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CHARACTERIZING THE SOUND ABSORPTION OF WOOD CONCRETE

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ABSTRACT

One of the applications of wood concrete is the absorptive highway noise barrier. In this paper, the sound absorbing performance of wood concrete was investigated. The effects of density and thickness on the sound absorption were discussed. The models which are used to predict the sound absorption of rigid-frame porous materials were introduced and the suitability of these models in predicting the sound absorption of wood concrete was evaluated. Finally, the Attenborough model was found to give a good prediction of the sound absorption for the Durisol material.

KEYWORDS: sound absorption, wood concrete, processing parameters, model,

INTRODUCTION

Durisol, a wood concrete, is a lightweight wood-cement composite. It is made by bonding chemically mineralized and neutralized softwood shavings or chips with ordinary Portland cement. This material has been produced in Canada by Armtec Limited Partnership to build absorptive highway noise barrier panels for more than three decades. Therefore, sound absorption is an essential property of the Durisol material.

Despite the importance of sound absorption to Durisol material, the reports on this subject are scarce. Behar and May (1980) evaluated the ability and durability of sound absorption for different absorptive highway noise barrier materials, including the Durisol material. They found that the Durisol material was among the two tested materials having the highest sound absorbing ability. In addition, the sound absorbing ability of Durisol material did not show any change after eight months of highway exposure. Hajek (1983) studied the effect of the thickness of Durisol material on its sound absorption. It was reported that the average sound absorption coefficients (in the one-third octave bands from 160 to 2000 Hz) of Durisol material increased when the material thickness increased from 10 mm to 50 mm. However, the average sound absorption coefficient of Durisol material levelled off when the material thickness was in the range of 50 mm to 60 mm. In addition, the resonance frequency was found to shift to the lower frequency side with the increase of the material thickness. Based on a literature search, this publication is the only one available about the effect of processing parameters on the sound absorption of Durisol material and similar wood concretes.

According to the inner structure and the strength of Durisol material, it can be considered as a rigid-frame porous material. This type of material dissipates the energy of the incoming sound incidence mainly by the viscous-thermal effect, that is, the sound energy is converted into heat energy by the viscous friction and inertia along the passage of the sound wave through the network of the interlocking pores within the material. Theoretically, the porosity and airflow resistivity are the key material properties that govern the sound absorption of this type of material (Cox and D'Antonio 2009). The porosity is defined as the volume fraction occupied by the air voids in a porous material. The airflow resistivity is defined as the resistance of a porous material to the air traveling through it. Ideally, for a rigid-frame porous material to be efficient in absorbing sound, the porosity of the material should be as large as possible, while its airflow resistivity should be within limits. The effects of the porosity and the airflow resistivity on the sound absorption of a rigid-frame porous material under a variety of conditions are well presented by Ingard (1994). Other material properties that are believed to impact the sound absorption of a rigid-frame porous material include the tortuosity, viscous and thermal characteristic lengths.

Although it is understood that the porosity and airflow resistivity are decisive to the sound absorption of Durisol material, the measurements of these material properties are difficult and time consuming. It makes more sense for a material manufacturer to know how these material properties and the sound absorption are affected by the processing parameters. In the practice, the processing parameters can be far more easily measured and controlled than the porosity, airflow resistivity, etc.

Among the processing parameters that affect the sound absorption of Durisol material, the density and thickness of the material are the two most important ones. In the manufacture of Durisol material, the material is compressed to a certain degree in order to achieve the adequate strength and durability. Even though the density of a rigid-frame porous material does not directly affect its sound absorption, it has a close relationship to the porosity and airflow resistivity of the material (Ingard 1994). In addition, the density is directly linked to the weight and production cost of the material. Although the effect of thickness on the sound absorption of a rigid-frame porous material is well understood (Cox and D'Antonio 2009), a closer look at its effect on the sound absorption of Durisol material is still needed. Like the density, the material thickness also determines the weight and production cost. Furthermore, it is assumed that there might be an interaction effect between the density and thickness on the sound absorption. When the density reaches to a certain level, the increase of thickness might no longer be efficient in increasing the material's sound absorption.

This research studied the effects of density and thickness on the sound absorption of Durisol material. It was a part of a larger investigation undertaken to understand the effects of some important processing parameters on the sound absorption of Durisol material.

MATERIALS AND METHODS

Wood chips were obtained by processing recycled softwood offcuts to the desired gradation. The average density (oven-dry weight, air-dry volume) of the softwood offcuts was 450 kg/m^3. Ordinary Portland cement was used for sample making. Its specific gravity was assumed as 3.15. During batching, the cement/wood ratio was controlled at 2.45, and the water was added until the required material consistency was achieved.

In this research, a general factorial design was chosen to investigate the effects of density and thickness on the sound absorption of Durisol material. As shown in Table 1, the targeted material density varied from 540 to 630 kg/m^3, while the thickness from 50 to 100 mm. The ranges of these two independent variables represented the values achievable in production.

Table 1. Design of Experiment (DOE)

Variables	Levels		
	1	2	3
Material Density (kg/m^3)	540	585	630
Material Thickness (mm)	50	75	100

According to Table 1, the experiment comprised a total of 9 (3x3) runs. For each run, the sample, measuring 500 mm long by 200 mm wide was made by filling the required weight of fresh material into a mould and then compressing the material to the targeted thickness. After a curing period of 8 weeks, 6 specimens were randomly taken from each sample. Three specimens (Φ60 mm) were used for the sound absorption measurements and the remaining 3 (Φ49 mm) for the airflow resistivity tests.

Figure 1. Impedance Tube System for Sound Absorption Test

The sound absorption was measured with an impedance tube testing system (Figure 1), following the ISO10534-2 standard. The sound absorption average (SAA), which was the average of the absorption coefficients for the twelve one-third octave bands from 200 to 2500 Hz, was used to rate the sound absorption of the tested specimens. The airflow resistivity tests were conducted in accordance with the ASTM C522 standard.

The porosity of each sample was calculated according to its density and the mix design. The equation for the porosity calculation is as following: : $\Omega = 1 - \sum \frac{m_i}{\rho_i}$, …… (1), where Ω is the porosity (%), m_i is the content (kg) of the i-th raw material in 1 m^3 of Durisol material, and the ρ_i is the density of the i-th raw material (kg/m^3).

RESULTS AND DISCUSSION

Non-acoustic Properties

The average density, airflow resistivity and porosity of the Durisol samples are recorded in Table 2. The actual densities of the measured samples were very close to the targeted values, meaning that the experiment was well controlled. The porosity decreased with the increase of material density since more raw material was consumed in each fixed volume of the sample, diminishing the air voids. Contrary to the porosity, the airflow resistivity increased with the density of material. Generally, the airflow resistivity of a porous fibrous sound absorber is directly related to its density and inversely related to the fibre diameter (Cox and D'Antonio 2009). In this experiment, the airflow resistivity of the material increased with its density since the wood chips were held constant for all samples. The airflow resistivity also showed a more abrupt change with the variation of density than did the porosity. No apparent effect was found on the porosity or the airflow resistivity by varying the thickness of Durisol material.

Table 2. Actual Density, Airflow Resistivity and Porosity of Durisol Material

Properties \ Thickness \ Targeted Density	540 kg/m^3			585 kg/m^3			630 kg/m^3		
	50 mm	75 mm	100 mm	50 mm	75 mm	100 mm	50 mm	75 mm	100 mm
Actual Density (kg/m^3)	532	554	547	607	584	587	629	612	625
Aiflow Reisitivity (Pa.s/m^2)	5472	5521	5807	14326	11096	9511	22362	16009	20298
Porosity (%)	53.0	51.0	51.7	46.4	48.4	48.1	44.4	45.9	44.8

By closely analysing the measured airflow resistivity and density of Durisol material, a power equation was created to express their relationship with a relatively high reliability (R^2=0.91), as shown in equation (2): $\sigma = 1.916 \times 10^{-21} \rho^{8.927}$, …… (2), where σ is the airflow resistivity (Pa.s/m^2), ρ is the density (kg/m^3). Such a relationship agreed with the observations made by Wassilieff (1996) for wood-based composite materials.

The accuracy of equation (2) in predicting the airflow resistivity of material with its density is displayed in Figure 2. A general approximation between the measured and predicted values can be seen in the graph although some deviations existed.

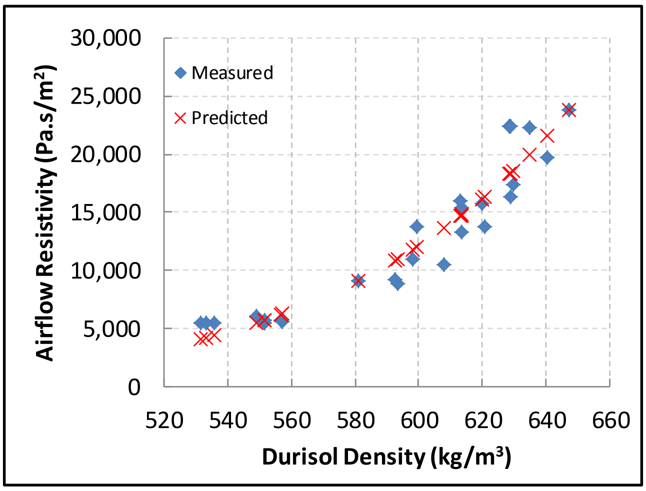
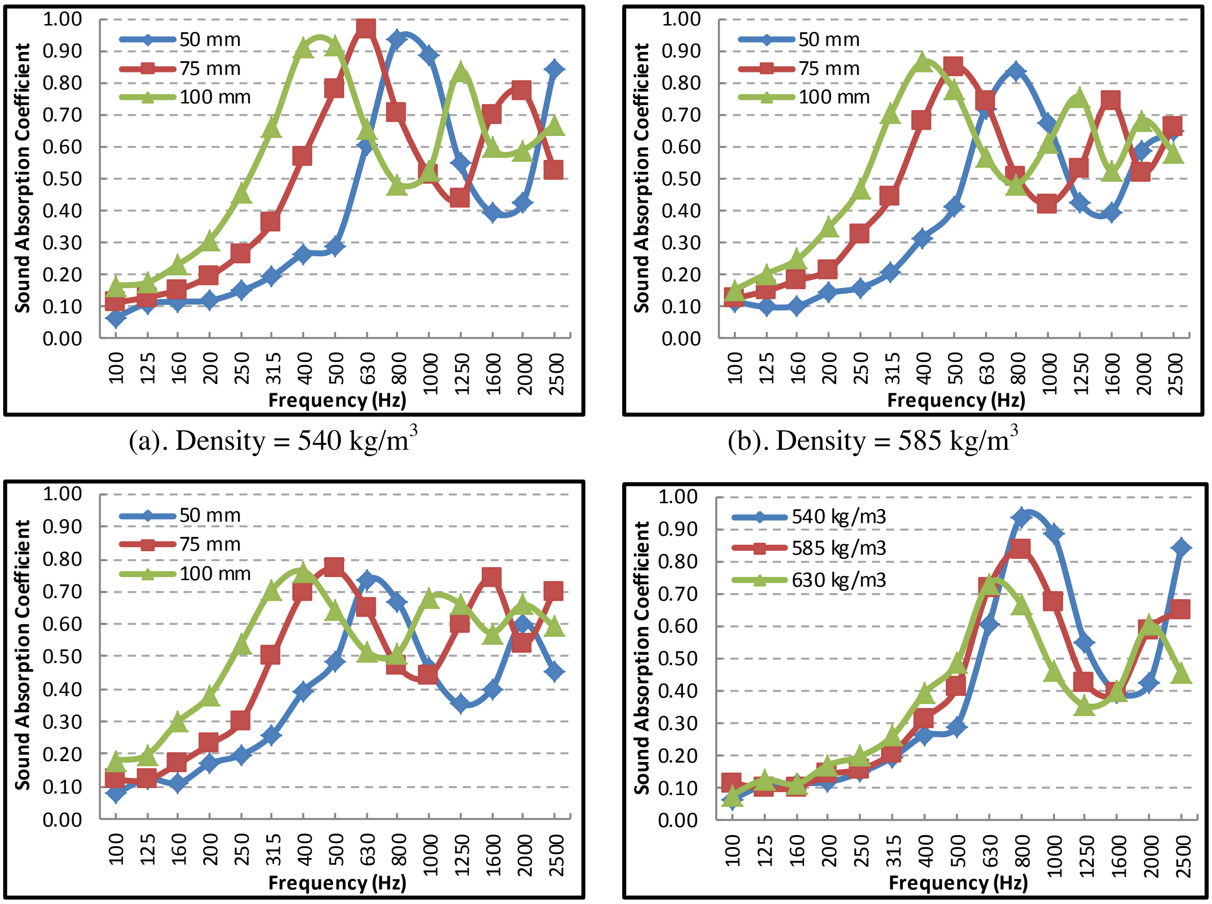


Figure 2. Airflow Resistivity versus Density

Acoustical Performance

The average sound absorption coefficients of the samples are shown in Figure 3. Durisol material had a sound absorption coefficient pattern similar to the ordinary rigid-frame porous sound absorbers. The sound absorption coefficient of Durisol material was a function of the frequency. The coefficient was lower at the lower frequencies but higher at the mid- and higher frequencies. The sound absorption gradually rose with the increase of frequency until the first peak of sound absorption, a resonance frequency, appeared. After reaching the first peak in sound absorption, the coefficient decreased gradually with the increase of frequency, until the valley of the sound absorption appeared. The sound absorption coefficient climbed again with the subsequent higher frequencies.

At the same density, the sound absorption coefficient pattern shifted towards the left (lower sound frequency) side with the increase of the material thickness. Therefore, the increase of material thickness greatly improved the sound absorption at lower frequencies. This outcome agreed with the observations made by Hajek (1983). Increasing the density of Durisol material from 540 kg/m^3 (Figure 3(a)) to 630 kg/m^3 (Figure 3(c)) did not alter the effect of material thickness on the sound absorption. The assumed interaction effect between the thickness and density on the sound absorption of the material was not observed in this experiment. In addition, the increase in thickness did not decrease the sound absorption at the higher frequencies and at the resonance frequency, but lifted the sound absorption coefficient in the valley. Interestingly, increasing the thickness from 50 mm to 75 mm appeared to have a greater impact on the sound absorption than further increasing it from 75 mm to 100 mm.



(a). Density = 540 kg/m^3 (b). Density = 585 kg/m^3

(c) Density = 630 kg/m^3 (d) Thickness = 50 mm

Figure 3. Sound Absorption Affected by Density and Thickness

Figure 3(d) gives an example of the density effect at the 50 mm thickness. It can be seen that the sound absorption coefficients at lower frequencies (≤ 630 Hz) were improved with the increase of density, perhaps resulting from the increase in the airflow resistivity. This effect was more prominent when the density increased to 630 kg/m^3. Due to the increase in sound absorption at lower frequencies, the resonance frequency became lower with the increase of Durisol density. However, unlike the effect of thickness on the sound absorption, increasing the density resulted in a lower peak sound absorption coefficient and a general loss in sound absorption at higher frequencies. Similar results were found for the material at 75 mm and 100 mm thicknesses.

The combined effect of density and thickness on the sound absorption average (SAA) of Durisol material is shown in Figure 4. The SAA was significantly affected by these two variables. However, the thickness had a greater effect on the SAA than did the density. When increasing the density of the material, the SAA decreased significantly. At higher density, the airflow resistance of the material increased, leading to the increase in sound reflection, thus decreasing the sound absorption. In addition, the decrease of material porosity with the increase of density made the material less transparent to the incoming sound incidence.

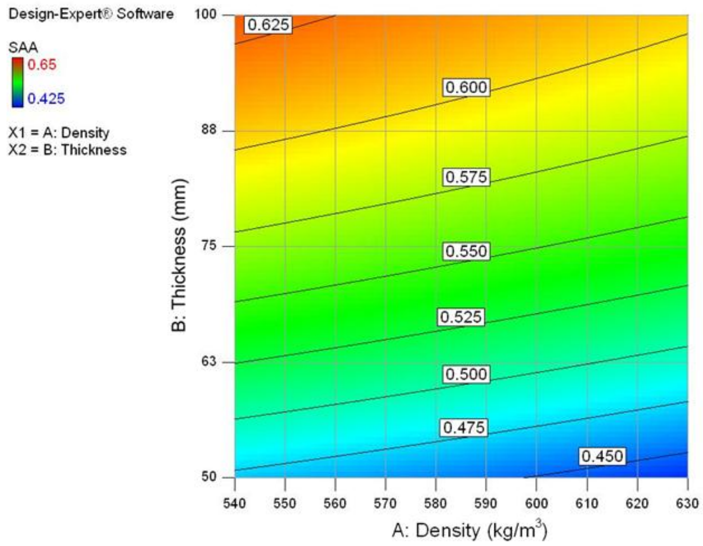


Figure 4. Effects of Density and Thickness on Sound Absorption Average

A significant increase of SAA was observed with the increase of material thickness. The thicker Durisol material offered longer paths to dissipate the energy of the incident sound thus leading to a higher sound absorption. The increase in material density did not affect the positive effect of thickness on sound absorption. In fact, the loss in SAA with the increase of material density could be compensated by increasing the thickness. The positive effect of thickness (greater than 50 mm) on the sound absorption of Durisol material disagreed with the observation of Hajek (1983).

Although the interaction effect between the density and thickness was not significant on SAA, the SAA gained more with the increase of thickness when the density was lower (540 kg/m^3). In addition, the increasing rate of SAA became slower with the increase in material thickness. In other words, the increase in SAA was greater in the thickness range of 50-75 mm than in the 75-100 mm range.

Sound Absorption Modeling

Extensive efforts have been made to predict the sound absorption of rigid-frame porous materials. Many semi-empirical models have been developed (Allard and Atalla 2009, Cox and D’Antonio 2009). Among them, the Delany-Bazley model is the classic and the simplest one. It only requires one parameter – the airflow resistivity – to calculate the sound absorption coefficients. It has been successfully used for many years to estimate the sound absorption of extremely porous materials but was found to be unsuitable for the Durisol material. Other than the Delany-Bazley model, the Johnson-Allard model has gained in popularity in recent years. It puts five parameters into consideration: porosity, airflow resistivity, tortuosity, viscous characteristic length and thermal characteristic length. It has been proven reliable in many cases to predict the sound absorption of rigid-frame porous sound absorbers. The main drawback of this model is the difficulty in measuring the tortuosity and the two characteristic lengths. The advancement in measuring instruments and the development of the inverse numerical approximation technology should help to widen the acceptance of this model.

The Attenborough model, detailed by Champoux and Stinson (1992), was used to predict the sound absorption of Durisol material in this investigation. This model requires four parameters to calculate the sound absorption coefficient: porosity, airflow resistivity, tortuosity, and shape factor. These parameters are needed to determine the dynamic density and bulk modulus which can then be used to predict the sound absorption coefficient. The theory behind this model is that the dynamic density describes the viscous effect in sound energy dissipation, while the dynamic bulk modulus describes the thermal effect.

The calculation of the dynamic density, ρ(ω), is shown in equation (3): $\rho(\omega) = \alpha_\infty \rho_0 (1 - \frac{2}{\lambda\sqrt{-i}} \mathrm{T}(\lambda\sqrt{-i}))^{-1}$, …… (3), with dimensionless parameter $\lambda = \frac{1}{2s_A}(\frac{8\alpha_\infty \rho_0 \omega}{\sigma\Omega})^{½}$, …… (4), and the $T(\zeta)$ is the ratio between Bessel functions of the first and zero order,$T(\zeta) = J_1(\zeta)/J_0(\zeta)$, …… (5). In the equations (3) to (5), the α_∞ is the tortuosity, ρ_0 is the density of the air, s_A is the shape factor, σ is the airflow resistivity, Ω is the porosity, and ω is the angular frequency.

The calculation of the dynamic bulk modulus is shown in equation (6): $K(\omega) = \gamma P_0 (1 + \frac{2(\gamma-1)}{{N_{pr}}^{½}\lambda\sqrt{-i}} \mathrm{T}({N_{pr}}^{½}\lambda\sqrt{-i}))^{-1}$, …… (6), where γ is the specific heat ratio, P_0 is the atmosphere pressure, and N_{pr} is the Prandtl number.

By knowing the dynamic density and bulk modulus, the complex wave number (or propagation constant) m(ω), characteristic impedance $Z_c(\omega)$, surface impedance Z, and sound absorption coefficient α can be calculated, as shown in equations (7) to (10), where t is the material thickness, and Z_0 is the impedance of air.

$m(\omega) = \omega[\rho(\omega)/K(\omega)]^{½}$, …… (7)

$Z_c(\omega) = (\frac{1}{\Omega})[\rho(\omega)K(\omega)]^{½}$, …… (8)

$Z = -iZ_c(\omega)\coth(m(\omega)t)$, …… (9)

$\alpha = 1 - \left|\frac{Z-Z_0}{Z+Z_0}\right|^2$, …… (10)

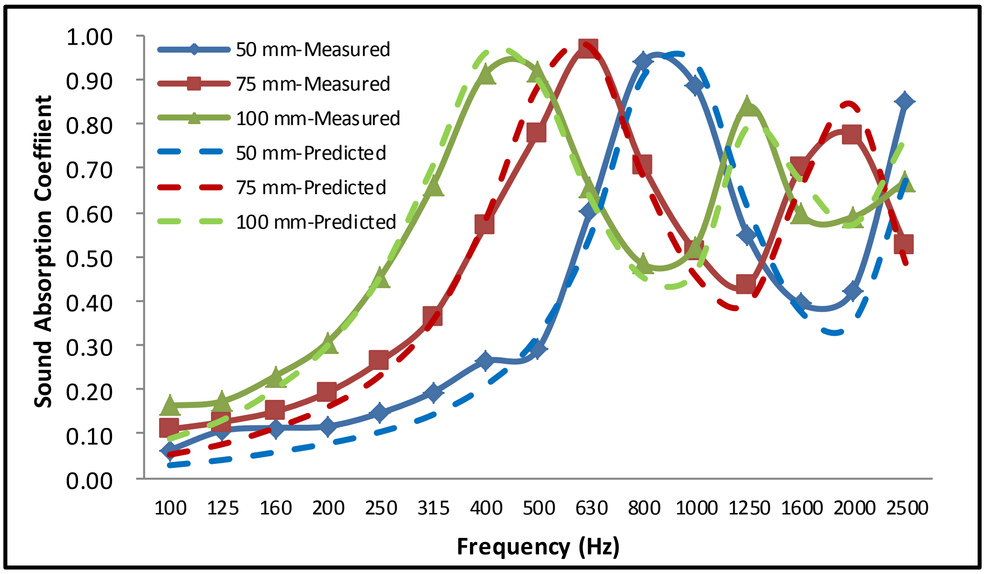


Figure 5. Sound Absorption– Predicted vs. Measured (Density = 540 kg/m^3)

By fitting the calculated sound absorption coefficients with the measured data, it was found that the sound absorption of Durisol material could be predicted relatively well with the Attenborough model, when the shape factor s_A was equal to 0.56, and the tortuosity could be calculated by adding a constant into the formula presented by Connelly (2013), as shown in equation (11), $\alpha_\infty = \frac{k}{\Omega^2}$, …… (11), where Ω is the porosity, the constant k = 0.75. The results of the model fit can be seen in Figure 5. Similar results were found for Durisol material with density of 585 or 630 kg/m^3.

CONCLUSIONS

An increase in material thickness resulted in a gain in overall sound absorption. However, an increase in material density resulted in a decrease in the overall sound absorption. Although the increases in thickness generally improved the sound absorption across the entire frequency range, the increase in density enhanced, predominantly, the coefficients of the low frequencies but sacrificed those at the high frequencies. The loss in the overall sound absorption due to higher material densities can be recovered by increasing material thickness.

Measurements of air flow resistivity of the material indicated that it increased with material density but remained unaffected by material thickness.

The suitability of the Attenborough model in predicting the sound absorption of the Durisol material was examined. General agreements were found between the predicted and the measured sound absorption coefficients throughout the frequency range for the 3 densities investigated.

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