board	3	
		4	Mineral wool	37	
			Cuboid polyurethane cushion	37	
Half-filled floating floor	Type 2	1	Mortar	40	96
		2	Polypropylene (PP) board	3	
		3	Expanded Polystyrene (EPS)	30	
		4	Polypropylene (PP) board	3	
		5	Cone polyurethane cushions	20	

2. Concept of the novel floating floor with polyurethane cushions

This study presents a novel floating floor system designed to enhance impact sound reduction using 3D-shaped polyurethane cushions as resilient elements. These cushions are strategically positioned within the system, with sound-absorbing materials filling the spaces between them to optimize acoustic performance. The modular design allows for adjustments in the number, shape, size, and arrangement of the cushions, tailoring the system's stiffness and damping properties to specific acoustic requirements. Its panel-based construction ensures consistent performance, simplifies installation, and supports adaptability for both new construction and retrofitting in diverse building types.

The concept includes two primary configurations of floating floor systems with polyurethane cushions: fully-filled and half-filled systems. The fully-filled systems are presented in two types. Type 1a is a 3-layer system that includes (1) a mortar layer, (2) a Polypropylene (PP) sheet, and (3) cuboid-shaped polyurethane cushions paired with a mineral wool layer that matches the cushions' height (see Fig. 2a). Type 1b is a 4-layer structure, incorporating (1) a mortar layer, (2) a lightweight concrete layer, (3) a PP sheet, and (4) a mineral wool layer aligned with the cushion height (see Fig. 2b).

The half-filled system, designated as Type 2, features a 5-layer structure composed of (1) a mortar layer, (2) a PP sheet, (3) an Expanded Polystyrene (EPS) layer, (4) an additional PP sheet, and (5) cone-shaped polyurethane cushions strategically arranged to maximize sound reduction (see Fig. 2c).

This modular approach effectively addresses low-frequency noise, a known challenge in conventional systems, and enhances adaptability to diverse architectural and acoustic needs. The system's practicality for retrofitting and its ability to meet varying structural demands make it a versatile solution for residential and commercial applications.

3. Experimental program

3.1. Floating floor specimen description

Vibro-acoustic tests were conducted to assess the impact sound reduction capabilities of two novel types of fully-filled floating floor systems and one half-filled floating floor system, with bare slabs serving as a reference for comparison. Each specimen was tested under identical conditions using a simplified method that enables the testing of small specimens.

To create each specimen, three panels with identical dimensions of $600{\times}600$ mm were assembled and overlaid with a mortar layer measuring 1100×2000 mm, forming a complete test unit (Fig. 3). The layer composition and thickness for each panel configuration in the full-filled and half-filled floating floor systems are detailed in Table 1. In the Type 1a full-filled floating floor system, the structural composition included three primary layers: a 40 mm mortar layer, a 3 mm PP sheet, and cuboid-shaped polyurethane cushions embedded within a 25 mm mineral wool layer. The Type 1b configuration extended this by introducing an additional 30 mm lightweight concrete layer beneath the mortar. In this modified setup, the cuboid polyurethane cushions measured 37 mm in height and were similarly embedded within a 37 mm mineral wool layer for consistent layer alignment. In contrast, the Type 2 half-filled system is designed with five layers, including a 40 mm mortar layer, a 3 mm PP sheet, a 30 mm EPS layer, an additional 3 mm PP sheet, and cone-shaped polyurethane cushions with a height of 20 mm.

To optimize impact sound performance, the study investigated five design parameters: polyurethane cushion section and height, arrangement of cushions on each panel, material composition of the polyurethane cushions, and the effect of incorporating a lightweight concrete layer. These parameters were evaluated in detail to enhance the overall acoustic properties of the floating floor systems. Eight layouts (L1-L8) were implemented to analyze the effect of polyurethane cushion distribution and quantity on acoustic performance (Fig. 4). Layouts L1 to L6 featured cushions of identical size, evenly distributed across the panel, with cushion numbers increasing from 6 to 49. Layouts L7 and L8 included mixed cushion sizes to examine the influence of varying cushion geometries.

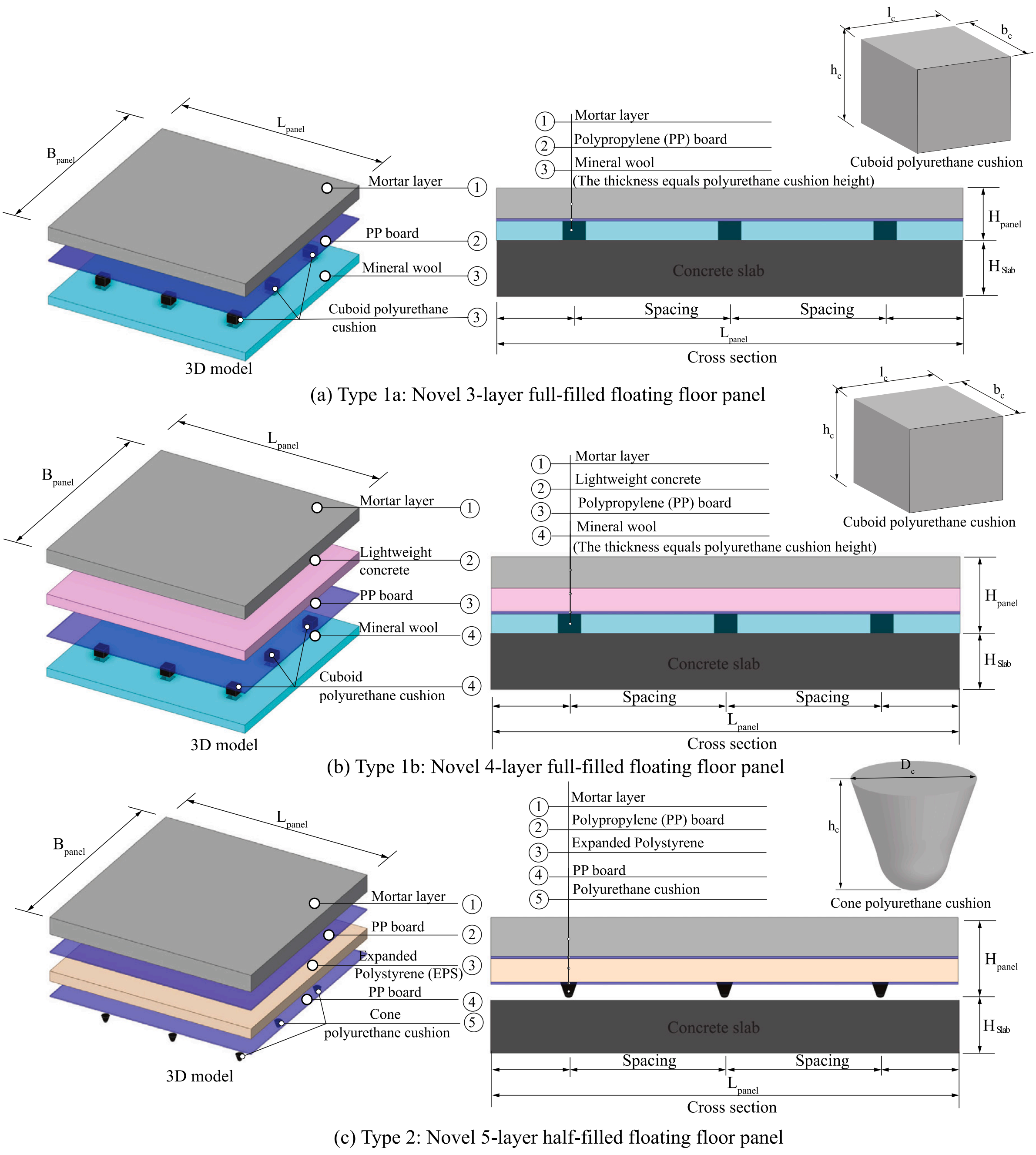


Fig. 2. Configuration and cross-section of a module of novel floating systems.

The study further explored the impact of cushion section and height on acoustic performance. For the full-filled systems, cuboid-shaped cushions in five different sizes (C1 to C5) were utilized, while a single cone-shaped cushion (Co1) was employed in the half-filled system. The specifics of each cushion shape and height are outlined in Table 2 and Fig. 2.

Damping elastomers, such as Sylomer and Sylodyn, are recognized for their positive impact on sound insulation [32]. In this study, seven polyurethane-based elastomers, including Sylodyn NC, Sylodyn NE, Sylomer SR-110, Sylomer SR-220, Sylomer SR-450, Sylomer SR-850, and Sylomer SR-1200, with Young's moduli ranging from 1.1 to 9.37 MPa, were selected for use in cushion fabrication. The material properties of the polyurethane cushions, as well as those of mineral wool, mortar, expanded polystyrene (EPS), and lightweight concrete used in the specimens, are provided in Table 3.

A total of 22 specimens were prepared to support a comprehensive analysis, including 18 Type 1a (T1 A) full-filled specimens, 1 Type 1b (T1B) full-filled specimen, and 3 Type 2 (T2) half-filled specimens. Each specimen was labeled to indicate the floating

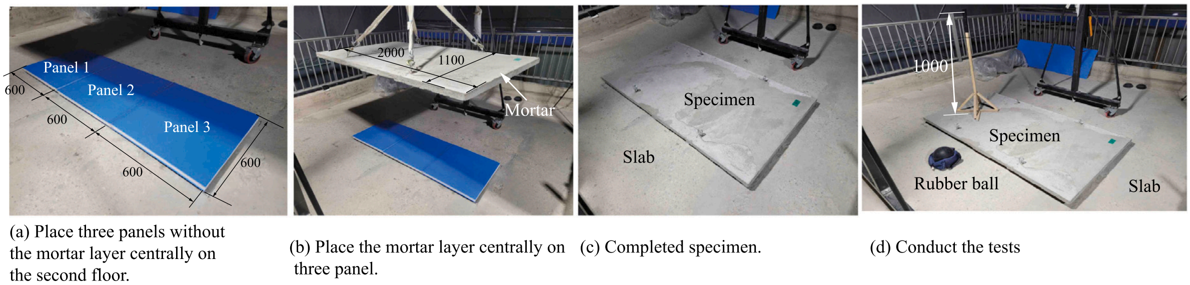


Fig. 3. The experimental procedure.

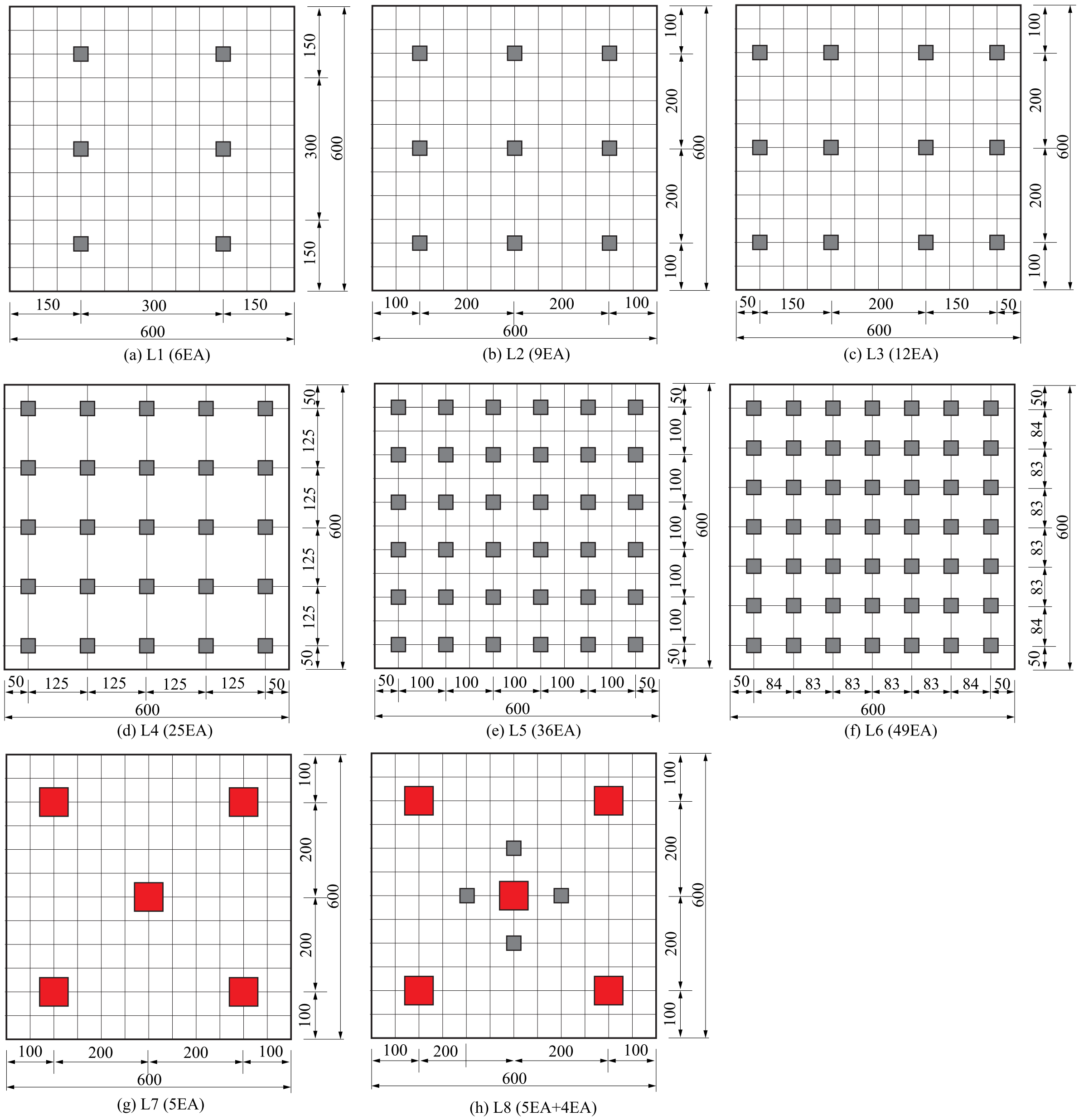


Fig. 4. Arrangement of polyurethane cushions in the panel.

Table 2
Configuration of the polyurethane cushions.

No	Ruber cushion	Type	Height (h_c) (mm)	Width (b_c) (mm)	Length (l_c) (mm)	Thickness (t_c) (mm)	Diameter(D_c) (mm)
1	Cuboid	C1	25	15	15	–	–
2		C2	25	30	15	–	–
3		C3	25	30	30	–	–
4		C4	25	60	60	–	–
5		C5	37	30	30	–	–
6	Cone	Co1	20	–	–	–	20

Table 3
Material properties.

No.	Material	Density (kg/m3)	Young's Modulus (MPa)	Poisson's ratio
1	Polyurethane Sylodyn NC	1000	1.1	0.4
2	Polyurethane Sylodyn NE	1000	6.55	0.4
3	Polyurethane Sylomer SR-110	1000	0.83	0.4
4	Polyurethane Sylomer SR-220	1000	1.47	0.4
5	Polyurethane Sylomer SR-450	1000	3.36	0.4
6	Polyurethane Sylomer SR-850	1000	7.23	0.4
7	Polyurethane Sylomer SR-1200	1000	9.37	0.4
8	Mineral wool	32	0.1	0.05
9	Concrete	2400	27 000	0.167
10	Expanded Polystyrene (EPS)	25	8	0.3
11	Mortar	2100	11 000	0.167
12	Lightweight Concrete	500	1200	0.2

Table 4
Description of the specimen structures.

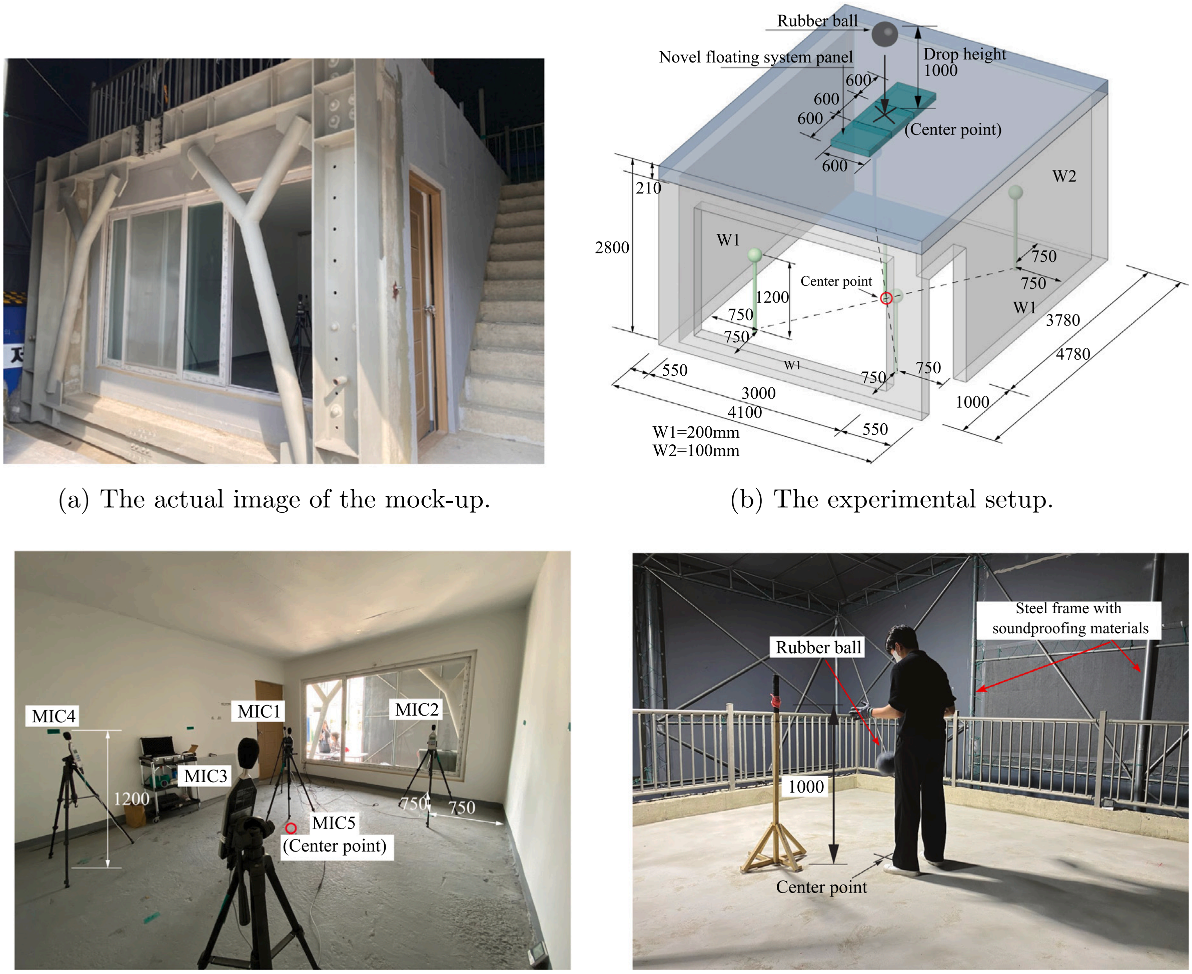
No.	Type	Specimens	Cushion shape	Type	Layout	Cushions per a panel	Cushion's material
1	–	Bare slab	–	–	–	–	–
2	Type 1a (T1A)	T1A-NC-C3-L2	Cuboid	C3	L2	9	NC
3		T1A-NE-C1-L2	Cuboid	C1	L2	9	NE
4		T1A-NE-C1-L5	Cuboid	C1	L5	36	NE
5		T1A-NE-C2-L5	Cuboid	C2	L5	36	NE
6		T1A-NE-C3-L2	Cuboid	C3	L2	9	NE
7		T1A-NE-C3-L3	Cuboid	C3	L3	12	NE
8		T1A-NE-C3-L1	Cuboid	C3	L1	6	NE
9		T1A-NE-C5-L2	Cuboid	C5	L2	9	NE
10		T1A-SR110-C3-L2	Cuboid	C3	L2	9	SR110
11		T1A-SR110-C4-L7	Cuboid	C4	L7	5	SR110
12		T1A-SR220-C3-L2	Cuboid	C3	L2	9	SR220
13		T1A-SR450-C1-L5	Cuboid	C1	L5	36	SR450
14		T1A-SR450-C2-L5	Cuboid	C2	L5	36	SR450
15		T1A-SR450-C3-L2	Cuboid	C3	L2	9	SR450
16		T1A-SR850-C2-L5	Cuboid	C2	L5	36	SR850
17		T1A-SR850-C3-L2	Cuboid	C3	L2	9	SR850
18		T1A-SR1200-C3-L2	Cuboid	C3	L2	9	SR1200
19		T1A-(SR110-C3+SR1200-C4)-L8	Cuboid	C3 C4	L8	4 5	SR110 SR1200
20	Type 1b (T1B)	T1B-NE-C5-L2	Cuboid	C5	L2	9	NE
21	Type 2 (T2)	T2-NE-Co1-L4	Cone	Co1	L4	25	NE
22		T2-NE-Co1-L5	Cone	Co1	L5	36	NE
23		T2-NE-Co1-L6	Cone	Co1	L6	49	NE

Note: Each specimen was labeled as follows: Floating floor type-Cushion material-Cushion Shape-Cushion Layout.

floor type, cushion material, cushion shape, and cushion layout, as detailed in Table 4. For example, the label "T1A-NE-C1-L2" corresponds to a Type 1a floating floor system utilizing NE material cushions with shape C1 and layout L2.

3.2. Experimental setup

In South Korea, reinforced concrete (RC) bearing wall structures are the predominant choice for multi-story residential buildings due to their cost-effectiveness and expedited construction process. For this study, a one-story mock-up was constructed at the Korea Disaster Prevention Technology Company Ltd. research facility in Gyeonggi Province to simulate typical residential settings (see Fig. 5(a)). The mock-up was designed according to the Korean standard KS F 2810-2, which outlines testing protocols for heavy-weight impact noise [31].



(a) The actual image of the mock-up. (b) The experimental setup.

(c) Microphones in mock up. (d) Impact applied on the floating floor.

Fig. 5. The experimental setup for impact sound measurement.

To ensure measurement accuracy, the mock-up was constructed in an isolated location, away from residential areas, and enclosed in a steel frame with soundproofing materials. Additional soundproofing was applied to the door to further reduce background noise.

Fig. 5(a) presents the RC one-story, one-room mock-up building with dimensions of 4630×3900 mm and a height of 2590 mm [33]. The structural slab is 210 mm thick, reflecting typical multifamily housing characteristics in Korea [34]. Walls W1 and W2 are 200 mm and 100 mm thick, respectively. Five measurement points were selected in the room: one at the center of the first floor and four 750 mm from each wall [35]. Fig. 5(b) illustrates the experimental setup. Microphones were installed at a height of 1200 mm, as shown in Fig. 5(c).

To obtain response variable data, measurements were performed on various novel floating floor system panels. Each floating floor specimen, comprising three novel floating panels, was sequentially installed at the center of the mockup's second floor. A standard rubber ball drop [35–39] was used to generate the impact force at the center of each specimen, simulating low-frequency impact sources such as human footsteps. The impact ball, a hollow sphere with a 32-mm-thick silicone rubber wall and an external diameter of 178 mm, was dropped from a height of 1000 mm, resulting in an impact time of 20 ms (see Fig. 5(d)). Fig. 6 shows the force spectrum for the impact ball.

The impact force exposure level created by rubber ball, L_{FE}, is determined using Eq. (1) [40].

$$L_{FE} = 10\log\left(\frac{1}{T_{ref}}\int_{t_1}^{t_2}\left(\frac{F(t)}{F_0}\right)^2 dt\right) \tag{1}$$

where $F(t)$ is the instantaneous force acted on the floor under test when the rubber ball is dropped on the floor, $F_0 = 1\,\mathrm{N}$ is the reference force, $t_2 - t_1$ is the time duration of the impact force [s], $T_{\mathrm{ref}} = 1\,\mathrm{s}$ is the reference time interval.

The experimental procedure, as shown in Fig. 3, involves the following steps:

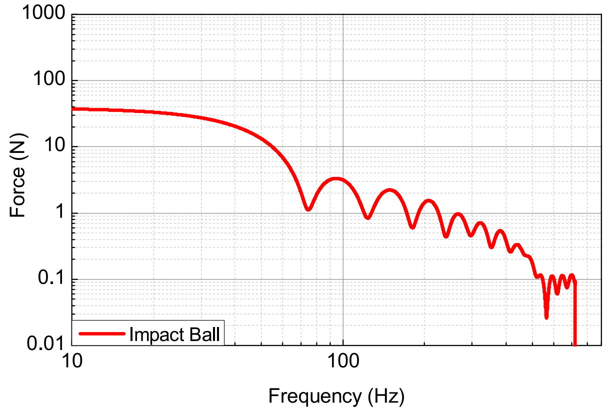


Fig. 6. Force spectrum of the impact ball.

(a) Place three panels without the mortar layer centrally on the second floor.
(b) Place the mortar layer centrally on the three panels.
(c) The specimen is completed with the mortar layer placed on the three panels.
(d) Conduct the tests using a rubber ball dropped from a height of 1000 mm onto the completed specimen to measure the impact sound.

Both Korean and ISO standards [36,41,42] recommend single number quantities (SNQs) for evaluating heavyweight impact sounds in buildings. The three SNQs presented in KS F 2863-2 include $L_{i,\mathrm{Fmax,Aw}}$ (inverse A-weighted impact sound pressure level), $L'_{iA,F_{\max}}$, and $L_{i,\mathrm{Avg,Fmax(63\text{-}500)}}$ (arithmetic average of maximum sound pressure levels in octave bands from 63 Hz to 500 Hz). Among these, $L'_{iA,F_{\max}}$ is used to classify the floor impact sound level. This study adopts the A-weighted maximum impact sound pressure level $L'_{iA,F_{\max}}$ as the primary SNQ, calculated as follows:

1. *Sound Pressure Level Measurement*: Sound pressure levels were recorded at five locations per tapping point. Corrections for background noise were applied when the difference between the background noise and the measured sound levels was between 6 dB and 15 dB. The corrected sound pressure level, L, was determined as follows:

$$L = 10\log\left(10^{L_{sb}/10} - 10^{L_b/10}\right) \tag{2}$$

where:

- L: corrected sound pressure level in decibels (dB),
- L_{sb}: measured sound pressure level including background noise in dB,
- L_b: background noise level in dB.

2. *Averaging maximum sound pressure levels*: The maximum sound pressure levels from the five positions on the floor below each tapping point were averaged as follows:

$$L_{i,F_{\max},j} = 10\log\left(\frac{1}{m}\sum_{k=1}^{m} 10^{L_{F_{\max},k}/10}\right) \tag{3}$$

where:

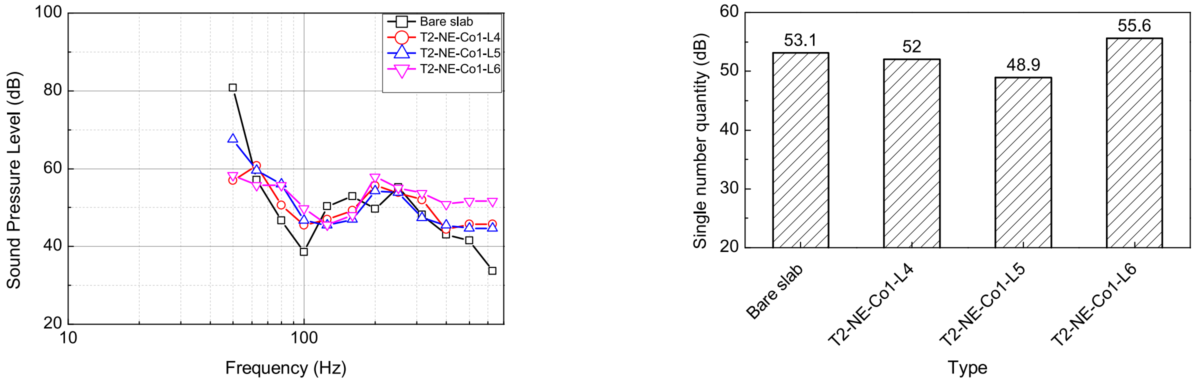
- $L_{i,F_{\max},j}$: average maximum sound pressure level at the i-th tapping point,
- $L_{F_{\max},k}$: maximum sound pressure level at the k-th microphone position.

3. *Final impact sound level calculation*: The final impact sound level, averaged across all tapping points, was calculated as:

$$L_{i,F_{\max}} = 10\log\left(\frac{1}{n}\sum_{k=1}^{n} 10^{L_{i,F_{\max},k}/10}\right) \tag{4}$$

where:

- $L_{i,F_{\max}}$: average maximum sound pressure level for the i-th tapping point.



(a) Sound pressure level

(b) Single number quantity

Fig. 7. Comparison of impact noise response test results of half-filled floating floors (Type 2) and bare slab.

4. *Applying A-weighting for the final SNQ*: To calculate the SNQ $L'_{iA,F_{\max}}$, A-weighting adjustments were applied to account for human hearing sensitivity, as follows:

$$L'_{iA,F_{\max}} = 10\log\left(\sum_j 10^{(X_{i,F_{\max},j}+A_j)/10}\right) \tag{5}$$

where:

- $X_{i,F_{\max},j}$: maximum sound pressure level for each frequency band,
- A_j: A-weighting correction factor for each frequency band.

Values for $L_{i,F_{\max},j}$, $L_{i,F_{\max}}$, and $L'_{iA,F_{\max}}$ were computed at each octave band center frequency, excluding one-third octave bands below 50 Hz and above 630 Hz. All sound pressure levels are reported in dB.

4. Test results

This section provides an analysis of the test measurements for sound pressure levels and SNQ values ($L'_{iA,F_{\max}}$), comparing the impact sound performance of full-filled and half-filled floating floor systems against a bare slab. The detailed measurement data are presented in Table A.5.

4.1. The impact noise reduction performance of the half-filled floating floor

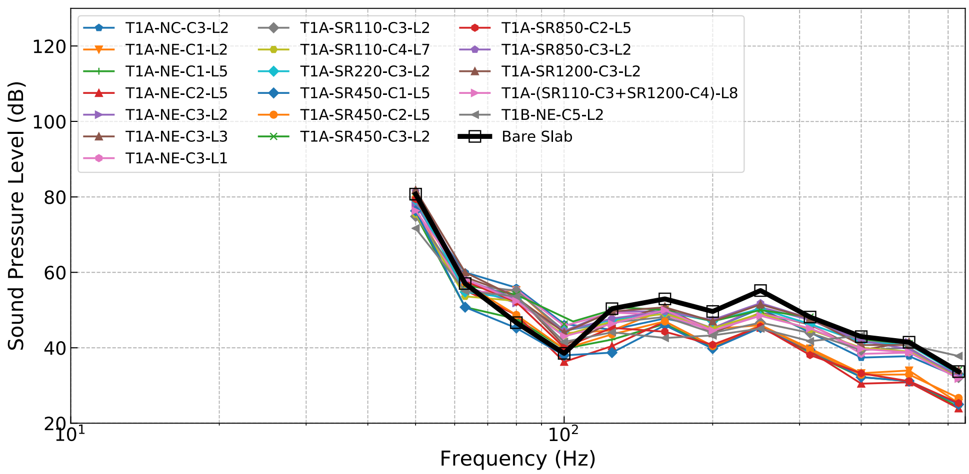
The half-filled floating floor system, utilizing cone-shaped polyurethane cushions (Co1) in configurations such as L4, L5, and L6, demonstrated strong performance in reducing low-frequency noise, particularly at 50 Hz, with sound pressure reductions of 13.24 to 23.84 dB compared to bare slabs (Fig. 7(a)). However, its performance declined notably at higher frequencies (63 to 630 Hz). This reduction can be attributed to the gaps between the polyurethane cushions, which create resonance effects between the concrete slab and the mortar layer, amplifying mid-to-high frequency sounds and limiting the system's overall efficiency. The SNQ reduction was moderate, ranging from 1.1 to 4.2 dB, and in certain configurations, such as L6, sound levels even increased by 2.5 dB (Fig. 7(b)), reflecting inconsistency in performance across different setups.

The non-linear acoustic behavior caused by these gaps complicates optimization, as changes in cushion configuration lead to unpredictable variations in noise reduction. This makes the half-filled system less versatile and reliable for applications requiring comprehensive noise control across a wider frequency range.

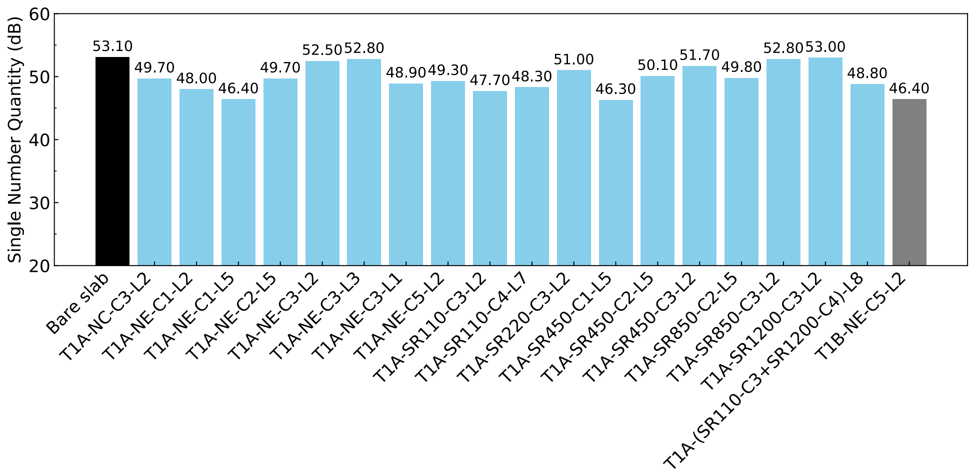
4.2. The impact noise reduction performance of the full-filled floating floor systems

The comparison of impact noise response test results, illustrated in Fig. 8, underscores the varying effectiveness of the novel floating floor systems (Type 1) in reducing sound impact across frequency ranges. The performance of these systems is shown to depend significantly on their configuration and the frequency range.

As shown in Fig. 8(a), the 3-layer floating floor systems (Type 1a) demonstrated limited effectiveness in reducing impact noise within the low-frequency range (50–100 Hz). Configurations employing cushions such as C3 with panel layout L2 (e.g., specimens T1A-NC-C3-L2, T1A-NE-C3-L2, T1A-SR110-C3-L2, T1A-SR220-C3-L2, T1A-SR450-C3-L2, T1A-SR850-C3-L2, and T1A-SR1200-C3-L2) exhibited sound pressure levels 5.18 to 9.26 dB higher than the bare slab at 80 Hz. This outcome suggests that Type 1a systems may amplify impact noise in this frequency range, where structural vibrations and room acoustic modes are predominant [29].



(a) Average sound pressure level:1/3 Octave band



(b) Single number quantity

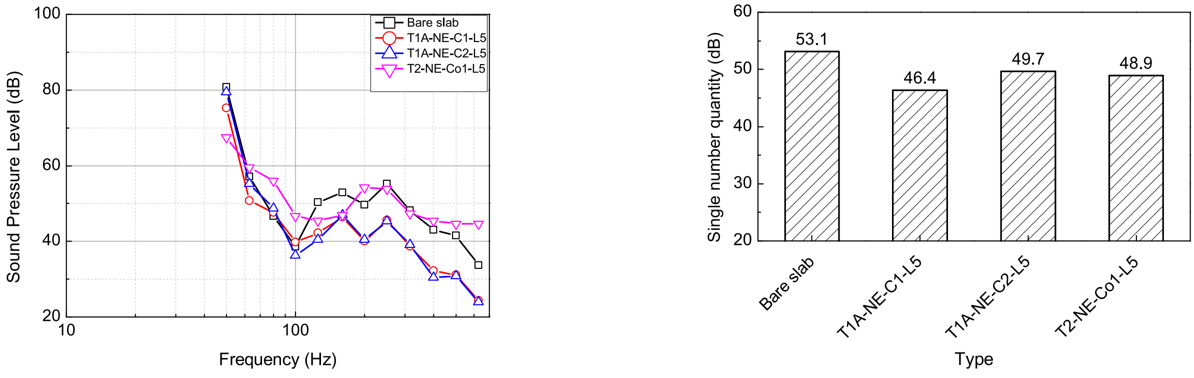
Fig. 8. Comparison of impact noise response test results of full-filled floating floors (Type 1a and Type 1b) and bare slab.

Configurations utilizing cushions C1 and C2 with layouts L5 (e.g., T1A-NE-C2-L5, T1A-NE-C1-L5) achieved modest improvements, with reductions ranging from 3.52 to 6.27 dB at 63 Hz and up to 2.24 dB at 100 Hz. These findings emphasize the inherent limitations of the 3-layer systems in addressing low-frequency impact noise, primarily due to their insufficient ability to mitigate structural resonances effectively. Such limitations highlight the need for further design optimizations to enhance the performance of Type 1a systems in the low-frequency range.

Conversely, the 3-layer systems exhibited notable improvements in the mid to high-frequency range (100–630 Hz). For instance, configurations such as T1A-SR110-C3-L2 achieved reductions of up to 8.51 dB at 250 Hz, while T1A-NE-C2-L5 and T1A-NE-C1-L5 achieved reductions of 12.47 dB and 10.74 dB at 400 Hz, respectively. These results indicate that although Type 1a systems are less effective at low frequencies, they deliver robust noise reduction at higher frequencies. This makes them suitable for applications prioritizing mid to high-frequency sound insulation.

The 4-layer floating floor systems (Type 1b) demonstrated superior performance across all frequency ranges compared to the 3-layer systems. In the low-frequency range (50–100 Hz), the T1B-NE-C5-L2 configuration exhibited significant reductions, with the bare slab showing higher sound pressure levels by 9.06 dB at 50 Hz. Additionally, in the mid to high-frequency range (100–630 Hz), the 4-layer systems maintained their effectiveness, achieving reductions of up to 10.35 dB at 160 Hz. These findings emphasize the versatility of Type 1b systems in providing sound insulation across a broader frequency spectrum than their 3-layer counterparts.

The novel floating floor systems achieved reductions in impact sound levels of up to 6.8 dB, as indicated by SNQ values (see Fig. 8(b)). Among the configurations tested, T1A-SR450-C1-L5 from the 3-layer systems and T1B-NE-C5-L2 from the 4-layer systems demonstrated the highest effectiveness. While the 3-layer floating floor systems (Type 1a) generally performed well in mitigating



(a) Sound pressure level (b) Single number quantity

Fig. 9. Comparison between the impact sound performance of the full-filled and half-filled novel floating floors.

impact noise, they exhibited limitations in the low-frequency range, where they could potentially amplify impact noise due to structural vibrations and room acoustic modes. In contrast, the 4-layer systems addressed these low-frequency shortcomings by incorporating a lightweight concrete layer, resulting in a more balanced and effective solution for impact noise control across a broader frequency spectrum.

This study underscores the importance of configuration-specific optimization to maximize performance. By integrating advanced polyurethane cushion designs and structural enhancements, such as lightweight concrete layers, the novel systems significantly outperformed traditional floating floors, which often exacerbate low-frequency noise due to resonance effects. These findings provide critical insights for the development of next-generation floating floor systems tailored to diverse acoustic requirements, particularly for residential and commercial buildings where sound insulation is paramount.

5. Evaluation of test results

This section presents a comparative analysis of the impact noise reduction performance of full-filled and half-filled floating floor systems. Additionally, the influence of five key parameters on the impact sound reduction performance of the full-filled floating floors was examined. These parameters include the material properties of polyurethane cushions, cushion arrangement, cushion cross-sectional design, cushion height, and the inclusion of the lightweight concrete layer.

5.1. The full-filled floating floors vs. half-filled floating floors

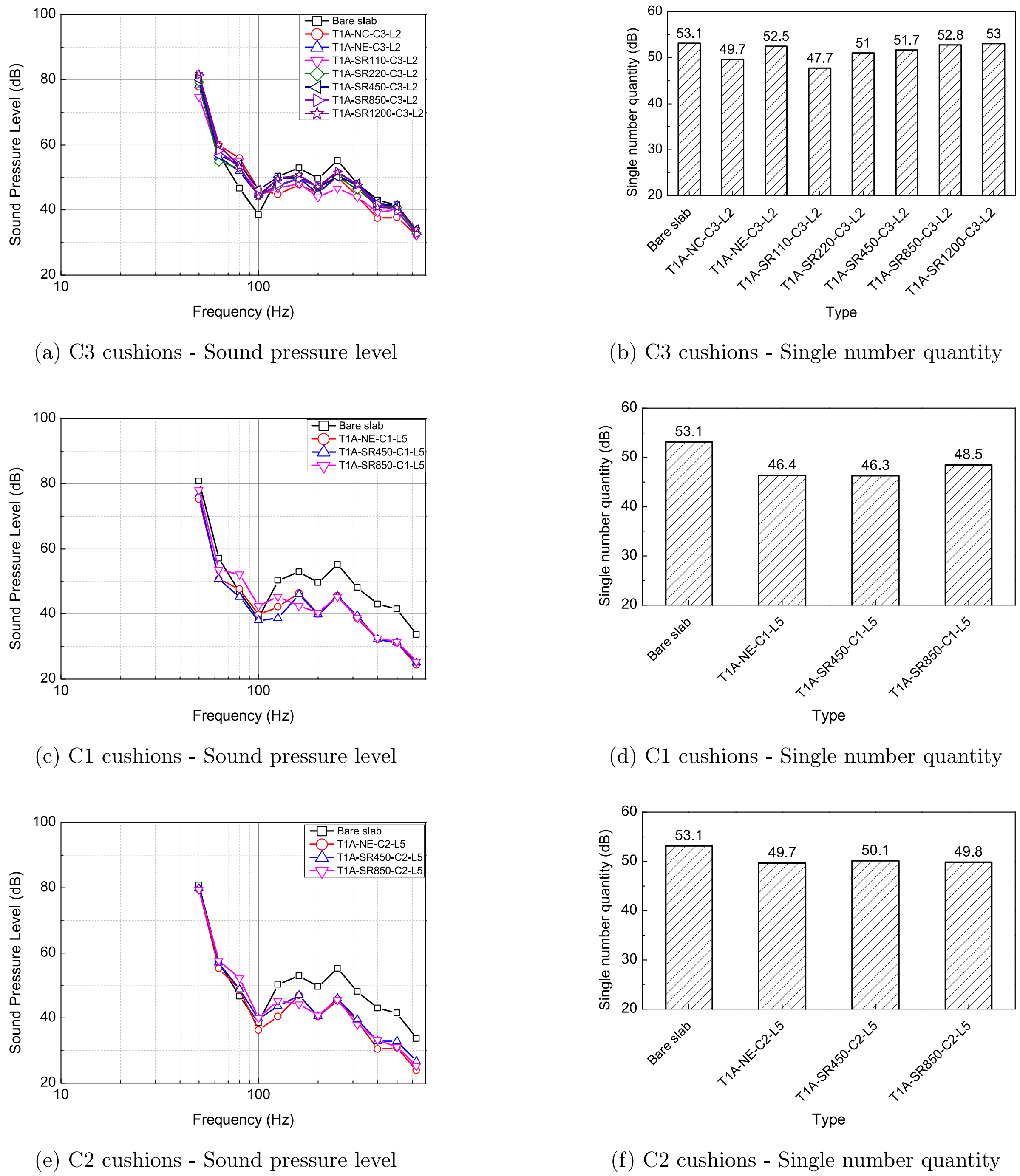
Fig. 9(a) compares the impact sound pressure levels of both fully-filled and half-filled floating floor systems, with cuboid-shaped and cone-shaped polyurethane cushions, respectively. Both systems utilized the same polyurethane materials and panel layout L5 (see Fig. 4). The fully-filled floating floor system, which uses mineral wool to fill the gaps, demonstrated superior performance over a wider frequency range. Reductions of up to 10.74 and 12.47 dB at 400 Hz were achieved for specimens T1A-NE-C2-L5 and T1A-NE-C1-L5, outperforming the half-filled system, especially at higher frequencies. By eliminating gaps and addressing resonance effects, the fully-filled system provides more consistent sound insulation, resulting in an overall SNQ reduction of 6.7 dB—a significant improvement over the half-filled system's 4.2 dB (Fig. 9(b)).

Overall, while the half-filled floating floor system performs well at controlling low-frequency noise, its efficiency is constrained by resonance effects and sensitivity to configuration changes, making it less effective for broader frequency noise reduction. On the other hand, the fully-filled system addresses these limitations, offering improved and consistent sound insulation across a wider frequency range, making it the preferred solution for environments requiring comprehensive acoustic management. Future research should focus on optimizing the half-filled design to reduce resonance effects and enhance its applicability in more diverse environments.

5.2. Influence of the material properties of polyurethane cushions

Three polyurethane cushion shapes (C1, C3, C4) and seven materials (NC, NE, SR110, SR220, SR450, SR850, SR1200) were analyzed for impact sound reduction performance, revealing distinct acoustic behaviors across materials.

Based on Fig. 10(a), polyurethane cushions of shape C3 and panel layout L2 showed that higher elastic modulus polyurethane cushions were less effective in reducing sound pressure levels, with frequency-dependent differences. For example, specimens T1A-SR110-C3-L2 and T1A-SR1200-C3-L2, with elastic moduli of 0.83 and 9.37 MPa respectively, showed significant differences in the low-frequency range, ranging from 3.33 to 7 dB. In the mid and high-frequency range, differences ranged from 1.34 to 4.81 dB. The overall impact sound level based SNQ increased from 47.7 dB to 53 dB as the modulus increased from 0.83 MPa to 9.37 MPa (see Fig. 10(b)).



(a) C3 cushions - Sound pressure level

(b) C3 cushions - Single number quantity

(c) C1 cushions - Sound pressure level

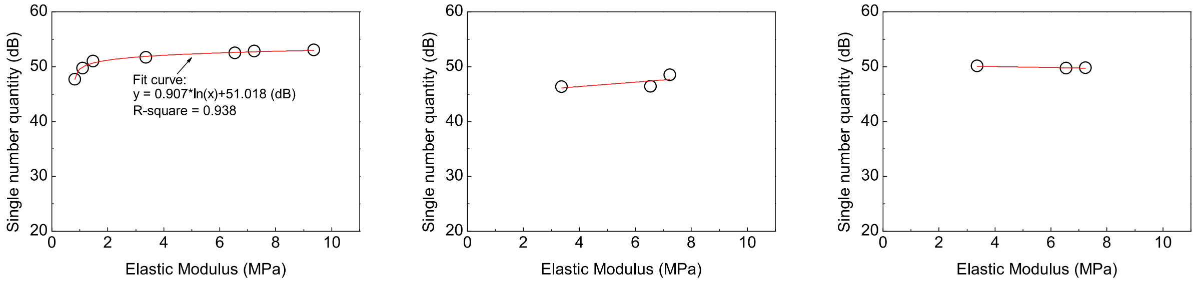
(d) C1 cushions - Single number quantity

(e) C2 cushions - Sound pressure level

(f) C2 cushions - Single number quantity

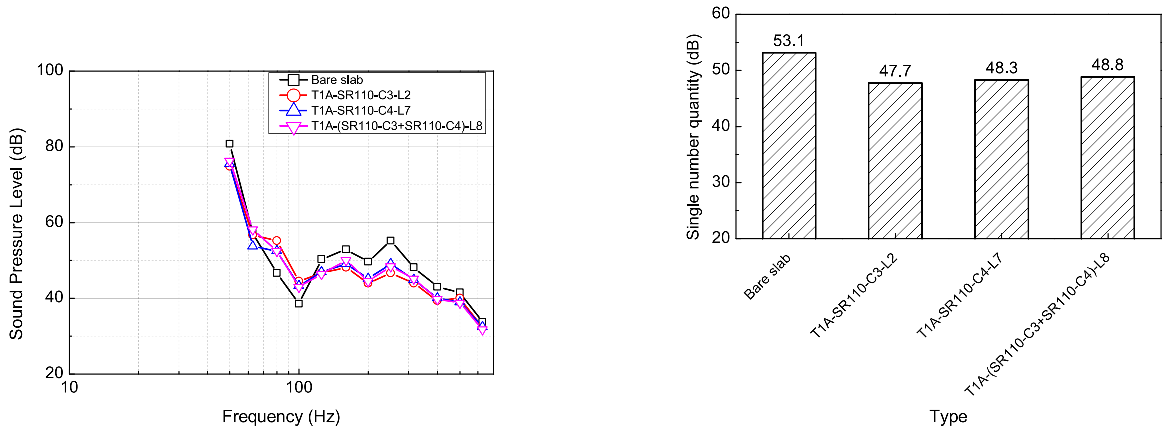
Fig. 10. mpact of polyurethane cushion properties on sound response in the full-filled floating floors using C3, C1 and C2 cushions.

According to Figs. 10(c) and 10(e), polyurethane cushions of shapes C2 and C1 with panel layout L2 showed that higher elastic modulus polyurethane cushions had minimal impact on sound pressure levels. Differences were small in the low-frequency range and negligible in the mid and high-frequency range. The overall impact sound level based SNQ showed a slight increase of 2.2 dB and a decrease of 0.3 dB as the modulus increased from 3.36 MPa to 7.23 MPa (see Figs. 10(d) and 10(f)). Figs. 11(b) and 11(c) show that the relationship between the elastic modulus and overall impact sound level remained almost unchanged with the same cushion shapes and layout.



(a) Polyurethane cushion C3 (b) Polyurethane cushion C1 (c) Polyurethane cushion C2

Fig. 11. The relationship between elastic modulus and impact sound performance of the full-filled novel floating floors.



(a) Sound pressure level (b) Single number quantity

Fig. 12. Impact of polyurethane cushion arrangement on sound response of the full-filled novel floating floors.

Fig. 11(a) shows that the relationship between elastic modulus and impact sound level is not linear. As the modulus increased from 0.83 to 1.47 MPa, the sound level increased by 3.3 dB, but only by 2 dB from 1.47 to 9.37 MPa. The fitting curve for this relationship is logarithmic ($R^2 = 0.938$), indicating high accuracy. Overall, the test results indicate that decreasing the elastic modulus of polyurethane cushions enhances overall impact sound reduction due to higher energy dissipation.

5.3. Influence of the polyurethane cushion arrangement

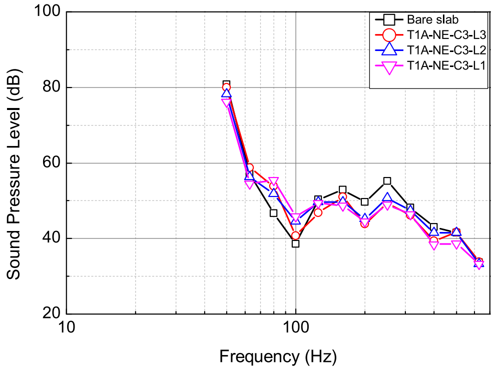
Six novel full-filled floating floor configurations with different polyurethane cushion arrangements (L1, L2, L3, L7, and L8, as shown in Fig. 4) were analyzed for their impact sound reduction performance.

With an arrangement combining cushions of different cross-sections, changes in the polyurethane cushion cross-section and the number of cushions significantly influence sound pressure levels, with variations depending on the frequency range (Fig. 12(a)). For panel layout L2 (9 cushions, C3 – 30×30×25 mm) and layout L7 (5 cushions, C4 – 60×60×25 mm), layout L7 exhibited lower sound pressure levels in the low-frequency range (50–100 Hz) but higher levels in the mid and high-frequency ranges compared to layout L2. Overall, the impact sound level, as indicated by the SNQ, of layout L2 was 0.6 dB lower than that of layout L7 (Fig. 12(b)).

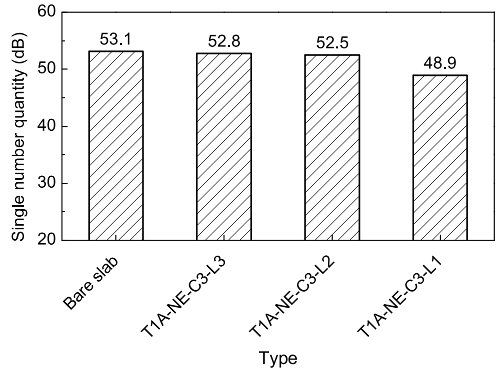
When comparing layout L7 (5 cushions, C4 – 60 × 60 × 25 mm) to layout L8 (5 cushions, C4 – 60 × 60 × 25 mm, and 4 additional cushions, C3 – 30×30×25 mm), the addition of smaller cushions (C3) in layout L8 increased sound pressure levels in the low-frequency range (50–100 Hz) while maintaining similar levels in the mid and high-frequency ranges. The overall impact sound level, based on the SNQ, of layout L8 was 0.5 dB higher than that of layout L7 (Fig. 12(b)).

Based on Fig. 13(a), increasing the number of polyurethane cushions C3 in Layouts L1 (6 cushions), L2 (9 cushions), and L3 (12 cushions) affects sound pressure levels. For layouts L2 and L3, increasing the number of cushions in L3 led to higher impact sound levels in the low-frequency range with a maximum difference of 2.41 dB, while reducing sound pressure levels in the mid and high-frequency range with a maximum difference of 2.86 dB compared to L2. The overall impact sound level based SNQ of L3 was slightly higher than L2 by 0.3 dB (see Fig. 13(b)).

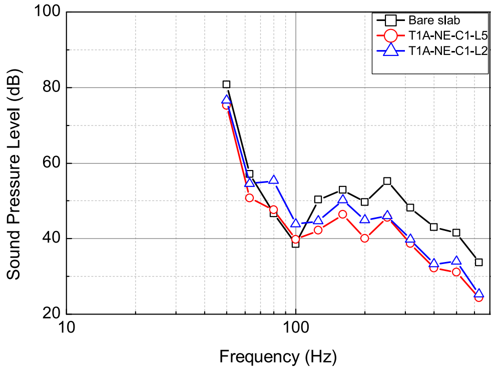
For layouts L1 and L2, reducing the number of cushions in L1 led to lower impact sound pressure levels in both low-frequency and mid and high-frequency ranges compared to L2, with maximum differences of 2.41 dB and 3.09 dB respectively (see Fig. 13(a)). The overall impact sound level based SNQ of L2 was higher than L1 by 3.6 dB (see Fig. 13(b)).



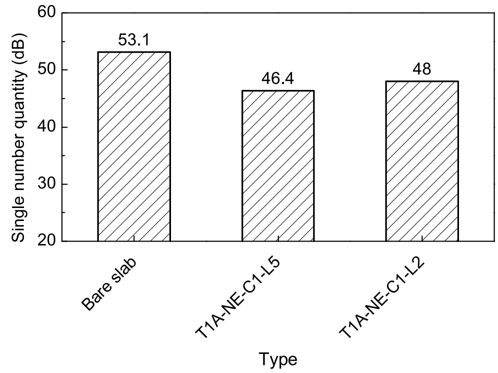
(a) C3 cushions - Sound pressure level



(b) C3 cushions -Single number quantity



(c) C1 cushions -Sound pressure level



(d) C1 cushions -Single number quantity

Fig. 13. Impact of polyurethane cushion arrangement on sound response in the full-filled novel floating floors using C3 and C1 cushions.

Based on Fig. 13(c), increasing the number of polyurethane cushions C1 in Layouts L2 (9 cushions) and L5 (36 cushions) affects sound pressure levels. For layouts L2 and L5, increasing the number of cushions in L5 led to lower impact sound pressure levels in the low-frequency range, with a maximum difference of 7.6 dB at 80 Hz, and reduced sound pressure levels in the mid and high-frequency range with a maximum difference of 4.85 dB at 200 Hz. The overall impact sound level based SNQ of L5 was lower than L2 by 1.6 dB (see Fig. 13(d)).

Fig. 14 shows that significantly increasing the number of polyurethane cushions with small cross-sections from 9 to 36 (C1), and reducing the number from 9 to 6 for large cross-section polyurethane cushions, decreased the overall impact sound level based on SNQ of the floating floor systems. Slight increases in the number of cushions did not effectively reduce the overall impact sound level.

5.4. Influence of the polyurethane cushion's sections

For the novel floating floor system with layout L5 using NE polyurethane cushions, increasing the cross-section of the cushions from 15×15 mm (C1) to 30×15 mm (C2) led to increased impact sound pressure levels in the low-frequency range, with a maximum difference of 4.47 dB at 63 Hz, and slightly reduced impact sound levels in the mid and high-frequency range, with a maximum difference of 1.73 dB at 400 Hz (see Fig. 15(a)). The overall impact sound level based on SNQ of the floor with polyurethane cushion C1 was lower than that with polyurethane cushion C2 by 3.3 dB (see Fig. 15(b)). Thus, increasing the cross-section of polyurethane cushions decreased the overall impact sound reduction of the novel floating floor.

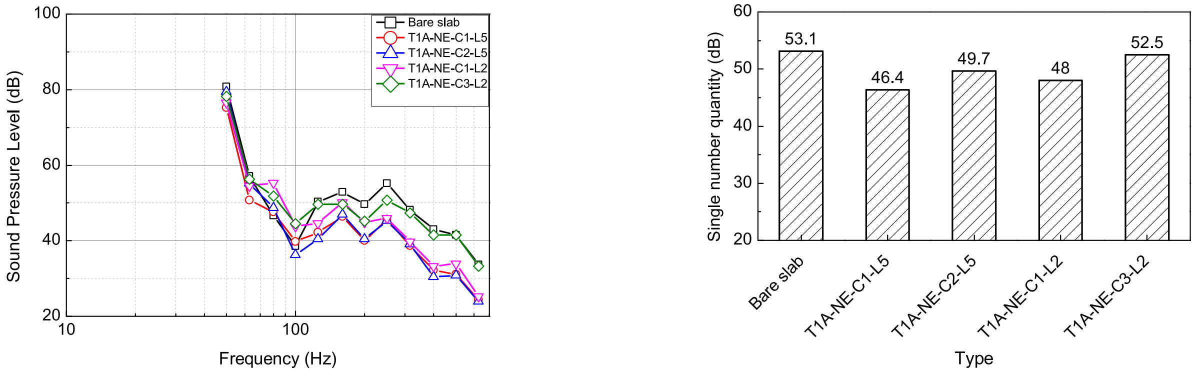
For the novel floating floor system with layout L2 using NE polyurethane cushions, increasing the cross-section of polyurethane cushions from 15×15 mm (C1) to 30×30 mm (C3) led to slightly decreased impact sound pressure levels in the low-frequency range, with a maximum difference of 1.76 dB at 63 Hz, and significantly increased impact sound levels in the mid and high-frequency range, with a maximum difference of 8.22 dB at 400 Hz (see Fig. 15(a)). The overall impact sound level based on SNQ of the floor with polyurethane cushion C1 was lower than that with polyurethane cushion C3 by 4.5 dB (see Fig. 15(b)). Again, increasing the cross-section of polyurethane cushions decreased the overall impact sound reduction of the novel floating floor.

For the novel floating floor system with layout L5 using polyurethane cushions made of SR450, increasing the cross-section of polyurethane cushions from 15×15 mm (C1) to 30×15 mm (C2) led to increased impact sound pressure levels in the low-frequency

(a) polyurethane cushion C3

(b) Polyurethane cushion C1

Fig. 14. Impact of the number of polyurethane cushions on sound response in full-filled floating floors.



(a) Sound pressure level

(b) Single number quantity

Fig. 15. Impact of polyurethane cushions' cross section on sound response in the full-filled floating floors using NE polyurethane cushions.

range, with a maximum difference of 6.22 dB at 63 Hz, and increased impact sound pressure levels in the mid and high-frequency range, with a maximum difference of 4.85 dB at 125 Hz (see Fig. 16(a)). The overall impact sound level based on SNQ of the floor with polyurethane cushion C1 was lower than that with polyurethane cushion C2 by 3.8 dB (see Fig. 16(b)). Increasing the cross-section of polyurethane cushions decreased the overall impact sound reduction of the novel floating floor.

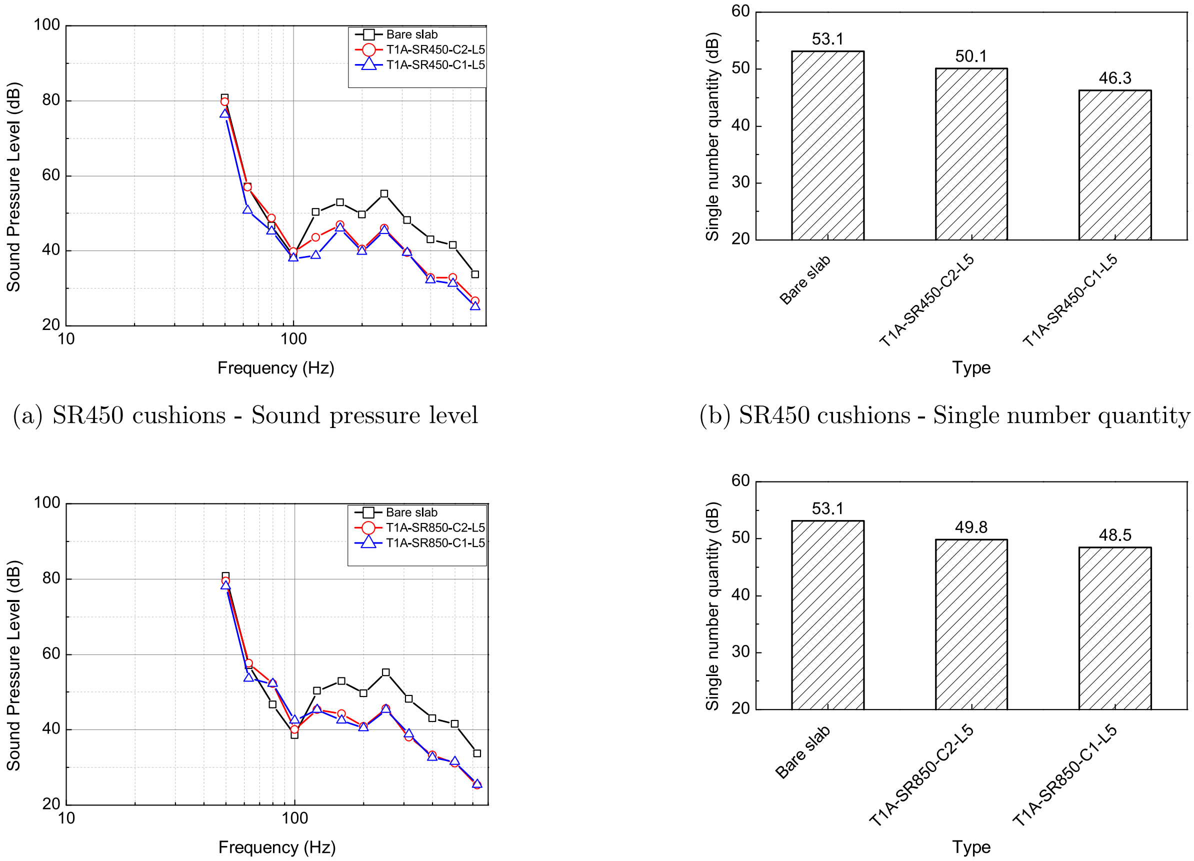
For the novel floating floor system with layout L5 using polyurethane cushions made of SR850, increasing the cross-section of polyurethane cushions from 15 × 15 mm (C1) to 30 × 15 mm (C2) led to increased impact sound pressure levels in the low-frequency range, with a maximum difference of 4.14 dB at 63 Hz, and slightly decreased sound pressure levels in the mid and high-frequency range, with a maximum difference of 1.74 dB at 160 Hz (see Fig. 16(c)). The overall impact sound level of the floor with polyurethane cushion C1 was lower than that of the floor with polyurethane cushion C2 by 1.3 dB (see Fig. 16(d)). Increasing the cross-section of polyurethane cushions decreased the overall impact sound reduction of the novel floating floor. Additionally, with higher elastic modulus, the effect of increasing the cross-section on the overall impact sound level decreases.

5.5. Influence of the polyurethane cushion's height

For the novel floating floor system with layout L2, increasing the height of polyurethane cushions from 25 mm (C3) to 37 mm (C5) led to increased impact sound pressure levels in the low-frequency range, with a maximum difference of 6.70 dB at 63 Hz, and decreased sound pressure levels in the mid and high-frequency range, with a maximum difference of 6.24 dB at 125 Hz (see Fig. 17(a)). The overall impact sound level based SNQ of the floor with polyurethane cushion C3 was lower than that of the floor with polyurethane cushion C5 by 3.2 dB (see Fig. 17(b)). Increasing the height of polyurethane cushions decreased the overall impact sound reduction of the novel floating floor. This result was expected due to the higher thickness of sound-absorbing material, which provides better impact sound absorption.

5.6. Influence of the lightweight concrete layer

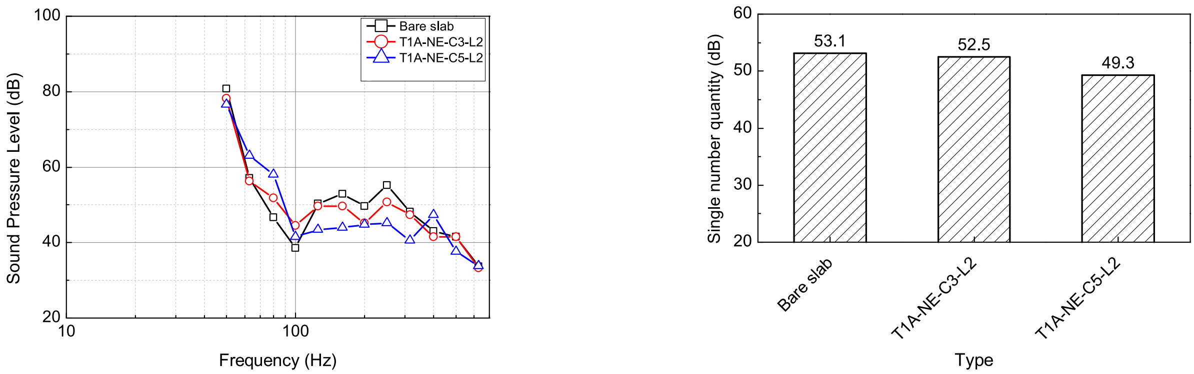
For the novel floating floor system with layout L2 and polyurethane cushion shape C5, comparisons were made between the configuration without (T1A-NE-C5-L2) and with (T1B-NE-C5-L2) the lightweight concrete layer. Adding the 30 mm lightweight



(a) SR450 cushions - Sound pressure level (b) SR450 cushions - Single number quantity

(c) SR850 cushions - Sound pressure level (d) SR850 cushions - Single number quantity

Fig. 16. Impact of polyurethane cushion dimension on sound response in the full-filled floating floors using SR450 and SR850 polyurethane cushions.

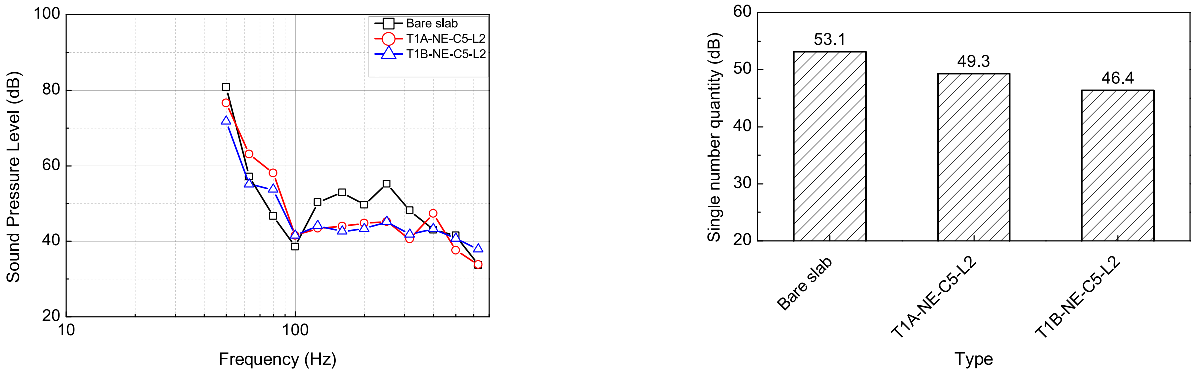


(a) Sound pressure level (b) Single number quantity

Fig. 17. Impact of polyurethane cushion's height on sound response in the full-filled floating floors using NE polyurethane cushions.

concrete layer significantly decreased impact sound pressure levels in the low-frequency range, with a maximum difference of 7.98 dB at 50 Hz, and slightly decreased impact sound pressure levels in the mid and high-frequency range, with a maximum difference of 4.13 dB at 125 Hz (see Fig. 18(a)). The overall impact sound level based SNQ of the novel floating floor with the lightweight concrete layer was lower than that of the floor without the lightweight concrete layer by 2.9 dB (see Fig. 18(b)).

Adding the lightweight concrete layer decreased the overall impact sound level based SNQ of the novel floating floor, especially in the low-frequency range. This mitigated the disadvantage of the novel floating floor, which previously only reduced impact sound



(a) Sound pressure level (b) Single number quantity

Fig. 18. Impact of the lightweight concrete layer on sound response in the full-filled floating floors.

levels in the high-frequency range. This result was expected due to the increased thickness and higher mass, known to exhibit better acoustic performance [43].

6. Conclusions

This research presents an innovative modular floating floor system incorporating polyurethane cushions with various 3D shapes and sound-absorbing materials. The system offers customizable stiffness and damping properties, enabling flexible installation, maintenance, and retrofitting. Unlike traditional systems, it adapts to a wide range of building types and effectively addresses critical challenges in low-frequency noise mitigation. By optimizing material properties and configurations, this approach enhances impact sound performance, providing practical and versatile solutions for improving acoustic comfort in diverse residential environments. The impact sound performance of two types of these novel floating floor systems was experimentally investigated on 22 specimens under controlled laboratory conditions, yielding valuable insights for advancing acoustic management solutions. Based on this investigation, the following findings can be drawn, however, these conclusions are limited to the scope of this study:

- The proposed modular system leverages adjustable polyurethane cushion configurations to address stiffness and damping requirements, making it adaptable to a range of acoustic scenarios. This flexibility facilitates efficient installation, maintenance, and optimization, distinguishing it from traditional floating floor systems.
- Fully-filled floating floor systems demonstrated a consistent ability to mitigate impact noise across a broad frequency range, addressing the limitations of traditional floating floors that often amplify low-frequency sound due to resonance effects. These systems showed significant potential for environments requiring comprehensive acoustic management.
- Half-filled floating floor systems provided localized effectiveness at low frequencies (e.g., 50 Hz) but exhibited limited performance across higher frequencies. The resonance effects and sensitivity to configuration changes constrained their broader applicability, highlighting the need for further refinement.
- The test results underscored the importance of cushion material properties and configurations. The research highlights the potential of reducing the elastic modulus of cushions to enhance sound energy dissipation, supported by a strong logarithmic correlation between elastic modulus and impact sound levels. The study also demonstrated that increasing cushion height and adding lightweight concrete layers effectively addressed low-frequency sound insulation challenges.

In this study, the proposed floating floor systems were designed to reduce heavy-weight floor impact noises and were tested under controlled laboratory conditions. While the results demonstrated the effectiveness of these systems, future research should explore further optimization of half-filled systems and test additional polyurethane cushion shapes and configurations. Comprehensive experimental testing in real building environments, with panels installed across entire slabs, is also recommended to validate the practical performance of the proposed floating floor systems.

CRediT authorship contribution statement

Tran-Van Han: Writing – review & editing, Writing – original draft, Validation, Methodology, Formal analysis, Data curation, Conceptualization. **Gayoon Lee:** Writing – review & editing, Investigation, Formal analysis, Data curation. **Sang Whan Han:** Writing – review & editing, Conceptualization. **Tae-Sang An:** Investigation, Formal analysis, Conceptualization. **Chan-Yu Jeong:** Investigation, Formal analysis, Conceptualization. **Kihak Lee:** Writing – review & editing, Supervision, Resources, Project administration, Funding acquisition, Formal analysis.

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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Appendix

See Table A.5.

Table A.5
Sound pressure level measurement data.

No	Type	Specimens	Frequency (Hz) (1/3 octave band)												SNQ (dB)
			50	63	80	100	125	160	200	250	315	400	500	630	
			Sound Pressure level (dB)												
1	–	Bare slab	80,74	57,04	46,67	38,52	50,37	52,96	49,63	55,18	48,15	42,96	41,48	33,70	53,10
2	Type 1a (T1A)	T1A-NC-C3-L2	77,78	60,00	55,93	46,29	44,81	47,78	45,19	50,37	44,07	37,40	37,78	32,22	49,70
3		T1A-NE-C1-L2	76,64	54,54	55,27	43,87	44,60	50,12	44,95	46,01	39,81	33,26	33,98	25,33	48,00
4		T1A-NE-C1-L5	75,27	50,77	47,67	39,75	42,18	46,33	40,10	45,65	38,74	32,22	31,16	24,30	46,40
5		T1A-NE-C2-L5	79,40	55,24	48,71	36,28	40,45	47,00	40,46	45,31	39,10	30,49	30,85	23,94	49,70
6		T1A-NE-C3-L2	78,15	56,30	51,85	44,44	49,63	49,63	45,18	50,74	47,41	41,48	41,48	33,33	52,50
7		T1A-NE-C3-L3	80,00	58,71	53,87	40,65	46,77	50,97	43,87	49,35	46,13	39,35	41,61	33,87	52,80
8		T1A-NE-C3-L1	76,12	54,51	55,48	45,81	49,35	48,71	44,52	49,03	46,45	38,39	38,71	33,23	48,90
9		T1A-NE-C5-L2	76,62	63,01	57,99	41,55	43,38	43,97	44,75	45,12	40,54	47,41	37,59	33,74	49,30
10		T1A-SR110-C3-L2	74,85	56,67	55,15	44,55	46,67	48,18	43,94	46,67	43,94	39,40	40,00	32,12	47,70
11		T1A-SR110-C4-L7	75,45	53,64	52,42	43,33	46,97	49,09	45,15	49,09	44,84	40,00	39,01	32,42	48,30
12		T1A-SR220-C3-L2	79,26	54,81	52,96	44,44	47,41	49,63	47,03	50,37	46,29	41,48	40,74	32,96	51,00
13		T1A-SR450-C1-L5	76,30	50,77	45,23	38,00	38,72	45,98	39,78	45,33	39,45	32,20	31,19	24,99	46,30
14		T1A-SR450-C2-L5	79,73	56,99	48,71	39,72	43,57	47,00	40,45	46,00	39,46	32,85	32,92	26,70	50,10
15		T1A-SR450-C3-L2	80,00	56,67	54,07	46,29	50,00	50,00	47,04	50,00	48,15	42,22	41,11	34,07	51,70
16		T1A-SR850-C2-L5	79,40	57,66	52,15	40,08	45,29	44,26	40,82	45,65	38,07	33,22	31,15	25,34	49,80
17		T1A-SR850-C3-L2	81,48	58,15	52,96	44,44	47,78	49,63	47,41	51,85	47,78	41,85	39,63	32,59	52,80
18		T1A-SR1200-C3-L2	81,85	60,00	53,33	44,07	49,63	50,74	47,04	51,48	47,78	40,74	40,74	34,07	53,00
19		T1A-(SR110-C3+SR1200-C4)-L8	76,36	58,18	52,43	43,03	46,37	50,01	44,54	48,49	45,15	39,70	38,79	31,82	48,80
20	Type 1a(T1B)	T1B-NE-C5-L2	71,68	55,03	53,65	41,56	44,12	42,61	43,28	45,12	41,75	43,27	40,77	37,82	46,40
21	Type 2(T2)	T2-NE-Co1-L4	56,90	60,70	50,60	45,50	47,00	49,30	55,60	53,90	51,90	44,40	45,70	45,70	52,00
22		T2-NE-Co1-L5	67,50	59,50	56,00	46,70	45,40	46,90	54,30	53,90	47,30	45,40	44,60	44,60	48,90
23		T2-NE-Co1-L6	58,30	55,80	55,70	49,80	45,60	48,00	57,90	55,00	53,70	50,90	51,70	51,70	55,60

Note: SNQ : Single Number Quantity the A-weighted maximum impact sound pressure level $L'_{iA,F_{\max}}$.

Data availability

The authors do not have permission to share data.

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