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Evaluation of the Floor Impact Sound Insulation Performance of a Voided Slab System Applied to a High-Rise Commercial Residential-Complex Building

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Abstract

Multi-unit dwellings, such as apartment housing, town houses, and flats, are some of the most common housing types in Korea, as well as in other countries. Such multi-unit dwellings are considered an effective means to overcome the housing problems of high-density population in urban areas, owing to their high efficiency of land utilisation. However, interlayer noise complaints, such as footsteps or dragging items in apartment housing, are an inevitable problem in apartment dwelling conditions, because each household in an apartment shares walls and ceilings with other households. This paper presents the results acquired from the field test of the floor impact sound insulation performance of a voided slab system as applied to a commercial residential-complex building in South Korea. The results have shown that adopting the voided slab system for a commercial residential-complex building increased floor impact sound insulation performance. The test results show that the sound insulation performance of the voided slab system applied in the building for lightweight and heavyweight floor impact sound reached (47 and 41) dB, respectively. Based on the results of the field tests, it is expected that the application of the voided slab systems to the slabs of the apartment dwellings would be effective, and offer outstanding sound insulation performance. Moreover, it is expected that the floor impact sound insulation performance would be further improved, if the floor finishing materials, such as carpet or other types of flooring material, would first be installed onto the floor.

Keywords: high-rise commercial–residential building, heavyweight floor impact sound, lightweight floor impact sound, sound insulation, void slab, high rise building

1 Introduction

Multi-unit dwellings, such as apartment housing, town houses, and flats, are some of the most common housing types in Korea, as well as in other countries. According to the Population and Housing Census 2016 (Statistics Korea 2016), approximately 45% of the population of South Korea reside in apartment housing. Moreover, Eurostat (EUROSTAT Statistics Explained 2017) indicates that the proportion of people living in flats account for the highest proportion of housing occupants among the EU member states. The data showed that in the EU member states, more than 4 out of every 10 persons lived in flats. Such multi-unit dwellings are therefore considered as an effective means to overcome the housing problems in high-population density urban areas, owing to their high efficiency of land utilisation.

Recently, the construction of high-rise apartment housing has increased in South Korea, with the planning of urban restoration or refurbishment projects. There are several advantages to constructing high-rise apartment housing, such as efficient utilisation of the land, improved accessibility to urban areas, and conveniences available to residents in apartment housing. On the other hand, the apartment dwellings provide a number of disadvantages

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for the residents. The most common problems associated with high-rise apartments are the effects of wind, the difficulty of accessing the upper level floors, the difficulty of evacuation in the case of fire or earthquakes, and the problem of interlayer noise complaints from neighbours (Casniato et al. 2015; Jeon 2001; Jeon et al. 2010; Park and Lee 2017; Kim et al. 1998). In particular, interlayer noise complaints, such as footsteps or dragging stuff in apartment housing, are an inevitable problem in apartment dwelling conditions, because each household in an apartment shares walls and ceilings with other households (Jeon et al. 2010; Kim et al. 1998; Cha 2014). In South Korea, this type of interlayer noise problem is becoming increasingly serious, and has become one of the most common social issues in urban life, compared to other minor or individual matters arising amongst residents in apartment housing.

The South Korean Government has recognised the seriousness of such problems in apartment housing, and has begun imposing measures through the revision and enactment of laws (Ministry of Land 2015). As part of this effort, the government revised the 'Criteria on the recognition and management of block structures for floor impact sounds in multi-dwelling houses' in 2014. According to the revised criteria, the newly introduced 'Certified Floor Structures' have replaced the existing standard floor structures (Ministry of Land 2015). The suggested certified floor structures are applied to apartment buildings when the sound insulation performance of the floor impact sound satisfies all the requirements and predetermined criteria. Along with legal regulations, various studies and methods have been proposed in order to reduce the interlayer noise issues generated by floor impact (Kim et al. 1998; Warnock 2000; Casniato et al. 2015; Cha 2014; Christian et al. 2008; Jeon et al. 2010; Lee et al. 2017; Park and Lee 2017).

Floor impact noises are considered as structure-borne sounds that are caused by either impacting on or vibrating directly on the structure, and then travelling through the entire building (Uno 1992). In general, one of the effective methods to lower the floor impact sounds is to separate or isolate the noise from its source. There are a number of approaches to lower the influence of floor impact noise, such as increasing the thickness of concrete slab, inserting sound absorptive materials, and creating space to isolate the sound sources. A number of studies point out that one of the most effective methods to separate the floor impact sounds in concrete structures is through the use of floating floors (Schiavi 2018; Miškinis et al. 2012; Martins et al. 2015; Faustino et al. 2012; D'alessandro et al. 2014; Sipari 2002). A floating floor is a combination of concrete slab and resilient, as well as sound absorbing, material, such as rubber (D'alessandro et al. 2014; Jeon et al. 2006; Schiavi 2018). Neves e Sopusa and Gibbs (2011) compared both homogeneous concrete floors and floating floors in dwellings. In their study, the floating floor would be beneficial to insulate low frequency impact sound transmission. Schiavi (2018) tested various resilient materials, such as glass fibre, polyester fibre, cork, and rubber grains, to form floating structures in the concrete slab. Cho (2013) indicated that the concrete slab with resilient layers would be useful to insulate floor impact sound, compared to the normal concrete slab. In this study, the voided slab system, which is filled with lightweight expanded polystyrene (EPS), is suggested as one of the floating floor systems to isolate and separate the floor impact sounds in a commercial–residential complex building. The EPS void formers were designed as a means of isolating floor impact sound in the concrete structure. In order to verify the usefulness and effectiveness of the voided slab systems for lightweight and heavyweight floor impact sound insulation, a field test was conducted to evaluate the sound insulation performance in the studied building.

2 Literature Review

A voided slab system is an efficient construction method that reduces the concrete dead-load or self-weight, to enable an increase in the span of a building or structure (Aguado et al. 2016; Aldejohann and Schnellenbach-Held 2002; Brunesi and Nascimbene 2015; Chung et al. 2009; Hwang et al. 2015). It has a number of advantages, such as economic efficiency, usability, and environmental friendliness. On the other hand, it also presents several disadvantages, such as difficulty of construction, decrease in construction quality, and deterioration of economic efficiency when the void part is not properly installed (Chung et al. 2013; Bhagat and Parikh 2014; Lee et al. 2011). In order to overcome such disadvantages of the voided slab systems, various academics and practitioners have tried to find solutions.

The studies of voided slab systems that have been carried out have focused on the development of anchoring methods and devices, shape of void formers for optimal void ratio, structural performance, such as shear and flexural capacity, and shear reinforcement. Considering the aspect of structural performance, voided slab systems are vulnerable to shear capacity, when compared to solid slabs (Aldejohann and Schnellenbach-Held 2002; Hegger et al. 2009; Jung et al. 2016; Miwa et al. 1995; Chung et al. 2009; Lee et al. 2011). Schnellenbach-Held and Pfeffer (2002) found that while the so-called control perimeter is treated as a shear resistance section in flat slab designs, the shear area within the bubble-containing voided slab could be reduced. Chung et al. (2009) indicated that the shapes of the void formers might be crucial factors that determine the capacities of the shear forces in voided slab systems. They maintained that donut-shaped void formers could resist approximately 20% more shear strength over other shapes of void formers. Lee et al. (2011) performed experimental studies to evaluate the punching shear of two-way voided slab-to-column connections with TVS lightweight balls. Along with the shear resistance performance of the voided slab system, various studies have also attempted to evaluate the flexural performance of the voided slab. Many studies have confirmed that the flexural capacities of the voided slab are similar in performance to the solid slab system for equal depth (Chung et al. 2010; Jung et al. 2016; Yu et al. 2014). Chung et al. (2013) demonstrated that two-way slab systems with donut type void formers showed similar flexural capacities, when compared with the conventional reinforced concrete slabs.

In addition, while the voided slab systems have generally been applied to long-span structures and buildings, the voided slabs have also been adopted in apartment housing in Japan as a means of reducing noise complaints. Studies on the sound insulation performance of voided slabs were conducted in Japan in the 1990s. In addition, there are different aspects to the domestic residential characteristics in Korea, when compared to those in Japan. Owing to such different attributes, studies regarding the sound insulation performance of voided slabs, as applied to apartment housing, have been conducted by the Seoul Housing & Communities Corporation and Korea Land and Housing Corporation, with consideration of the domestic conditions and features (Shin et al. 2013). However, in comparison with other research topics, research regarding the sound insulation performance of voided slab systems is relatively scanty. In this study, the floor impact sound insulation performance of the voided slab applied to a high-rise commercial residential-complex building was evaluated through a field test.

3 Research Method: Overview of the Field Test

3.1 Material Properties and Characteristics

The voided slab system applied in the commercial and residential-complex building is a combination of void formers with T-shaped deck plates. The voided slab system is composed of T-shaped steel deck plates, lightweight EPS void formers, and anchoring devices. Figure 1 shows that the EPS void formers are placed between the ribs of the T-shaped steel deck plate, and anchored firmly using the proposed anchoring devices.

In this study, the anchoring devices for the void formers were designed using EPS, which is the same material used to manufacture the void formers. The anchoring devices are installed by insertion, then turning them 90°, for ease of construction. Such ease of installation makes it possible for novice workers to install and fix the void formers with a high level of precision, while preventing detachment from the designed locations.

T-shaped deck plates were used in this study to anchor the void formers, to prevent detachment from the designed locations, which is generally caused by buoyancy. In addition, the deck plates not only serve as a concrete framework, but also operate as a part of the structural member, imparting additional structural strength, thereby enhancing the structural stability of the entire building. Figure 1a shows a cross-sectional view of the voided slab system used in this field test.

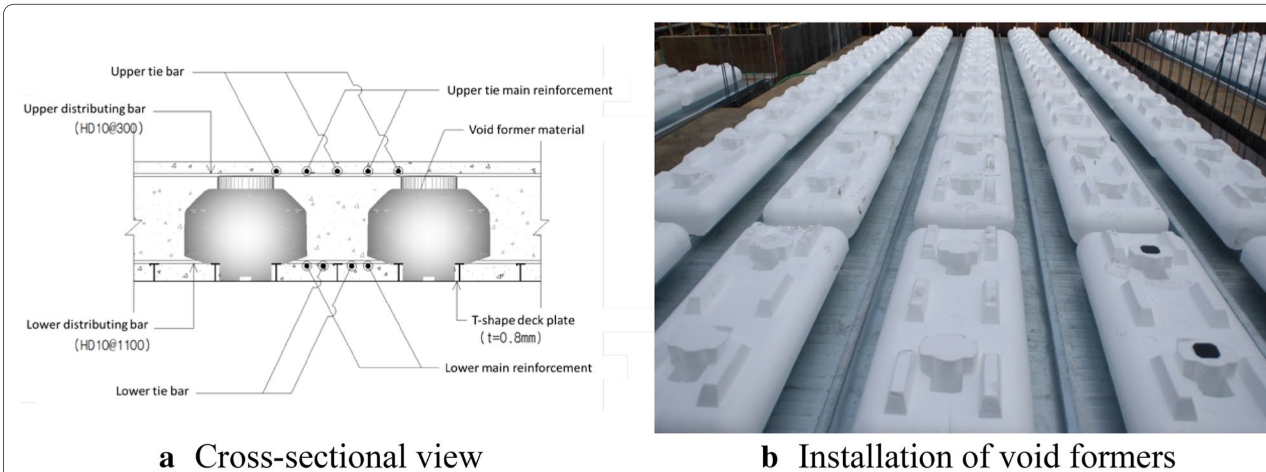


Fig. 1 Details of the voided slab system.

3.2 Test Site Description

Field tests were performed to evaluate the floor impact sound insulation performance of reinforced concrete slabs applied to voided slab systems in an existing building (Fig. 2). The test building is located in Yangcheon-gu, Seoul, South Korea, and the voided slab system was applied to the first three floors in the commercial areas of the building.

Fig. 2 Aerial perspective showing the design of the tested building.

The building has twenty stories in total, and the commercial area where the voided slab system was used has a span of 9.0 m (Fig. 3). In this building, it was possible to remove the bearing walls, which were acting as pillars, by applying the voided slab. The concrete and reinforcing bars used for this building have a compressive strength of 24 MPa, and tensile strength of 400 MPa. The thickness of the reinforced concrete slab is 300 mm without the use of any finishing material, such as carpet, tiles, or rubber.

3.3 Measurement and Evaluation

Figure 4 and Table 1 describe the equipment used for generating and measuring the floor impact sound. There were two types of sound generators for lightweight and heavyweight floor impact sounds used in this field test. The standard lightweight and heavyweight floor impact sounds were generated 0.75 m away from the wall in a room, and the impact sound sources were established at three points, including the centre

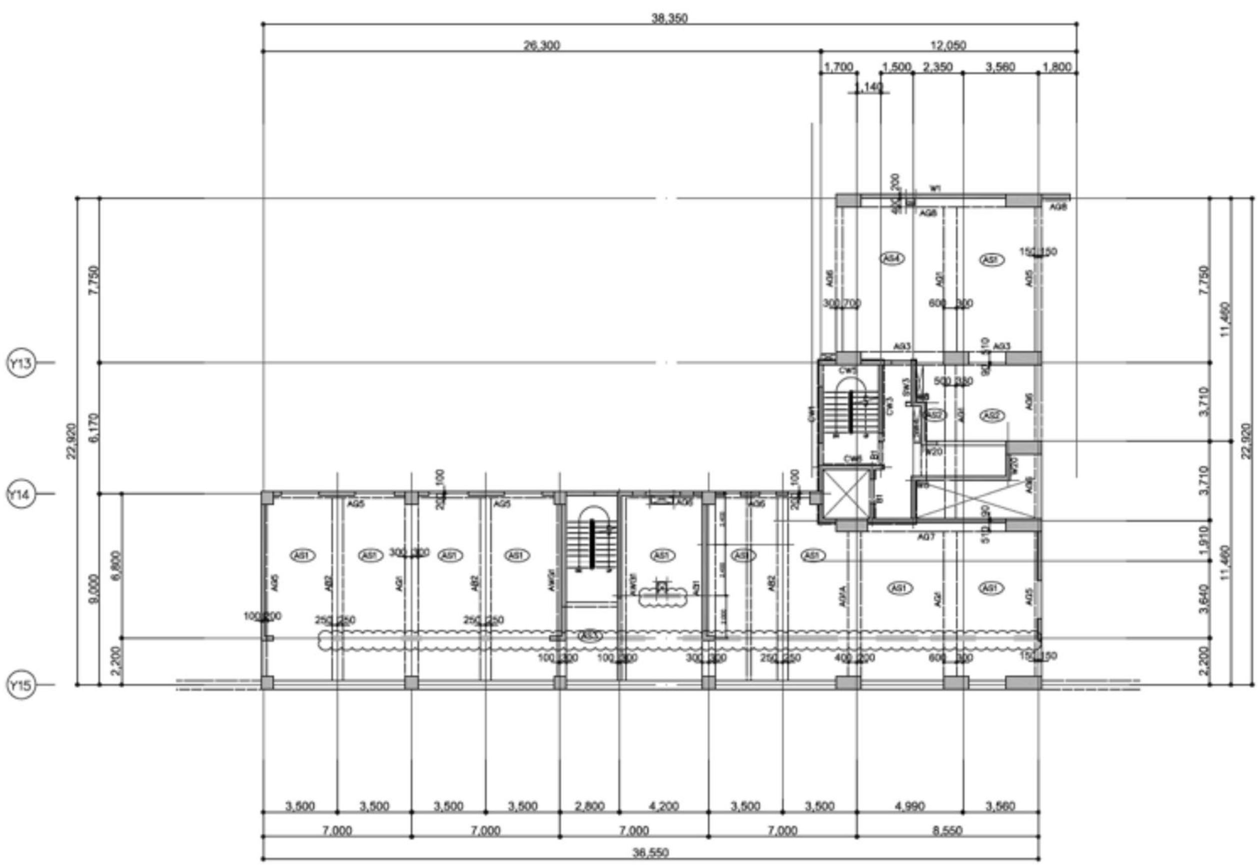
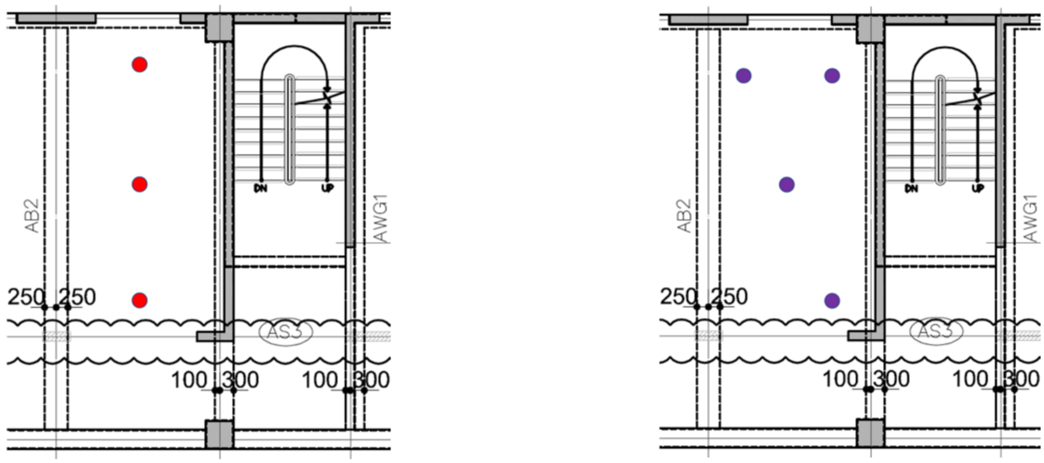


Fig. 3 Floor plan of the tested building.



a Sound source points on the 2nd floor **b** Sound receiver points on the 1st floor

Fig. 4 Sound sources and receiver points.

Table 1 Devices of the floor impact sound test.

Measurement devices	Model and manufacturer
Standardised floor impact	
Lightweight floor impact sound source (tapping machine)	Norsonic, N-211A, France
Heavyweight floor impact sound source (bang machine)	SNVT
Sound receiver and reverberation time measurement devices	
Real time analyser	RION Co., LTD., SA-30, Japan
Sound level calibrator	RION Co., LTD., NC-74, Japan
Microphone set	RION Co., LTD., UC-53A, Japan
Sound power source	PISTOL

of the room. In the case of the standardised heavyweight floor impact sound generation, a bang machine was utilised, and the tests were conducted at a tyre air pressure of $(2.5 \pm 0.1) \times 10^6$, according to the Korean Standards (KS) (Korea Standards Association 2001, 2012). Moreover, the standardised lightweight floor impact sound was generated using a standardised tapping machine. The standardised tapping machine has five rubber-tipped steel hammers, each weighing 0.5 kg. The hammers were dropped from a height of 40 mm, and impacted the surface in question at an operating frequency of 10 Hz, in accordance with the KS.

The standard lightweight and heavyweight floor impact sounds were measured 0.75 m away from each of the walls of the room, and four points, including the centre of the room, were selected for the measurement locations in the field test. Microphones were also located to acquire the floor impact sound data at distances of 0.75 m from the walls of the room and situated at a height of 1.2 m from the floor. Figure 4 indicates the locations of the sound and receiver points on the floor of the room.

The floor impact sound was measured for conditions where the influence of the ambient noise was at a minimum level. In addition, when the ambient noises affected the measurement of the floor impact noise for each frequency level, the effect of the ambient noise was calibrated before collecting the impact noise data. When the level difference between the background and measured noise was (6 to 15) dB, the acquired data were compensated with the following expression. However, when the level difference was less than 6 dB, the received data were not used for the floor impact sound measurement test.

$$L = 10log_{10}\left(10^{L_{sb}/10} - 10^{L_b/10}\right)[\text{dB}] \quad (1)$$

where L is the compensated sound pressure level (dB), L_{sb} represents the combined level of the acquired sound level data and ambient noise level (dB), and L_b indicates the

Table 2 Ambient noise in the field test.

Frequency (Hz)	63	125	250	500	1000	2000
Sound pressure level (dB)	45.5	39.6	37.5	34.2	31.4	31.7

Table 3 Size of the receiver room.

Size of the room	Width (m) × length (m) × height (m)
Measurements of the receiver room	3.4 × 6.7 × 2.5

Table 4 Reverberation time of the receiver room for various frequencies.

Frequency (Hz)	Reverberation time (s)
125	0.80
250	0.86
500	0.91
1000	1.09
2000	1.10

sound pressure level of the ambient noise (dB). Table 2 shows the results of the ambient noise calibrations in the field tests:

The floor impact noise level L, which indicates the floor impact sound isolation performance of the floor structure, was obtained according to the following expression for each measured frequency:

$$L_{F_{max,k}} = 10log_{10}\left[\frac{1}{m}\sum_{j=1}^{m}\frac{L_{F_{max,j}}}{10}\right][\text{dB}] \quad (2)$$

where $L_{F_{max,j}}$ is the maximum sound pressure level measured at point j, and m represents the number of measurement points.

In the case of measuring the lightweight impact sound level, the sound absorption area of the receiving room was corrected through the following equation, after the level of the normalised floor impact sound pressure level (L_n) was computed:

$$L_n = L_i + 10log_{10}\frac{A}{A_0}\,[\text{dB}] \quad (3)$$

where L_i is the sound pressure level measured at point i, A_0 is 10 m^2, A is equal to $\frac{01.6V}{T}$, which represents the area of absorption (m^2), V indicates the volume of the receiver room (m^3), and T is the reverberation time of the receiver room. Tables 3 and 4 summarise the volume (V) and the reverberation time (T) of the receiver room.

Table 5 Lightweight floor impact noise data.

Frequency (Hz)	Measured value (dB)	Normalised floor impact sound level (dB)	Reverse A characteristic curve (dB)
125	53.2	53.8	60
250	54.7	55.0	53
500	51.3	51.3	47
1000	47.1	46.3	44
2000	36.4	35.6	43

3.4 Evaluation Method of the Floor Impact Sound Insulation

The evaluation method adopted for the insulation performance of floor impact sound was legislated by the KS in 2002. The tests were conducted in accordance with KS F 2863-1: 2002 (Rating of floor impact sound insulation for impact source in buildings and building element-Part 1: Floor impact sound insulation against standard light impact source) and KS F 2863-2:2007 (Field measurement of floor impact insulation of buildings-Part 2: Method using standard heavy impact sources), which use the inverse normalised curves. The frequencies used for the light impact sound test were (125, 250, 500, 1000, and 2000) Hz. Moreover, the heavy impact sound frequencies were measured using 1/1 octave bands at (63, 125, 250, 500, 1000, and 2000) Hz.

4 Results and Discussions

4.1 Analysis of the Insulation Performance of the Floor Impact Sound

Tables 5 and 6 and Figs. 5 and 6 show the sound pressure levels of the lightweight and heavyweight floor impact tests using the voided slab system in a commercial residential-complex building.

The evaluation result of the single-value quantity applying the inverse A characteristic curve for the lightweight floor impact sound ($L'_{n,AW}$) was 47 dB. The measured values of the lightweight floor impact noises were (53.2, 54.7, 51.3, 47.1, and 36.4) dB for (125, 250, 500, 1000, and 200) Hz, respectively. When the frequencies for the lightweight floor impact sound were observed, the 250 Hz showed the highest value for the sound pressure, while the 2000 Hz indicated the lowest value for the sound pressure. The normalised floor impact sound levels were

Table 6 Heavyweight floor impact noise data.

Frequency (Hz)	Measured value (dB)	Reverse A characteristic curve (dB)
63	71.9	64
125	53.9	54
250	44.9	47
500	40.3	41

(53.8, 55.0, 51.3, 46.3, and 35.6) dB for (125, 250, 500, 1000, and 200) Hz, respectively. Comparing the normalised floor impact sound levels with the single-value quantity applying the inverse A characteristic curve for the lightweight floor impact source, the values above the normalised curve were (2.0, 4.3, and 2.3) dB for 250, 500, and 1000 Hz, respectively. Additionally, the compared values for 125 and 2000 Hz were less than zero; thus, these values were excluded.

The test result of single-value quantity using the inverse A characteristic curve for the heavyweight floor impact sound ($L'_{i,F_{max},AW}$) was 42 dB. The measured values of the heavyweight floor impact noises were (71.9, 53.9, 44.9, and 40.3) dB for (63, 125, 250, and 500) Hz, respectively. Based on the measured values, the values above the normalised curve were also examined for the heavyweight floor impact source. Comparing the normalised floor impact sound levels with the single-value quantity using the inverse A characteristic curve for the heavyweight floor impact source, the frequency of 63 Hz was observed to be the only value that exceeded the normalised curve, and the corresponding value was 7.9 dB.

According to "The provisions for the housing construction standards—The Ministry of Construction and Transportation" enforced since July 2005 in South Korea, the lightweight and heavyweight floor impact sound sources should be below (58 and 50) dB for lightweight and heavyweight floor impact sound insulation, respectively (see Table 7). The test results indicated that the insulation performance against the lightweight and heavyweight floor impact is superior compared to the conventional insulation by approximately (11 and 9) dB respectively, which indicates a grade of 2 for both the lightweight and heavyweight floor impact sound insulation performances. It is therefore considered that the evaluated data of the lightweight and heavyweight floor impact sound for the building measured in this test satisfies the values in the code, which prescribes below (58 and 50) dB for the lightweight and heavyweight floor impact sound, respectively.

4.2 Discussions

In the field tests, it must be noted that the floor impact sound insulation performance of the voided slab systems was performed without any floor finishing material or covering. The floors of apartment housing in South Korea commonly use standard floor finishings and structures for interlayer noise prevention, which generally consist of

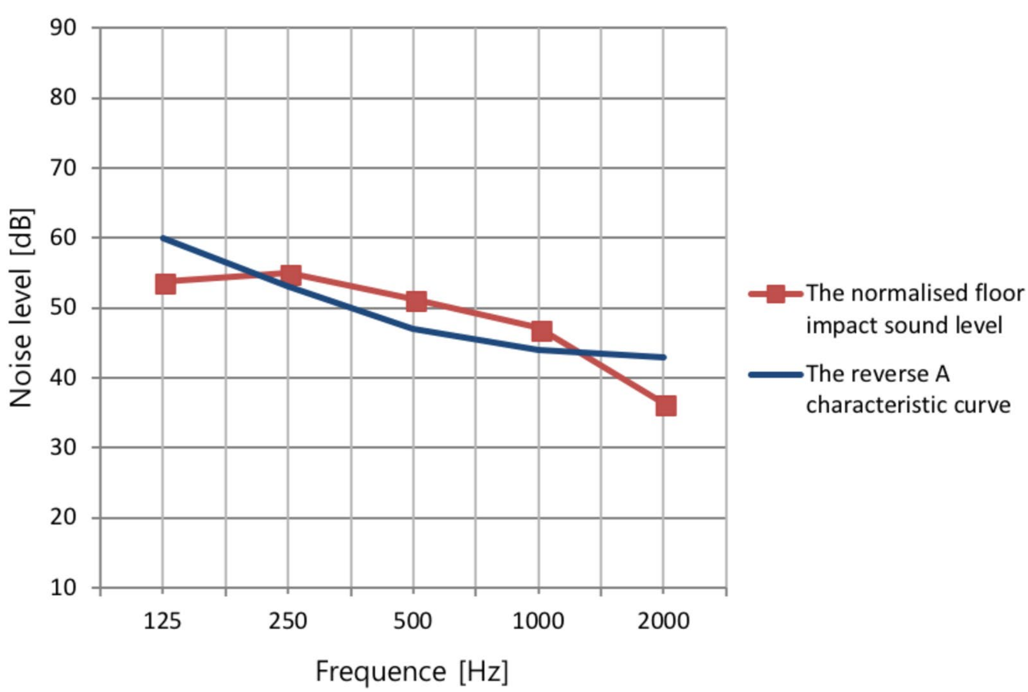


Fig. 5 Test result of the lightweight floor impact noise.

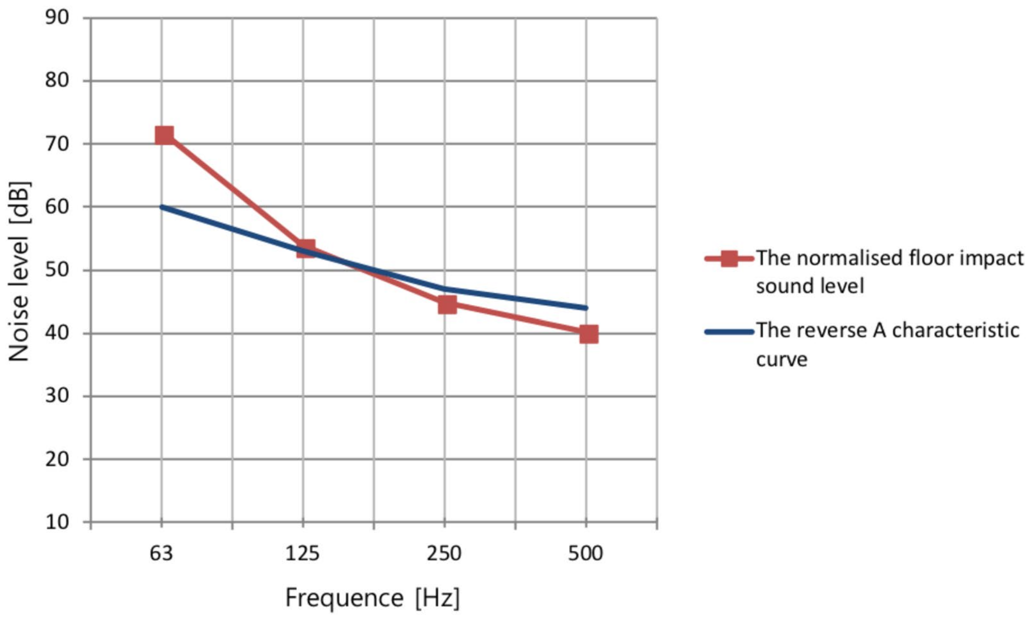


Fig. 6 Test result of the heavyweight floor impact noise.

Table 7 Standard level of floor impact sound insulation (unit: dB).

Grade	Inverse A normalised floor impact sound level (lightweight floor impact noise)	Inverse A normalised floor impact sound level (heavyweight floor impact noise)
1	$L'_{n,AW} \leq 43$	$L'_{i,F_{max},AW} \leq 40$
2	$43 < L'_{n,AW} \leq 48$	$40 < L'_{i,F_{max},AW} \leq 43$
3	$48 < L'_{n,AW} \leq 53$	$43 < L'_{i,F_{max},AW} \leq 47$
4	$53 < L'_{n,AW} \leq 58$	$47 < L'_{i,F_{max},AW} \leq 50$

Hz, frequency; S, reverberation time (second); dB, sound level; $L'_{n,AW}$, inverse A normalised floor impact sound level for lightweight floor impact noise; $L'_{i,F_{max},AW}$, inverse A normalised floor impact sound level for heavyweight floor impact noise.

gypsum panels, lightweight porous concrete, side insulation, and finishing mortar. Additionally, it is reported that carpets and other soft resilient floor finishing material, such as carpet with rubber underlay, would be useful for reducing the influence of impact sound levels. However, the floor of this field test was bare, which means the finishing material or any type of noise resilient layers would be applied on top of the voided slab system. If the floor impact sound insulation performance test could be conducted after applying the construction finishing materials on top of the voided slab system, the floor impact sound insulation performance might be slightly better than that of the bare floor without finishing.

The floor impact sound insulation performance of this study further evaluated only the sound insulation performance of the voided slab system applied to one building. However, further research is required to compare data from similar sized buildings with other structural systems, which are commonly built into existing high-rise apartment housing. Through comparisons with other structural systems, the floor impact sound insulation performance of the voided slab systems can be determined more accurately.

In recent years, subjective assessments of sound insulation are one of the measures considered for evaluating the extent of discomfort and annoyance generated by unwanted noise. In order to expand the possibility of applying, as well as enhancing, the effectiveness and usefulness of the floor impact sound insulation of the voided slab system in this study, further studies would be necessary to assess subjective evaluations.

5 Conclusions

This paper presents the results acquired from the field test of the floor impact sound insulation performance of a voided slab system, as applied to a commercial residential-complex building in South Korea.

The acquired results have shown that adopting the voided slab system for a commercial residential-complex building increased the floor impact sound insulation performance. The test results show that the sound insulation performance of the voided slab system applied in the building for lightweight and heavyweight floor impact sound reached (47 and 41) dB, respectively.

According to the sound insulation performance rating criteria in South Korea, the measured values were grade 2 for both lightweight and heavyweight floor impact sound insulation. Based on these results, it is expected that the application of the voided slab systems in high-rise apartment housings would be one of the effective methods to insulate floor impact sound, regardless of the type of sound source.

In addition, the conducted noise insulation performance test specimen was bare floor, which means that no flooring material, such as carpet or rubber material, was applied on top of the floor. It is considered that the performance of the noise insulation for the voided slab system would be enhanced if the floor impact sound insulation tests were carried out after applying the finishing materials.

In summary, the sound insulation performance of the voided slab system in the commercial residential-complex building was concluded to completely satisfy the criteria of the certified floor structure for multi-unit dwellings in South Korea. Based on the results of the field tests, it is expected that the application of the voided slab systems to the slabs of apartment dwellings would be effective, and provide outstanding sound insulation performance. Moreover, it is expected that the floor impact sound insulation performance would be improved if floor-finishing material, such as carpet or other types of flooring material, would first be installed on the floor.

Authors' contributions

All authors contributed substantially to all aspects of this article. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

Availability of data and materials

The data used to support the findings of this study are included within the article. In addition, some of the data used in this study is supported by the references mentioned in the article.

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