Advanced Composite Materials
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/tacm20

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Version of record first published: 02 Apr 2012.

To cite this article: Qing-Qing Ni , Enjie Lu , Naoya Kurahashi , Ken Kurashiki & Teruo Kimura (2008): Development of Insulation Sheet Materials and Their Sound Characterization, Advanced Composite Materials, 17:1, 25-40

To link to this article: http://dx.doi.org/10.1163/156855108X292657

VSP Advanced Composite Materials 17 (2008) 25–40
ADVANCED COMPOSITE MATERIALS
www.brill.nl/acm

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Received 12 September 2006; accepted 27 March 2007

Abstract

The research and development in soundproof materials for preventing noise have attracted great attention due to their social impact. Noise insulation materials are especially important in the field of soundproofing. Since the insulation ability of most materials follows a mass rule, the heavy weight materials like concrete, lead and steel board are mainly used in the current noise insulation materials. To overcome some weak points in these materials, fiber reinforced composite materials with lightweight and other high performance characteristics are now being used.

In this paper, innovative insulation sheet materials with carbon and/or glass fabrics and nano-silica hybrid PU resin are developed. The parameters related to sound performance, such as materials and fabric texture in base fabric, hybrid method of resin, size of silica particle and so on, are investigated. At the same time, the wave analysis code (*PZFlex*) is used to simulate some of experimental results. As a result, it is found that both bundle density and fabric texture in the base fabrics play an important role on the soundproof performance. Compared with the effect of base fabrics, the transmission loss in sheet materials increased more than 10 dB even though the thickness of the sample was only about 0.7 mm. The results show different values of transmission loss factor when the diameters of silica particles in coating materials changed. It is understood that the effect of the soundproof performance is different due to the change of hybrid method and the size of silica particles. Fillers occupying appropriate positions and with optimum size may achieve a better effect in soundproof performance. The effect of the particle content on the soundproof performance is confirmed, but there is a limit for the addition of the fillers. The optimization of silica content for the improvement of the sound insulation effect is important. It is observed that nano-particles will have better effect on the high soundproof performance. The sound insulation effect has been understood through a comparison between the experimental and analytical results. It is confirmed that the time-domain finite wave analysis (*PZFlex*) is effective for the prediction and design of soundproof performance materials. Both experimental and analytical results indicate that the developed materials have advantages in lightweight, flexibility, other mechanical properties and excellent soundproof performance.

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Edited by the JSCM

 DOI:10.1163/156855108X292657

Keywords
Transmission loss, sound insulation, sheet material, lightweight, PU hybrid resin

1. Introduction

Noise has become a significant problem that severely affects the daily life of many people [1–4]. Thus, to prevent noise with sound isolation materials has attracted much attention from many researchers. According to the property or application fields of soundproof materials, they may be classified into several categories: insulation materials, sound absorption materials, vibration isolation materials, damping materials, etc. [5]. Among them, insulation materials are the most important and these have been widely used in the building industry, the electronics industry, automobile industry and other fields. However, most insulation materials are heavy, hard and thick, such as concrete, lead and steel plate; these will limit other optimal design parameters and will give rise to various restrictions in construction [6].

On the other hand, flexible sheet insulation materials have been developed recently for soundproof constructions in buildings, interior design, and other aspects of daily life [7, 8], and many more kinds of applications are expected. The advantages of using such composite sheet insulation materials are their high performance due to not only the sound insulation effect but also material properties such as light weight, specific rigidity, specific strength, low cost and easier design. Thus, the development of new flexible sheet insulation materials has been progressing in recent years [9–11].

In the present paper, materials with light weight, high specific rigidity, specific strength and high sound performance have been developed in order to replace the traditional metal or concrete materials. Glass fabric and/or carbon fabric was used as the reinforcement base, while nano-silica hybrid resin was used as coating layers. This new sheet material has been created for a variety of uses in soundproof structures. Since there are many factors that have an influence on soundproofing performance, the design of composite structure may lead to a whole range of variation of sound performance in such materials. Thus the material factors such as filler content, combination of reinforcement and matrix, fabric texture and so on that may contribute to sound performance for the developed materials were investigated. Their sound performance and mechanism were explored both experimentally and by theoretical analysis in order to obtain a practically useful structure.

2. Materials

Four fabrics, one glass fabric and three carbon fabrics, with different textures were used as the base reinforcement of sheet materials. The glass fiber fabric (GF) was plain texture (Kanebo Ltd.) and three carbon fiber fabrics (Toray Ltd.) were of the texture of plain (CF1), twill (CF2) and satin (CF3), respectively. These four dif-

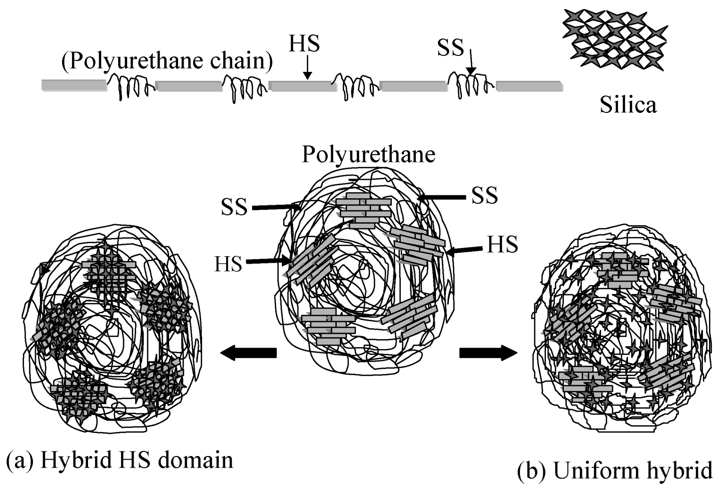

Figure 1. Schematic of polyurethane silica hybrid methods.

ferent textures were used in order to examine the influence of weave structure on soundproofing performance.

Polyurethane (PU) nano-hybrid resin was used as a coating material. The schematic presentation of structure for the polyurethane (PU) nano-hybrid resin is shown in Fig. 1. It is composed of two segments — soft-segment and hard-segment. The nano-silica particles are arranged only in the hard segment by a positional selection technology during the gel hybrid process (see Fig. 1(a)) [12]. In order to investigate the influence of the content rate of silica particles, three different weight fractions of silica particles (0 wt%, 7 wt%, 14 wt%) in the PU resin were used, which are referred to as the materials H0, H1 and H2, respectively. Other important factors affecting soundproofing properties, such as hybrid method and particle size, were also investigated. Using H0 material (neat PU), another two PU hybrid resins with different sizes of silica particle, Si1 (350 mesh, 73 μm) and Si2 (100 mesh, 254 μm), respectively, were fabricated uniformly by the physical mixture method. The weight fractions of silica particles for Si1 and Si2 were 7 wt%.

The parameters for four fiber fabrics used as base reinforcement are shown at Table 1. The materials were fabricated by the hand lay-up method. The resin was immersed into the base reinforcement and several coating layers were added afterwards for better soundproofing performance. Based on different combinations, eight types of materials were prepared (see Table 2). A1, A2 and A3 were the materials with the same glass fabric (GF) but different weight fractions of silica particles in coating layers, i.e. PU bulk resin (H0, 0%), 7 wt% (H1) and 14 wt% (H2), respectively. The materials, B1, B2 and B3, are of different textures of carbon fabrics, CF1, CF2 and CF3 as base reinforcement, respectively, while the same H1 was used as the coating layer material. Another two materials, C1 and C2, were prepared with uniform dispersion of silica particles but different sizes, Si1 and Si2. Figure 2 shows an example of the appearance of the cross-section for the developed materials.

Table 1.
Components of four base fabrics

Cloth	Product number	Density (One/25 mm) Warp∗Weft	Weight (g/m^2)	Texture
GF	KS 2492	29∗32	343	Plain
CF1	CO 6343	12.5∗12.5	119	Plain
CF2	CO 6347	12.5∗12.5	198	Twill
CF3	CO 6141	40∗40	214	Satin

Table 2.
Basic structures of innovated materials

Symbol	Constitution	Side density (g/m^2)	Silica content (%)	Thickness (mm)
A1	[H0/H0/H0/GF/H0/H0/H0]	0.89	0	0.7–0.8
A2	[H1/H1/H1/GF/H1/H1/H1]	0.89	7	0.7–0.8
A3	[H2/H2/H2/GF/H2/H2/H2]	0.89	14	0.7–0.8
B1	[H1/H1/H1/CF1/H1/H1/H1]	0.89	7	0.7–0.8
B2	[H1/H1/H1/CF2/H1/H1/H1]	0.89	7	0.7–0.8
B3	[H1/H1/H1/CF3/H1/H1/H1]	0.89	7	0.7–0.8
C1	[Si1/Si1/Si1/GF/Si1/Si1/Si1]	0.89	7	0.7–0.8
C2	[Si2/Si2/Si2/GF/Si2/Si2/Si2]	0.89	7	0.7–0.8

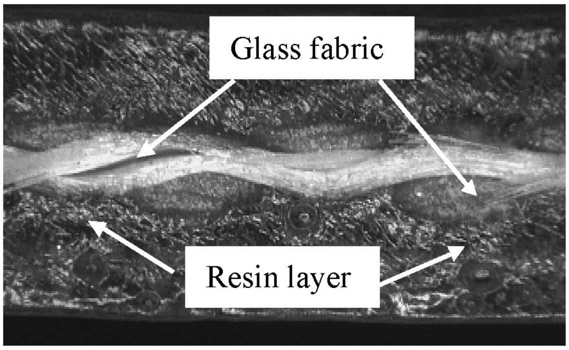

Figure 2. Microphotograph in the cross-section of material A2.

3. Experimental

3.1. Soundproof Measurement

The energies of sound waves for reflection, absorption and transmission in a material are shown in Fig. 3. The soundproof property of a material can be evaluated

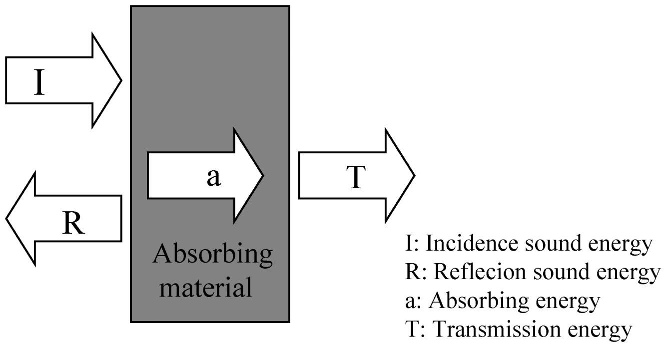

Figure 3. Diagram of energies of sound waves for incidence, reflection and transmission.

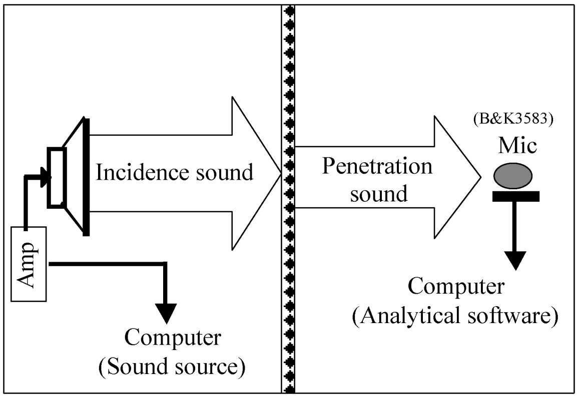

Figure 4. Schematic of measurement system for sound performance evaluation.

through the parameter, transmission loss factor T_D, defined by the following equation:

$$T_D = 10\log\frac{I}{T} = 20\log\frac{P_i}{P_T}, \qquad (1)$$

where P_i and P_T designate incident and transmitted sound pressure, respectively.

The experiments were carried out in a half anechoic room with 5 m × 5 m × 3 m high, based on the JIS Z 8732. The distance between speaker and sample, and between microphone and sample, were both 100 mm. The measuring blocks for transmission loss factor are shown in Fig. 4 [13]. Here, the series of white noise (M signals) as incident source waves are created by computer simulation and come out from a speaker amplified by a power amplifier. For the sound source reconnaissance and acoustic power-level measurement, the acoustic intensity probe with two microphones (B and K 3583) was used. The output of analog signals is transformed into digital data to a computer by the DAT (SONY DTC-ZE700, analog-to-digital converter 14 bits; sampling frequency 100 kHz). Then the acoustic data were analyzed by a PULSE system (Bruel and Kjaer Ltd.) and the transmission sound pressure was calculated by the 1/3 octave band method. The experiments were conducted twice with or without samples inserted between the speaker and microphone, and then the transmission loss factor was obtained. Moreover, to exclude the detour sound from the speaker, the size of test samples was 800 × 800 mm. For several samples, the measurement was conducted also according to JIS A1416 standard in order to compare the present measuring system, and almost the same results were confirmed.

4. Results and Discussion

4.1. Contribution of Base Fabric

The results of transmission loss for 4 types of base fabrics used in this research are shown in Fig. 5. The values of transmission loss were in the order of GF > CF2 > CF1 > CF3 (see Table 1). It was found that both bundle density and fabric texture play an important role in the soundproof performance. According to the weight density, the order of transmission loss may be GF > CF3 > CF2 > CF1. However, the CF3 fabric is of smallest transmission loss due to fabric texture of 8 satin, which has the smallest cross points between weft and warp bundles. This will result in the fact that the CF3 fabric has the lowest air tightness among these four fabrics. It is thought that the ventilation property of a material may play a vital role in soundproofing performance [14, 15]. The GF fabric with good air tightness due to both plain texture and the largest weight density showed the maximum transmission loss of about 10 dB, which is the highest soundproofing performance in these four base fabrics.

Figure 6 shows the results of transmission loss for the four flexible sheet materials composed of the above different four base fabrics but with the same coating

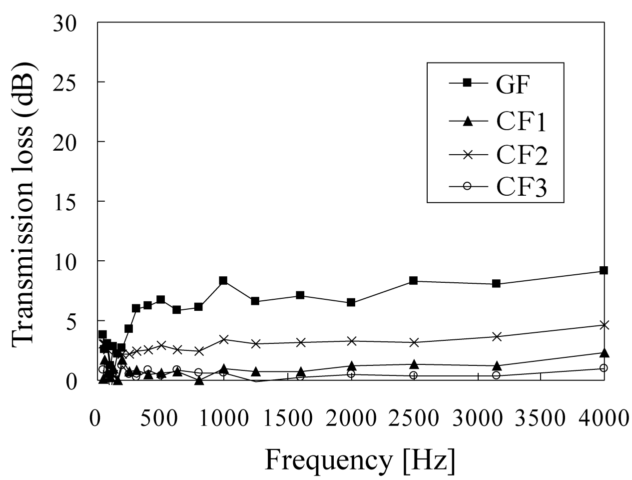

Figure 5. Transmission loss in four base fabrics: GF: plain glass fiber fabric; CF1: plain carbon fiber fabric; CF2: twill carbon fiber fabric; CF3: satin carbon fiber fabric.

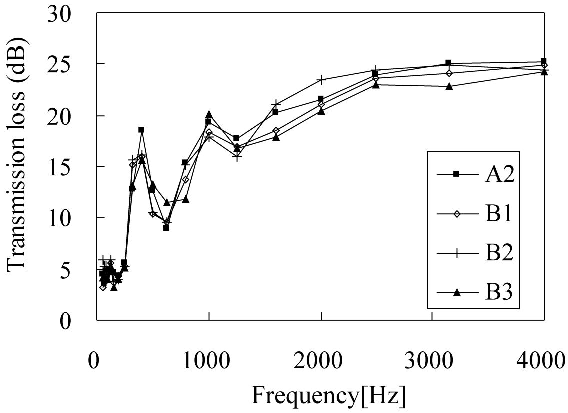

Figure 6. Transmission loss for materials B1, B2 and B3.

resin of 7 wt% nano-silica hybrid (H1). The materials B1, B2 and B3 have the same coating layers but the textures of their base fabric are different. They are of the texture of plain (CF1), twill (CF2) and satin (CF3), respectively. Compared with Fig. 5 for base fabrics, it is observed that the transmission loss increased even more than 10 dB in the high frequency region in all samples, even though the thickness of the sample was only about 0.7 mm. The big difference as shown in Fig. 5 due to different base fabrics was mostly covered by coating layers of resin. The average value of transmission loss in a wide frequency region up to 4000 kHz shows the order of B2 > A2 > B1 > B3, which corresponds well to the soundproof performance of base fabrics except B2 > A2. As for B2 > A2, this may have resulted from several factors, such as fabric texture, the difference between glass fiber bundles and carbon fiber bundles and the interfacial property of fiber/resin.

The change rate of material B1 and B2 to material B3 is shown in Fig. 7, where only the texture of base fabric is different. Making comparison between B2 and B3, the weight density of base fabric in B2 is about 8% less than that in B3, while the transmission loss in B2 is about 3 dB larger than that in B3, on average. The change rate of transmission loss increased with an average of 10% and 5%, respectively, for materials B2 and B1. Especially, a big difference was observed in the region of 1200–2500 Hz. This may have resulted from different air tightness abilities due to the change of fabric texture and weight density. It is obvious that the fabric texture of the base material contributes greatly to transmission loss in sheet soundproofing materials. Thus, the selection of the texture of base fabric according to practical use may be also very important in the improvement of soundproofing performance. However, besides the texture, the weight and the material type are also important factors for soundproofing performance. For the materials B1 and A2 with the same texture but different weight and fiber type, a big change rate of transmission loss with the average of 10% and the maximum 40% are observed, as shown in Fig. 8. So we can understand that from the view of all frequency regions and their frequency

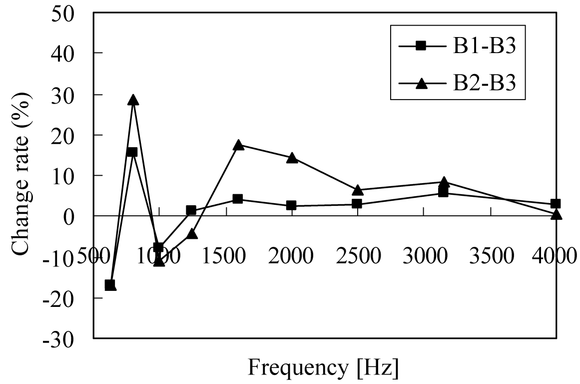

Figure 7. Change rate of transmission loss between B1 and B3, B2 and B3 due to different textures of base fabric.

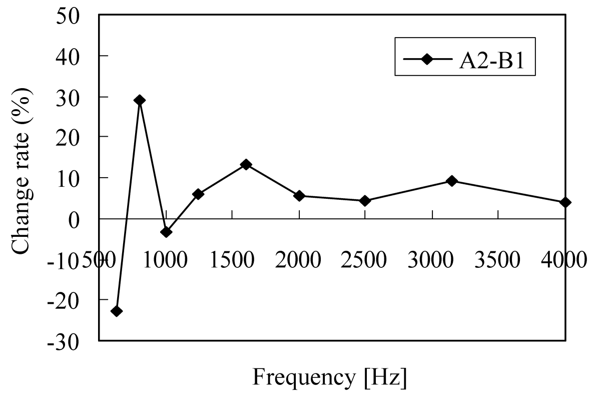

Figure 8. Change rate of transmission loss between B1 and A2 due to different weight density and material type.

stability, the large weight density of base fabrics will result in better soundproofing performance.

4.2. Effect of Fillers

Figure 9 shows the transmission loss for materials A2, C1 and C2 with the same weight content but different diameters of silica particles. The transmission loss for each material denoted the increasing tendency with the frequency, and remarkable frequency dependence. The transmission loss factor is in the order of A2 > C2 > C1 except the beginning of the low frequency region. The difference in transmission that occurred in these three materials could only have resulted from the distribution and size of silica particles, since no other factor was changed.

As for A2 > C2 and A2 > C1, this shows that the silica distribution by the segment selection results in a better soundproofing performance than that by the uniform mixture method. From this result, it is suggested that the silica particles of

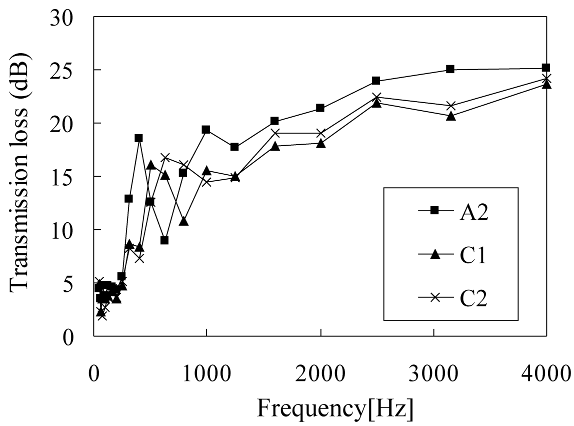

Figure 9. Transmission loss factor for materials A2, C1 and C2.

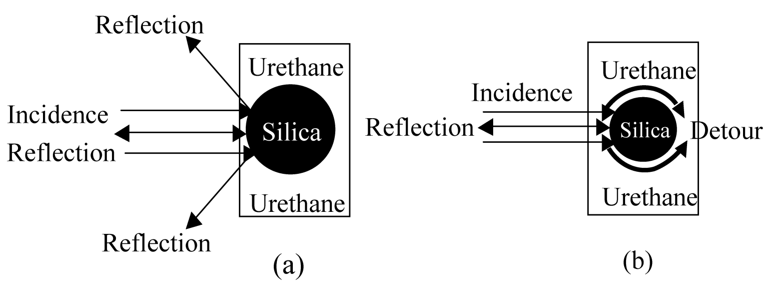

Figure 10. Size effect of silica particles due to detour propagation.

nano-order that existed only in the hard segments caused the material to have two different regions — a hard segment region and a soft segment region, distributed everywhere in the material. That is, there are many micro interfaces formed between these segment regions, which may contribute to the effectiveness of the transmission loss factor. As for the C2 (254 μm) > C1 (about 73 μm), this shows that, even with the same method of adding the particles into the polymer, the transmission depends on the difference of the diameter of silica particles. Since the wavelength of incidence is much larger than the diameter of particles, the size effect will make a much greater contribution than the surface area to the soundproofing performance for its lower detour propagation (see Fig. 10) and this may produce the finding of the result in the C2 > C1.

However, the change in rate of transmission loss when comparing these three materials with the material A1 gives about 10% up for A2–A1, but little minus variation for both C1–A1 and C2–A1 as shown in Fig. 11. The mechanism for filler effect may be considered as follows. For the former case of A2–A1, the nano-silica particles are formed by a sol gel method and distributed in the hard segments of PU resin by a position selection technology. This will result in the fact that the viscoelasticity of the hybrid resin mainly contributed by soft segments is almost

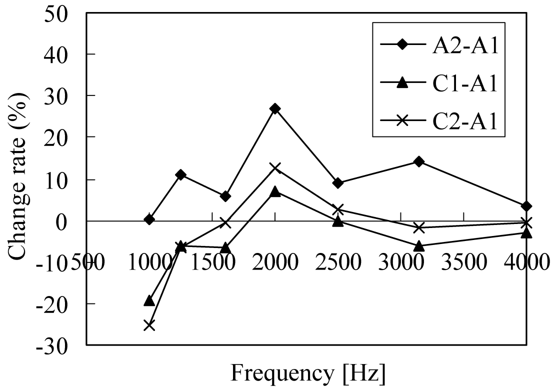

Figure 11. Change rate of transmission loss factor between A2 and A1, C1 and A1, C2 and A1 due to different sizes and distributions of silica particles.

unchanged, but the hard segments with nano-silica particles will disperse the waves and produce the soundproofing performance. However, for the latter cases, the viscoelasticity of hybrid resin reduces remarkably due to the uniform addition of micro silica particles (physical mixture) and this will cause reduction of sound absorption ability although the micro fillers will disperse the waves. These two effects on soundproofing performance may cancel each other and, as a result, there is no obvious variation in the value of change rate.

With the above results, even if the same content of silica particles is used for these materials, it is understood that the effect of the soundproofing performance is different due to the difference of hybrid method and the size of silica particles. It indicates that fillers being in suitable positions and of optimum size may achieve a better effect on the soundproofing performance.

4.3. Influence of Silica Particle Content

The transmission loss is shown in Fig. 12 for materials A1, A2 and A3 with different silica particle content. The transmission loss is found to have strong frequency dependence and to increase with the increment of frequency. A big drop at the frequency of about 700 Hz is observed, which may result from the coincident effect or the ventilation [16, 17]. The transmission loss for materials A2 and A3 is larger than that for material A1. The material A2 with 7 wt% of silica particles had the largest transmission loss factor of about 26 dB among these three materials and is about 10% larger than the material A1 in the middle and high frequency region. Its transmission loss is also larger that in the material A3, which has 14 wt% of silica particles. The mechanism for the change of transmission loss may be considered as follows. The transmission loss depends on the energy loss due to the reflection energy and absorption energy from incidence energy as shown in Fig. 3. The reflection energy is contributed by the reflections on the material surface and interfaces between layers and between silica particles and matrix. The silica particles have a multi-reflection effect, which will also contribute to the reflection energy. The

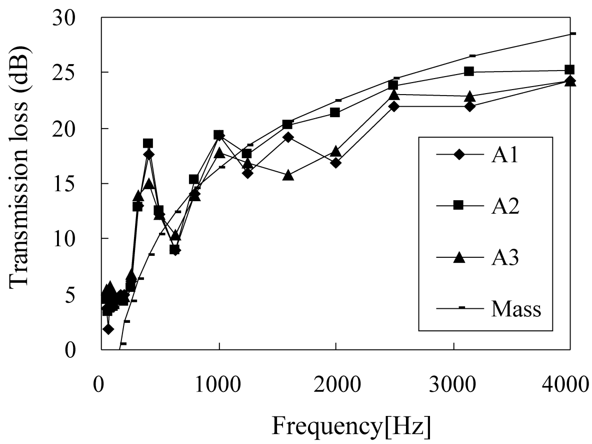

Figure 12. Influence of silica contents on transmission loss factor.

absorption energy is mainly determined by soft segments in a PU resin due to its viscoelasticity and the inner fraction on the silica/matrix interfaces. Thus, it is obvious that the high soundproofing performance effect can be obtained by filling nano-particles.

However, the material A3 with silica content 14 wt%, which is the largest content rate among these three materials, had the lower transmission loss factor compared with the A2 material. It seems hard to explain this phenomenon by a filling model with rigid fillers [18]. Thus it may be considered that the change of viscoelastic property in PU hybrid resin due to too many particles play an important role in the soundproofing performance. The increase of silica content resulted in the decrease of viscoelasticity and then the reduced absorption ability for sound waves [14]. The reduction of viscoelasticity for the material will be caused when the silica content is over a threshold value that hard segments can contain. In this case, the remaining silica particles may move to the soft segments and result in the decrease of viscoelasticity. So, this suggests that there should be an optimum silica content for these materials.

4.4. Analysis of Soundproofing Performance

One of the authors has used the ultrasonic analysis code (*PZFlex*) developed recently to analyze the ultrasonic wave propagation in composites [19, 20]. Here, the ultrasonic analysis code (*PZFlex*) is used to predict soundproofing performance for the developed materials A1, A2 and A3. In the model (Fig. 13), the developed material is placed in the position C–C′, and a 2-dimensional model is used and time domain analysis is conducted. The unit cell [21–23] used for meshing the material is assumed in Fig. 13(b). An acoustic field domain for air area is divided into 100 by 50 elements with an element size of 1 mm by 10 μm, while for the sample area the element size is 10 μm by 10 μm. The incident sine wave with the frequency from 250 Hz to 4000 Hz is placed on the left edge with the power of 80 dB just as

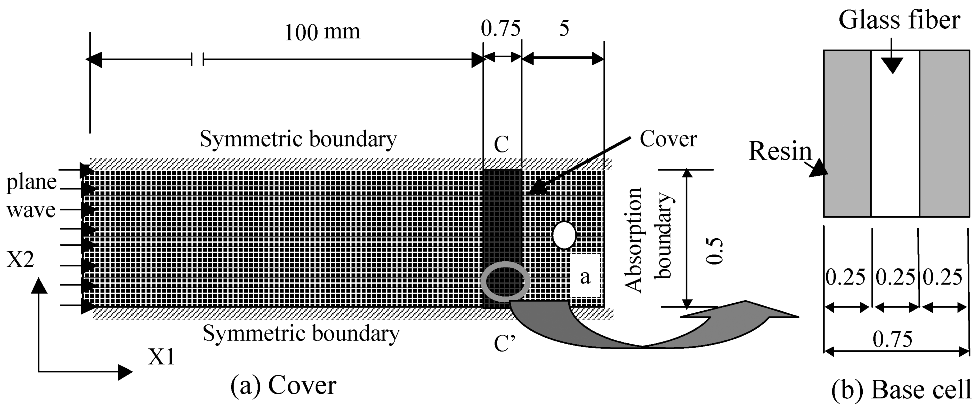

Figure 13. Two-dimensional model with the developed material placed in the position C–C′ for sound propagation simulation.

Table 3.
Material parameters used for sound simulation

	Speed of sound (m/s)		Density (kg/m^3)	Damping coefficient (dB/m)
	Longitudinal wave	Transverse wave		
Air	340		1.2	
H0	1900	1000	1245	174
H1	2300	1300	1508	260
H2	2800	1500	1769	348
GF	5000	2500	1372	

in the experiments. In order to prevent the influence of reflection of the sound from boundaries, a perfect absorption boundary is assumed at the right edge while the up and down edges are assumed as symmetrical. The sound source frequency was changed from 250 Hz to 4000 Hz and the sound insulation effect was evaluated by the difference of sound pressure level with or without the inserted material, just as was performed in the experiments. In addition, the transmission loss factor is then obtained from the sound pressure level as in equation (1) based on the sound pressure measured. The material parameters used for the analysis are listed in Table 3.

The frequency response result of the transmission loss analysis and the mass law for the materials A1, A2 and A3 are shown in Fig. 14. In general, if the material with the same area density is used it is known that almost the same soundproofing performance will be obtained by the mass law. However, in this analysis, as Table 2 shows, although A1, A2 and A3 material have the same field density, it turns out that soundproofing performance shows some differences due to the variation of silica content. Moreover, this corresponds closely to the experimental results. All of the three materials studied here indicate a transmission loss value below the mass

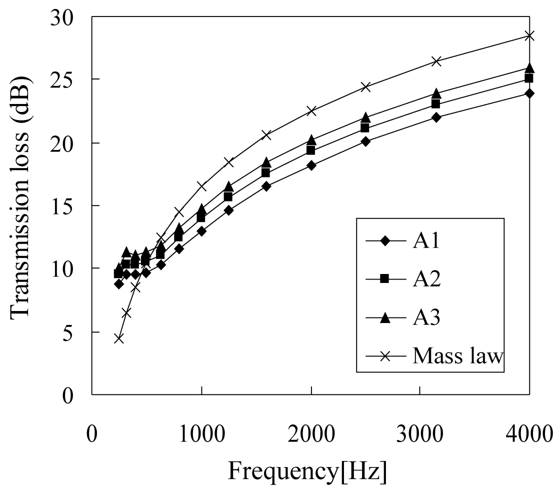

Figure 14. Comparison between mass law and analytical results for materials A1, A2 and A3.

rule, but the materials A2 and A3 show better soundproofing ability compared with the material A1 and their results are comparable with the theoretical analysis. This gives a comprehensive relationship between the interception performance and the effect of the silica particle fillers.

The transmission loss larger than the mass law appeared in the frequency region less than 630 Hz. The transmission loss moves closer to the value by the mass law in the frequency region larger than 630 Hz [24]. The comparison of transmission loss between experiment and analysis for A1, A2 and A3 is shown in Fig. 15, respectively, although some differences between experimental and analytical results are observed. Especially, a big variation appeared in the low frequency region in the experiments. But, both the analytical value and the experiment value of transmission loss become large with the increment of frequency and show a quite reasonable agreement between them. Moreover, although the degree of change is small, the variation of transmission loss due to the change of nano-silica coating layer is predicted (see Fig. 14). Therefore, it is considered that this time-domain finite analysis is effective for the prediction and design of soundproof performance materials.

5. Conclusions

This paper describes the development of innovative insulation sheet materials with carbon and/or glass fabrics and silica hybrid PU resin. The parameters related to sound performance, such as materials and fabric texture in base reinforcement, hybrid method for resin, size of silica particle and so on, are investigated. At the same time, the wave analysis code (*PZFlex*) is used to simulate some of the experimental results. As a result, the following findings were obtained.

It is found that both bundle density and fabric texture will play an important role in soundproofing performance. Compared with the effect of base fabrics, it is

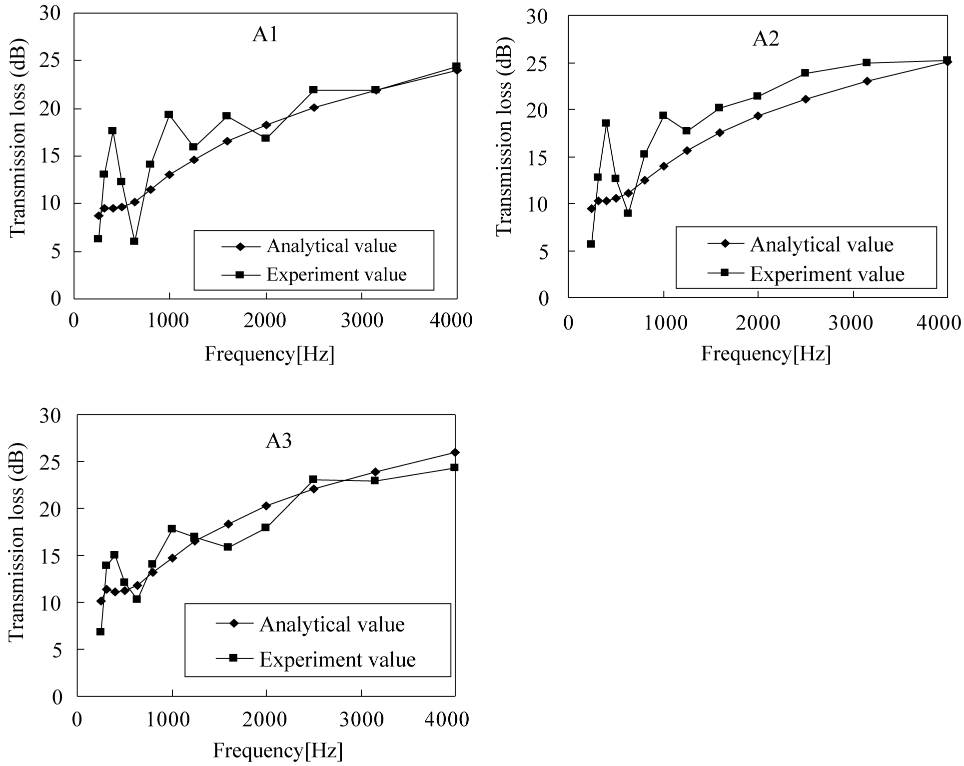

Figure 15. Comparison between experimental results and analytical results for materials A1, A2 and A3.

observed that the transmission loss increased even more than 10 dB in the high frequency region in all samples, even though the thickness of the sample was only about 0.7 mm. The big difference in transmission loss factor due to different base fabrics will be mostly explained by coating layers of resin. However, the difference in sound performance due to the combination of materials and several other factors is still great and parameters besides the mass law, such as raw fiber materials, texture of fabric and its compactness, the properties of the fiber–resin interface, and so on, need to be considered in the design of optimum soundproofing insulation materials.

For the materials with the same weight content, but different diameters of silica particles, the results show different values of transmission loss factor. The difference that occurred in these materials only resulted from the distribution and size of silica particles, since no other factor was changed. Thus, from consideration of the microscopic constitution of the materials, even if the same content of silica particles is used, it is understood that the effect of the soundproofing performance is different due to the difference of hybrid method and the size of silica particles. Filler particles that occupy appropriate positions and with optimum size may achieve a better effect in the soundproofing performance.

The effect of the particle content on the soundproofing performance is confirmed. Simultaneously, it turned out that there is a limit for the addition of the fillers. The optimization of silica content contributes to improvement in the sound insulation effect. The nano-particles will have a greater effect on the high soundproofing performance. However, the change of viscoelastic property in PU hybrid resin due to too many particles should be noted, since it may also play an important role in the soundproofing performance.

The sound insulation effect has been understood through the comparison between the experimental and analytical results. The possibility of the prediction of transmission loss is discussed. Both the analysis value and experimental value become large with the increment of frequency and show quite reasonable values and agreement between them. Although the degree of change is limited, the variation of transmission loss due to the change of nano-silica coating layer is predicted. It is considered that this time-domain finite analysis (*PZFlex*) is an effective one for the prediction and design of materials to be used for soundproofing.

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