Sound Absorption Properties of Unbleached Cellulose Loose-Fill Insulation Material

Jorge P. Arenas,[a,]* Juan Rebolledo,[a] Romina del Rey,[b] and Jesús Alba [b]

Recyclable cellulose loose-fill insulation has been commonly used in heavy timber construction for treating attic areas, under floors, and wall cavities. Through the kraft process, the unbleached cellulose adopts a texture characterized by small crumbs, forming a porous medium. In this work, different samples of a single layer of loose-fill cellulose insulation with different thicknesses were tested to measure their sound absorption properties, the airflow resistivity, and porosity for both dry and moist samples. The regression coefficients for an empirical model were calculated using a numerical optimization method. It is concluded that the model predicts the acoustical performance of this material well and that the sound absorption properties of the material are similar to those of mineral fiber-based materials.

Keywords: Sound absorbing materials; Cellulose; Sound absorption; Porous material; Recyclable insulation; Eco-materials

*Contact information: a: Institute of Acoustics, University Austral of Chile, P. O. Box 567, Valdivia, Chile; b: Centro de Tecnologías Físicas: Acústica, Materiales y Astrofísica. Escuela Politécnica Superior de Gandía. Universitat Politècnica de València, Valéncia, Spain; *Corresponding author: jparenas@uach.cl*

INTRODUCTION

The use and variety of available materials for noise control has greatly increased over the past few years, mostly due to both technological advancements and increasing public concern regarding noise pollution and the environment. Although noise control in buildings can be achieved using heavy screens, vibration isolation, modifying service machinery design, and using floating slabs, the use of sound-absorbing materials is the most common alternative. Architects and engineers can now choose from a wide variety of sound-absorbing materials that not only provide the desired acoustical properties but also offer an extremely diverse array of other properties (Crocker and Arenas 2007).

The great majority of sound-absorbing materials, independent of composition, are the porous and/or fibrous type. Many studies have focused on the absorption mechanisms of acoustic energy in the interior of porous materials and also on differentiating the distinctive mechanisms observed as a function of type of pore composing each material (Arenas and Crocker 2010).

When a porous material is exposed to incident sound waves, the air molecules at the surface of the material and within the pores of the material are forced to vibrate and in doing so, they lose some of their original energy. This loss occurs because part of the energy is converted to heat due to thermal and viscous losses of air molecules at the walls of the interior pores and tunnels within the material. At low frequencies, these changes are isothermal, whereas at high frequencies they are adiabatic (Crocker and Arenas 2007).

Over the past years, research on the use of eco-materials derived from residues from industrial plants or processes has received much attention (Asdrubali 2006). A number of authors have presented studies on the sound-absorbing properties of this type of material. Sun *et al.* (2013) presented a study on the acoustical and thermal properties of glass fibers recovered from waste printed circuit boards. The authors showed that the sound absorption of this material can meet the requirement of national standards over a wide frequency range. Zheng *et al.* (2013) studied the sound absorption effects of yarn sizes, fiber diameters, and hybrid stacking of different fibers. The authors showed that the thicker the fabric yarn is and the larger the fiber diameter, the better sound absorption properties can be obtained in natural-fiber-reinforced sandwich structures. More recently, nonwoven sandwich structures were tested by Liu *et al.* (2014). The authors used a general regression neural network to predict the acoustic properties of these structures from some easily measured structural parameters and demonstrated the method to be reliable and efficient.

A number of sustainable sound absorbers derived from biomass were tested by Oldham *et al.* (2011), including cotton, wool, jute, sisal, flax, and ramie fibers. Sedeqq *et al.* (2013) investigated the sound absorption properties of recycled fibrous materials, including natural fibers, synthetic fibers, agricultural lignocellulose fibers, and biocomposites from agricultural wastes. Their results indicated that recycled fibrous materials exhibit good sound-absorbing properties and are inexpensive, lightweight, and biodegradable. Faustino and his collaborators (Faustino *et al.* 2012) studied a sustainable low-technological corn cob particleboard. The acoustic insulation provided by this board is comparable to that of traditional materials used for building purposes, such as glass wool. The use of mechanical wood fibers for acoustical applications has been investigated by other authors (López *et al.* 2012).

The sound absorption properties of different materials made from ground polyurethane foam waste were studied by del Rey *et al.* (2012). The acoustical characterization of this recycled material was performed by curve-fitting a large number of experimental results. The model converged and yielded acceptable results for predicting the sound absorption coefficient of this recycled material. Zhu *et al*. (2014) have recently presented a new technology for sound insulation using a plastic composite filled with natural fibers.

On the other hand, several studies have proposed empirical and theoretical models for interpreting the acoustic behavior of porous sound-absorbing materials. Many of these models are based on determining the characteristic wave impedance, Z, and the propagation constant, k', of a plane wave traveling inside the absorbing material, both as a function of frequency, given the physical properties of the materials, such as the porosity, tortuosity, and airflow resistivity. Although the models can be phenomenological or microstructural, empirical models have afforded simple yet accurate prediction results in most practical cases.

In a seminal study on glass fibers and mineral wools (Delany and Bazley 1970), simple power-law relations obtained by curve-fitting a large amount of experimental results were presented. The success of the authors' model is explained by the model's requirement of the airflow resistivity as the only input parameter, which can be readily determined from sampling measurements. This empirical model was analyzed later by Miki (1990a,b). Other authors have used the same relations and calculated the corresponding regression constants for different materials.

Empirical models have been subsequently applied to characterize polyurethane foams (Dunn and Davern 1986), plastic open-cell foams (Wu 1988), textile fibers (Garai and Pompoli 2005), different vegetal fibers (Ramis *et al.* 2010; Fatima and Mohanty 2011; Oldham *et al.* 2011; Navacerrada *et al.* 2014), and recycled polyester fibers (del Rey *et al.* 2011). In fact, the European standard on building acoustics (EN 12354 2003) recommends using the regression coefficients of Delany and Bazley (1970) for the prediction of the sound absorption of materials composed of fibers and the results of Dunn and Davern (1986) for foam materials. Oliva and Hongisto (2013) presented a comprehensive study on the accuracy of several empirical approaches for predicting the impedance of mineral wool configurations. However, there is no information about the corresponding regression coefficients for cellulose in the technical literature.

The aim of the present work was to characterize the sound-absorbing properties of loose-fill cellulose material through experimental tests. The results were used to estimate the regression coefficients for an empirical model in which the input parameter is the measurable airflow resistivity of the material. The results would be useful for predicting the acoustical response of loose cellulose in various building applications.

EXPERIMENTAL

Materials

Cellulose sound absorbing material

Current research has focused on the application of sound-absorbing materials in different environments, with the goal of improving acoustic comfort, as well as searching for alternative methods for fabricating sound-absorbing materials. Furthermore, enormous importance is placed on the development of environmentally friendly materials (also known as green building products), *i.e.*, a material that leaves a minimal ecological footprint. These types of materials should be made free of chemicals, and the manufacturing of these products should also be harmless to humans and to the environment, as in the case of natural fiber production (Arenas and Crocker 2010). An example of a material synthetically made from natural fibers is cellulose.

The paper industry widely uses eucalyptus and conifer trees as raw material for producing cellulose, which constitutes approximately 50% of the composition of wood. Wood cellulose is a natural polymer and is probably the most abundant biopolymer on earth. Cellulose is a long chain of smaller, linked sugar molecules that gives wood its outstanding strength. Through an industrial process called the kraft process, the lignin is removed, releasing cellulose as a raw pulp paste. Before the bleaching process, the resulting material is a fiber suspension in a water solution, known as brown stock. Following that, there is a drying process in which the unbleached cellulose adopts the texture of small cellulose fiber crumbs forming a porous medium. This medium contains approximately 5% of residual lignin, which is responsible for the brown color.

It is important to note that although the kraft pulping process for extracting lignin is the dominant process in the pulp and paper industry, it cannot be considered environmentally benign. However, cellulose can easily be recycled and is considered a renewable resource.

Loose-fill cellulose-based materials, such as recycled newspaper, have been commonly used as thermal and acoustical insulation in attic areas, under floors, and in wall cavities for several years. The material can be either hand-poured or pneumatically dry-injected to fill in gaps, obstacles, and difficult spaces in building construction, thus reducing energy loss. This type of insulation is lightweight, non-irritating, and both biodegradable and recyclable, making its use a sustainable product choice. In addition, several manufacturers add appropriate additives to provide resistance to fire, fungi, corrosion, and pests, although it is known that materials that are largely composed of cellulose are not generally attractive to insects (Oldham *et al.* 2011). Cellulose insulation exhibits thermal resistance values comparable to those of glass fiber products.

In the present work, experiments were conducted on samples of unbleached loose-fill cellulose crumbs. The cellulose material was obtained directly from pine (*Pinus radiata*) through the kraft pulping process. To determine any possible effect of humidity on the sound absorption properties of the material, measurements were conducted under two different relative humidity conditions (0% and 69%). The moisture content of the samples was determined using the primary oven-drying method described in the ASTM standard (ASTM D4442 2007). For preparing the 0%-relative-humidity samples they were dried in a temperature-controlled furnace at 105 °C until there was no change in their weight. The specimens were conditioned to the desired levels of relative humidity, transported in sealed containers, and tested within a few minutes after removal from the containers. In all tests, the cellulose was poured, simulating a realistic loose-fill disposition, and care was taken to avoid compacting the material inside the sample holders.

Methods

Measurement of airflow resistivity

Airflow resistivity is the resistance experienced by air as it passes through a material of thickness, *d*. It is well known that this property is directly related to the capacity of a material to absorb sound energy. Airflow resistivity is mathematically expressed as $\sigma = \Delta p/(Vd)$, where Δp is the differential pressure created across the sample and V is the velocity of the airflow passing through the specimen cross-sectional area (Crocker and Arenas 2007).

Although alternative methods have been devised for measuring σ (del Rey *et al.* 2013), the standardized testing procedure is based on the passing of steady-state airflow through a sample according to the recommendations provided in the ISO standard (ISO 9053 1991). A device was built according to the standard to measure this parameter (Rebolledo 2014). During the experiments, a unidirectional, controlled constant airflow was ensured. The differential pressure, Δp for a known volume velocity of steady airflow passing through the sample under study, was measured by a digital differential manometer. Measurements for four different thicknesses (d = 25, 50, 75, and 100 mm) were performed, and the corresponding airflow resistivity values were averaged. Airflow was created by a custom-made pump-controlled water column (Iannace *et al.* 1999). The airflow velocity was varied between 0.01 and 0.1 m/s and was plotted against the pressure drop. The airflow resistivity was determined by extrapolating to an airflow rate of 0.5×10^{-3} m/s. The test specimens of loose-fill cellulose were poured in a vertical sample holder tube and supported by an acoustically transparent mesh.

Measurement of porosity

The porosity of a porous material is defined as the ratio of the volume of air in the void space in the sample to the total volume of the sample. Although porosity has been measured through scanning electron microscopy and ultrasound, a more direct way to measure it is to employ a porosimeter. In the present work, the device presented by Champoux *et al.* (1991) was built. In the technique used to measure porosity, which is based on the ideal gas law, the isothermal pressure change in a closed volume containing the sample material is measured for a known change in volume. A sealed sample container with a moving piston of a precisely known diameter was used to produce a change in volume, while the change in pressure was measured by a digital differential manometer. The change in volume was determined from the readings on a micrometer drive. The device was calibrated using metal samples of precisely known open porosities (Rebolledo 2014). This method has a reported accuracy of better than 1% in determining the porosity of a given material.

In addition, tortuosity, *i.e.*, a measure of the shape of air void passages, was determined from the empirical formula presented in the work by Fatima and Mohanty (2011).

Measurement of sound absorption coefficient

Measurements of the normal-incidence sound absorption coefficient were performed using the two-microphone transfer function method using a standing wave tube, which is a standard method for testing the acoustic properties of sound-absorbing materials. This method has been standardized by the American Society for Testing and Materials and the International Standardization Organization as ASTM E1050 (2008) and ISO 10534-2 (2001), respectively. The transfer function technique uses a broadband stationary random signal and involves the decomposition of the sound field into incident and reflected waves. The method has been comprehensively described in the literature (Crocker and Arenas 2007).

In general, the method involves the measurement of the transfer function between the signals of two microphones mounted flush on the wall of a standing wave tube. An acoustic driver is located at one end of the tube and the other end is closed with a sample holder. The technique is valid for measuring the normal-incidence reflection factor, sound absorption coefficient, specific acoustic impedance, and specific acoustic admittance.

To test the cellulose material in the loose-fill disposition, the standing wave tube was placed upright. Figure 1 shows photographs of the experimental arrangement (Rebolledo 2014). The sample holder was made of transparent polycarbonate cylindrical tube of 200 mm length and 50.8 mm diameter. The upper frequency limit for this tube is 3400 Hz. The material was poured inside the tube, simulating a realistic loose-fill disposition of the material without compacting. A rigid plunger with an adjustable depth was placed behind the sample to provide a reflecting surface. Sound absorption coefficients were measured for different thicknesses d = 25, 50, 75, and 100 mm. The average of 10 samples was reported. Because of the random characteristics of the noise signal, for each sample, a total of 200 spectral averages were taken to measure the transfer function between the microphones. The transfer functions were measured at increments of 1 Hz using Fast Fourier Transform (FFT) digital analyzer over a frequency range between 100 and 3000 Hz.

Numerical model

The sound absorption process in cellulose crumbs can be considered a combination of fiber and granular absorption mechanisms. The scattering and vibration of the individual fibers produce acoustic absorption, while friction from the fibers dissipates sound energy. In a bulk granular material, the solid structure can be regarded as ideally rigid and stationary and thus the sound energy absorption is mainly produced by the viscosity of the air inside the voids that separate the granules. Other thermal mechanisms of sound absorption have been discussed in the literature (Crocker and Arenas 2007; Arenas and Crocker 2010).

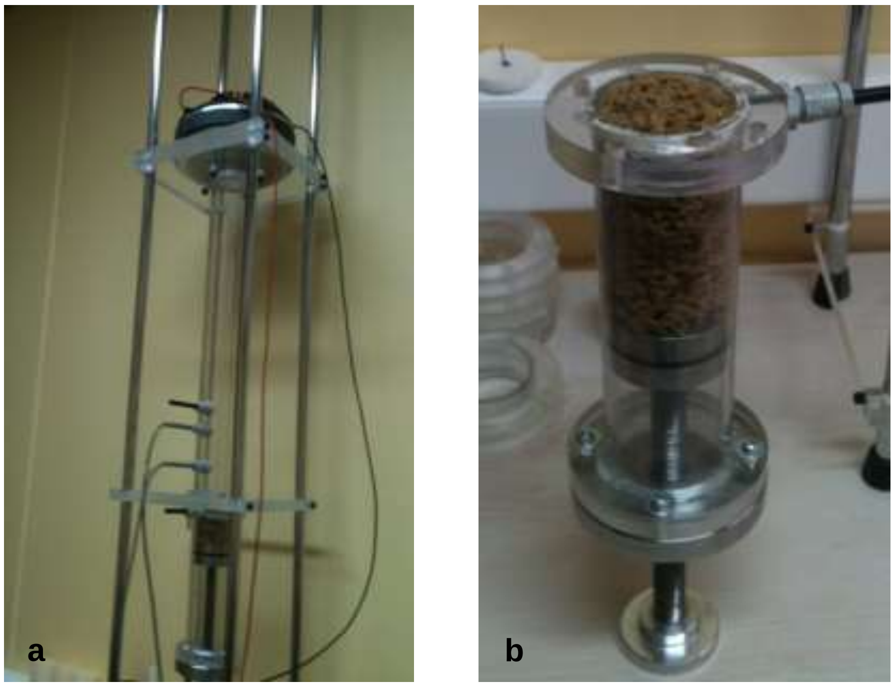

Fig. 1. Experimental setup for measuring sound absorption of the cellulose material. The photograph shows the (a) upright disposition of the standing wave tube and (b) the cellulose loose-fill material after being poured inside the sample holder

In the empirical model proposed by Delany and Bazley (1970), sound propagation through a homogeneous and isotropic material in the frequency domain is determined by two complex values: (1) the characteristic wave impedance (Z) and (2) the characteristic propagation constant (k'). The model determines the real constants C_i (i = 1… 8) that best fit the following equations:

$$Z = Z_0\left(1 + C_1\chi^{-C_2} - jC_3\chi^{-C_4}\right) \tag{1}$$

$$k' = k\left(C_5\chi^{-C_6} + j\left(1 + C_7\chi^{-C_8}\right)\right) \tag{2}$$

where $k=\omega/c=2\pi f/c$ is the free field wavenumber, f is the frequency of the sound, c is the speed of sound in air at room temperature (≈343 m/s), $\chi=\rho f/\sigma$ is a dimensionless parameter, ρ is the air density at room temperature (≈1.2 kg/m^3), $Z_0=\rho c$ is the characteristic impedance of air, and σ is the airflow resistivity. In their original work, Delany and Bazley (1970) stated the range over which the model is valid to be $0.012 \leq \chi \leq 1.2$.

The normal-incidence sound absorption coefficient can be determined by Eq. 3 (del Rey *et al.* 2012):

$$\alpha = \frac{4Z_0 Z_{dR}}{\left|Z_d\right|^2 + 2Z_0 Z_{dR} + Z_0^2} \tag{3}$$

where the rigid-backing specific surface impedance of the material is given by:

$$Z_d = Z_0 \coth(k' d) = Z_{dR} + jZ_{dI} \tag{4}$$

In Eq. 4, d is the thickness of the material layer, and Z_{dR} and Z_{dI} are the real and imaginary parts of Z_d, respectively.

Some authors have determined the regression coefficients by directly measuring the characteristic wave impedance and propagation constants and subsequently applying curve-fitting (Delany and Bazley 1970; Dunn and Davern 1986; Oliva and Hongisto 2013). Because measuring these constants can be a difficult and lengthy process, an alternative may include determining the regression coefficients, C_i, from the measured data for the normal-incidence sound absorption coefficient in the frequency domain for a known airflow resistivity of the material sample.

To obtain the regression coefficients that best fit the measured sound absorption coefficient of the cellulose samples, an iterative method based on a minimization of a quadratic error function is used. Several values proposed by different authors have been used as initial values, and they all converge to the obtained coefficients presented later in this paper.

The quadratic error function used in the iterative process is defined as,

$$\varepsilon = \sum_{i=1}^{N} (\alpha_i - \hat{a}_i)^2 \tag{5}$$

where α_i is the measured normal-incidence sound absorption coefficient for a material sample at the i-th frequency and $\hat{a}_i$ is the corresponding value estimated from Eqs. 1 and 2. Minimization of Eq. 5 implies that:

$$\frac{\partial \varepsilon}{\partial C_i} = 2\sum_{i=1}^{N} (\alpha_i - \hat{a}_i) \frac{\partial \hat{a}_i}{\partial C_i} = 0 \tag{6}$$

for all i=1…8.

A MATLAB computer program was implemented to minimize the nonlinear Eq. 6 and obtain the corresponding values of C_i. The optimization process was performed using the Nelder-Mead simplex (direct search) method (Lindfield and Penny 1995). Acceptable values of χ were constrained to fall between 0.04 and 1.0. The regression coefficients of the empirical model proposed by Delany and Bazley (1970) were used as initial values in the iterative method.

RESULTS AND DISCUSSION

Samples of loose cellulose having 0% humidity resulted in a bulk density of 96.4 kg/m^3. The measured airflow resistivity in this case was 3471 ± 158 Ns/m^4, the porosity was 0.98 ± 0.01, and the tortuosity was 1.01. Figure 2 shows plots of the sound absorption coefficient as a function of frequency for different thicknesses of d = 25, 50, 75, and 100 mm averaged for 10 samples each.

The plots are typical for the sound absorption coefficient for porous sound-absorbing materials placed against a hard wall. Curves of the sound absorption coefficient versus frequency have a succession of peaks and troughs. It is noted that the sound absorption properties are substantially better at high frequencies than at low frequencies. In addition, increasing low-frequency sound absorption is observed with increasing thickness.

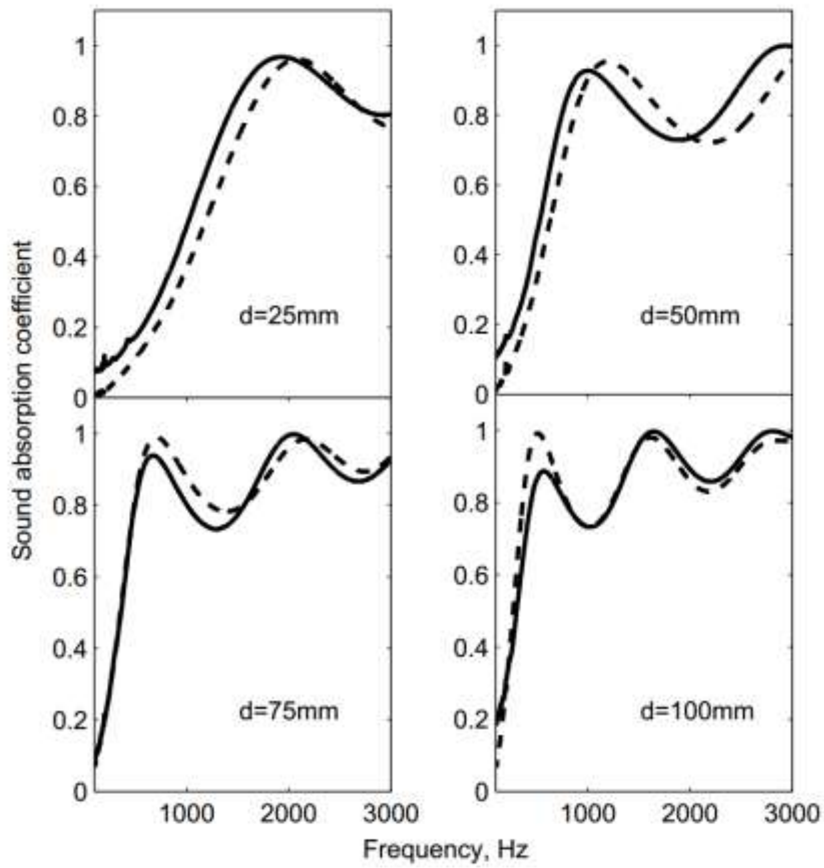

Fig. 2. Sound absorption for different thicknesses of cellulose material samples; **—** 0% relative humidity, – – 69% relative humidity

In practical applications of sound-absorbing materials, condensation is a difficult problem to address. Fibers can absorb incident moisture, thus degrading the performance of the material. It is well known that if moisture reaches the dew point, condensation problems occur. Therefore, the requirement of a well-sealed vapor barrier is necessary when using this type of sound-absorbing material.

To observe the effect of moisture on the sound absorption of the test material, some samples were measured without drying. The samples had a measured relative humidity of 69% and a mass density value of 264 kg/m^3. The measured airflow resistivity in this case was 5470 ± 277 Ns/m^4, porosity was 0.75 ± 0.03, and tortuosity was 1.16. As expected, the humidity reduced the number of open pores in the material while increasing the resistance experienced by air as it passed through the material. For most porous materials, an increase in moisture content will result in a decrease in porosity. The sound absorption coefficient was also measured for different thicknesses of d = 25, 50, 75, and 100 mm, and the averaged results for 10 samples are also shown in Fig. 2.

It can be observed that the results for moist material samples measuring up to 50 mm in thickness were similar to those obtained for dry cellulose. The shapes of the sound absorption curves were similar and were slightly shifted towards higher frequencies. Small differences were observed for larger thicknesses, for which the sound absorption coefficients became somewhat higher. This behavior was caused by the changes in density, airflow resistivity, and porosity that occurred in the moist samples of cellulose. Another source of discrepancy is the standard deviation of the measured airflow resistance. It was observed that the maximum resonance values of the sound absorption coefficient occurred at similar frequencies for the dry and moist samples measuring 75 and 100 mm in thickness. These results are in agreement with those reported in previous studies indicating that no significant change in sound absorption is generally observed with respect to relative humidity at room temperature for wood-based materials (Godshall and Davis 1969). However, if exposed to water, these materials can be subject to fungal attack (Oldham *et al.* 2011).

In a previous study (Arenas and Rebolledo 2013), measurements of the normal-incidence sound absorption coefficient of rigidly-backed samples of loose cellulose were compared with the values predicted by the regression coefficients of the empirical model proposed by Delany and Bazley (1970). The results showed that the model does not fit the measured results well, yielding inaccurate predictions of the sound absorption coefficient at all frequencies.

Because the model was originally developed for fibrous materials, although the model has been applied to several kinds of materials, it can be concluded that the loose-fill cellulose material does not behave like a pure glass or rock wool fibrous material, and new regression coefficients must be determined using the numerical method described in this paper. Table 1 shows the corresponding regression coefficients obtained after the optimization process compared to those obtained by Delany and Bazley for fibrous mineral wools. The resulting equations for the characteristic wave impedance and the characteristic propagation constant are:

$$Z = Z_0\left(\left(1 + 0.6224\chi^{-0.0892}\right) + j0.4816\chi^{0.6147}\right), \quad (7)$$

$$k' = k\left(0.3952\chi^{0.1273} + j\left(1 + 0.5823\chi^{0.0872}\right)\right). \quad (8)$$

Figure 3 graphically compares the measured and predicted values of sound absorption for dry loose cellulose for different values of thickness. Although at first sight the sound absorption values of the cellulose material appear similar to those obtained for mineral wools of the same thickness, the values of the regression coefficients in the model are very different for both materials, as shown in Table 1.

Table 1. Values of the Regression Coefficients

Material	C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
Cellulose	0.6224	0.0892	-0.481	-0.614	0.3952	-0.127	0.5823	-0.087
Rockwool/Fiberglass	0.0571	0.7540	0.0870	0.7320	0.1890	0.5950	0.0978	0.7000

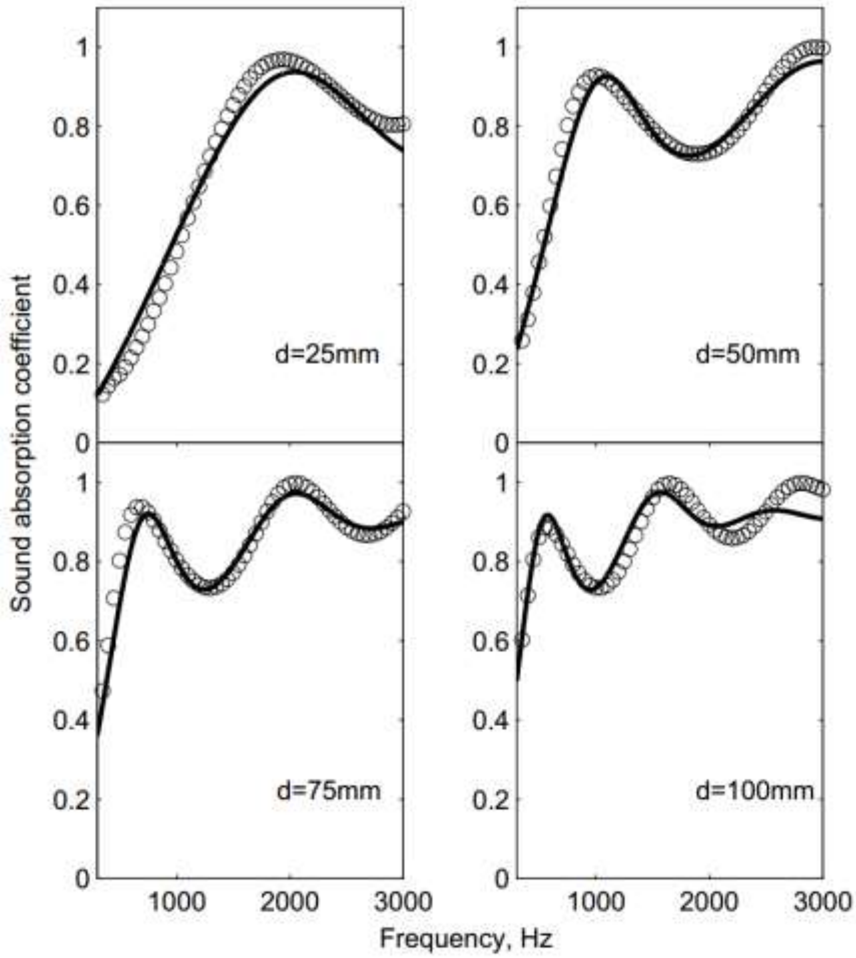

Fig. 3. Comparison of predicted and measured values of normal incidence sound absorption coefficients of dry loose-fill cellulose of different thicknesses; — prediction method, O experimental results

To quantitatively describe how much the empirical model either overestimated or underestimated the measured sound absorption coefficients, the relative prediction error was calculated using the following equation (Oliva and Hongisto 2013),

$$\bar{\varepsilon} = \frac{1}{N}\sum_{i=1}^{N}\frac{\left|\hat{a}_i - \alpha_i\right|}{\alpha_i}, \tag{9}$$

where α_i is the measured normal-incidence sound absorption coefficient, $\hat{a}_i$ is the corresponding value estimated from the empirical model, and N is the number of tests (10 measurements for each of the four thicknesses, therefore N=40).

The results for the relative prediction error of the sound absorption coefficient as a function of frequency are shown in Fig. 4. It can be observed that the relative prediction error was large for low frequencies, with a relative error of over 35% at 100 Hz. At higher frequencies, this error became lower than 10%. The average relative prediction error was 4.17%, considering a frequency range between 300 and 3000 Hz. The average error for all data was 4.85%. These error values are common for this type of empirical method, and the results are in agreement with the observations made recently by authors using empirical prediction methods to study typical mineral wools (Oliva and Hongisto 2013). Therefore, the calculated regression coefficients can be applied with sufficient confidence in the model to predict the acoustic behavior of this cellulose material.

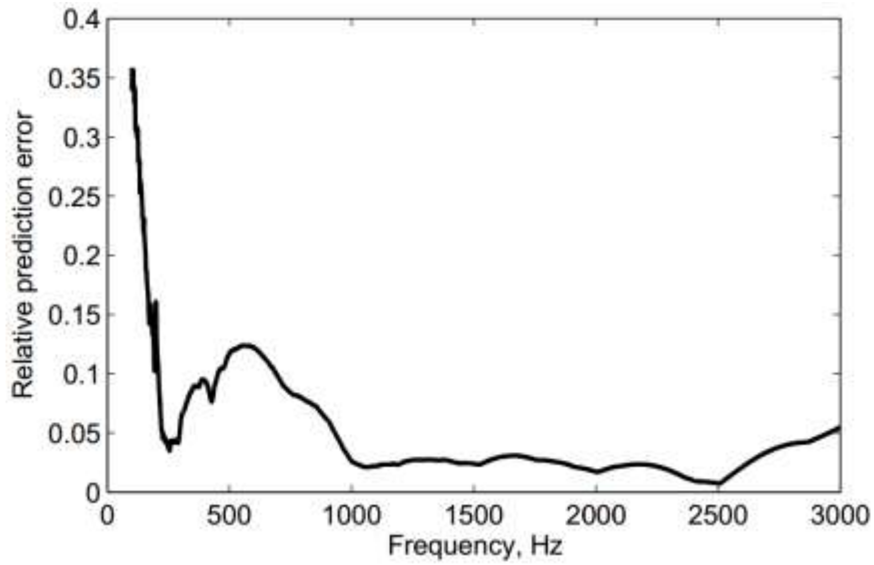

Fig. 4. Relative prediction error of normal-incidence sound absorption coefficient for the prediction method used for loose-fill cellulose material

Further work is currently in progress to study the effect of incorporating additives into cellulose, in particular non-toxic additives to provide fire resistance, on the sound absorption properties.

CONCLUSIONS

1. Unbleached loose-fill cellulose material obtained directly from pine through the kraft pulping process exhibits sound absorption coefficient values comparable to those of mineral-fiber-based products. Thus, this recyclable material can be considered to be a viable alternative to other conventional acoustical materials for current and future applications in building construction, particularly when used as insulation in attic areas, under floors, and in wall cavities.
2. Humidity in the material caused an increase in the airflow resistivity value and a decrease in the material's porosity, which caused a slight increase in the sound absorption for thick layers. Little effect on sound absorption is caused by humidity for thin layers of the material. However, in general, no significant change in sound absorption is observed with respect to relative humidity at room temperature.
3. The predictions made using a simple empirical model for the acoustical characteristics are in very good agreement with the measured data when appropriate regression coefficients are calculated, particularly at middle and high frequencies. Thus, the model appears to be very useful for predicting the sound absorption properties, as a function of frequency, of a layer of loose-fill cellulose of given thickness, and airflow resistivity.

ACKNOWLEDGMENTS

The authors are grateful for the support of CONICYT-FONDECYT under the research grant No. 1110605, project BIA2013-41537-R of the Spanish Ministry of Economy and Competitiveness/cosponsored by FEDER funds.

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Article submitted: June 13, 2014; Peer review completed: August 9, 2014; Revised version received and accepted: August 24, 2014; Published: August 28, 2014.