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Soundproofing effect of nano particle reinforced polymer composites

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Abstract

In this paper, the effects of soundproofing by polymer and carbon-nanotube (CNT) composites were investigated. The specimens for sound insulation measurement were fabricated with Acrylonitrile Butadiene Styrene (ABS)/CNT composites. Tests showed that sound transmission loss of ABS/CNT 15 vol.% composite was higher by 21.7% (4.1 dB) than that of pure ABS specimen at a frequency of 3400 Hz. It was found that the principal factor influencing the improvement of sound insulations of ABS/CNT composites was increased stiffness by CNT additives. To demonstrate the practical applicability of polymer/CNT composites, tests were conducted for the reduction of operational noise from mechanical relay.

Keywords: Carbon-nanotube; Polymer; Soundproof; Sound insulation; Nano particle reinforced polymer composites

1. Introduction

Noise has become an environmental issue, and legislation on noise regulation is under review and being drafted in industrialized countries, especially those in Europe. Recently, the reduction of noise from machinery, automobile, and appliances has been studied extensively [1-4]. The techniques using sound absorption and insulation materials to reduce ambient noise have received much attention in this area of research [5-9]. In this study, sound insulation characteristics, properties, and dispersion of composites made by mixing CNT with polymer were investigated.

2. Theory of sound insulation

The sound characteristics of space can be affected by the material, size and shape of the space wall. The acoustic energy that is incident on the wall is converted into reflected acoustic energy, energy loss, and transmission acoustic energy.

The ratio of reflected acoustic energy to incident energy is defined as the reflectivity, and the ratio of the sum of energy loss and transmitted energy to incident energy is defined as acoustic absorption. The ratio of transmitted energy to incident energy is defined as acoustic transmissibility.

To increase soundproofing efficiency, the transmitted energy must become lower. Therefore, energy loss and reflected energy must be maximized to minimize the transmitted energy, but energy loss by sound absorption becomes limited by the wall thickness of material. Therefore, the most efficient method of increasing the soundproofing efficiency is to reflect the incident energy in the incidence direction.

In sound insulation, the efficiency would depend on the weight (mass), stiffness, homogeneity, and uni-

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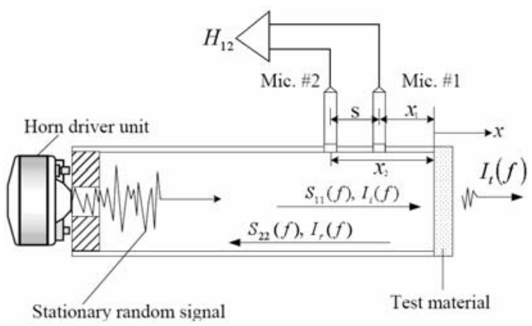

Fig. 1. Schematic of impedance tube.

formity of the wall material. The sound insulation ability of a wall is measured by sound transmission loss (TL). TL can be defined as the difference between the sound power level of the incident wave and the transmitted sound power [10, 11].

TLs of specimens were measured by two serially located microphones attached to an impedance tube, as shown in Fig. 1. Test material is attached at the end of the impedance tube. The distances between the specimen's surfaces and two microphones are x_1 and x_2, respectively, and the distance between the two microphones is s [12, 13].

When the impedance tube supplies a normal irregular sound signal through a speaker, the sound intensity $I_i(f)$ of the incident wave and the sound intensity $I_r(f)$ of the reflection wave are calculated by the sound transfer function $H_{12}(f)$ between points x_1 and x_2, and the magnetic spectral density function $S_{11}(f)$ at point x_1, and $S_{22}(f)$ at point x_2, as expressed in Eq. (1) and (2) [14, 15].

$$I_i(f) = \frac{S_{11}(f)\left\{\begin{array}{l} 1+\left|H_{12}(f)\right|^2 - 2\,\mathrm{Re}\left[H_{12}(f)\right]\cos k\left(x_1-x_2\right) \\ +2\,\mathrm{Im}\left[H_{12}(f)\right]\sin k\left(x_1-x_2\right) \end{array}\right\}}{4\rho c \sin^2 k\left(x_1-x_2\right)} \tag{1}$$

$$I_r(f) = \frac{S_{22}(f)\left\{\begin{array}{l} 1+\left|H_{12}(f)\right|^2 - 2\,\mathrm{Re}\left[H_{12}(f)\right]\cos k\left(x_1-x_2\right) \\ -2\,\mathrm{Im}\left[H_{12}(f)\right]\sin k\left(x_1-x_2\right) \end{array}\right\}}{4\rho c \sin^2 k\left(x_1-x_2\right)} \tag{2}$$

where c and f are the speed and frequency of sound in air, ρ is density of air, and $H_{12}(f)$ is the impulsive response corresponding to the combined incident and reflected waves evaluated between the two microphone locations. Im and Re are the imaginary and real parts, respectively, of the transfer function. Wave number k is $2\pi f/c$, and ρc expresses the air characteristic of impedance.

Table 1. Material properties of multi-walled carbon nanotube (MWCNT).

MWCNT (ILJIN CM-95)	
Bulk Density	0.1 g/cc
Average Diameter	10~15 nm
Length	10~20 μm
Purity	95 vol.% (95 wt.%)

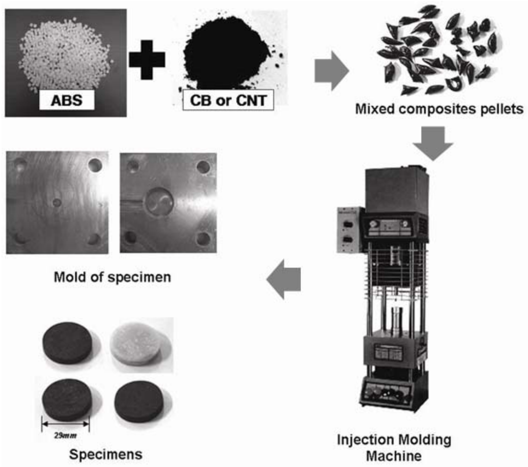

Fig. 2. Manufacturing process of ABS/CNT composite specimens.

When a sound wave emitted from a test material does not return to the inside of the tube and the sound absorption ability of a specimen can be ignored, the transmission loss about the normal incidence signal can be given as Eq. (3) from Eq. (1) and Eq. (2) [16].

$$TL_{H_{12}}(f) = 10\log_{10}\left\{\frac{1+\left|H_{12}(f)\right|^2 - 2\mathrm{Re}\left[H_{12}(f)\right]\cos ks + 2\mathrm{Im}\left[H_{12}(f)\right]\sin ks}{4\mathrm{Im}\left[H_{12}(f)\right]\sin ks}\right\} \tag{3}$$

ere the TLs of sound insulation materials depend on the sound transfer function $H_{12}(f)$ between two points.

3. Fabrication of polymer/CNT composites

Specimens for TL measurement were fabricated by mixing thermoplastic ABS pellets and CNT (Table 1) [17]. Four kinds of specimens were prepared with 0, 5, 10, and 15 volume percent (vol.%) of CNT, respectively. The mixed materials were melted together and mechanically stirred, then cut into about 5-8 mm to form composite pellets for injection molding.

The temperatures of the barrel and nozzle of the injection molding machine were fixed at 225 ℃, and the molten composite pellets were injected into the mold to form disc specimens. The dimensions of the specimens were 29 mm in diameter and 3.2 mm in thickness (Fig. 2).

4. Measurement of sound insulation

In this research, Power Amplifier AX7030G, 1/4" Microphone B&K 4096, Nexus B&K 2690, and Analyzer HP 35670A were used as signal generating device, signal measurement device, signal amplifier device, and signal analyzer, respectively.

Fig. 3 shows the average values of the measured TL. TL tended to increase with increase of sound frequency.

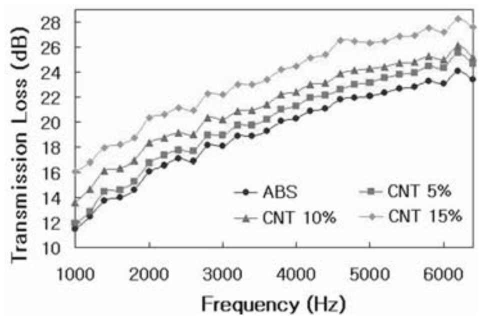

Fig. 3. Transmission loss of ABS/CNT composites (1000-6400 Hz)

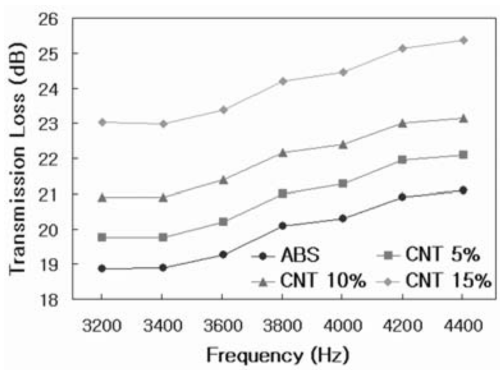

Fig. 4. Transmission loss of ABS/CNT composites (3200-4400 Hz).

Fig. 4 shows the tendency of TL values in 3400~4400 ㎐ range in more detail. The TL values were increased with the volume content of CNT in the ABS/CNT composites.

For a more accurate comparison of the specimens, the TL values at 3400 ㎐ with error ranges were plotted in Fig. 5.

The average TL values of specimens with CNT 5, 10, and 15 vol.% were higher than those of the pure ABS specimens by 4.6, 10.7, and 21.7%, respectively.

5. Analysis of different parameters

To identify the main factors affecting TL tendency, the potential parameters of sound insulation were investigated.

5.1 Measurement of density

When sound impacts a wall, the wall vibrates according to the change of the atmospheric pressure. This vibration energy dissipates during the transmissible process from inside to outside of the wall and increases according to the increase of the weight of the wall. This relation is called the Mass Law of Sound Insulation [18].

In the mass Law, the TL of the sound insulation material is calculated by Eq. (4) [19].

$$TL(\theta, f) = 10\log_{10}\left\{1 + \left(\frac{\omega m \cos\theta}{2\rho c}\right)^2\right\} \tag{4}$$

where ω, m, and θ are the angular frequency, surface mass of the specimen's unit area, and angle of incidence, respectively.

The densities of the fabricated specimens are calculated by using the measured masses and volumes of

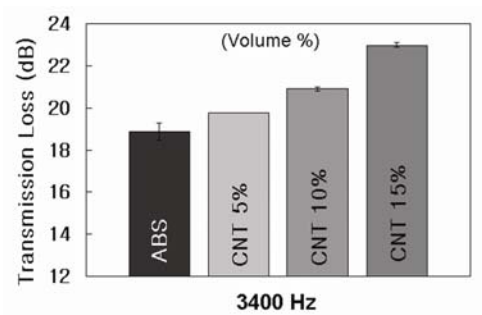

Fig. 5. Transmission loss of ABS/CNT composites at 3400 Hz

the fabricated specimens and the normalized masses are obtained by using the calculated densities and volume of specimen.

As shown in Fig. 6, normalized masses of ABS/CNT composites hardly change with the increase of CNT ratio because 15 % increase of CNT in volume corresponds only to 2.18 % weight increase in the specimen [20]. Thus, the mass law was not the main factor which influenced the TL.

5.2 Measurement of stiffness

Stiffness also affects the efficiency of sound insulation. Therefore, the stiffness of the specimens was measured by a micro indenter according to ISO 14577-1 as shown in Fig. 7.

The measured results showed that the average stiffness values of CNT 5, 10, and 15 vol.% were higher by 2.1, 5.3, and 18.5%, respectively, compared with the value of pure ABS specimen. The stiffness is proportional to the amount of CNT in the ABS/CNT composites [21] and this proportional tendency is similar to the tendency of TL, as shown in Fig. 5. Therefore, it might be concluded that the increased stiffness according to the increase in the amount of CNT affects the improved TL of ABS/CNT composites.

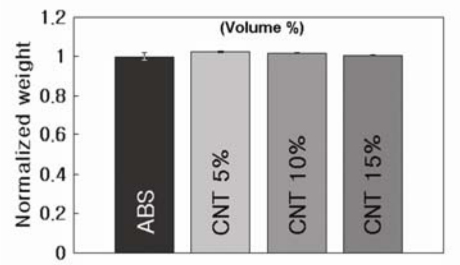

Fig. 6. Normalized weight of ABS/CNT composites.

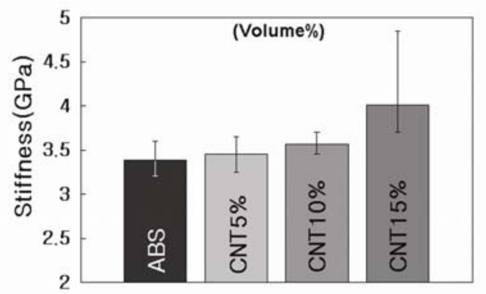

Fig. 7. Measured stiffness of ABS/CNT composites by micro indenter.

5.3 Homogeneity of composite material

Specimens were cut into layers with thickness of tens of micrometer, and the cut cross section of the specimen was observed by an optical microscope to investigate the homogeneity and dispersion of CNT particles (Fig. 8). From the observation, pores or cracks were not observed, and the small carbon lumps were dispersed in the ABS matrix.

6. Application to mechanical relay

Currently, relays have often been used in automobiles and electrical devices. A mechanical relay is an electrical switch operated by an electromagnet. Dur-

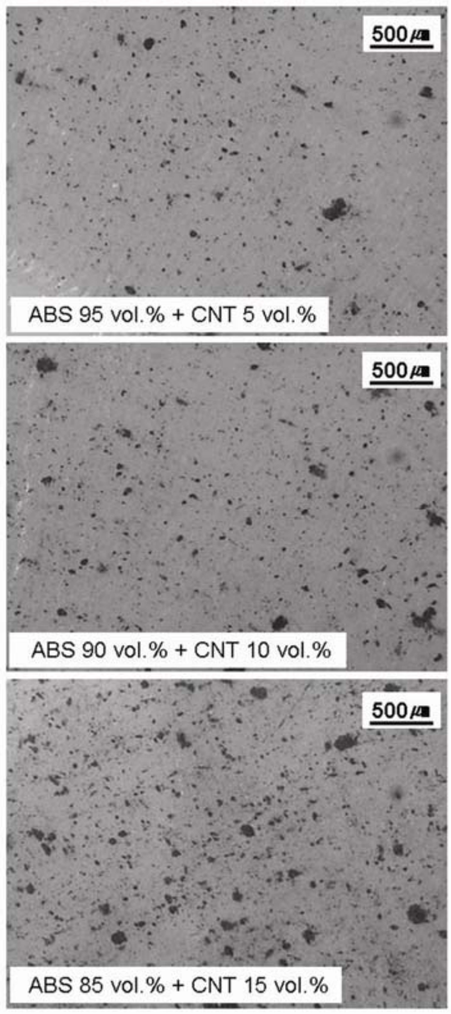

Fig. 8. Cross sections of ABS/CNT composites by optical microscope.

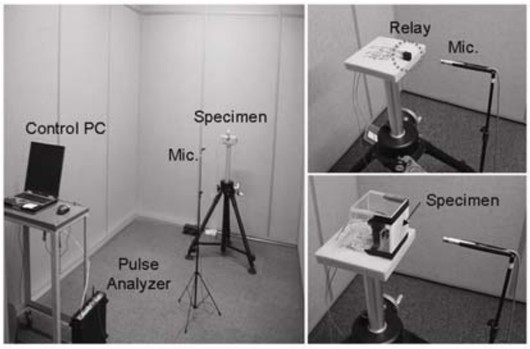

Fig. 9. Test setup for soundproof measuring of mechanical relay.

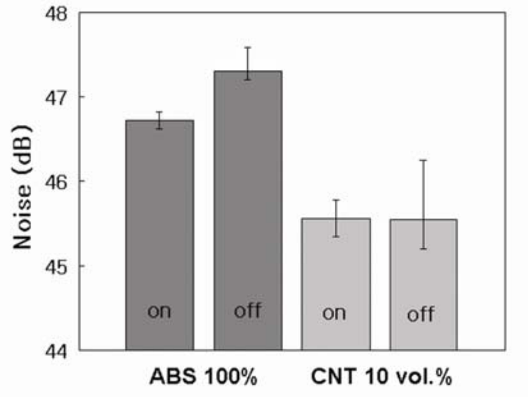

Fig. 10. Comparison of noise data during operation of mechanical relay – plates made of ABS vs. ABS/CNT.

ing its operation, the contact between moving part of relay and the stationary metallic knob makes a noise. The presence of audible noise from mechanical relays in an automobile could be a source of complaint by sensitive drivers. Thus, researchers have tried to reduce the noise of mechanical relays, and relay cases made of the soundproof composite were tried in this research. To measure the soundproofing characteristic of relay cases made of ABS/CNT composites, a Pulse Analyzer B&K 3109 was used, and experimental instruments were installed in an anechoic chamber as shown in Fig. 9. The distance between the microphone and specimen was 100 mm, and a mechanical relay (G8HM) of Omron Corporation was used as the sound source.

First, experimental specimens were made of ABS at zero vol.% and 10 vol.% CNT with 100×100×5 mm plate shape. The experimental result showed that the average sound pressure level of 10 vol.% CNT

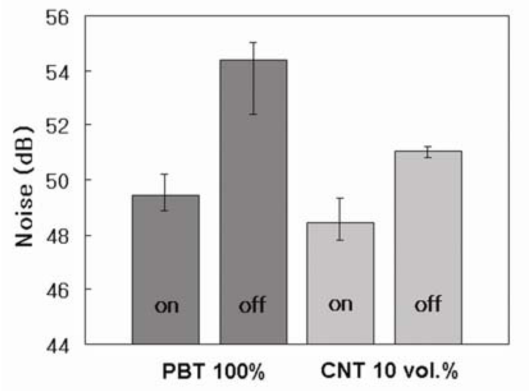

Fig. 11. Comparison of noise data during operation of mechanical relay – relay case made of PBT vs. PBT/CNT.

composite was lower than pure ABS specimen by 3.9 % (1.8 dB) in power-on mode and by 2.5 % (1.2 dB) in power-off mode as shown in Fig. 10.

In the second experiment, ABS was replaced by PBT (Polybutylene terephthalate), and specimens were made into the shape of a relay case to simulate the commercial relay. Specimen materials were PBT 100 % and PBT 90 vol.% with CNT 10 vol.%. In the experimental result, the average sound pressure level of 10 vol% CNT with PBT was lower than the average sound pressure level of PBT 100 % specimen by 2.0 % (1.0 dB) for power-on mode and by 6.2 % (3.3 dB) for power-off mode, respectively, as shown in Fig. 11.

7. Conclusions

In this research, polymer/CNT composites were investigated to improve the soundproofing property of polymers. The sound insulation efficiency of ABS/CNT composites was increased with an increase in the amount of CNT. Since the sound insulation of ABS/CNT composite was improved with higher stiffness due to CNT, it might be concluded that stiffness is one of principal factors influencing the improvement of TL of polymer/CNT composites. The application of the composite materials to the mechanical relay proved the effect of CNT on soundproofing. The reduced average sound pressure level of relay by 1.0 dB-3.3 dB can be a significant value in practical noise reduction. As a future work, soundproof effect of less expensive nano-carbon-particles such as carbon black will be investigated in order to reduce the cost of composite materials.

Acknowledgments

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Nomenclature

c	: Speed of sound in air [m/sec]
f	: Sound frequency [Hz]
$H_{12}(f)$	: Sound transfer function between points x_1 and x_2
$I_i(f)$	: Sound intensity of the incident wave [W/m^2]
$I_r(f)$	: Sound intensity of the reflection wave [W/m^2]
Im	: Imaginary parts
k	: Wave number ($2\pi f/c$)
m	: Mass of the unit area [kg/m^2]
ρ	: Density of air [kg/m^3]
Re	: Real parts
$S_{11}(f)$	: Magnetic spectral density function at point x_1 [Pa^2]
$S_{22}(f)$	: Magnetic spectral density function at point x_2 [Pa^2]
θ	: Angle of incidence [rad]
ω	: Angular frequency [rad/sec]

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