Acoustical Properties and Absorption Performance of Steel-Wire Fabrics

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ABSTRACT: Acoustic performances of the steel-wire fabrics manufactured from the crushed tires were experimentally investigated for various thicknesses and bulk densities. The well-known two-cavity method was used to measure the characteristic impedances, the propagation constants, and the absorption coefficients. The normal absorption coefficients measured by the two-cavity method agreed well with those measured by the two-microphone impedance tube method. The experimental results showed that the magnitude and frequency range of the absorption coefficient were controllable by changing the thickness and the bulk density of the steel-wire fabrics. Therefore, the steel-wire fabrics from the crushed tires can be successfully used as a good sound absorbing material.

Nomenclature

c : speed of sound [m/s]
f : frequency [Hz]
$H(f)$: acoustic transfer function
k : wave number $(=\omega/c)$
l : thickness of the sound absorbing material [m]
L : depth of cavity [m]
Z_{air} : characteristic acoustic impedance of air [Pa.s/m]
Z_b : rear side surface acoustic impedance of the sound absorbing material [Pa.s/m]
Z_c : characteristic acoustic impedance of the sound absorbing material [Pa.s/m]
Z_s : front side surface acoustic impedance of the sound absorbing material [Pa.s/m]

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Greek symbols

α : normal incident absorption coefficient
γ : propagation constant [rad/m]
ω : angular frequency [rad/sec]

1. Introduction

As the healthful living environment is getting more important, the condition for sound absorbing materials has been changed.[1-4] Sound absorbing material recently requires not only the absorption performance but also good drainage, non-inflammability, high insulation, and long durability. Even though the fiberglass has the excellent absorption performance, its use was prohibited by the law due to the harmful effects. Although the polyurethane has the excellent absorption performance like the fiberglass, its use was restricted because of high risks of fire. The sound absorbing materials used for the jet noise, the tunnel sounds from the subway and the high-speed train, or the mechanical sounds from the industry machines, require non-toxicity and non-inflammability in addition to good absorption performance. Considering these requirements for sound absorbing materials, the objective of this study is to develop a new sound absorbing material by utilizing the wires from crushed tires and to evaluate the absorption performance.

The used tire can be crushed into rubber chips, carbon steel wires, and nylon yarns. The rubber chips are used for sidewalk blocks or building materials, and the nylon yarns are used for combustion fuels for boilers. And the steel wires are used only for the iron scraps. However the wire fabrics made of the steel wires can be used as sound absorbing material. They are heavy in weight and safe from the toxicity and the inflammability. The only thing to be checked is the sound absorbing performance.

This study assessed the acoustical performance of the steel-wire fabrics manufactured from the steel wires of 2 mm in diameter obtained from the recycled tires.[5] Those tested fabrics had various thicknesses and bulk densities. The characteristic impedances and the propagation constants were measured using the two-cavity method suggested by Utsuno et al.[6] In order to validate the absorption coefficients measured by the two-cavity method, they were compared with the measured values by the two-microphone impedance tube method.[7]

2. Theory

There are two well known methods for estimating the performance of the sound absorbing materials. One is the two-thickness method suggested by Smith and Parrott,[8] and the other is the two-cavity method suggested by Utsuno et al.[6] Both of them were based upon Yanvi's[9] method. The two-thickness method estimates the absorption coefficient by measuring the surface acoustic impedances for two tested samples of the same thickness in the impedance tube. However, the two-cavity method estimates the absorption coefficient by measuring twice the surface acoustic impedances for one sample for different cavity depths. As it is difficult to manufacture the fabrics having the same thicknesses and bulk densities for the former method, this study estimated the absorption coefficients using the two-cavity method of the latter method.

Two-cavity method as shown in Fig. 1 is based on the estimation of the characteristic acoustic impedance Z_c and the propagation constant γ by measuring the front side surface acoustic impedance Z_{s1} and the rear side surface acoustic impedance Z_{b1} for cavity depth L_1, and the front side surface acoustic impedance Z_{s2} and the rear side surface acoustic impedance Z_{b2} for cavity depth L_2.[6]

The following Eqs. of (1) and (2) is the formulation for the estimations of Z_c and γ:

$$Z_c = \pm\left\{\frac{Z_{s1}Z_{s2}(Z_{b1}-Z_{b2})-Z_{b1}Z_{b2}(Z_{s1}-Z_{s2})}{(Z_{b1}-Z_{b2})-(Z_{s1}-Z_{s2})}\right\}^{1/2} \quad (1)$$

$$\gamma = \frac{1}{2l}\ln\left(\frac{Z_{s1}+Z_c}{Z_{s1}-Z_c}\,\frac{Z_{b1}-Z_c}{Z_{b1}+Z_c}\right) \quad (2)$$

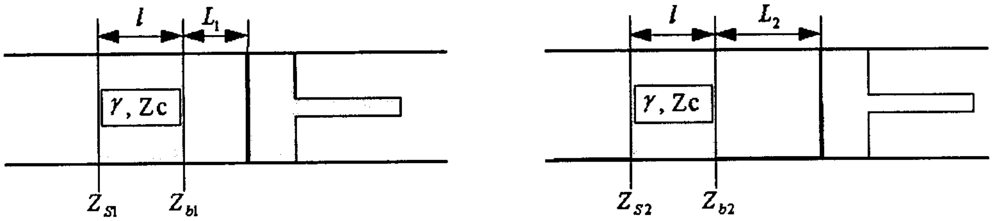

Fig. 1 Configurations for the two-cavity method.

Either one of the signs in Eq. (1) is selected to make the positive real number of the characteristic impedance. In Eq. (2), l represents the thickness of the material. While Z_{s1} and Z_{s2} in Eqs. (1) and (2) are experimentally measured, Z_{b1} and Z_{b2} are evaluated using the following Eqs. (3) and (4):

$$Z_{b1} = -jZ_{air} \cot kL_1 \tag{3}$$

$$Z_{b2} = -jZ_{air} \cot kL_2 \tag{4}$$

Where, Z_{air} is the characteristic impedance of the air, j is the imaginary number $\sqrt{-1}$, and k is the wave number.

With the known values of Z_c and γ from Eqs. (1) and (2), the surface acoustic impedance Z_s is calculated using the following Eqs. for different thicknesses of the materials and the cavity depths:

$$Z_s = Z_c \coth(\gamma l) \tag{5a}$$

$$Z_s = Z_c \frac{Z_{b1}\cosh(\gamma l) + Z_c \sinh(\gamma l)}{Z_{b1}\sinh(\gamma l) + Z_c \cosh(\gamma l)} \tag{5b}$$

Then the normal absorption coefficient α can be calculated using the following Eq. (6):

$$\alpha = 1 - \left| \frac{Z_s - Z_{air}}{Z_s + Z_{air}} \right|^2 \tag{6}$$

3. Experiments

Figure 2 shows the crushed tire chips and the molded test sample of the wire fabrics manufactured from those crushed tire chips. The procedures of making the steel-wire fabrics are as follows. First, as shown the lefthand side of Fig. 2, those rubber chips attached on the crushed tires of 20~30 mm length and of diameter around 0.2~1.0 mm were melted down by heat. Then, the steel wires of 0.2 mm in diameter were selected. Due to the carbonization on the steel wires during the combustion of the rubber chips, a carbonized film forms on the steel wires, which protects the steel wires against the steel oxidization.(5) In order to improve the flexibility, the steel wires were annealed. Steel wires obtained from the above procedures were inserted into the molding machine and then compressed as shown in righthand side of Fig. 2. Table 1 shows the specifications of the manufactured steel-wire fabrics.

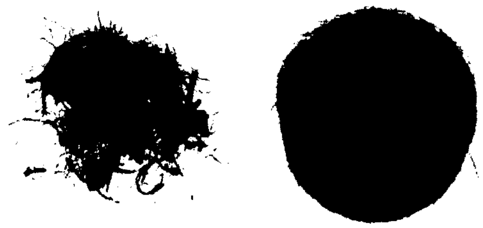

Fig. 2 Crushed tire chips (left) and the test sample of the steel-wire fabric (right).

In the process of inserting the steel wires into the molding machine, a uniform test sample is obtained only when they are completely inserted at once. If they are inserted into the molding machine in several times, then non-uniformity appeared in the sample. In order to investigate the effects of the non-uniformity, a several layered test sample was manufactured.

Table 1 Specifications of the steel-wire fabrics

	Thickness (m)	Bulk density (kg/m^3)	Remarks
Steel-wire No. 1	0.018	147	Z, γ, α
Steel-wire No. 2	0.023	194	Z, γ, α
Steel-wire No. 3	0.030	167	Z, γ, α
Steel-wire No. 4	0.040	133	Z, γ, α
Steel-wire No. 5*	0.026	170	Z, γ, α
Steel-wire No. 6	0.020	133	α
Steel-wire No. 7	0.025	212	α
Steel-wire No. 8	0.060	89	α
Steel-wire No. 9	0.060	133	α

No. 5 marked by * in Table 1 is the non-uniform test sample. No. 6, No. 7, No. 8, and No. 9 in Table 1 were manufactured to investigate the effects of the thicknesses and bulk densities. Remarks in Table 1 represent the measured values for each samples.

Figure 3 shows the experimental setup for measuring the surface acoustic impedance of the steel-wire fabrics. The used impedance tube was 1,000 mm in length and 70 mm in inside diameter. At the entrance of the impedance tube, a speaker was attached, and the sound with large frequency band created by the sound generator (B&K, type 2825) was supplied into the impedance tube. At the end of the impedance tube, 1/4 inch condenser type microphones (B&K, type 4938) were installed. The bottom faces of the microphones were accurately inserted for flush mounting in the impedance tube. Also, the end of the impedance tube was completely sealed with an steel piston. Tested fabric was inserted in front of the piston and the surface acoustic impedance was measured with a specific cavity length.

The surface acoustic impedance was measured by the two-microphone method[7] as shown in Fig. 3. With the measured acoustic transfer function, $H(f)$, between the two microphones, the surface acoustic impedance was evaluated by the following relationship:[10]

$$Z_{s1}, Z_{s2} = jZ_{air} \frac{\sin[k(x-s)] - H(f)\sin(kx)}{H(f)\cos(kx) - \cos[k(x-s)]} \quad (7)$$

In Eq. (7), x represents the distance between the face of the tested sample and the first microphone, s indicates the distance between the two microphones, and f means the frequency. At the end of the impedance tube, the test sample with thickness of l was inserted.

After changing the cavity depth from L_1 to L_2, the impedance change from Z_{s1} to Z_{s2} was evaluated from the measured acoustic transfer function. In this study, L_1=20 mm and L_2=60 mm.

4. Results and discussion

Figure 4 shows the measured characteristic impedances for the samples of No. 1, No. 2, No. 3, and No. 4 based on the non-dimensionalized values using the characteristic impedance of air, Z_{air}. In the figures, Re represents the real numbers and *Im* indicates the imaginary numbers of the impedances.

Since the characteristic impedance implies the resistance of the sound waves passing through the test sample, it is closely related to the density of the test sample. Thus, the characteristic impedances in Fig. 4, the values of Re

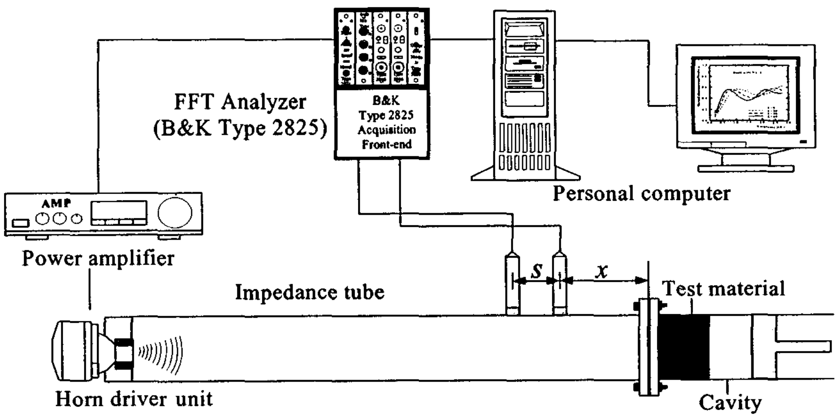

Fig. 3 Experimental setup for measuring the surface acoustic impedance of the steel-wire fabrics.

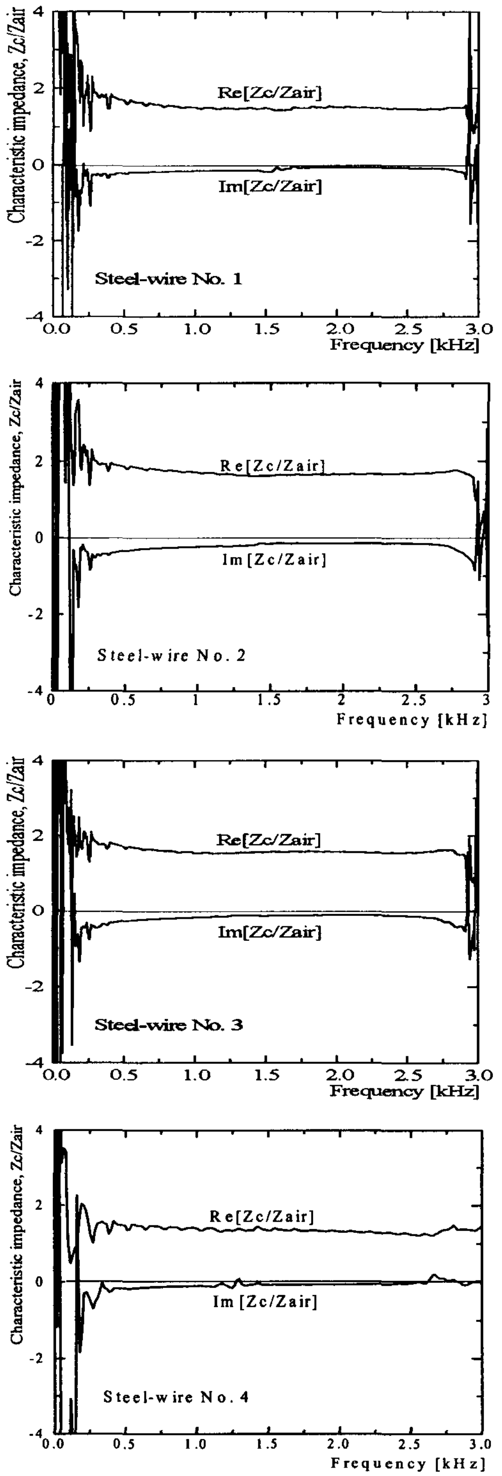

Fig. 4 Characteristic impedances of steel-wire fabrics.

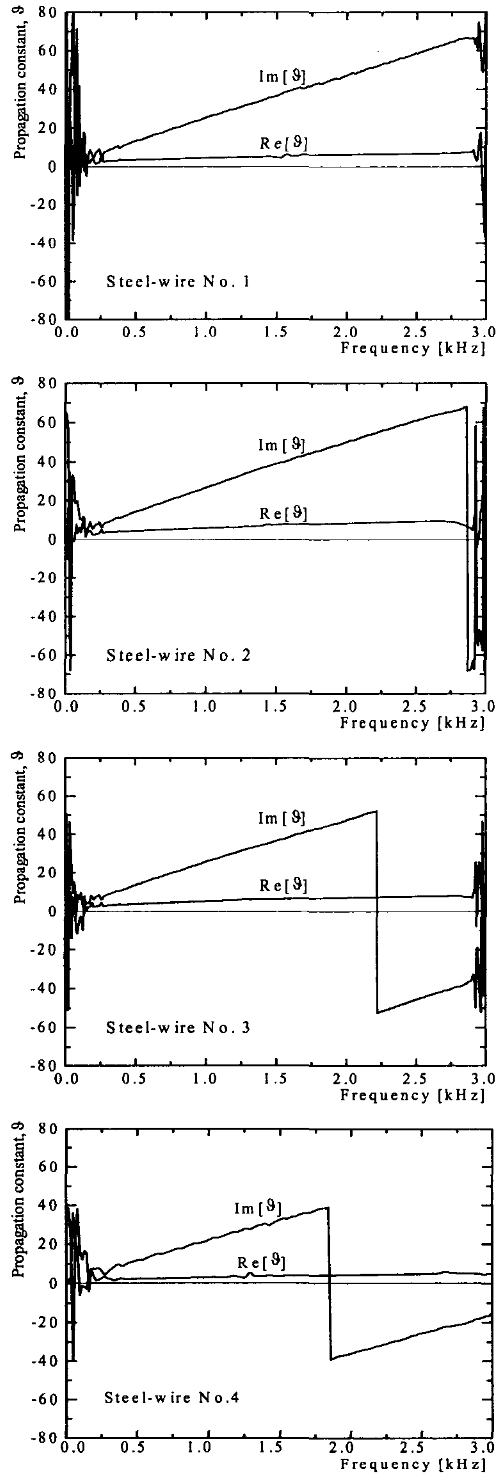

Fig. 5 Propagation constants of steel-wire fabrics.

and *Im* for No. 2 are larger than those for No. 1, No. 3, No. 4. These results show the relationship of the impedances with densities in Table 1. In addition, we can see the incident waves of high frequencies are relatively less resistant than those of low frequencies. Hence, the characteristic impedance for all of the four cases gradually decreased as the frequency is increased. However, due to the measurement errors, the characteristic impedances fluctuations appear in at frequencies lower than 200 Hz.[2]

Figure 5 shows the measured propagation constants for the test samples of No. 1, No. 2, No. 3 and No. 4. The propagation constant has the unit of *radian/m*. The real number, Re, indicates the sound attenuation per unit length, and the imaginary number, *Im*, expresses the changes of the phase angles for the sound waves propagating through the steel-wire fabrics. As can be seen from Fig. 5, the real numbers gradually increased as the frequencies increased for all cases. Since the real numbers for No. 2 and No. 3 were greater than for No. 1 and No. 4, we can see the absorption performances of the steel-wire fabrics for No. 2 and No. 3 are better than those for No. 1 and No. 4.

While, associated with the imaginary numbers for the four cases in Fig. 5, the signs change from (+) to (−) at the frequencies of 2,875 Hz for No. 2 and 2,250 Hz for No. 3. In this way, the sign changes of the phase angle from (+) to (−) or from (−) to (+) take place when the particle velocity of the sound wave in steel-wire fabrics becomes maximum value.

Figure 6 shows the measured sound absorbing coefficients for No. 1, No. 2, No. 3, and No. 4. In order to assess the validity of the absorption coefficients measured by the two-cavity method, the two-microphone method[7] was additionally employed to evaluate the absorption coefficients shown in Fig. 6.

Substituting the measured characteristic im-

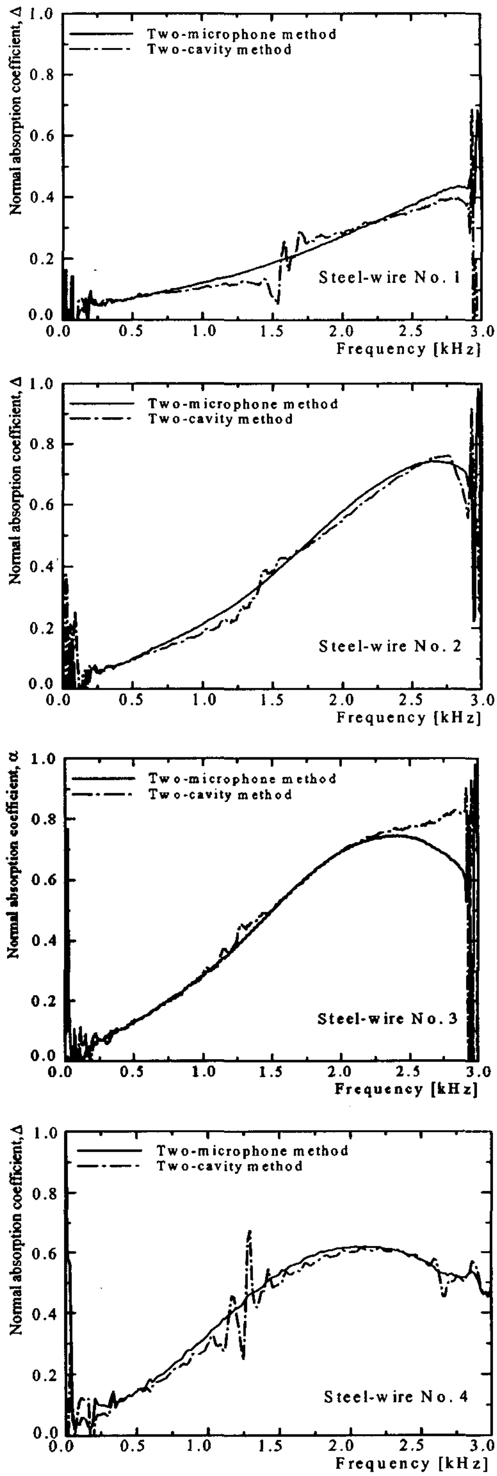

Fig. 6 Absorption coefficients of steel-wire fabrics.

pedances and the propagation constants into Eqs. (5a) and (6), the absorption coefficients could be readily evaluated by the two-cavity method. Comparing the absorption coefficients evaluated by the two-cavity method with those obtained by the two-microphone method, we can see they do not consistent at some frequencies. For the test sample of No. 1, at 1,500 Hz there are significant deviations between the absorption coefficients by the two-cavity method and by the two-microphone method. For the test samples of No. 3 and No. 4, the prominent deviations appear at 2,500 Hz and 1,250 Hz, respectively. The occurrence of those deviations can be explained by the non-uniformity in manufacturing the test samples, and it will be discussed in Fig. 7.

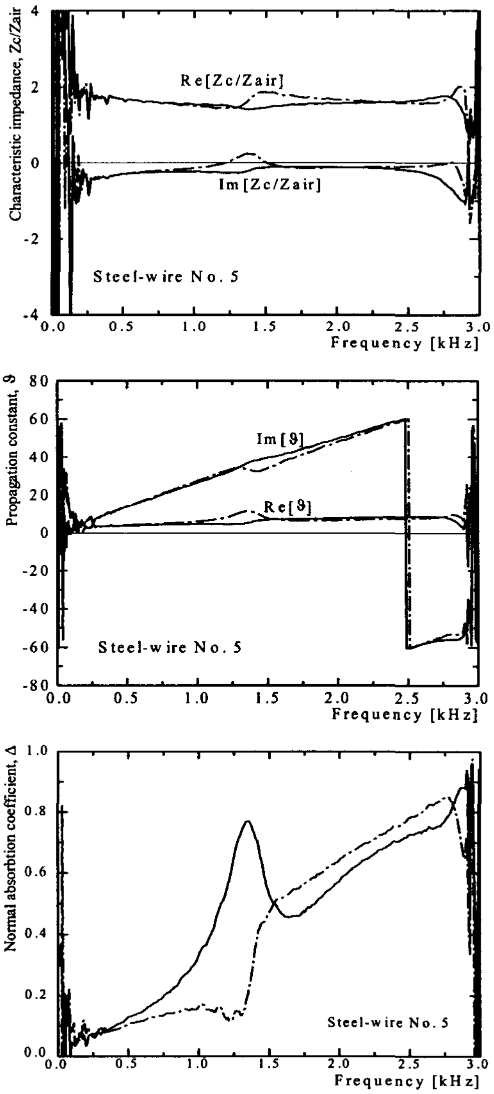

Fig. 7 Acoustical characteristics of a non-homogeneous steel-wire fabrics.

While, if we compare Fig. 5 with Fig. 6, the absorption characteristic in Fig. 6 coincided with that of the phase angles in Fig. 5. For instances, in the measured results in Fig. 5 and Fig. 6 for No. 2, the frequencies at which the signs of the phase angles change were at the peak points of the absorption coefficients. For the sample of No. 3, the signs of the phase angles changed at 2,250 Hz where the absorption coefficients become maximum as we can see in Fig. 5 and Fig. 6. Besides, since the real numbers of the characteristic impedances and the propagation constants for No. 2 and No. 3 are larger than those for No. 1 and No. 4, the absorption coefficients for No. 2 and No. 3 are greater than those for No. 1 and No. 4.

Figure 7 shows the characteristic impedances, the propagation constants, and the absorption coefficients measured by the two-cavity method for No. 5. It was particularly manufactured to be inhomogeneous in density. The solid line and the dotted line represent those measured values at the rear side and the front side of the test sample directing to the incident sound waves, respectively.

In the first place, if we look at the characteristic impedances and the propagation constants in Fig. 7, significant deviations are found at frequencies between 1,000 Hz and 2,000 Hz, and beyond 2,500 Hz. In addition, the normal absorption coefficients show greater difference at frequencies greater than 1,000 Hz.

Based on the above results in Fig. 7, the discrepancies between the absorption coefficients measured by the two-cavity method and the two-microphone method in Fig. 6 for No. 1 near

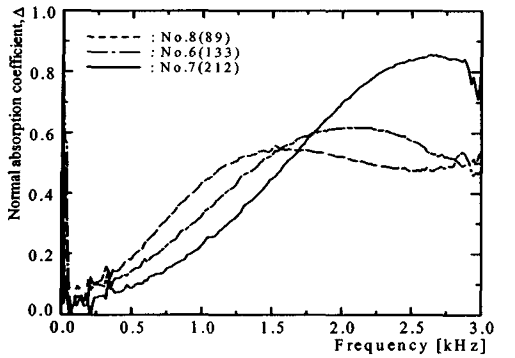

Fig. 8 Absorption coefficients of steel-wire fabrics with different bulk densities.

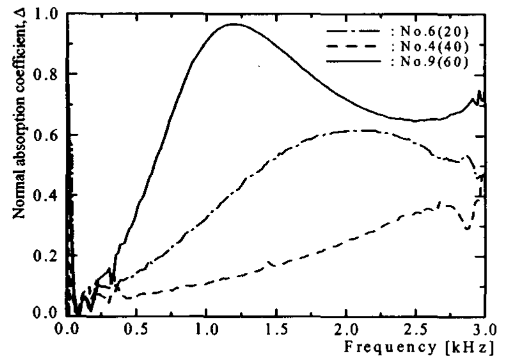

Fig. 9 Absorption coefficients of steel-wire fabrics with different thickness.

the frequency of 1,500 Hz, No. 3 over the frequency of 2,500 Hz, and No. 4 near the frequency of 1,250 Hz can be explained by the non-homogeneity of the test samples.

Figure 8 shows the absorption coefficients measured by the two-microphone method for No. 6, No. 7, and No. 8. Those samples are different in densities. The numbers in parentheses on Fig. 8 indicate the densities of the measured samples respectively. As we can see from the figure, the absorption coefficients increase with increase in the frequency. The larger the densities, the greater absorption coefficients at the high frequencies.

Figure 9 shows also the absorption coefficients measured by the two-microphone method for No. 4, No. 6, and No. 9. However, those samples had the same density of 133 kg/m^3. The numbers in parentheses on Fig. 9 are the thicknesses (mm) of the measured samples respectively. As the thicknesses of the test samples become thicker, the maximum values of the absorption coefficients appeared at the lower frequency. Especially, due to the relatively large porosity, the sample of No. 9 with thickness of 60 mm had good absorption performance at low frequencies[2,11] like the perforated panel system.[12] Based on the above results, it can be concluded that the performance of the steel-wire fabrics can be controlled using the thicknesses and the bulk densities such as the polyurethane and the fiberglass.

Figure 10 shows the absorption coefficients measured by inserting the test samples of No. 4 and No. 9 into the impedance tube with different cavity depths (L) of 0, 20, 40, and 60 mm. From the figure, we can see that as the cavity depth increases, the frequency of the

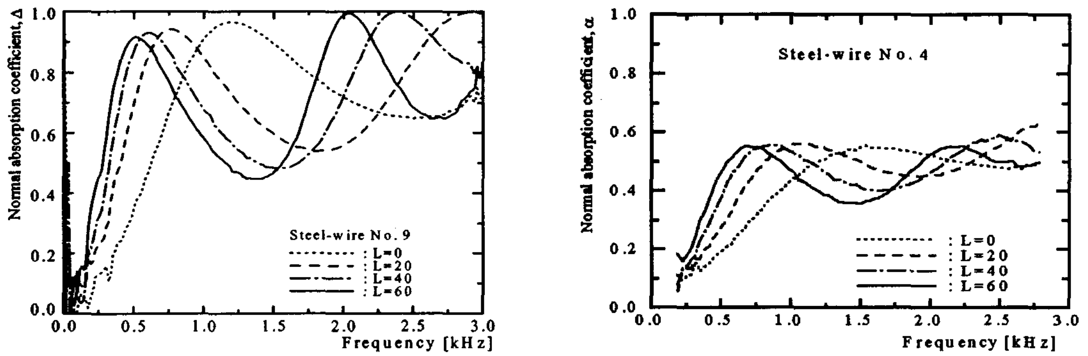

Fig. 10 Effect of the air cavity depth on the absorption coefficient of the steel-wire fabrics.

maximum value of the absorption coefficients decreases. Besides, the maximum values of the absorption coefficients occur when the sum of the thickness and the cavity depth equal to quarter wavelength of the incident sound.[13]

5. Conclusions

In this study, the characteristic impedances, the propagation constants, and the normal absorption coefficients were measured and discussed to evaluate the acoustic performance of the steel-wire fabrics manufactured from the used tires. Based on the experimental results, the following conclusions may be drawn put down:

(1) The steel-wire fabrics have good sound absorption performance, and the magnitude and frequency range of absorption coefficients could be easily controlled using the thickness and the bulk density of the steel-wire fabrics.

(2) The characteristic impedances, the propagation constants, and the normal absorption coefficients for the steel-wire fabrics with good homogeneity in density are efficiently evaluated by the two-cavity method.

(3) The homogeneity in density should be carefully considered in the manufacturing process of the steel-wire fabrics for the acoustic performance and the quality control.

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