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Characterization of a Material Based on Short Natural Fique Fibers

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Fique is a biodegradable natural fiber derived from the Colombian Agavaceae family, originating in tropical America and traditionally used for the manufacture of packaging and cordages. Today, however, new uses are being developed. To meet the need for new good-quality, sustainable, low-cost construction materials for social housing, construction materials have been produced that combine different kinds of natural fibers, including fique, to improve their strength and physical properties. To assess these potential new construction materials made with fique fiber, we have characterized samples of different grammages and thicknesses manufactured using short fique fibers extracted from long fibers. We have measured the sound absorption coefficient at normal incidence in an impedance tube, air flow resistivity, and thermal conductivity as a function of grammage.

Keywords: Sustainability; Natural fibers; Fique; Physical properties

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INTRODUCTION

The term fiber is applied to a broad group of plant-based materials that have considerable value due to their length/diameter ratio (Eder and Burgert 2010). Fique fibers are extracted from the leaves of the plant, and due to their rigidity are classified as hard fibers (Álvarez 2008).

In recent years, several sectors are promoting the use of natural fibers (Li *et al.* 2010), and the construction sector is no exception to this renewed interest. To replace the use of steel, fiberglass, polypropylene, or nylon as reinforcements for concrete and mortar, natural fibers are proving to be a low-cost, environmentally-friendly alternative. Various laboratories and research groups around the world have conducted studies on construction materials based on or reinforced with plant fibers (Ramis *et al.* 2010; Glé *et al.* 2011; Oldham *et al.* 2011; Asdrubali *et al.* 2012; Ekici *et al.* 2012; Suhawati *et al.* 2013). Among the natural reinforcing filler materials the fique fiber appears to be one of the most promising fibers, due to its high mechanical strength (Delvasto *et al.* 2010). The favorable performance can be attributed to the structural characteristics of fique fibers, namely their thickness, roughness, and rigidity, which are typical of hard fibers (Pérez 1974). It has been reported that fique fibers consist of walls built up from fibrillae that at the same time have a reticulated structure in the outer wall. The fibrillae are, in turn, composed of microfibrillae. Additionally, a fique fiber in cross-section is built up of

many fiber cells that consist of the lamellae of hemicellulose, lignin, and pectin linked together (Tonoli *et al.* 2011).

The main producers of these natural fibers are low-income countries where there is a pressing need for economical housing. The natural habitat of the fique plant is the Andean region of Colombia, where it is the most cultivated natural fiber plant. Composites with fique fibers are important for construction of inexpensive buildings in developing regions of the world. At the same time, in our noisy cities the various standards pose ever greater demands on admissible noise levels in enclosures. The materials normally used for these objectives are not easily recyclable, or else not recommended for human contact. So there is an urgent need for sustainable architecture to improve habitability conditions with a lower energy consumption and improved thermal and acoustical comfort for the occupants; ideally this can be done using environmentally-friendly materials as a viable alternative to conventional materials (Asdrubali *et al.* 2012; Nick *et al.* 2002; Zhu *et al.* 2014). Indeed, use of the term "green building materials" is becoming ever more frequent.

As a result of this increasing demand for environmentally friendly construction materials, applications of fique composites are being extensively investigated. In particular, the fique fibers are usually mixed with epoxy (Gómez Hoyos and Vázquez 2012), cement (De Gutiérrez and Delvasto 1993; Delvasto *et al.* 2010; Tonoli *et al.* 2011), and with thermoplastic matrices (Gañán and Mondragón 2005; Hidalgo-Salazar *et al.* 2011; Hidalgo-Salazar *et al.* 2013). Also there is a great interest in the manufacture of geotextiles based on fique used to separate, filter, reinforce, protect, and drain the soil as geocells to control the erosion of soil (Gomez Hoyos and Vázquez 2012). However, the thermal and acoustical properties of the samples based on fique have not habitually been studied (Gañán and Mondragon 2003). The research is principally focused on the mechanical properties of the manufactured materials and on the effects of the exposition to both alkaline and humidity environmental on these properties.

Our research group has developed a line of manufacture and characterization of ecofriendly materials mainly focused on their thermal and acoustical properties. We have published a paper on the thermal and acoustical properties of aluminum foams, produced by means of a process of infiltration using recycled aluminum (Navacerrada *et al.* 2013). In another work, we analyzed the possible applications of reed panels (Diaz *et al.* 2012). In this line, in the present work we analyze the thermal and acoustical properties of a material made from short fique fibers resulting from the extraction process applied to large fique fibers as a byproduct of the manufacture of cordage and packaging from long fibers. The use of this sub-product could add new value to the use of this plant. This manufactured material has comparable thermal and acoustical properties to mineral wools, with the advantage that it is easy to produce, readily available, low-cost, and biodegradable

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EXPERIMENTAL

Materials

The fique is a tropical plant from which is extracted the natural fiber called fique fiber or cabuya. The fique plant belongs to the *Furcraea microphylla* genus and species (Delvasto *et al.* 2010). The stalk of the plant is small but strong, and the leaves are rigid with a sword shape and thorns at the edges. A picture of the fique plant is shown in Fig. 1. At the north zone of South America, this plant grows wild and is only cultivated in the equatorial area. The natural habitat of the fique plant is the Colombian Andean region, where the fique fiber is industrialized, and from there the plant has been spread to other world regions and countries as Venezuela, Brazil, and some countries of Asia and Africa, where it is known with different names. In Colombia, the plant is cultivated in fifteen departments, and in Cauca, Santander, Nariño, Antioquia, and Boyacá, the production is considered to be industrial. In fact, Colombia is the main worldwide producer of fique, with around 20.000 hectares of fique field that produce around 93.400 tons of fique´s bagazo per year; only four percent of the biomass has commercial applications, while the remaining residues (96%) are underutilized, causing serious contamination problems (Quintero *et al.* 2012). Table 1 shows the main properties of fique fibers, extracted from the data reported by different authors.

Fig. 1. Picture of the fique plant

There is an important variation in fiber diameter among fique fibers of the same batch and along the fiber, as it is typical for natural fibers. This variation in the fiber diameter and in the mechanical properties along the length of a fiber are due to the physical necessary response along the length of a leaf for supporting its weight (Delvasto *et al.* 2010).

Table 1. Properties of the Fique Fibers

Properties	Value	References
Equivalent diameter (mm)	0.16 - 0.4 0.85 – 2.36	(Delvasto *et al.* 2010) (Castro *et al.* 2012)
PH	4	(Castro *et al.* 2012)
Apparent density, (g/cm^3)	0.723*	(Delvasto *et al.* 2010)
Real density (g/cm^3)	1.47*	(Delvasto *et al.* 2010)
Water absorption (%)	60.0*	(Delvasto *et al.* 2010)
Cellulose (%)	63.0 70.0* 18.7 - 23.4	(Gañán and Mondragon 2002) (Delvasto *et al.* 2010) (Castro *et al.* 2012)
Hemicellulose (%)	24.8 - 27.1	(Castro *et al.* 2012)
Lignin (%)	14.5 10.1* 6.81 – 15.5	(Gañan and Mondragon 2002) (Delvasto *et al.* 2010) (Castro *et al.* 2012)
Tensile Strength (MPa)	43 – 571 132 - 262	(Delvasto *et al.* 2010) (Gómez and Vásquez 2012)
Elongation (breaking) (%)	6 – 9.8 4.8 – 10.6	(Delvasto *et al.* 2010) (Gómez and Vásquez 2012)
Elasticity modulus (GPa)	8.2 – 9.1 3.9 – 7.5	(Delvasto *et al.* 2010) (Gómez and Vásquez 2012)
Degradation Temperature (°C)	220	(Hidalgo *et al.* 2011)

 * Average Value

The fiber is extracted from the plant leaves using a technique called decortication. This extraction process can be manual or mechanical; after extraction, the fiber has to be dried. During the drying procedure, it is estimated that only 4 to 5% of the mass of the plant will be dry fiber. A short fiber results as a byproduct of the manufacture of the large fique fiber, and also as the waste from the traditional uses of the large fibers, such as cordage and packaging. The present work characterized fique samples of different grammages (mass per unit area, kg/m^2) constituted by these short fique fibers arranged in a "non-textured" way with a superficial covering of polymer. The samples were provided by La Compañía de Empaques from Colombia. Samples of three thicknesses (0.5, 1, and 1.5 cm) and five grammages (0.7, 0.85, 1, 1.2, and 1.5 kg/m^2) were considered. Figure 2 shows some of the samples characterized.
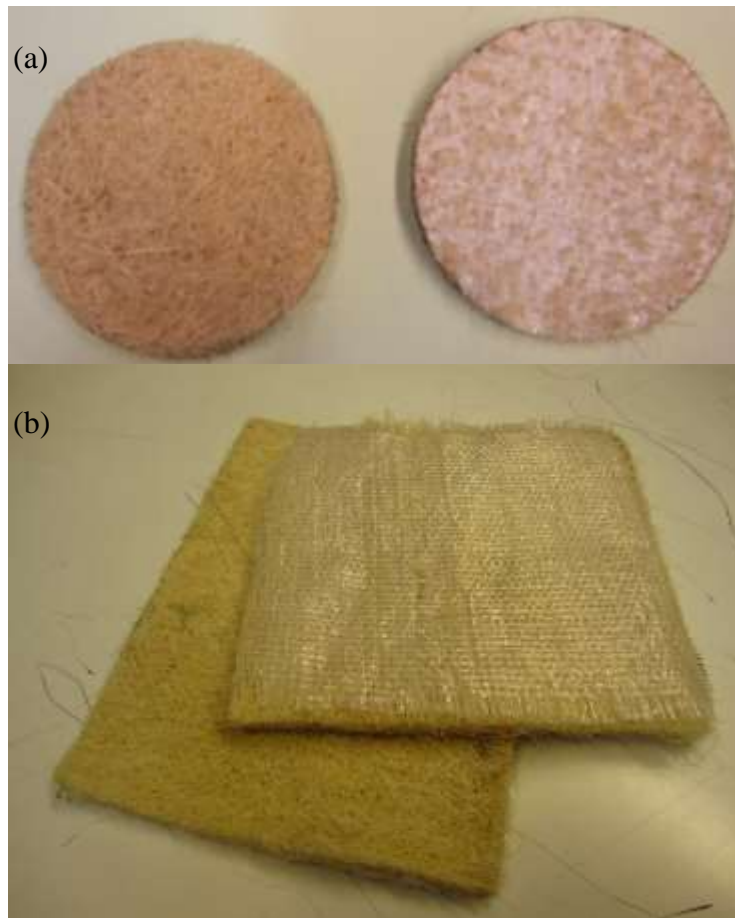
Fig. 2. Pictures of both sides of the fique samples used for (a) the acoustical and (b) the thermal characterization
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Methods

The sound absorption coefficient at normal incidence in impedance tube

The absorption coefficient of the fique samples was measured in an impedance tube following standard ISO 10534-2:1998. The transfer function technique is based on the fact that the sound reflection factor at normal incidence, *r*, can be determined from the measured transfer function, H_{12}, between two microphones positioned in front of the material being tested (Seybert and Ross 1977). A Model 4206 impedance tube with two Model 4186 B&K microphones and a 3560 C Pulse Analyzer were used to process the signal using the Material Testing software. The Pulse Analyzer and a Pioneer A-305 R amplifier generated the signal at the impedance tube.

For the correct measurement of the sound absorption coefficient in the tube, the samples must have the exact diameter of the tube, without any air gaps, which can alter the results (Seybert and Ross 1977; Bodén and Abom 1986). This means that the mounting of the sample is a critical factor. The acoustic measurements for the frequency ranges below and above 1000 Hz were carried out separately in 100- and 29-mm-diameter impedance tubes. The sound absorption coefficient measured is the average of

the measurement of three samples of the same characteristics. To check reproducibility, all measurements were performed on two different days.

Static Airflow Resistivity

Among the various parameters that may affect the acoustic performance of a porous or fibrous material, it has been well established that static flow resistivity σ is one of the most important factors. The specific static flow resistance is defined as,

$$R = \frac{\Delta PS}{F} \qquad (1)$$

where ΔP is the pressure drop across the sample, F is the volume flow rate of air, and S the area of the section of the sample (Allard 1993). The static airflow resistivity σ is the static flow resistance by unity of thickness d in the direction of the air flow:

$$\Delta \sigma = \frac{\Delta P}{F}\frac{S}{d} \quad (\text{Nm}^{-4}\text{s}) \qquad (2)$$

This parameter is appropriated as a descriptor of the acoustic behaviour of homogeneous materials. The static airflow resistivity σ of the fique samples was measured by an experimental device designed in our laboratory following the standard specifications of standard ISO 9053:1991. This device consists of an air supply system, a flow meter, and a manometer. A digital manometer with a resolution of 0.1 Pa was used to measure the pressure drop of the airflow across the specimen after the flow reached a steady stage. A number of readings were made at different flow rates to check whether the flow was in the laminar regime. The ratio ($\Delta P/F$) has been calculated as the slope of the pressure drops ΔP *versus* F measured at the different flow rates.

Thermal conductivity

The thermal conductivity λ of the samples was measured using a high-insulating box of 400 x 400 x 400 mm dimensions closed with a removable lid. The lid is insulated by a 5-cm-thick Styrofoam plate, fixed to the angle pillars of the base rack with four screws. The base rack is also ground-insulated through another 5-cm-thick Styrofoam plate. The high-insulation box has a large square aperture in each side wall of 210 x 210 mm. These apertures are closed by the measuring walls, in the present case the fique samples, which are fixed in their positions by means of two tensioning screws. Each of these exterior walls carries a profile and a small eccentric plate to hold supplementary insulating material. Every angle pillar has a foam-insulated hole for insertion of a temperature probe into the house. The temperature inside the high insulating house is raised by means of a 100-W light bulb. Two diode sockets on the outer wall serve to connect a thermal regulation and the temperature probe supplied with it. The temperature switch is set on the fourth graduated division, thus producing in the steady state an internal temperature of about 50 °C.

The temperatures of the air inside and outside the house and on the internal and external walls of the sample were recorded by means of thermocouples inserted in the house across the holes in the corner posts of the house. The reading was taken when the thermocouples reached a constant value, to ensure that the system was near the steady state (five hours after the beginning of the measurement). The measurement method does not exactly follow the standard specifications; however, it is a reliable method with an uncertainty of less than 10%.

The phenomena participating in the transfer of heat through the layer are the conduction, convection, and radiation. The light bulb of the high insulating house is placed inside a small black box to reduce the radiation effects. In this same line, the house allows the collocation of measuring of samples until 5 cm of thickness. In general, the flux fraction transmitted by radiation, that in the case of parallel surfaces is independent on the distance between them, can be comparable to the flux transmitted by conduction (proportional to the inverse of the thickness of the sample) when the thickness of the measuring wall increases (PHYWE). The thickness of the wall exerts a considerable influence, especially in the case of bad heat conductors. Therefore, the thermal energy flow through a vertical, homogeneous, flat wall at moderate temperatures is mainly determined in the steady state (permanent state) by means of the air-wall heat transfer and the heat conduction in the wall (PHYWE).

The heat transfer by convection between internal air and internal wall of the fique sample is given as follows,

$$\Phi = h_{int} \cdot S \cdot (t_1 - t_2)$$
(3)

where h_{int} is the convection coefficient of the interior air, S is the wall area of the sample in m^2, and t_2 and t_2 are the temperatures inside the box and of the internal wall of the fique sample, respectively, in ºC.

The heat transfer by conduction across the sample is given by,

$$\Phi = \lambda \cdot S \frac{(t_2 - t_3)}{d}$$
(4)

where λ (W/K.m) is the thermal conductivity, t_3 is the temperature of the external wall of the sample, and d the thickness of the sample. The heat transfer by convection between external wall of the fique sample and the external air is,

$$\Phi = h_{ext} \cdot S \cdot (t_3 - t_4)$$
(5)

where h_{ext} is the convection coefficient of the external air and t_4 is the outer air temperature.

An experimental average value of the ratio (Φ/S) was estimated from Eqs. 3 and 5. Using this value, the λ value was calculated using Eq. 5. For h_{int} and h_{ext} coefficients, a value of 8.1 $(W / K \cdot m^2)$ was used as recommended by the manufacturer of the equipment (PHYWE) in the case of natural air movement in enclosed rooms.

RESULTS AND DISCUSSION

Acoustic Parameters: Absorption Coefficient at Normal Incidence and Static Air Flow Resistivity

A non-textured fique sample is a fibrous material composed of a large number of crossed and compressed fibers. Natural fibers such as fique are assumed to have the same mechanism for acoustic absorption as other conventional synthetic fibrous materials, such as glass fiber or mineral wool (Ballagh 1996). The sound absorption in porous materials is considered to be mainly due to the consumption of sound energy by the viscosity when the sound is propagated into a thin tube. The sound wave penetrates the material and, once inside, the amplitude of vibration of the air molecules is progressively damped due to friction with the cavity surfaces. Nevertheless, other physical processes may also be involved; for example, heat transfer will occur due to the temperature difference between the different fibers, and this process will dissipate sound energy. The vibration of air in the bulk materials also leads to the vibration of the fibers. The typical absorption coefficient of a fibrous material is characterized by a maximum absorption peak whose position is dependent on the density and thickness of the material. In any case, it is important to note that the structure of natural fibers allows the use of more diversified modes to attenuate the sound wave energy. Glass fiber has the same regular and solid construction, whereas samples based on natural fibers are more irregular.

The absorption coefficient was measured by placing the fique samples directly against the wall of the impedance tube. To illustrate the behavior described in Fig. 3, the sound absorption coefficient was plotted at normal incidence and measured for samples of different thicknesses and a grammage of 1.2 kg/m^2. The figure shows that the position of the maximum sound absorption peak depended on the thickness; the low frequency position of the maximum absorption peak corresponded to the 1.5-cm-thick sample. To highlight the influence of the sample density on the sound absorption coefficient measured in Fig. 4, the absorption coefficient was plotted for the three manufactured thicknesses, and only two different grammages: 0.85 and 1.2 kg/m^2. The influence of the density was evident for the 0.5-cm-thick samples: the higher the packaging and the smaller the empty space, the lower the frequency position of the maximum absorption peak.

When the thickness of the samples was increased, the maximum absorption peak was displaced to lower frequencies. However, the absorption coefficient curve was practically independent on the grammage of the samples when the thickness is 1.5 cm (Fig. 4c). Although for the sake of clarity only two grammages were plotted, this behavior was observed for all the grammages: for the 1.5-cm-thick samples the curves practically coincide.
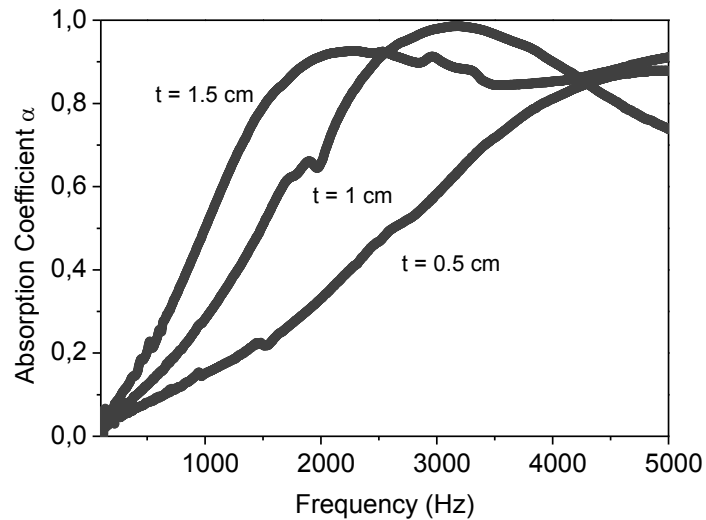
Fig. 3. Absorption coefficient at normal incidence of 0.5-, 1-, and 1.5-cm-thick (*t*) fique samples of 1.2 kg/m^2 grammage

The acoustic performance of a porous material is also described by the static flow resistivity, σ. Sound is produced by air vibrations, and it is therefore only natural that sound cannot easily be propagated by materials through which air passes with difficulty. Thus, flow resistivity represents the difficulty of air propagation in porous materials. This parameter is dependent on the size, shape, density, and distribution of the fibers. The values of σ for the different grammages are shown in Table 2.

Table 2. Values of the Static Flow Resistivity for the Fabricated Fique Samples

Grammage (kg/m^2)	σ (Nm^{-4}s)
0.70	1.57×10^4
0.85	1.57×10^4
1.00	1.64×10^4
1.20	2.04×10^4
1.50	2.60×10^4

In general, resistivity values increase with the density of the material. The values of this parameter for the fique samples were almost constant for the 0.7-, 0.8-, and 1-kg/m^2 samples, and its value slightly increased for samples with grammages of 1.2 or 1.5 kg/m^2. In general, the values measured were of the order of magnitude of those measured for mineral wool.
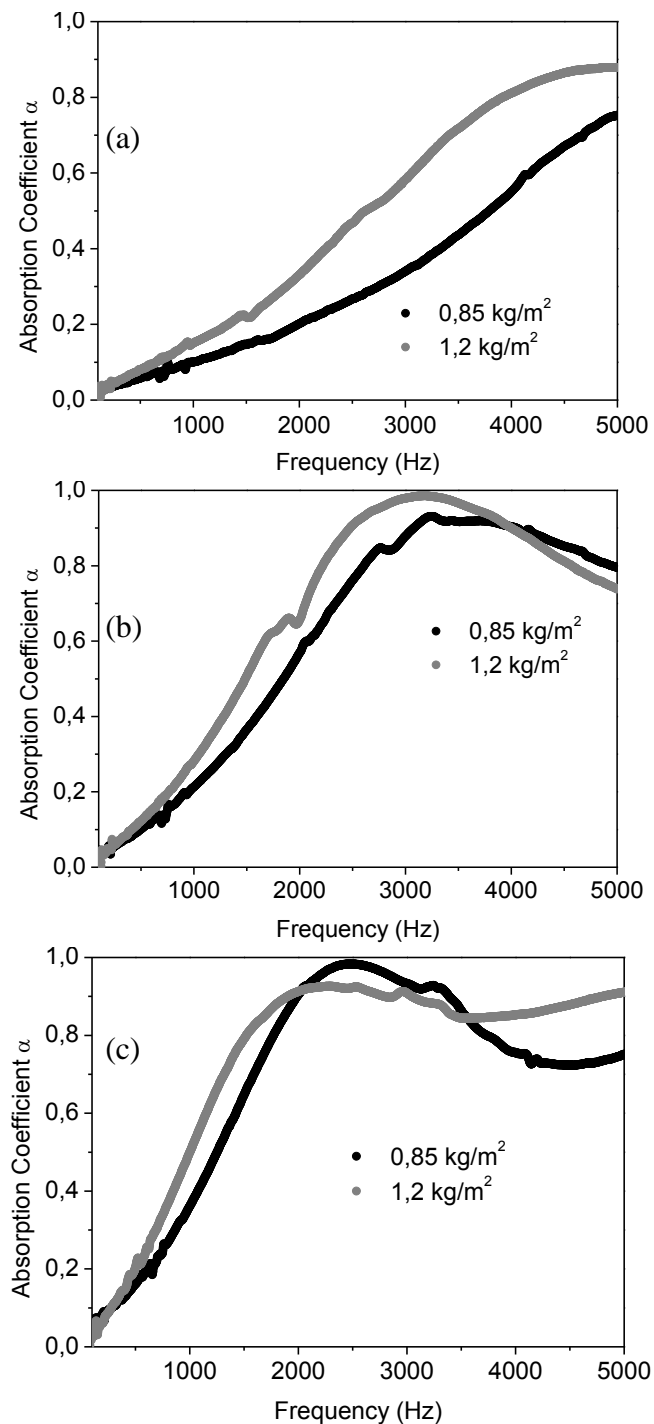
Fig. 4. Absorption coefficient at normal incidence of fique samples with grammages of 0.85 and 1.2 kg/m^2 and of three different thickness: (a) 0.5 cm, (b) 1 cm, and (c) 1.5 cm

For use as insulation in construction, the optimum value of this parameter should range between 5 and 10×10^3 Nm^{-4}s. Below 5×10^3 Nm^{-4}s the acoustic muffling was insufficient, and above 10×10^3 Nm^{-4}s, the material was too compact and the sound propagation took place primarily through the material. In any case, for materials designed to fill cavities, a static flow resistivity above 5×10^3 Nm^{-4}s is recommended.

Thermal Conductivity

The values of thermal conductivity λ *versus* the grammage of the fique samples are shown in Table 3. The λ values are a combination of the thermal conductivity of the fique and the air. The heat transported by conduction in the solid is reduced by decreasing the volume fraction of the solid: when the cross-sectional area of the solid is reduced, the heat flow will encounter resistance. Thus the value of λ increases with the packaging density of the sample, although the values of the samples fabricated correspond to a good thermal insulator. In fact, textured fique samples made with long fibers are used for the conservation of some farming and livestock products.

Table 3. Thermal Conductivity for the Different Grammages of the Fabricated Fique Samples

Grammage (kg/m^2)	λ (W/K × m)
0.70	0.037
0.85	0.044
1.00	0.052
1.20	0.066
1.50	0.078

Predictive Models during the Fabrication Process of a Material

Because of structural and geometrical complexities, it is extremely hard to define the acoustical behavior of most sound absorbers based on a theoretical model. Thus, different empirical models have been developed to model the behavior of absorbent materials with various compositions as a function of frequency: mineral wool, glass wool, foams, and polyester fibers (Attenborough 1982, 1983, 2011). These models have certain limitations, but they can be used to predict the acoustical behavior of a material during the manufacturing process by establishing the values of parameters such as thickness and density, to determine an optimal acoustical behavior.

As has been mentioned in various sections of this work, absorbent materials made from natural fibers are fibrous and porous, and this structure indicates that the properties should be comparable to those of other fibrous and porous materials already established on the market such as mineral wools. A semi-empirical model (Ramis *et al.* 2010) based on the Garai-Pompoli model (Garai and Pompoli 2005) is therefore proposed to calculate the value of the coefficients that best describe the behavior of materials derived from natural fibers. Specifically the model has been applied to a material manufactured from natural kenaf fibers. This model describes the acoustical behavior of the material using the experimental values measured for air flow resistivity and the absorption coefficient at normal incidence as a function of frequency. The expressions used for the model are described in detail in the references Ramis *et al.* (2010) and Del Rey *et al.* (2012).

The possibility of applying this semi-empirical model was evaluated with respect to the manufactured fique samples in the present work. To calculate the coefficients that best describe the acoustical behavior of the fique samples, the fitting process was initialized using the coefficients calculated for kenaf as input values (Ramis *et al.* 2010). The iterative method was used, based on decreasing the squared error function, as

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proposed by the authors of the model (Ramis *et al.* 2010; Del Rey *et al.* 2012). Table 4 shows the values calculated for the coefficients, and the coefficients calculated for the kenaf samples have also been included for the purposes of comparison. As an example, Fig. 5 shows the curves for the absorption coefficient at normal incidence measured for a 1.5-cm-thick sample and a grammage of 1.2 kg/m^2, and the curve calculated using the coefficients in Table 4. Although the semi-empirical model agreed well with the experimental results, for higher grammages the model had a tendency to underestimate the sound absorption values in the lower frequency range.

Table 4. Coefficients Derived from the Fitting to the Semi-Empirical Model of the Absorption Coefficient at Normal Incidence for Natural Fique Fibers and the Coefficients Obtained by Ramis *et al.* for Kenaf Fibers

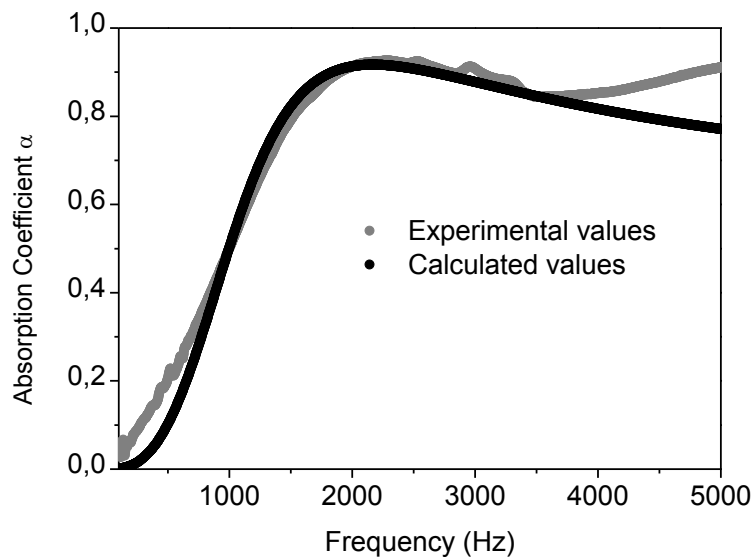| Fiber	C1	C2	C3	C4	C5	C6	C7	C8
fique	0.095	1.150	0.311	0.910	0.060	1.256	0.039	0.541
kenaf	0.046	0.255	0.112	0.967	0.060	1.256	0.039	0.541

Fig. 5. Absorption coefficient at normal incidence measured and calculated using the coefficients of Table IV for a 1.5-cm-thick sample and a grammage of 1.2 kg/m^2

A comparison can be established between the coefficients shown in Table 4; the coefficients derived from the fitting of the absorption coefficient at normal incidence for both materials –kenaf and fique– were the same, except for coefficients C1, C2, and C3. The morphology of the natural fibers may be very different; irregularities can be found between natural fibers of the same type, which does not occur in the case of artificial fibers. Artificial fibers are generally more homogeneous. The absorbent behavior of materials is related to structural characteristics such as the diameter or density of the fibers, which are difficult to take into account explicitly in the semi-empirical model. For example, the diameter of the natural fiber is an important microscopic parameter

affecting its acoustical behavior and is directly related to the absorption characteristics of the material. The diameter of the fique fiber is between 8 and 10 times higher than the diameter of the kenaf fiber, whose medium diameter is 20 µm (Ramis *et al.* 2010). This could explain the different values of coefficients C1, C2, and C3 for two natural fibers such as fique and kenaf with a different structural morphology.

In any case, the main aim of a semi-empirical model is to describe the acoustical behavior of a fibrous material using the lowest number of physical parameters. This model can therefore be easily applied as a basis for predicting the acoustical behavior of a material in the preliminary phases of its design. In the present case, after fixing the values of the coefficients (from C1 to C8) for the fique fiber, a simulation of the absorption coefficient curve was performed at normal incidence, increasing the value of the grammage of the material, namely the packaging of the sample. For values of grammages over 1.2 kg/m^2, the maximum absorption peak maintained this position, whereas the value of the absorption coefficient decreased. When the density was close to 1.7 kg/m^2, the maximum absorption peak started to move towards higher frequencies. This result is reasonable, taking into account that the width of the space is reduced for high packaging amounts, which impedes the propagation of the sound wave through the material.

Uses of the Fique and Future Work

Although all materials absorb some incident sound, the term "acoustical material" has been primarily applied to materials produced for the specific purpose of providing high absorption values (Arenas and Crocker 2010). Most practical sound absorbing products used in the building industry consist of glass-fiber or mineral-fiber materials. These absorbents are used mainly to control noise, to reduce the reverberation time in enclosed areas, and for airborne sound insulation as components of multilayer systems (classical or in superimposed panels, floating floors or suspended ceilings). The main drawback of wool is that the small fibers become detached during the manufacturing and installation process, and considerable energy is required for its manufacture.

In recent years, considerable progress has been made in the field of fibrous absorbent substances of particular interest for the design of sustainable and environmentally-friendly materials. The use of natural fibers in the production of absorbent materials is not new, and numerous works have been published (Ballagh 1996; Zulkifli *et al.* 2008; Koizumi *et al.* 2002; Del Rey *et al.* 2012; Navacerrada *et al.* 2013; Díaz *et al.* 2012). Absorbent materials based on natural fibers have also been favored, as natural fibers are biodegradable and modern technological developments have led to economically-viable and environmentally-friendly processing methods. These new methods and processes can be used to produce high-quality fibers of an industrial standard at competitive prices. Moreover, the acoustical, mechanical, and thermal properties of some of these plant-fiber based absorbent materials are comparable to materials derived from minerals.

Specifically, as mentioned in the introduction to this work, long fique fibers and the textured samples made with them already have numerous uses in a range of sectors. In addition to their traditional uses, in the construction sector the long fique fibers are used mainly as molding agents in undulating elements such as tiles, and as reinforcement for materials. The material made using short fique fibers, whose preliminary studies have

been presented in this work, can be classified as fibrous absorbing material. In Fig. 6, the sound absorbent coefficient at normal incidence measured for the 1.5-cm-thick samples is compared to the absorbent coefficient of mineral wool of the same thickness. Based only on the acoustical measurements and the information from the fitting to the semi-empirical model proposed for kenaf, the behavior of 1.5-cm-thick fique samples with a grammage of between 0.85 and 1.2 kg/m^2 is comparable to mineral wool. For this thickness and grammage, the acoustical properties are practically independent of the grammage. This result indicates that the sample density must be chosen based on other properties, such as thermal or mechanical behavior. The mechanical behavior is another aspect to be analyzed in future works. With regard to thermal properties, the thermal conductivity value for mineral wool is in the order of 0.04 W/(K·m), while the values measured for the fique samples range between 0.036 and 0.066 W/(K·m) depending on the grammage (see Table 3). The static flow resistivity of mineral wool is around 10^5 Nm^{-4}s. Thus, this simple comparison reveals that in view of the morphology and properties of the samples produced, similar usages to mineral wool could be contemplated. A preliminary step for future work would be to produce long samples using short fibers and replace the mineral wool with a fique sample in a multilayer or sandwich structure configuration to perform airborne sound insulation measurements.
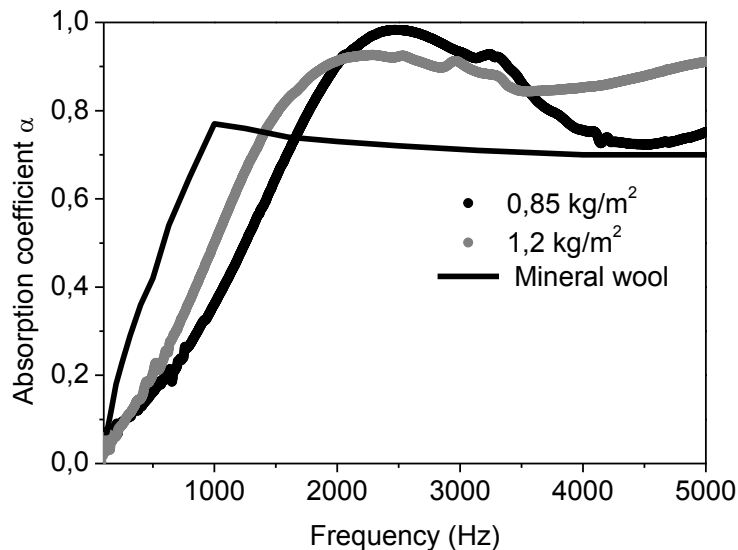

Fig. 6. The sound absorbing coefficient at normal incidence measured for 1.5-cm-thick fique samples compared to the absorbing coefficient of mineral wool of the same thickness

CONCLUSIONS

1. A preliminary study was completed on the acoustical and thermal properties of samples manufactured using short fique fibers arranged in a non-textured shape. Samples were characterized for three thicknesses (0.5, 1, and 1.5 cm) and five different grammages (0.7, 0.85, 1, 1.2, and 1.5 kg/m^2).

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2. The fique samples present the typical absorption coefficient of a fibrous material: a maximum absorption peak whose position is dependent on the density and thickness of the material. Nevertheless, the sound absorption coefficient at normal incidence is practically independent on the grammage of the sample when the thickness is 1.5 cm. In fact, the behavior of 1.5-cm-thick fique samples with a grammage of between 0.85 and 1.2 kg/m^2 is comparable to a mineral wool. In this same line, the values measured for the static flow resistivity are of the order of 10^4 Nm^{-4}s also comparable to those measured for a mineral wool.

3. Concerning the thermal properties, the λ values range between 0.04 and 0.08 W/K.m depending on the packaging density of the sample. The values correspond to a good thermal insulator material. As reference for a mineral wool λ is in the order of 0.04 W/(K·m).

4. The sound absorption coefficient at normal incidence measured for the fique samples was fitted to a semi-empirical model. Fixing the values of the coefficients to the model yielded the following predictions of the acoustical behavior of the material:

    - For grammages over 1.2 kg/m^2 the maximum absorption peak maintains the position whereas the value of the absorption coefficient decreases.

    - When the density is close to 1.7 kg/m^2 the maximum absorption peak starts to move towards higher frequencies.

5. In summary, fique samples have comparable properties to mineral wools, with the advantage of easy processing, availability, low weight, low cost, and high mechanical resistance and biodegradability. In future work we propose testing the samples in different horizontal and vertical constructive systems replacing mineral wool.

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