INVESTIGATING THE CHARACTERISTICS OF FLOOR IMPACT SOUNDS IN A BOX-FRAME TYPE REINFORCED CONCRETE STRUCTURE

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1 INTRODUCTION

Most apartment buildings in Korea are box-frame type structures built with reinforced concrete. Because frame walls bear structural loads, box-frame type structures do not require columns or beams, thereby offering advantages of reduced structural height, enlarged room space, and reduced air-borne sound transmission. In addition, box-frame type structures have a complex floor composition because of heating systems under the floor being installed. This combination of complex floor structure and box-frame type construction facilitates the propagation of structure-borne sound between apartment units, particularly between upper and lower units. Currently, floor impact noise is an important issue that has significant influence on the apartment living. One of the most annoying noises for apartment residents is heavy-weight impact noise caused by children running and jumping[1].

To reduce floor impact noise, several insulation methods have been used, such as elastic surface layers, floating floors, and double ceilings. Floating floors, in which resilient isolators are inserted between a structural slab and an upper layer of the floor, are have heretofore been generally used because of their effectiveness in controlling structure-borne and airborne noise. Ver[2] introduced a procedure for calculating impact sound levels of floating floors when using a tapping machine (ISO 140-6). His investigation showed improvement of impact noise isolation below 100 Hz, which would be reversed in a concrete floating floor. Other researchers, Josse and Drouin[3] also noted the negative reduction value of a concrete floating floor near the resonance frequency of the floor structure. Stewart and Craik[4] investigated impact sound transmission using a statistical energy analysis (SEA) of a chipboard floating floor attached to battens, the battens being supported by a concrete slab. Stewart and Craik's theoretical model is in good agreement with measured results in the high frequency range. However, the model's predicted results are not in good agreement in the low frequency range. From these researches on the reduction of the floor impact sound, the low frequency performance of a slab structure when using a heavy-weight impact source is a significant problem in floor impact sound insulation.

Viscoelastic damping materials are widely used to reduce noise in vehicles, ships, and machinery; however, there has not been a report of their use in apartment building concrete slabs to reduce floor impact sounds. In this study, the effects of typical resilient isolators and viscoelastic damping materials on floor impact noise in box-frame structures with reinforce concrete slabs were investigated and compared in real apartment buildings.

2 MEASUREMENT METHODS FOR FLOOR IMPACT

2.1 Standard floor impact sources

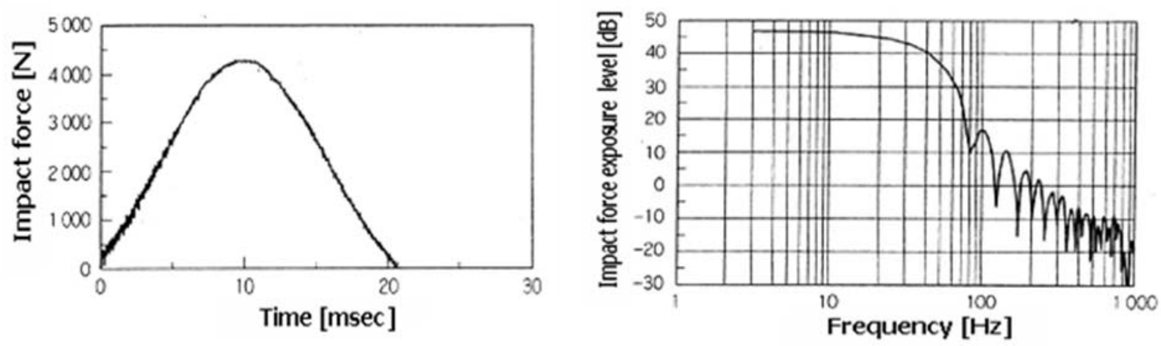
Standard floor-impact sources were considered for this study. For example, the International Standards Organization (ISO) suggests using a tapping machine as an impact source, and to measure light-weight impact sound transmission through floors. This tapping machine has 5, 0.5 kg, steel-faced hammers that strike the floor 10 times per second from a height of 40 mm. However, a low-frequency isolation performance of the tested floor structure cannot be evaluated by this type of tapping machine because it does not have enough impact force at low frequencies. Research has

shown that the rating of sound insulation in floor materials on with a tapping machine is not as reliable as testing done by human footsteps[5, 6].
Another third standard test is called a *banging* test. It is the Japanese Industrial Standard test for low-frequency impact sound and calls for a small automobile tire to be dropped from a height of 0.85 m onto a test floor. The resulting sound pressure levels (SPL) are measured in the room below the test floor. The dropped tire, which has an effective mass of 7.3 kg, 2.4×10^5 Pa in air pressure and 0.8 in coefficient of restitution generates an impact on the floor. This Japanese Industrial Standard (JIS A 1418-2) has been used in Japan and Korea to evaluate low-frequency impact sound [7]. However, since the impact force generated by this machine is excessive impact force level below 63 Hz, this bang machine is not appropriate for reproducing human impacts, such as the running and jumping of children.
In this study, the banging test is used for the investigating of the low frequency isolation performance in reinforced concrete slabs. Since the natural frequency of the concrete slab in box-frame type structures coincides with its resonance frequency (i.e., below 40 Hz) of the slab structure generated by the bang machine, the floor-impact sound level is amplified at low frequency bands. A measured impact sound using the bang machine is affected by the resonance of the slab structure below 63 Hz, i.e., near the natural frequency of the slab. Therefore, the low frequency isolation performance, which is related to dynamic characteristics of the floor structure using various isolators, can be classified by this *banging* test.

2.2 Measurement and evaluation procedure

The tapping machine (RION, FI-01) and the bang machine (RION, FI-02) were used to simulate light-weight and heavy-weight impact sources, respectively. The tapping machine was used to produce impact sounds whose dominant frequencies were high, such sounds simulating walking in high heels or the dropping of a lightweight object. The bang machine produced a larger impact force in the low frequency range (i.e., below 100 Hz) similar to the force caused by a person walking or running. The peak levels of impact sound and vibration produced by the bang machine were measured. The steady-state levels of sound and vibration produced by the tapping machine were measured by averaging 6-second impact intervals. Four microphones (B&K, Type 4165) were installed 1.2 m above the floor of receiving room to measure the SPLs. The height of the receiving microphone was 1.2 m above the floor. This position is almost half the height of a typical apartment room ceiling, and is at the level of actual listening. At low frequencies (e.g., 63 Hz in octave band frequency), the sound levels at 1.2 m are lower than at other heights in the same room due to room modes[8]. In the field measurement condition, the sound fields at low frequencies in the room were not diffuse and varied greatly depending on room conditions, which is determined by shape of the room and finishing materials used on the floor of the room. Thus, the fixed position method for the microphones is deemed reliable for this investigation because the performance of various isolators was evaluated using comparative test methods in terms of insertion loss in the same building structure.
The measured data were evaluated in accordance with a single-number rating method using an inverse, A-weighted impact-sound level. The inverse, A-weighted light-weight impact-sound level ($L'_{n,AW}$) values from the tapping machine were calculated according to JIS A 1419-2, which uses a reference curve for impact-sound levels that differ from the reference curve used in ISO 717-2. JIS A 1418-2 states that the light-weight impact-sound level must have an equivalent sound level (L_{eq}) at all 5 octave band frequencies from 125 to 2,000 Hz. It also states that the total deviation above the inverse A-weighted reference curve in each of the measured 5 octave bands should not exceed 10 dB. On the other hand, to determine the heavy-weight impact sound level of a given floor, $L_{i,Fmax,AW}$, the measured maximum impact sound levels (L_{max}) were plotted against 4 octave band frequencies ranging from 63 to 500 Hz, according to JIS A 1419-2. The fitting procedure for single number rating value allows for a total deviation of 8 dB above the inverse A-weighted reference curve in each of the measured 4 octave bands. The inverse A-weighted impact sound level of the floor is the impact sound level at 500 Hz on the inverse A-weighted reference curve. Heavy-weight impact sound is then measured at the maximum level using a sound level meter set at a time constant of Fast; On the other hand, light-weight impact sound is measured by a time-averaged level[9].

The frequency characteristics of the floor structure were analyzed by their vibration measurements. Because a high energy level is required to produce frequencies below 100 Hz, the bang machine was chosen as the heavy-weight impact source. The bang machine impacted the center of the source room and produced a heavy-weight impact with the characteristics of a 20 ms, half-sine wave (as shown in Figure 1). An accelerometer was installed near the excitation point (center) of the floor to determine the trigger signal and the reference signal. The vibration acceleration was then measured 10 times at the excitation point, and the measurements were averaged.
The sound and vibration of each floor structure were measured and analyzed using a real-time frequency analyzer (B&K Type 3560c, PULSE Lapshop). Measurements were taken 6 months after building construction was complete, thereby ensuring consistent compressive strength of the concrete structure.



(a) (b)

Figure 1. Impact force characteristics of the bang machine: (a) impact force level spectrum at sampling rate 24Hz, (b) frequency resolving power 2.93Hz

3 REDUCTION OF FLOOR IMPACT SOUND LEVELS

3.1 Reduction through the use of resilient isolators

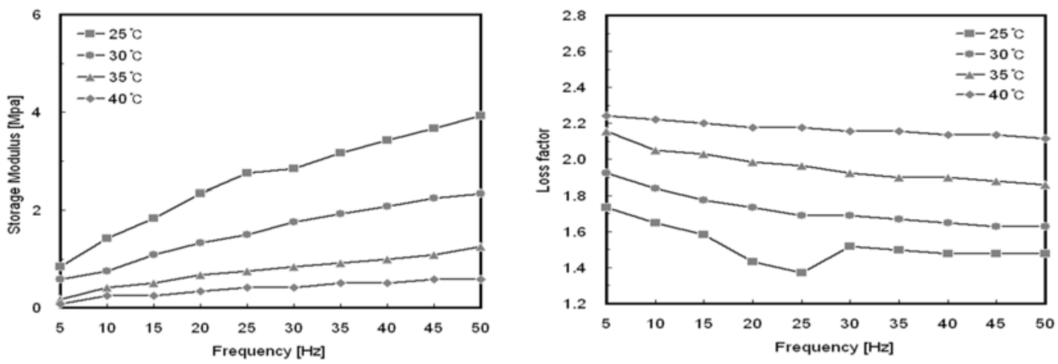
Generally, a floating floor consists of a resilient material, or isolator, which insulates structure-borne sound propagation between a given structural slab and a wall frame. Typical resilient isolators are often made of materials such as polyethylene, expanded polystyrene, cellular rubber, polyurethane and rock wool. The material properties of resilient isolators are evaluated in terms of their dynamic stiffness and loss factor. DIN 18164 recommends that a floating floor be designed with a natural frequency below 100 Hz, and a dynamic stiffness no greater than 30 MN/m^3. Generally, light-weight impact sound decreases as dynamic stiffness of a floor increases. Also, increasing the dynamic stiffness of a floor increases its hardness and durability. In Korea, the dynamic stiffness and loss factor of the resilient materials used in a floating floor is should be smaller than 40 MN/m^3 and the loss factor should be between 0.1 and 0.3.
To measure the dynamic stiffness and loss factor of the resilient isolators used under floating floors in dwellings, isolators were placed between the two horizontal surfaces under the floor, the base plate and the load plate, according to ISO 9052-1, Part 1. The dynamic stiffness was determined by using impulse signal sources. Using this method, the dynamic stiffness of the two resilient isolators was measured and the isolators' dynamic performances were compared.
For determining the dynamic stiffness, the response time and peak amplitude of the resulting vibration signals were measured using an impact hammer (Endevco, Type 2302-10) and accelerometers (Endevco, Type 751-10). The material properties determined from this experiment are given in Table 1.

Type	Composition	Thickness [mm]	Dynamic stiffness [MN/m^3]	Loss factor
I-R1	PE foam + PE plate + PE foam	22	20.5	0.17
I-R2	PE foam+ PVC perforated sheet + PE foam	20	23.7	0.19

Table 1. Dynamic properties of the resilient isolators

3.2 Reduction through the use of viscoelastic damping materials

Viscoelastic polymeric materials is used to constrain layers damping in concrete floor slabs especially when significant increases of slab thickness are not practical. Viscoelastic materials absorb vibrational energy through longitudinal contractions and expansions as the structure is excited. As the slab surface was impacted, shear forces generated by the differential strain cause vibration energy dissipation in the damping layer.
The performance of damping materials generally depends on temperature and frequency[10]. The properties of the viscoelastic material are analyzed according to temperature variations using a thermal-mechanical analyzer (TA Instruments, DMA 2980). In this dynamic mechanical analysis, a harmonic force that causes deformation of the sample of damping material generates the harmonic stress in the sample. As shown in Figure 2, the dynamic characteristics of the damping material show strong frequency dependent variation.



(a) (b)

Figure 2. Storage modulus (a) and loss factor (b) of the viscoelastic damping material according to temperature variation

The purpose of using viscoelastic materials instead of resilient isolators is to reduce heavy-weight impact sound while not changing the floor structure. When the floor surface is impacted, the vibrational energy inside the floor structure is transformed into heat due to the energy-absorbing properties of the viscoelastic damping materials. Viscoelastic materials are easily constructed and have some adhesive properties that allow for easy attachment to a structural slab and the lightweight concrete layer (the upper layer for heating). Since effective noise reduction is achieved from the damping layer, viscoelastic materials can function as impact sound insulators for constrained layer damping (CLD) of low-frequency structure-borne noise. The structural loss factor of concrete is very small (less than 0.01)[11]. In the light of this, viscoelastic damping treatment on a concrete slab is an effective method to reduce heavy-weight impact sound.

4 INVESTIGATION OF VIBROACOUSTIC CHARACTERISTICS OF CONCRETE SLABS

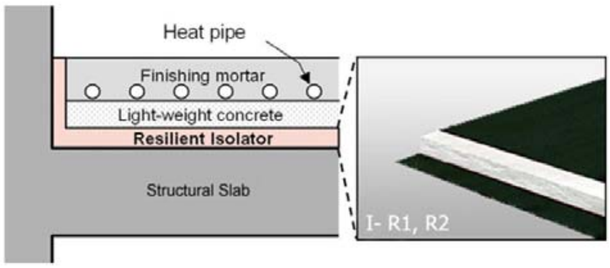
4.1 Effects of resilient isolators (Experiment I)

4.1.1 Floor structures

In Experiment I, the floor-impact sound levels recorded from floors, with and without resilient isolators in the floor structures, were compared. The experiment was conducted in 8, 100 m2 units in a box-frame type, reinforced concrete, high-rise apartment building.
Four of the units had a plain floor structure (I-P) (i.e., without resilient isolators) while the other four units had either a resilient isolator I-R1 or a resilient isolator I-R2 inserted into the floating floor structures on two units respectively. Four identical units from the floors of a 25-story apartment building were selected. The floor dimension of the room is 3.0 m by 2.7 m with rectangular shape. The plain floor structure was composed of a structural slab and an upper layer for installation of a heating system in the floor (lightweight concrete and finishing mortar). Table 2 shows the thickness and material properties of the floors. Figure 3 illustrates the structure of the floating floors with resilient isolators. Resilient isolators are installed on top of the structural slab and inserted between the floating floor slab and the walls in order to isolate the propagation of the structure-borne sound from vertical and horizontal vibration caused by light-weight floor impact.

Type	Reinforced concrete		Lightweight concrete		Finishing mortar	
	T [mm]	ρ[kg/m^3]	T [mm]	ρ[kg/m^3]	T [mm]	ρ[kg/m^3]
I-P	150	2400	60	600	50	2100
I-R1, R2	150	2400	40	600	50	2100

Table 2. Thickness and density of the resilient floor structures



FIigure 3. The resilient isolator used in the floor structure (Experiment I).

4.1.2 Test procedure

Both the I-R1 and I-R2 resilient isolators consist mostly of polyethylene (PE) foam. The structural difference between the two isolators is that a PE plate was used in I-R1, whereas a PVC-perforated sheet and water-resistant foil were used in I-R2. The foil was added to prevent moisture from entering the resilient isolators during the laying of the lightweight concrete.
The above mentioned 8 apartment units were tested using both a tapping machine and a bang machine. Natural frequencies, vibration acceleration levels and SPLs were all measured. As shown in Table 3, light-weight impact sound levels were measured and compared with those of heavy-weight impact sound levels.

Type	Natural frequency[Hz]	VALd [dB]	VALc [dB]	$L'_{n,AW}$ [dB]	$L_{i,Fmax,AW}$ [dB]
I-P	64	99	88	59	53
I-R1	50	111	94	55	61
I-R2	57	112	97	56	59

* VALd: Vibration acceleration level at the source (driving) room
* VALc: Vibration acceleration level at the receiving room
* Measurements were made with a heavy-weight source, except for $L'_{n,AW}$

Table 3. Vibroacoustic characteristics of reinforced concrete floors using light-weight ($L'_{n,AW}$) and heavy-weight ($L_{i,Fmax,AW}$) impact sources (EXPERIMENT I)

4.1.3 Measurement results

As shown in Table 3, the average natural frequency of the floating floor structures (I-R1 and I-R2) was about 53.5 Hz, which is 10 Hz lower than that of plain floor structures. In the plain floor structures (I-P), the structural slab and the upper layer of the floor were strongly bonded after construction resulting in a floor structure that behaved similarly to a single body, and generated a bending vibration mode. For the other floating floor structures (I-R1 and I-R2), the resilient isolator acted as a spring that yielded rigid body modes for the structural slab and the upper layer of the floor.

As shown in Table 3, the ceiling acceleration levels of the floor structures with resilient isolators were 6-9 dB higher than those of the plain floor structures. In the floating floor structures, the reduction of the vibration acceleration levels (i.e., difference between VALd and VALc) exceeded that of the plain floor structure by 4-6 dB. The ceiling-vibration acceleration levels (VALc) of the floating floor structure were also higher than that of the plain floor structure. This is because the floating floor slab moved more freely, and, therefore, increased vibration propagation. Table 3 also shows that both vibration acceleration levels and impact sound levels increased as the natural frequency decreased. When the natural frequency decreased by about 10 Hz between the plain floor and the floating floor structures, the light-weight impact sound level ($L'_{n, AW}$) decreased about 3 dB, whereas the heavy-weight impact sound level ($L_{i,Fmax,AW}$) increased by about 7 dB. This behavior illustrates the difficulty of simultaneously reducing light-weight and heavy-weight impact sound levels. As a result, the most effective method for reducing impact sound and vibration acceleration levels from heavy-weight sources is to increase the natural frequency of the floor structure, in box-frame type structures built with reinforced concrete.

Figure 4 shows the frequency domain spectrum of floor impact sound produced by the light-weight and heavy-weight impact sources. As shown in Figure 4(a), the dominant frequencies of the light-weight floor impact sound level were in the 125-800 Hz range. The average light-weight impact sound level in the structure with resilient isolators decreased by 5-10 dB in the high-frequency range (i.e., over 125 Hz), but increased at the low-frequency range (below 100 Hz). These results show that the resilient isolators are not effective for reducing the impact sound level at low frequencies. Figure 4(b) shows the frequency characteristics of all the floor systems impacted by the heavy-weight source. The dominant frequencies were below 80 Hz, which are much lower than the frequencies produced by the light-weight impact sound. The peak level for each floor structure was about 50 Hz. At frequencies above 80 Hz, the sound level decreased dramatically with increasing frequency. In the low-frequency range, the floating floor structures had a sound level that was 5-7 dB higher than that of the plain floor structure.

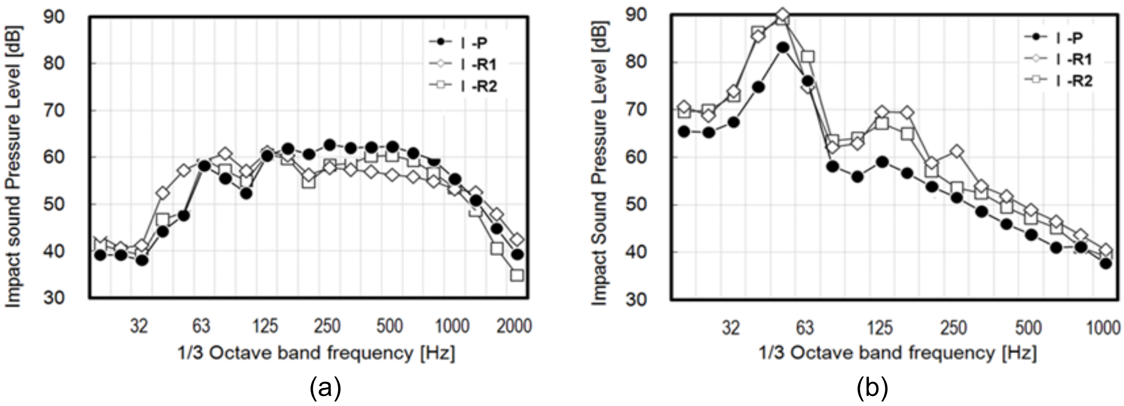


Figure 4. Light-weight (a) and heavy-weight (b) floor impact sound levels observed at 1/3 octave frequencies for the floor structures with bare concrete (P) and resilient isolators (R1 and R2).

4.2 Comparison of treatment results between resilient isolator and viscoelastic damping materials (Experiment II)

4.2.1 Floor structures

In this experiment, the vibration and noise characteristics of floor impacts produced by light-weight and heavy-weight impact sources in two separate rooms for typical high-rise apartment buildings in Korea were investigated. As shown in Table 4, one floor system contained a resilient isolator within the structure (II-R) and another contained damping material (II-D, shown in Figure 5). The dynamic stiffness as a result of a resilient isolator was 7.2 MN/m^3 with a loss factor of 0.13. This dynamic stiffness was 13 MN/m^3 lower than that resulting from the use of an isolator in Experiment I. Therefore, using isolators in floor structures with heavy- and light-weight impact sound levels produces improved the floor impact isolation performance compared to that in Experiment I. The honeycomb structure of II-D is placed between the damping layer and the upper surface of the floor (lightweight concrete). The resilient isolator layer was 20 mm thick, and the damping material layer with the honeycomb structure was 15 mm thick.

Type	Floor Area [m^2]	Floor System Composition [Thickness: mm]
II-R	18.4	Concrete (150) + resilient isolator (20) + lightweight concrete (40) + finishing mortar (50)
II-D	14.6	Concrete(150) + damping material (3) + honeycomb structure (12) + lightweight concrete (45) + finishing mortar (50)

Table 4. Details of floor systems in the apartment building

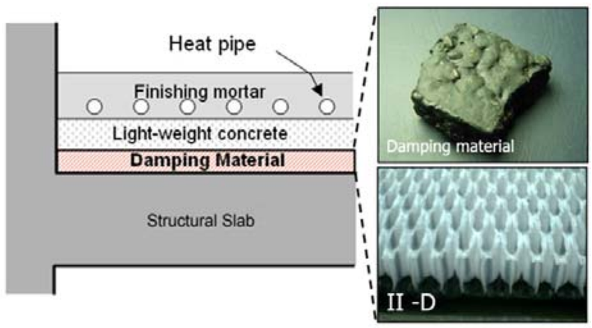


Figure 5. The damping material in the floor structure (Experiment II)

4.2.2 Test procedure

The vibrations and sound levels generated by the light-weight and heavy-weight impact sources were measured. The measurement method and equipment were the same as in Experiment I. The vibration acceleration was measured both for the structural slabs and for finished floors with resilient or damping materials. The impact sound level was measured when the walls, floor and ceiling were covered with finishing materials.

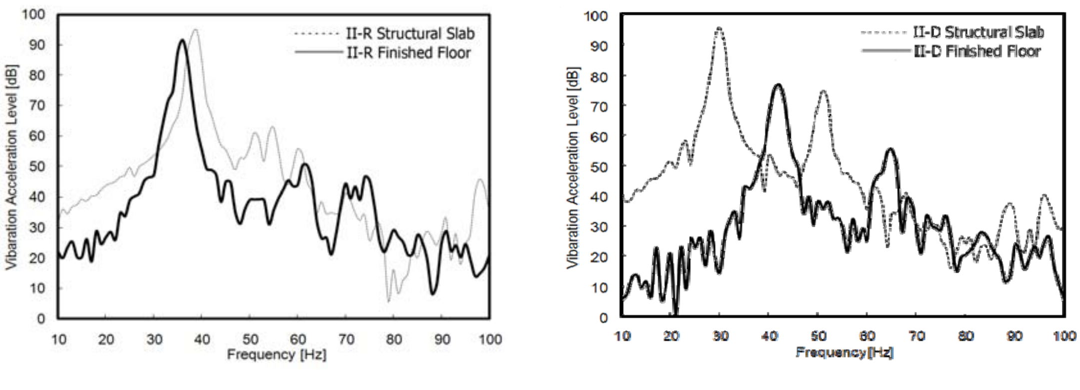
4.2.3 Measurement Results

Type	Natural frequency [Hz]		Acceleration level [dB]		$L'_{n,AW}$ [dB]	$L_{i,Fmax,AW}$ [dB]
	Structural slab	Finished floor	Structural slab	Finished floor	Finished floor	Finished floor
II-R	39	42	95	92	53	49
II-D	30	42	96	77	50	45

* Measurements were made with a heavy-weight source except for $L'_{n,AW}$

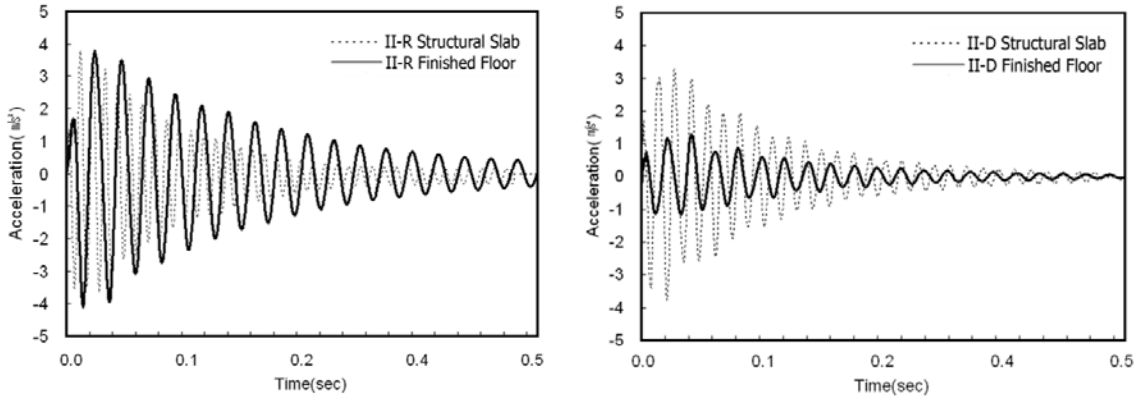
Table 5. Results of floor impact sound measurements using light-weight ($L'_{n,AW}$) and heavy-weight ($L_{i,Fmax,AW}$) impact sources (EXPERIMENT II).

Table 5 shows the natural frequency, acceleration, and vibration acceleration levels of the floor impact sounds. The resulting peaks and natural frequencies reflect the dynamic characteristics of the floor structures.
Figure 6 shows the frequency response spectrum in the II-R and II-D. The vibration acceleration levels decreased and the natural frequencies increased after the installation of finishing layers on all structures. The vibration spectra varied depending on the size and shapes of the room.
Table 5 shows that the vibration acceleration levels of the units with damping material installed (II-D) were 19 dB lower than in units with only a structural slab. The natural frequency of the slab structure increased by 12 Hz. Quite differently, in units with resilient isolators installed (II-R), the vibration accelerations levels decreased by 3 dB and the natural frequency increased by 3 Hz with a structural slab. In Experiment I, the resilient isolator reduced the natural frequency but was not effective in reducing the vibration acceleration level. This was also observed in Experiment II and was due to the floor functioning in a rigid body mode. This reconfirmed that a floating floor structure using resilient isolators was not effective in reducing heavy-weight impact sound. The changes in natural frequency show that changing the dynamic properties of the floor structure by altering the characteristics of the damping material can effectively reduce the acceleration level.
Figure 7 shows the time response of the vibration acceleration measured in the rooms with each type of floor structure. This figure illustrates the impact-energy absorption characteristics of the damping materials. Floor type II-D, which has damping material, exhibited a shorter response time and much better reduction of the vibration accelerations than did II-R, which contained a resilient isolator.
The data in Table 5 also show the effectiveness of each structure type for reduction of heavy-weight impact sounds using a single-number evaluation method. The decrease in the heavy-weight impact sound for structures with damping materials was about 3 dB greater than those with a resilient isolator.
Figure 8 shows the impact sound spectra. The floor impact sound levels produced by the bang and tapping machines were plotted at 1/3 octave band frequencies. As shown in Figure 8 (b), the dominant frequencies are below 80 Hz and the sound level has a peak around 50 Hz. The floor structure with a resilient isolator had a much higher SPL at low frequencies, and the reduction of the light-weight impact sound levels decreased below 125 Hz when damping material was used in the floor structure. The reduction of SPL between 125 Hz and 250 Hz was relatively small. The single number rating of the light-weight floor impact sound for the floor structure with the damping material was 5 dB lower than the floor structure with a resilient isolator.
In the view of the noise annoyance, the pitch sensation for the dominant frequency of the floor impact sounds, which is affected by the resonance frequency of the floor, is an important factor for evaluating heavy-weight floor impact sounds. In a previous study, the variation of the pitch strength of floor impact sounds was found to be the most influential for noise annoyance; the damped floor resulted in smaller variation of pitch strength causing less annoyance[12].



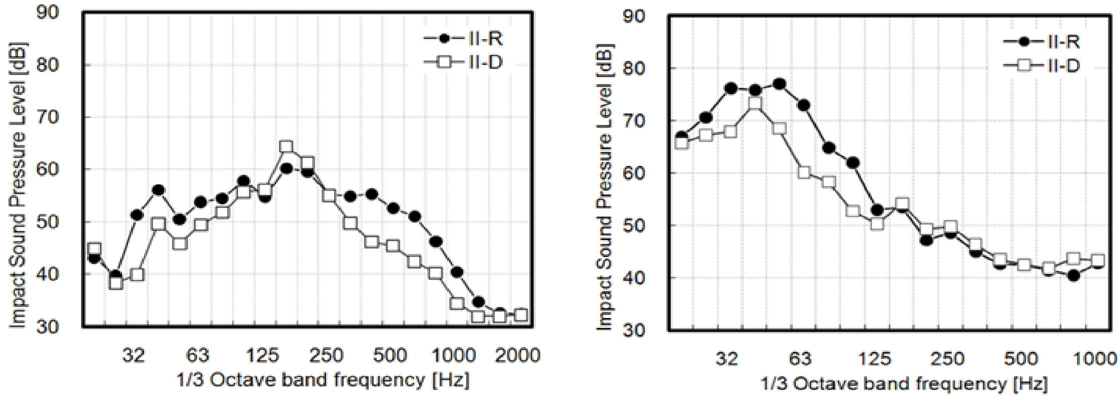
(a) (b)

Figure 6. Frequency responses with heavy-weight floor impacts for floor structures using (a) resilient isolators, and (b) viscoelastic damping materials.



(a) (b)

Figure 7. Time response spectra of different floor structures using (a) resilient isolators, and (b) viscoelastic damping materials.



(a) (b)

Figure 8. Light- (a) and heavy-weight (b) impact sound levels observed at 1/3 octave band frequencies for floor structures using resilient isolators (R) and viscoelastic damping materials (D).

5 DISCUSSION AND CONCLUSIONS

The isolation performances related to dynamic characteristics of the complex floor structures are investigated. This study showed that a determination of the resonance frequency of a box-type floor structure is important in relation to the force characteristics of a heavy-weight impact source. In the field measurements of impact sound insulation, the resonance frequency for the treated floors appeared around 40 Hz (20-60 Hz) for the various boundary conditions.

When resonance frequencies for structures treated with resilient isolators (i.e., floating floors) fell below 40 Hz, resilient isolators were not effective in reducing heavy-weight impact sound levels or vibration levels. Field measurements in real apartment buildings showed that the natural frequency of the floor structures containing resilient isolators was 15% lower than that of the plain floor structures and that the heavy-weight impact sound level increased at frequencies below 80 Hz. In other words, the heavy-weight impact sound level in floating floor is higher than that of the plain floors that does not contain resilient isolators, because each layer is separated by resilient isolators. This type of floating floor construction allows each layer to move freely, i.e., the floating floor to function in a rigid body mode. However, reducing impact sound level for light-weight impact sources does not give the same improvement as do heavy-weight impact sources.

Putting damping materials in the floor structure instead of resilient isolators, however, reduces the heavy-weight impact sound. This is because of the impact energy absorption of the constrained

damping layer and the adhesion properties of the viscoelastic damping materials, which form a single-body with the upper layers. Therefore, increasing the natural frequency of a reinforced concrete slab effectively reduces sound levels of heavy-weight impact sources. Moreover, damping material that incorporates a honeycomb construction is effective for the reduction of the heavy-weight impact sound, despite the small thickness of this type of damping material. From the measurement results, the reason for the reduction in the vibration and sound levels in the heavy-weight impact is thought to be the effect of the CLD. Therefore, floor structures in reinforced concrete, box-frame type structures the resonance frequencies should be designed to have resonance frequencies above 40 Hz (or higher than the resonance frequency of a bare concrete slab).
A need for developed discussion about viscoelastic damping materials on the structural slab of reinforced concrete box-frame type structures still exists. The next thing that should be done is to determine the optimum thickness and position of the damping materials in each construction method and sectional design. This should be done using computational analysis and experiments.

6 ACKNOWLEDGMENT

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