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ORIGINAL ARTICLE

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The amount of wooden material in a closed room and its effect on the reverberation time

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Abstract Optimal sound-absorbing materials are vital for desirable room acoustics. The effect of wood used for interior wall decoration on the acoustical environment is explored in a controlled room by changing the amount of wall wooden materials. The effect on the interior reverberation time (RT) is reported in this work. The experiment was conducted in a relatively small concrete brick house (approximate dimensions $4.6 \times 3.2 \times 4.2$ m). Results showed that room shape and the arrangement of wooden wall decoration materials were important factors affecting the RT at different receiving positions. As the amount of wall decorating wood materials increased, the interior RT in the house decreased linearly; however, the RT at low frequencies diverged. After the analysis of covariance, all frequency variables were adjusted to the same level and a general regressive formula was developed as $\mathrm{RT} = C - 0.005\,\mathrm{DR}$. Where RT is the reverberation time (s), DR is the amount of interior wood materials used (%), and the C values were constants that ranged from 0.888 to 1.606 and varied according to the different octave bands. Furthermore, it was found that the increasing influential effect with the DR showed diminishing marginal utility. This means that the influence of DR on RT was not linear, and, therefore, the marginal utility should be considered in order to use wooden panels economically.

Key words Amount of interior wood material · Reverberation time · Concrete brick house

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Introduction

Concert halls, recording studios, and lecture halls generally demand high-grade and special acoustic design. In addition, other buildings such as schools, residences, and hotels are also concerned about their exterior noisy environment[1–3] and have become interested in acoustic design. The ideal reverberation time (RT) for classrooms and lecture halls is 0.4–0.8 s.[4] Room acoustics can affect the physical and psychological conditions of humans. Hase et al.[5] indicated that the RT value of a classroom was 0.44–0.99 s for wood construction and 0.44–0.64 s for reinforced concrete construction.

Most schools and residences in Taiwan were constructed with reinforced concrete. Their walls provide a good sound barrier against exterior noise owing to the high-density surface. However, it also causes interior sound reflection and prolongs the reverberation time. As a result, the degree of articulation and learning effectiveness in the classroom are adversely affected. Excessive interior reverberation time would is harmful to speech intelligibility.[6] Furthermore, concrete buildings also cause negative effects on human physical and psychological conditions in residences. To reduce the negative effects of reinforced concrete (RC) buildings, wood is usually installed not only as an interior decorative material, but also as an acoustic one.

Solid wood and other wood-based composites can be considered as acoustic materials because of their ability to absorb significant levels of incident sound in order to reduce the sound pressure level or RT in a room.[7] For example, plywood or particleboard provides sound absorption in the lower-frequency region of the audible spectrum (<500 Hz) and porous artificial materials are remarkably efficient absorbers in medium and high frequencies (2–4 kHz).[8]

The objective of this study was to investigate the RT of a reinforced concrete room using different amounts of interior wall surface area of wood materials. The results of this study may provide some information toward the improvement of room acoustics for residences and schools.

Table 1. Interior decorative positions and the percentage of interior decorative surface area with wooden materials (groups A–G)

Room number	Group													
	A[a]		B		C		D		E		F		G	
	DP	DR (%)	DP	DR (%)	DP	DR (%)	DP	DR (%)	DP	DR (%)	DP	DR (%)	DP	DR (%)
1	⑥ f	15.2	a, f	27.5	a, b, f	45.6	a, b, c, f	60.8	b, c, d, e, f	82.2	Upper half walls	46.9	a, b, c, d, e, f	100
2			b, f	35.6	a, c, f	39.7	a, b, d, f	67	a, c, d, e, f	73.4	Lower half walls	47.7		
3			c, f	27.5	a, d, f	45.9	a, b, e, f	63.8	a, b, d, e, f	82.2				
4			d, f	33.7	a, e, f	42.7	① a, c, d, f	58.2	a, b, c, d, f	76				
5			e, f	30.4	b, c, f	48.6	a, c, e, f	54.9	a, b, c, d, f	79.2				
6					b, d, f	54.7	a, d, e, f	61.1						
7					b, e, f	51.5	b, c, d, f	67						
8					c, d, f	45.9	b, c, e, f	63.7						
9					c, e, f	42.7	b, d, e, f	70						
10					d, e, f	48.9	c, d, e, f	61.1						

DP, Decorative positions with wooden materials; DR (%), percentage of interior decorative surface area with wooden materials; a, west wall; b, north wall; c, east wall; d, south wall; e, ceiling; f, floor

[a]Cotrol group

Materials and methods

Experimental materials

China fir (*Cunninghamia lanceolata*) panels, 0.9 cm in thickness, were used as interior wall finishing materials. Lumber with cross-sectional dimensions of 27 × 40 mm was fixed horizontally at 45-cm spacings before the panel was installed vertically in order to create an air layer between the panel and the solid wall.

Experimental RC house

The acoustic experiments were carried out in a concrete brick house located on the campus of the National Taiwan University in Taipei. The exterior dimensions of this house were 4.6 m in length, 3.2 m in width and 4.2 m in height. The thickness of the walls was 0.3 m. Hence, the interior dimensions of the house are 4.0 m(L), 2.6 m(W), and 3.6 m(H). Facing south, the house had a 2 × 0.9 m door, and one 1.1 × 0.9 m window on the east wall and another on the west wall. Solid 12.5-mm-thick lauan (*Shorea* spp) panel flooring was installed on studs at 45-cm centers.[9] Lumber of 27 × 40 mm cross section was also fixed on slab at 45-cm spacings before the China fir panels were installed. The four interior walls and the ceiling were kept clean before the different amounts of interior wood were applied.

Proportion of interior wall surface area of wood materials

The four walls and the ceiling were installed in seven different patterns in regard to the wooden panels as shown in Table 1 and Fig. 1.

Experimental methods

In order to determine the practical condition of ordinary rooms, we referred to the experiment of Dance and Shield[10] and devised the experimental method in which we measured the RT of the experimental RC house in response to the different proportion of wood materials and their position. The data obtained were used to examine the influence on room acoustics.

The major acoustic experimental instruments were: sound-level meter–1/3 octave band analyzers (Rion NA-27) which measure RT, and a random noise generator (Rion SF-05) which generates both pink noise and white noise in eight different octave bands to push a loudspeaker. RT was measured at six different octave bands, that is, 125, 250, 500, 1000, 2000, and 4000 Hz. In the study, the octave bands below 125 Hz was referred to as low, 250 Hz to 4 kHz as middle, and 4 kHz and higher as high.

The white noise at 100 dB was set to generate for 5 s. Then, the sound level meter–1/3 octave band analyzer was set to trigger mode to measure the RT. The trigger threshold was set to 90 dB and the receiving range was set from 40 to 110 dB. The time of initial intensity decaying at 20 dB

(RT20) was recorded, and then, the RT, that is, the initial sound level decaying at 60dB, was calculated and stored in the computer for further analysis.

According to the acoustic theory, the sound source must be nondirectional in any acoustic experiment; however, the loudspeaker is always directional. Noticing these discrepancies, a pretest was carried out in order to determine the optimal sound source location. First of all, four lower corners were chosen as the sound source positions. The measuring positions were set at 90cm, 120cm, and 150cm in height along the central vertical axis of the room. The results were processed by variation analysis to find the nonhomogenous sound sources and measuring positions for the following experiment. The final sound sources and measuring positions are shown in Fig. 2.

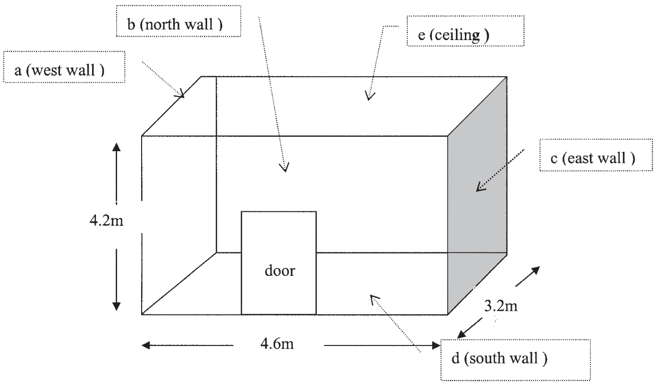

Fig. 1. The exterior dimensions of the experimental house

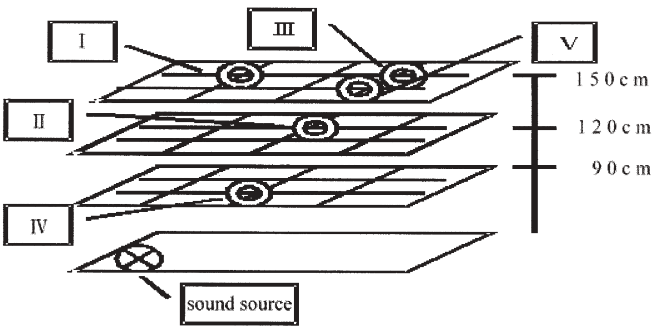

Fig. 2. Diagram of the sound sources and receiving positions (*I–V*) in the experiment

Results and discussion

Group A: control group

Only solid lauan panel flooring was fixed on the slab and the proportion of wooden material was 15.2% (Table 1). The RT at the high and medium octave bands was 0.78s and 0.89–1.37s, respectively, as shown in Table 2. There was no significant difference in RT from the measuring positions. However, RT at the low octave band was 2.05s, longer than that obtained at the high octave band and showed significant difference with measuring positions. This may be attributed to the poor sound absorption of concrete walls where most low-frequency sound energy is lost when propagated in the air. On the other hand, the high-frequency sound energy may be lost in the air or easily absorbed by objects, thus, its RT is shorter than that at low frequency.

An interesting result was obtained. The RT at positions II and IV (see Fig. 2) was significantly longer than that at the other positions. This may be attributed to the measuring positions just in front of the north and south wall and its distance was 2.6m. Hence, a stationary wave may have occurred between the two positions.

The above phenomena can be explained by the principle of resonance; the resonant frequency may be expressed as

$$f = \frac{c}{\lambda} = \frac{nc}{2L}$$

where λ is the wavelength, c is the velocity of sound in air (340m/s), L is the distance between two walls (2.6m), and n is an integer greater than zero.

Hence, the resonant frequency is a multiple of 65Hz. When n is 2, the frequency is 130Hz, which is included in the 125-Hz octave band. This result could explain why the RT at 125Hz is longer than the others.

Group B: wood material installed on two walls

The proportion of interior decorative surface area with wood materials ranged from 27.5% to 35.6% as shown in Table 1.

Under condition B1, the decrease in RT at octave bands over 1kHz was not significant (0.73–0.86s); however, it reduced significantly (0.85–0.96s) at octave bands of 250Hz and 500Hz, as shown in Table 2. This could be the effect of

Table 2. Reverberation time (s) at receiving position IV under various decorative wooden material conditions

Group	Conditions	DR (%)	Octave bands (Hz)					
			125	250	500	1k	2k	4k
A	A	15.2	2.05	1.37	1.23	0.93	0.89	0.78
B	B1	27.5	1.84	0.85	0.96	0.83	0.86	0.73
C	C1	45.6	1.54	0.53	0.66	0.75	0.81	0.68
D	D1	60.8	1.49	0.41	0.61	0.69	0.74	0.60
E	E1	82.2	1.73	0.39	0.50	0.64	0.68	0.56
F	F1	46.9	1.57	0.74	0.81	0.73	0.82	0.69
G	G	100	1.37	0.35	0.53	0.67	0.71	0.57

panel vibrating absorption of the wood panel at low frequency. The above phenomena and condition were similar to the results under condition B3.

Under condition B2, the decrease in RT at octave bands over 1 kHz was still not significant, but it reduced much more at 250 Hz. This may be attributed to the larger area of wood panel in the north wall, where absorption was proportional to the material area. Hence, when the octave band was at 125 Hz, the RT at positions I, II, and V was shorter than that under condition B1. However, the RT of positions II and IV was longer than that under condition B1. Conditions B3 and B4 were similar to condition B1.

Under condition B5, the ceiling was installed with wooden panels, and the reduction in RT at the high and medium frequencies was slight, and there was no effect at the low frequencies.

In general, with only two walls installed with wooden panels, the reduction in RT was insignificant at medium and high frequencies, but the effects varied with different measuring positions.

Group C: wood materials installed on three walls

With three walls installed with wood panels, the reduction in RT was more noticeable than in the group B experiments.

In group C, the proportion of interior decorative surface area of wood materials ranged from 39.7% to 54.7%, as shown in Table 1. Significant difference of RT under all conditions occurred at low octave bands (1.54 s); however, it was slight at medium, and high octave bands (0.53–0.86 s), as shown in Table 2. With one more interior wall installed with wood materials than those in group B, the sound-absorbing ability of group C increased especially at the medium and high frequencies. However, the reduction in RT was insignificant. Theoretically, two opposite walls installed with wooden panel under conditions C2 and C6 should be similar, but results were otherwise different. Obviously, the effects varied significantly with different measuring position at the low frequencies, but its influence was insignificant on the medium and high frequencies. Furthermore, the effect of the ceiling installed with wooden panel was not significant; the reduction in RT at the medium, and high octave bands was lower than that at the low octave bands. Because the increasing sound-absorbing ability with increased wooden panel area occurred in the medium and high frequencies, the decrease in RT was significant when wall was installed with wooden panel. The above phenomena did occur in all conditions which should be taken into consideration when room acoustics are designed.

Group D: wooden panel installed on four interior walls

In this group, the proportion of interior decorative surface area of wooden materials ranged from 54.9% to 70%, as shown in Table 1. When four interior sides of wall or ceiling were installed with wooden panels, the RT values were 1.49 s, 0.41–0.74 s, and 0.60 s for the low, medium, and high frequencies, respectively, as shown in Table 2. The amount of reduction in RT was greater than those of group C because more wooden panel was used as the absorbing material in high frequencies. RT at all measuring positions maintained a stable status after the proportion exceeded a specified percentage. However, it still showed irregular results in the low frequencies, especially at positions II and IV. Besides the occurrence of stationary waves, the uneliminated low-frequency background noise was also an influencing factor on the reduction of RT.

Group E: wood panel installed on five interior sides

In this group, only one interior surface of the room was not installed with the wood panels. Therefore, the proportion of interior decorative surface area of the wooden materials ranged from 73.4% to 82.2%, as shown in Table 1. The RT values were 1.73 s, 0.39–0.68 s, and 0.56 s, respectively for the low, medium, and high octave bands, as shown in Table 2. Although the proportion was greater than that of group D, the RT values were similar at the medium and high frequencies. In group E, the RT at all conditions (E1–E5) was reduced significantly.

Group F: wooden panel installed on upper or lower portion of four walls and the floor

In this group, all interior sides of the wall were installed with wooden panels. The proportion of wooden panel under conditions F1 and F2 was 46.9% and 47.7%, respectively, as shown in Table 1. The RT values were 1.57 s, 0.73–0.82 s, and 0.69 s for the low, medium and high octave bands respectively, as shown in Table 2. The RT values for conditions F1 and F2 were similar. Although the proportion of paneling was lower than that of groups D and E, the RT became longer and it was almost as long as that of group C. This means that the position of the installed wooden panel was also an influential factor on RT of a small room.

Group G: full installation with wooden panel

In this experiment, the proportion of wooden materials was 100%, as shown in Table 1. The RT values were 1.37 s, 0.35–0.71 s, and 0.57 s for the low, medium, and high octave bands, respectively, as shown in Table 2. The RT values at all measuring points were similar at the medium and high frequencies; however, the RT at positions II and IV was quite long. This may be caused by stationary waves and this problem should be treated carefully in the acoustical design of a room.

Comparison of group G with A

It was found that the RT values at all measuring positions (I–V) decreased with the increasing proportion of wood panel, and this trend seemed to be governed to a great extent by both measuring positions and wooden panel location. The change of RT value at position IV, for example, is shown in Fig. 3 and similar results were also found at other

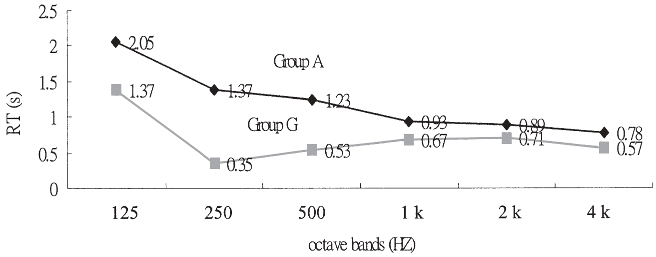

Fig. 3. Response of the reverberation time (*RT*) values at receiving position IV for *groups A* and *G*

positions I, II, III, and V. It showed that the RT values of group G decreased to below 0.5 s in the frequency range of 250 to 500 Hz.

Considering the coefficient of sound absorption in the group G experiment, it could be calculated from RT by the following foumula:[2]

$$\alpha = \frac{55.3V}{S \cdot c}\left(\frac{1}{T_2} - \frac{1}{T_1}\right)$$

where V is the volume of the experimental room (i.e., 37.44 m^3), S is the total area of wood panel (54.14 m^2), c is the sound velocity (340 m/s), T_1 is the RT before the interior is decorated with wooden material, and T_2 is the RT after the interior is decorated with wooden material.

The coefficients of sound absorption (α) at octave bands of 250 Hz and 500 Hz were 0.21–0.25 and 0.12–0.17, respectively, which were much greater than those of high octave bands. The α value was 0.05 in the high octave bands. We inferred that the major sound-absorbing mechanism comes from panel vibration rather than porous absorption in this study.

Relationship between the proportion of interior decorative wooden materials and RT value

The RT values decreased with the increasing proportion of interior decorative surface area of wooden materials at measuring positions I–V in all octave bands. A linear regression formula can be established. The R^2 values ranged from 0.267 to 0.781 and they were all statistically significant at the 1% level. Figure 4 shows the result obtained at receiving position IV. A similar trend was also obtained at other receiving positions of the different octave bands. At low octave bands, the R^2 values were generally lower; however, they were higher at medium and high octave bands. We could infer that the RT values were more unstable at low octave bands, because the sound energy was absorbed effortlessly and tended to form the resonant stationary wave.

Following the analysis of covariance, all frequency variables were adjusted to the same level and general regression formulas are shown as follows:

$$\mathrm{RT}_{125} = 1.606 - 0.005 \times \mathrm{DR}(\%)$$
$$\mathrm{RT}_{250} = 0.903 - 0.005 \times \mathrm{DR}(\%)$$
$$\mathrm{RT}_{500} = 0.940 - 0.005 \times \mathrm{DR}(\%)$$

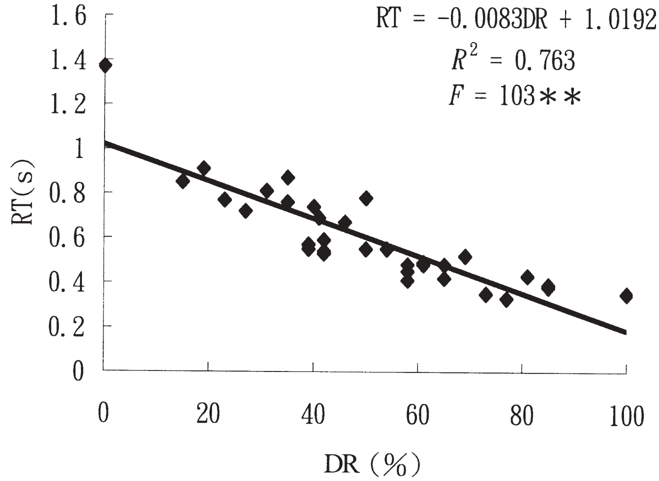

Fig. 4. Relationship between ratio of decorative surface area of wooden material (*DR*) and *RT* at receiving position IV for the 250 Hz octave band

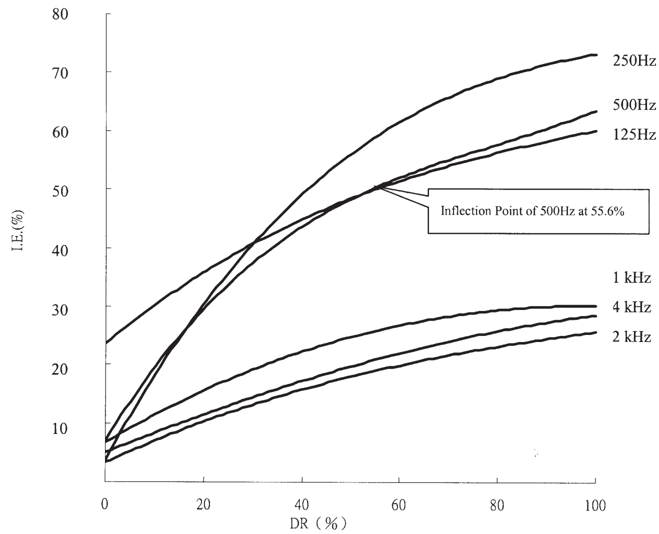

Fig. 5. The influential effect (*I.E.*) model for *DR* on RT at six different octave bands.

$$\mathrm{RT}_{1k} = 0.976 - 0.005 \times \mathrm{DR}(\%)$$
$$\mathrm{RT}_{2k} = 1.011 - 0.005 \times \mathrm{DR}(\%)$$
$$\mathrm{RT}_{4k} = 0.888 - 0.005 \times \mathrm{DR}(\%)$$

Where RT is the reverberation time (s), and DR (%) is the proportion of interior decorative surface of the wooden materials. The above formulas are useful to predict the RT according to various DR.

The influence of DR on the RT

Previous research showed the DR influence of reducing and controlling the RT. Before further discussing the influence and ignoring the difference of measuring position, the influential effect (IE) was obtained by following:

$$\mathrm{IE}\,(\%) = \left[\left(1 - \frac{\mathrm{RTexp}}{\mathrm{RTmax}}\right) \times 100\right]$$

Table 3. The inferential effect model equations for DR on RT at six different frequency bands

Octave bands (Hz)	Influential effect model equations	R^2	F
125	$Y = 10^{-7}x^3 - (5 \times 10^{-5})x^2 + 0.007x + 0.2363$	0.272	58**
250	$Y = (3 \times 10^{-7})x^3 - 0.0001x^2 + 0.0156x + 0.0365$	0.757	373**
500	$Y = (6 \times 10^{-7})x^3 - 0.0001x^2 + 0.0139x + 0.07$	0.836	522**
1k	$Y = (3 \times 10^{-8})x^3 - (3 \times 10^{-5})x^2 + 0.0051x + 0.0667$	0.578	186**
2k	$Y = (6 \times 10^{-8})x^3 - (2 \times 10^{-5})x^2 + 0.0039x + 0.0329$	0.680	322**
4k	$Y = (-2 \times 10^{-8})x^3 - (8 \times 10^{-6})x^2 + 0.0034x + 0.0501$	0.749	464**

In equations Y represents Influential Effect (%) = $\left[\left(1 - \frac{\mathrm{RT\,exp}}{\mathrm{RT\,max}}\right) \times 100\right]$; x represents DR (%)

** $P < 0.01$ as indicated by the F value test

where RTexp is the experimental value of each octave band under all conditions, and RTmax is the greatest experimental value of each octave band.

The above influential effect (IE) is shown in Fig. 5 and Table 3. It was found that the increase in IE with DR became slow, that is, a diminishing marginal utility was observed. This means that the influence on RT was not linear, and therefore the marginal utility should be considered in order to use wooden panels economically.

Owing to diminishing marginal utility, the maximum utility of wooden panel could be calculated by deriving the regression formula in Table 3 of each octave band in order to acquire the inflection point. At the inflection point, the curvature is zero, that is, the changing rate of the curve slope was reversed. The inflection point of the 500-Hz curve was at a DR of 55.6%, which meant when the DR was over 55.6%, the effect was more significant than when below it. However, in calculating other curves, all inflection points were over 100% which meant that the reducing rate of RT was a decline.

It was also found that the intercept for 125 Hz was the largest in Fig. 5, which means that the RT was the maximum when the DR was zero. It was much different from the other octave bands. The phenomenon could be attributed to the occurrence of a low-frequency stationary wave in a small room. This condition could cause serious interior acoustic defects. Hence, parallel wall surfaces should be avoided in the design of small rooms.

The influences of the proportion of wooden panel on RT at 125, 250, and 500 Hz were more significant than those in other octave bands, also shown in Fig. 5. Equivalent proportions of wooden panel produce a lower RT at 125, 250, and 500 Hz than at other octave bands. This means this effect was not so significant at 1, 2, and 4 kHz. The above-mentioned characteristic should be noted in application and design of room acoustics.

Conclusions

The conclusions drawn from this study are as follows:

1. The change in the sound source position did not make a significant difference to the RT at the same receiving position. The shape of the room and the arrangement of wooden wall-finished materials affect the RT value at different receiving positions. However, the RT values decreased as the proportion of the interior finished surface area (DR) in the enclosed room increased. The RT values were 0.78 s, 0.89–1.37 s, and 2.05 s for high, medium, and low octave bands, respectively, in the group A room; and they were 0.57 s, 0.35–0.71 s, and 1.37 s for high, medium, and low octave bands, respectively, in the group G room.
2. After all frequency variables were adjusted to the same level, a general regression formula developed as: RT = $C - 0.005$ DR. Where RT is the reverberation time (s), DR is the amount of interior wood materials used (%), and the C values were 0.888–1.606, which varied according to the different octave bands. The RT values can be predicted by substituting in formations on DR and characteristic octave bands.
3. It was found that the increasing IE with DR showed diminishing marginal utility. This means that the proportion influence on RT was not linear, and, therefore, the marginal utility should be considered in order to use wooden panels economically.

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