Sound Insulation in Polymer/Inorganic Particle Composites. I. Theoretical Model

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ABSTRACT: The sound insulation behavior of inorganic particulate-filled polymer composites was analyzed by means of acoustics theory in this article to reveal the mechanisms of sound insulation. On the basis of it, a physical model of the sound wave transfer in the composite system was established, and a relevant transmission loss equation was derived. The transmission loss of the glass bead-filled polyethylene composites was estimated by using this equation. The results showed that the calculated transmission loss of the composites increased linearly with an increase of the glass bead volume fraction, and it increased nonlinearly with increasing sound frequency. The sensitivity of the transmission loss to the sound frequency was significant at low sound frequency. The transmission loss decreased nonlinearly with the size of added glass bead when the volume fraction was constant. © 2011 Wiley Periodicals, Inc. J Appl Polym Sci 125: 676–681, 2012

Key words: polymer-matrix composites; functional materials; sound insulation; modeling

INTRODUCTION

A noise is recognized as a component of industrial pollution and an environmental issue that is a byproduct of technological development in modern society such as machinery, automobile, appliances, and so on.[1–3] Therefore, how to reduce the noise by means of various methods and ways has been studied extensively in recent two decades. It is generally believed that controlling noise source and sound transmission might be the effective and actual methods. For the latter, the studies on noise have been directed towards discovering materials and structures to insulate or to eliminate it, and the techniques using sound absorption and insulation materials to reduce ambient noise have received much attention in this area of research.[4–7]

As to material development, noise solution can be classified into two categories according to purpose: absorption and insulation. In other words, the major objective in removing noise is to obtain a kind of material with high absorption rate or insulation efficiency for the frequency of the noise source. Some materials such as hollow microsphere, porous particle, foam and fiber, which are designed to control noise effectively, are called sound materials. Research and development on composite materials and structures are quite advanced in many fields such as the building materials, mechanical manufacturing industry, automobile industry, etc.[8,9]

Inorganic particulate-filled polymer composites have good sound absorption and insulation characteristics besides light quality and high specific strength, and so on. Recently, the inorganic particulate-filled polymer composites as sound materials have been received much attention. Liang and Jiang[1] measured the sound insulation properties of glass bead filled polyvinyl chloride (PVC/GB) composite, calcium carbonate filled PVC (PVC/$CaCO_3$) composite, and hollow glass bead filled polypropylene (PP/HGB) composite, and found that the sound insulation property of the PP/HGB composite was the best. Lee et al.[6] investigated the soundproofing effect of carbon-nanotube (CNT) reinforced acrylnitrile-butadiene-styrene copolymer (ABS) composites. More recently, Lee et al.[7] studied the mechanical properties and sound insulation effect of ABS/carbon-black composites, and verified the sound insulation effect of ABS/carbon-black composites as a function of the carbon-black percentage.

However, the studies on the sound insulation mechanisms of these composites have not been deep, especially in quantitative description of the sound insulation properties. The objectives in this article are to study the sound insulation mechanisms of the inorganic particulate-filled polymer composites, so as to construct the relevant mathematical model of the sound insulation properties.

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BASIC EQUATIONS

Basic equations of sound wave transmission

Because sound vibration is a kind of macroscopic physical phenomenon, it should obey the second Newtonian law and quality conservation law, besides satisfy the three basic equations which describe the relationship among the state parameters such as pressure, temperature, volume, etc. Therefore, the motion equation, continue equation, and physical state equation may be proposed, respectively. From the three basic equations of idea fluid medium, the solution of the one dimension plane wave equation may be expressed as follows:[8]

$$P(t,x) = P_A e^{f(\varpi t - kx)} \tag{1}$$

$$v(t,x) = v_A e^{f(\varpi t - kx)} \tag{2}$$

where $P(t,x)$ is the pressure function, $v(t, x)$ is the velocity function. $k = \varphi / c_0$, φ is the circular frequency of sound wave simple harmonic vibration, c_0 is the sound velocity.

Basic theory equation of transmission loss

In practice engineering application, the sound transmission loss (sound insulation quantity) is usually used to describe the sound insulation property of materials. The expression of sound transmission loss is given by:[9]

$$\psi = 10\lg \frac{1}{\tau_I} \tag{3}$$

where τ_I is the transmission coefficient.

THEORY MODEL

Parameter description

The filler particles are the solid microspheres with uniform size, and the dispersion of the filler in the polymer matrix is uniform. The radius of the microsphere is R, the density is ρ_2, and the dissemination speed of the sound wave in it is v_2. The matrix density is ρ_1 and the dissemination speed of the sound wave in it is v_1. The density of the gas is ρ_0, and the dissemination speed of the sound wave in it is v_0. The sound insulation sheet thickness of polymer composites is L, and the filler particle volume fraction is ϕ_f.

Element analysis of sound insulation materials

In general, inorganic particulate-filled polymer composites are divided as binary or more than binary composites. The transmission of sound wave in these composite systems is different to the transmission of sound wave in unique medium. When one researches the sound insulation theory of polymer composites, he may analyze a volume element with a particle in the center, and the structure is as shown in Figure 1. Then the cross section of the particle in the element is analyzed, and the transmission process of the sound wave in it is as demonstrated in Figure 2. When the sound wave propagates in the element, the sound wave which does not contact the particle will go through the matrix and enter into the next element. While the sound wave which contacts the particle may be divided two parts: one part of sound wave will be reflected, the other will go through the microsphere to propagate and enters into the next element. Hence, the sound transmission in the element consists of the matrix and filler particle.

Sound transmission loss through matrix

As shown in Figure 2, a coordinate system is set up in it. When a bunch of plane sound wave (P_i,v_i) projects the surface of material, a part of it is reflected, this reflection wave is named as (P_{1r}, v_{1r}), while the wave which enters into the sound insulation material II is called as (P_{2t}, v_{2t}). When the sound wave go through the matrix and enters into air, a part of it on another interface of the matrix will be reflected, which is named as (P_{2r}, v_{2r}), while the transmission wave which enters into air I is called as (P_t, v_r). Let the characteristic impedance of the air $R_0 = \rho_0 c_0$, the characteristic impedance of the matrix $R_1 = \rho_1 c_1$ According to the expressions (1) and (2) of the wave equation solution of the plane wave, one can get the expressions of the each bunch of plane sound wave in the coordinate system show in Figure 2. In addition, the transmission wave (P_t, P_t, v_t) which enters into last the air propagates also at x direction.

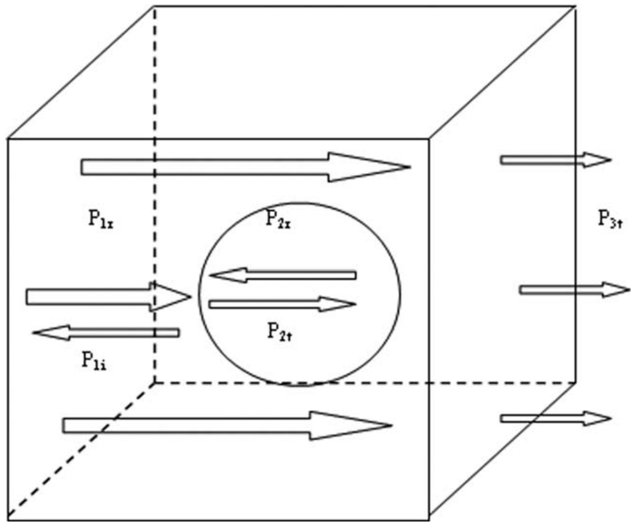

Figure 1 Diagram of sound insulation element of polymer composites.

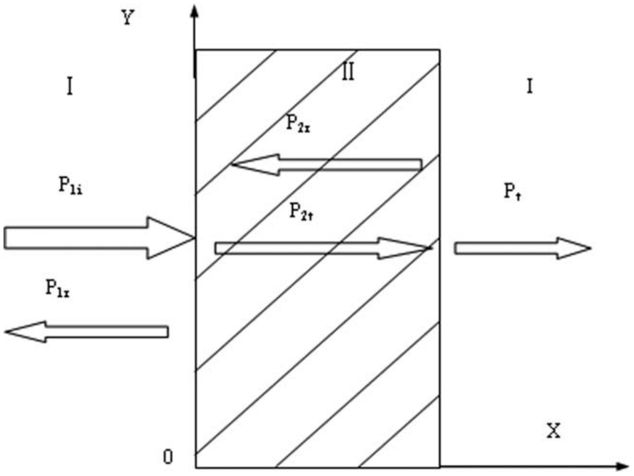

Figure 2 Diagram of sound wave propagation in matrix.

From the acoustics boundary conditions at the two special coordinate points $\chi = 0$, $\chi = L$, the transmission coefficient after the sound wave go through the matrix may be obtained as follows:

$$\tau_{I_0} = \frac{4}{4\cos^2 k_1 L + (R_{01} + R_{10})^2 \sin^2 k_1 L} \tag{4}$$

Combining eqs. (3) and (4), one may obtain the simplified transmission loss equation of the matrix:

$$\psi_0 = 201\mathrm{g}\rho_1 L + 201\mathrm{g}\varpi - 201\mathrm{g}2R_0 \tag{5}$$

Under standard state the sound impedance rate of the air is

$$R_0 = \rho_0 C_0 = 1.293\ \mathrm{kg/m^3} \times 331.5\ \mathrm{m/s} = 428\ \mathrm{N\ .s/m^3}$$

where φ is the circular frequency of sound wave simple harmonic vibration, namely it is the frequency f of the sound wave. Thus, the final expression of eq. (5) may be given by:

$$\psi_0 = 201\mathrm{g}\, f + 201\mathrm{g}\rho_1 + 201\mathrm{g}L - 42 \tag{6}$$

Sound transmission loss through filler particle

When the sound wave goes through the filler particle, the calculation method which is similar to take a medium into a relatively large space might be used because the filler particle volume is small comparing with the matrix. That is, the filler particle is considered as taking a medium into a relatively large space, and then the transmission loss through the sphere is calculated. On the basis of the above discussion, an element cross section is taken from the sphere, and the sound wave propagation in it is analyzed to derive the transmission loss equation of the element cross section, as shown in Figure 3. Then the integral to the whole sphere cross section is made, and is divided by the area of the sphere cross section. Finally, the equation of the average sound transmission loss when sound wave goes through filler particle may be derived.

From the coordinate system shown in Figures 3 and 4, an element through the center cross section is taken, and the coordinate of the element at the center cross section is (x, y, z). The value of $h_\triangledown$ is expressed as $h_\triangledown = 2\sqrt{R^2 - (x^2 + y^2)}$, R is the particle radius (see Fig. 4). Because the diameter of filler particle is relatively small, one may takes approximately $\cos k_2 h_\triangledown \approx 1, \sin k_2 h_\triangledown = k_2 h_\triangledown$, $R_2 = \rho_2 c_2$, $R_{21} = \frac{R_1}{R_2} = \frac{\rho_1 c_1}{\rho_2 c_2}$, $k_2 = \frac{\varpi}{c_2}$. Thus the expression of the transmission coefficient τ_{I_1} when the sound wave goes through the element cross section may be obtained as follows:

$$\nabla\tau_{I_1} = \frac{1}{1 + (R_{21} + R_{12})^2 k_2^2 (R^2 - x^2 - y^2)} \tag{7}$$

The integral of eq. (7) to the whole cross section is made, and then is divided by the total area of the zone, the average transmission coefficient τ_{I_1} of the whole cross section may be obtained. Then from eq. (3), the average transmission loss equation when the sound wave goes through the filler particle may be derived:

$$\psi_1 = 201\mathrm{g}\left[R(R_{21} + R_{12})\frac{f}{c_2}\right] + 101\mathrm{g}\ 2 - 101\mathrm{g}\left(\ln\left[(R_{21} + R_{12})^2 \frac{f^2}{c_2^2} R^2 + 1\right]\right) \tag{8}$$

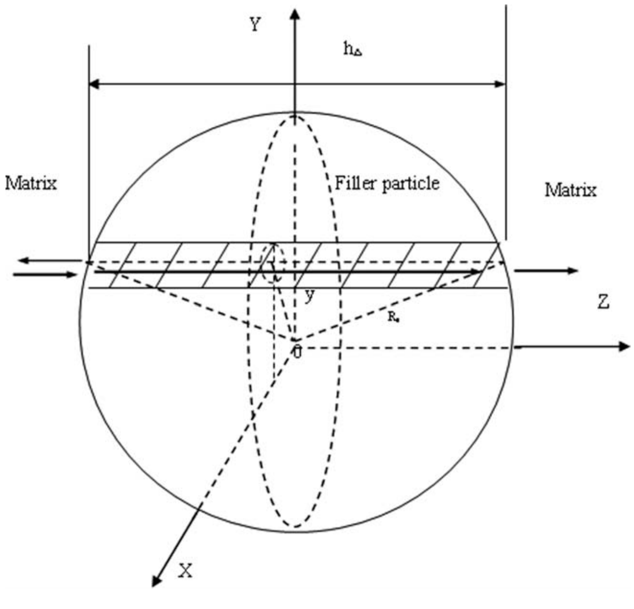

Figure 3 Sketch of sound wave transmission in filler particle.

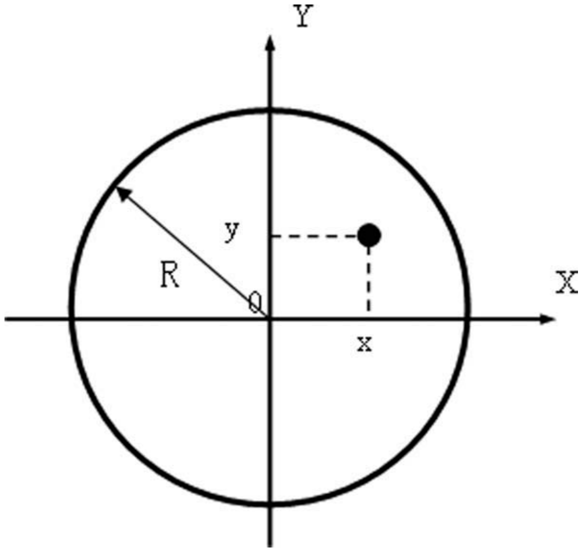

Figure 4 Integral area of sphere central section.

The transmission loss ψ_T of the element is the sum of the transmission loss of the filler particle and transmission loss of the matrix. The transmission loss through the matrix containing particle may be considered as the increasing insulation of the sphere to sound wave due to relatively large matrix volume. That is,

$$\psi'_T = \mathrm{n}.\psi_1 + \psi_0 = \sqrt[3]{\frac{3\phi_f}{4\pi}} \cdot \frac{L}{R} \cdot \left\{ 201\mathrm{g}\left[R(R_{21} + R_{12}) \frac{f}{c_2} \right] \right. \\ \left. +101\mathrm{g}2 - 101\mathrm{g}\left(\ln\left[(R_{21} + R_{12})^2 \frac{f_2}{c_2^2} R^2 + 1 \right] \right) \right\} \\ +201\mathrm{g}f + 201\mathrm{g}\rho_1 + 201\mathrm{g}L - 42 \quad (9)$$

Total transmission loss

The total transmission loss of the sheet is the sum of the transmission loss of the matrix and the transmission loss of the filler particles. The area ratio between the sphere cross section of the filler particle and the element cross section is $\eta_1 = \frac{S_{\text{spherecross section}}}{S_{\text{elementcross section}}} = \sqrt[3]{\frac{9\pi\phi^2}{16}}$, while the area ratio between the matrix and the element cross section is $\eta_0 = 1 - \eta_1$. Consequently, the total transmission loss equation ψ_T of the sheet is as follows:

$$\psi_T = \eta_0.\psi_0 + \eta_1 \cdot \psi_1 = (201\mathrm{g}f + 201\mathrm{g}\rho_1 + 201\mathrm{g}L - 42) \\ + \frac{3\phi_f L}{4R} \left\{ 201\mathrm{g}\left[R(R_{21} + R_{12}) \frac{f}{c_2} \right] + 101\mathrm{g}2 - 101\mathrm{g} \right. \\ \left. \times \left(\ln\left[(R_{21} + R_{12})^2 \frac{f^2}{c_2^2} R_2 + 1 \right] \right) \right\} \quad (10)$$

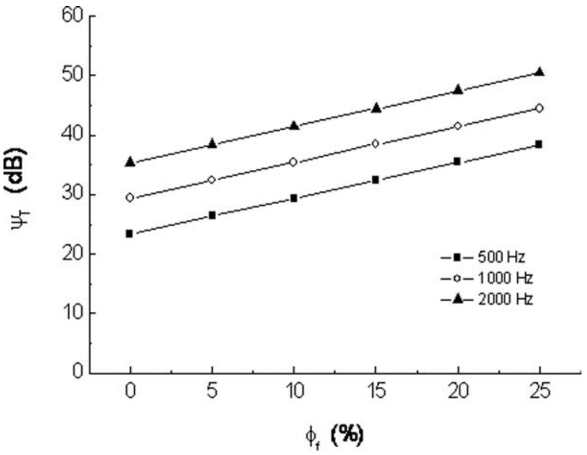

Figure 5 Relationship between transmission loss and filler volume fraction.

PREDICTION OF TRANSMISSION LOSS

Material and basic parameters

The sound insulation properties of glass bead-filled polyethylene (PE/GB) composites were estimated using eq. (10) in this article. The sheet thickness $L = 4 \times 10^{-3}$, the volume fractions of the glass beads were 0, 5, 10, 15, 20, and 25%, respectively. The other physical property parameters were follows:

$$\rho_0 = 1.2\mathrm{kg/m^3},\ \rho_1 = 930\mathrm{kg/m^3},\ \rho_2 = 2500\mathrm{kg/m^3},$$

$$c_0 = 340\mathrm{m/s},\ c_1 = 1950\mathrm{m/s},\ c_2 = 5640\mathrm{m/s},\ R_0 \\ = 415\mathrm{kg/m^2s}$$

$$R_1 = 1.8135 \times 10^6\mathrm{kg/m^2s},\ R_2 \\ = 14.1 \times 10^6\mathrm{kg/m^2s},\ R_{12} = 7.78,\ R_{21} = 0.129$$

Relationship between transmission loss and filler particle volume fraction

Figure 5 shows the relationship between the predicted transmission loss of the sheet and the glass bead volume fraction ϕ_f. Where, the average radius of the particle is 150 μm. It may be seen that when the sound frequency is constant, the predicted transmission loss of the sheet increases with an addition of ϕ_f, and the relationship between them is linear. This indicates that the sound insulation properties of the PE/GB composites obey the quality law.

Dependence of transmission loss on sound frequency

Figure 6 displays the dependence of the calculated transmission loss of the sheet on the sound frequency at various glass bead volume fractions. Where, the average radius of the particle is 150 μm. It can be observed that as the sound frequency is

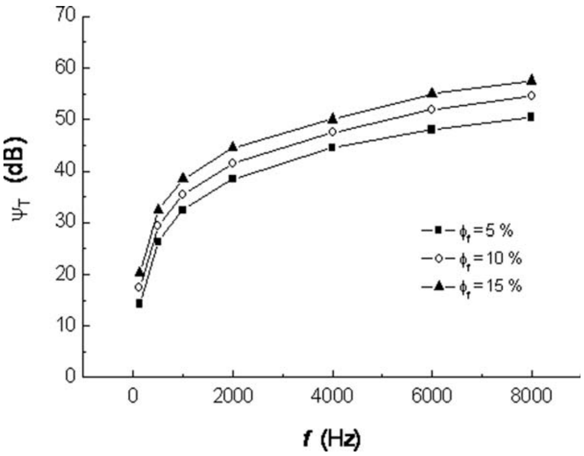

Figure 6 Dependence of transmission loss on sound frequency.

less than 1000 Hz, the transmission loss increases quickly with increasing the sound frequency, and then increases nonlinearly with increasing the sound frequency, and the increase of the transmission loss tends towards gently, especially as the sound frequency is more than 2000 Hz. This illustrates that the sensitivity of the sound insulation properties of the PE/GB composites to the sound frequency is strong in the case of low sound frequency.

Dependence of transmission loss on glass bead size

When the glass bead volume fraction is 10%, the dependence of the estimated transmission loss of the sheet on the glass bead radius (*R*) is presented in Figure 7. It can be seen that the estimated transmission loss of the sheet decreases nonlinearly with the increase of *R* as the sound frequency is fixed. This might be that the number of the glass beads reduces with an increase of *R* as the glass bead content is constant, and the distribution density of the glass beads in the matrix decreases correspondingly, leading to the reduction of the sound insulation properties of the sheet.

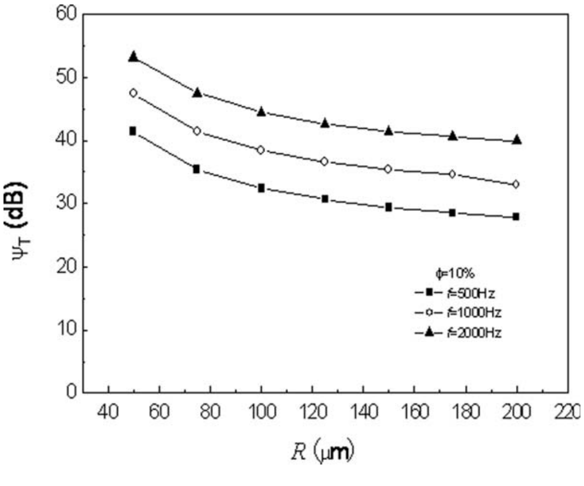

Figure 7 Dependence of transmission loss on filler particle radius.

DISCUSSION

In general, the transmission loss of materials obeys the mass law, and the density of glass bead is much greater than that of polymer. Consequently, the value of the ψ_T for the PE/GB composites increases with an increase of the glass bead volume fraction when the sound frequency is fixed (see Fig. 5). According to the mass law, the ψ_T of the sound insulation material is calculated by eq. (11):[10]

$$\psi_T(\theta, f) = 10\log\left[1 + \left(\frac{m\omega\cos\theta}{\rho c}\right)^2\right] \tag{11}$$

where ω, *m*, *c*, ρ, and θ are the angular frequency, surface mass of the specimen's unit area, speed of sound in air, density of air, and angle of incidence, respectively.

Equation (11) contains some parameters which are difficult to determine under general conditions, and there is some parameters for characterizing composites such as filler content. Equation (10) describes the relationship among the sound transmission loss of polymer composites filled with inorganic particles and the material density, the content and size of the filler particles as well as the sound frequency, etc. Hence, it is suitable to use in study on the sound insulation properties of inorganic particulate-filled polymer composite systems.

When the sound frequency is low, the composites can respond imitatively the vibration from the sound wave to make an equilibrium, and present obvious sensitivity of the transmission loss to the sound frequency (see Fig. 6). While in the case of high sound frequency, the composites cannot respond imitatively the vibration from the sound wave to make equilibrium, and present that the transmission loss increases slightly with an increase of the sound frequency (see Fig. 6). Lee et al.[7] investigated sound insulation effect of ABS/carbon-black composites, and found the transmission loss of the composites increases quickly with an addition of frequency when the frequency is lower than 800 Hz, and then increases slightly with an addition of frequency, as shown in Figure 8. These are similar to the phenomenon and regularity as shown in Figure 6. It means that the predictions of transmission loss by using eq. (10) are close to the experimental measurements from the inorganic particulate filled polymer composites.

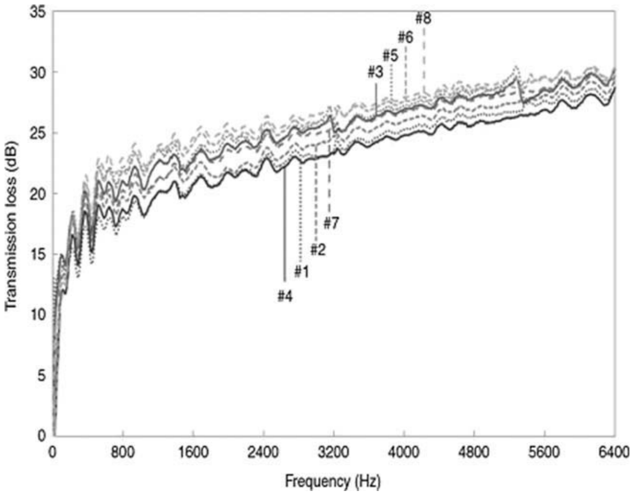

Figure 8 Average transmission loss of three specimens of ABS/carbon-black composites using DOE[7].

In short, the improvement of the sound insulation property of inorganic particulate filled polymer composites might be attributed to the behavior of reflection, scattering, and refraction of the sound wave generated in the composites when the sound wave contacted the filler particles.

CONCLUSIONS

The sound insulation properties of polymer composites filled with inorganic particles are closely related with the material density, the content, and size of the filler particles as well as the sound frequency, etc. On the basis of analyzing the sound transmission in the polymer/inorganic particle composites, a relevant physical model of sound transmission was set up in this article, and a transmission loss equation was derived. Equation (10) describes the relationship among these parameters, and the regularity of the sound insulation predicted was close to the experimental results reported from the literature.

The sound insulation properties of the glass bead filled polyethylene composites were predicted using this mathematical model. The results showed that the relationship between the estimated transmission loss of the sheet and the glass bead volume fraction was linear, and the sensitivity of the transmission loss to the sound frequency is strong at low sound frequency. When the glass bead volume fraction was 10%, the calculated transmission loss of the sheet decreased nonlinearly with an increase of the glass bead diameter.

The main reason for improving the sound insulation property of inorganic particulate filled polymer composites might be that the behavior of reflection, scattering, and refraction of the sound wave was generated in the composites when the sound wave contacted the filler particles.

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