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Recycling and natural fibers: an option for the development of sustainable materials

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ABSTRACT

The introduction of the concept of "sustainability" to the building sector has led to the manufacture of products made of natural or recycled materials. Based on this, the use of industrial waste debris together with natural materials should be considered in the production of new construction materials. Acoustical and thermal properties are key parameters to take into account in the design of new materials. A review of materials devised based on these principles and developed in the Laboratorio de Acústica at Universidad Politécnica de Madrid is presented in this work.

Keywords: waste treatment, physical properties
I-INCE Classification of Subject Number: 35

1. INTRODUCTION

The building sector is one of the biggest contributors to pollution on the planet. Therefore investigations should be oriented towards generating materials with minimal environmental impact that can replace the existing materials. Based on the growing concern, we have opted for a double alternative during the innovation process of construction materials. The circular economy based on the reuse of waste, introducing the material back into the production chain and the use of natural products that have less environmental impact and local to the places where they are manufactured. As a consequence, research has been carried out to find innovative and sustainable uses for these materials in the building sector [1] keeping in mind that the developmentof new materials has to be linked to the use and constructive disposition within the building. Being conscious with this new priority, in this work ways of developing and manufacturing sustainable materials are proposed in order to assess the possibility of using them in the building sector.

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We present materials made from recycled materials and materials composed of vegetable raw materials. The use of wasted components has two advantages, the reduction of their environmental impact and the reduction of energy consumption in the manufacturing of new ones with their reintroduction in the production line. The two examples of materials that include recycled products are aluminum foams and panels in which lime and textile fibers are combined. Other materials with a low impact on the environment and human health are materials procured from natural fibers and plants, as reed panels or acoustic absorbers made with short fibers of fique and coconut fibers as an alternative to synthetic ones. In some countries with these materials, this option is intended to take advantage of both the local natural resources and the labor of each community. Acoustic insulation and thermal insulation as two fundamental aspects that should be taken into account in the design process for buildings. So, the thermal and acoustic characteristics as well as the advantages and disadvantages of use in construction of these materials are fundamentally analyzed.

2. SUSTANAIBLE MATERIALS AND PROPERTIES

2.1 Metal foams made of recycled aluminum

Aluminum is a material that, due to its low weight, durability, resistance to corrosion and easy recycling, has become an essential product for the construction industry. It is one of the most abundant metals in nature and, despite the high energy consumption needed for its extraction and separation of other impurities, it can be recycled indefinitely. On the other hand, due to their properties (great capacity for deformation, resistance to fire, good acoustic absoption) the metallic foams have emerged as an attractive research field. There are several techniques to manufacture aluminum foams, as such seeking a technique that allows homogenous manufacture of the material at a low cost is not easy. A comparative study has been conducted between closed pore foams manufactured using the powder metallurgical technique [2] and open pore foams manufactured using the infiltration technique [3-4]. The recycled aluminum was supplied by a high voltage energy transmission company.

For the powder metallurgical technique, a compacted mixture of aluminum powders and a foaming agent is used in a mold that is introduced into an oven at 750ºC. At this temperature, inside the mould, the foaming agent decomposes, releasing gas and forcing the fused aluminum to expand, generating a porous structure in this way. Samples of different pore size were made using different foaming agents. A photo of the fabricated samples is shown in Figure 1.

Figure 1. *Aluminum foams of approximately 1 and 2 mm average pore size manufactured by the powder metallurgical technique*

The materials used for manufacturing the open cell metal foam were common salt and recycled aluminum. Salt was sieved to obtain particles according to the intended cell size of the final sponge: 2.0 mm, 1.2 mm and 0.5 mm sizes were used. Preforms were infiltrated at 700° C with molten aluminum under vacuum pressure and the salt was subsequently removed by dissolution in distilled water. In Figure 2 we show the samples fabricated by the infiltration process.

Figure 2. *Picture of the aluminium sponges fabricated by the infiltration process.*

Table 1 summarizes the values of density and the approximate pore size of the foams manufactured by the two techniques described. The sound absorption coefficient can be measured for small samples at normal incidence using an impedance tube in compliance with ISO 10534-2 [5]. For the aluminum foams the curve of the sound absorption coefficient measured is characterized by the presence of a maximum absorption [2,3]. In Table 1 we have included the value of the sound absorption coefficient for this maximum (α_M) and its frequency (f_M). The type of porosity of the foam, open or closed pore and the diameter of the pores are the fundamental parameters that determine the value of α_M. The sound energy is dampened through friction against the walls of the cavities; the greater length of these cavities (as is the case with open-pore foams where the cavities are connected to each other) and the smaller diameter cause greater resistance that results in greater sound absorption. The thermal insulation performance of a material is usually evaluated through thermal conductivity λ, measured in compliance with EN 12667 [6]. A material is usually considered a thermal insulator if its conductivity is lower than 0.07 W/m·K.

Table 1. *Physical properties of aluminum foams manufactured using the powder metallurgical Technique and by the infiltration method.*

Foam	**Method of fabrication**	**Density (kg/m^3)**	**pore in diameter (mm)**	**α_M/f_M(Hz)**	**Thermal Conductivity (W/m·K)**
1P	Powder metallurgy	900-1000	1	0,5 / 2800	1,5
2P	Powder metallurgy	850-1000	2	0,4 / 2900	4
1I	Infiltration	920-940	0,5	0,9 / 2300	0,6
2I	Infiltration	920-940	1	0,8 / 3100	1,1
3I	Infiltration	920	2	0,6 / 3200	3

The results obtained show that due to their acoustic properties, aluminum foams are good candidates for indoor noise control. Smaller pore sizes in aluminum foams also contribute to their thermal insulation. Indoors, they can be interesting as a decorative element due to their unusual appearance. In fact, they have already been used on ceilings and walls. Given their mechanical strength, they could also be used as perforated panels combined with a mineral wool or with an air chamber to control the reverberation time of an enclosure. For both combinations the absorption peak measured for the foam moves at lower frequencies, increasing its width and the maximum absorption value [2, 3]. In the case of closed pore foams, the thickness should be reduced to between 0.5 and 1 cm so that the pores or cavities pass through the material and achieve the geometry of the perforated panel. This is not necessary in the case of open pore foams where the pores appear interconnected with each other throughout the thickness of the sample. Due to its dynamic rigidity, it could be integrated into different customary constructive solutions such as a panel in multilayer facades or as a cladding layer linked to the building through the anchoring structure in ventilated facades. In fact, we are starting to see the façades of some modern buildings decorated with different lightweight rigid panels manufactured with aluminum foams.

2.2 Panels made with recycled textile fibers

The main difficulty with textile recycling is the diversity of the resulting waste, resulting in the selection and classification being oftentimes carried out thoroughly by personnel, which is very costly. The most common way to introduce these recyclables in the building sector is based on their use as fibers to increase strength, physical performance as well as durability by reducing cracking. We describe a proposal to rescue the textile fiber waste and incorporate it in a new life cycle, using it as fibrous and lightening material in a panel in which hydraulic lime has been used as the main binder [7, 8].

Table 2. *Values obtained for thermal conductivity and the NRC coefficient of sound absorption at normal incidence. The values of flexural and compressive strength of the manufactured panels have also been included in the Table. To describe each sample A, B and C in the first column the ratio of lime and water used and the value of the resulting density for the panel have been included*

Designation	Thermal Conductivity (W/mK)	NRC Coefficient	Flexural Strength (N/mm^2)	Compression Strength (N/mm^2)
A Dosage (lime: water): **1:1** Lime: 4500 g Water: 4500 g Density: 1013 kg/m^3 	0,21	0,2	0,976	3,22
B Dosage (lime: water): **1:1,5** Lime: 3000 g Water: 4500 g Density: 774 kg/m^3 	0,15	0,1	0,172	6,68
C Dosage (lime: water): **1:2** Lime: 2250 g Water: 4500 g Density: 716 kg/m^3 	0,14	0,1	0,110	7,62

For the manufacturing of the samples, dry textile fibers were mixed with lime and water. The fibers consisted of a by-product composed mainly of organic cotton fibers and synthetic fibers. The length of the textile fibers ranged from 4 to 82 cm and their thickness between 0.05 and 4 mm. The amount of water was fixed and the amount of lime was varied and therefore the amount of textile fibers, resulting in panels of three different densities. In Table 2, the three types of manufactured panels are specified in the first column: the dose, the lime and water content by weight and the density of the resulting panel. The thermal conductivity and absorption coefficient at normal incidence of the panel prototypes were measured. The sound absorption coefficient can be defined by means of a single rating value through NRC (noise reduction coefficient) that is the arithmetic average of the absorption coefficients measured in the octave bands between 250 and 2000 Hz. The value of thermal conductivity is determined by the proportion of water (0.5 W/m·K) of textile fibers, mainly cotton (0.06-0.08 W/m·K) and hydraulic lime (0.6-6). 0.8 W/m·K) in the sample. The thermal conductivity is reduced when the weight of the component with the highest thermal conductivity, the lime, decreases and the density of the sample is reduced. The NRC coefficient is also dependent on the proportions of each of the components in the sample. The decrease in lime content from sample type A to the sample type C translates into an increase in the porosity of the manufactured prototype. Therefore, the NRC coefficient is greater in sample C of lower density and greater porosity.

In this case, a mechanical assessment of the manufactured panels was also carried out. The values of mechanical resistance to bending and compression measured have been included in Table 2. The tests of flexural strength were carried out according to UNE EN 12089 [9] and those of compression resistance according to the UNE EN 826 standard [10]. The resistance to bending is reduced as the weight of lime in the sample is also reduced. Even so, in all cases large deformations were observed even when cracks appeared on the surface, indicating that the textile fibers increase the flexural performance of the samples. The effect of lime content on compression resistance is not as obvious, and an increase in strength is observed when the lime content is reduced. It should be noted that type B and C samples showed a higher resistance to compression than commercial gypsum plates (3.5 N/mm^2).

These results serve to show the potential of a real option for the recycling of textile fibers. From here it is necessary to specify that the most suitable composition for designing the panel depends on the constructive solution in which it is integrated. An industrial form of manufacturing based on a punching machine to link the textile fibers, replacing the artisan process, has been contemplated. The options considered most viable are a porous panel of low lime content, comparable to a mineral wool, used as an insulating element in construction or as an interior lining product to control the reverberation time of an enclosure and a higher density panel with higher lime content and greater mechanical resistance as a façade panel.

2.3 Reed panels

This plant is abundant in Spain and on a large part of the earth's surface. It is a low cost and aesthetically acceptable material which is easy to obtain and install, has excellent durability and has been more frequently used in construction since it allows the generation of different constructive systems. The usual use of the reed is together with other materials such as formwork, as roofs, as screens in fences and fences using mud or even as a vegetation cover in Central European countries. In this case, panels that were manufactured by compaction of reed stems were selected and then joined by galvanized wire [11]. In Figure 3 a photo of the manufactured panels is shown.

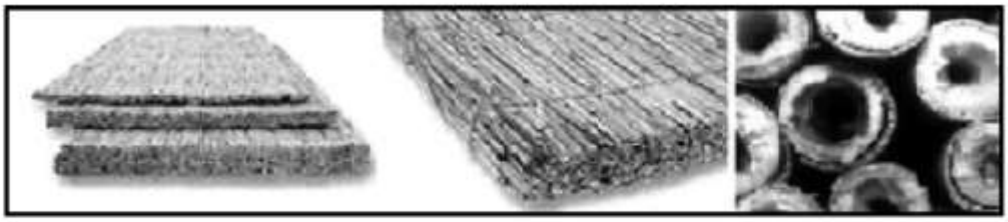

Figure 3. *Photograph of measured reed panels*

Table 3. *Properties of the reed panels*

Geometry: 5.10 and 15 cm thick panels produced by compaction of stems joined with galvanized wire of 1.5 and 2 mm	
Thermal conductivity: 0,055 W/m.K	
Values of the Rw Acoustic Reduction Weighted Index and its spectral adaptation terms for the reed panels of different thicknesses:	
Thickness (cm)	**R_w (C; C_{tr}) (dB)**
5	15 (0; 2)
10	20 (0; -3)
15	26 (-1; -5)
20	30 (-2; -6)
25	33 (-1; -6)
30	36 (-1; -6)
Values of the Rw Acoustic Reduction Weighted Index and its spectral adaptation terms for different combinations of the reed panels and medium density boards (MDF):	
Structure	**R_w (C; C_{tr}) (dB)**
MDF + reed panel + MDF	39 (0; -2)
MDF + asphalt cloth + reed panel	36 (-1; -4)
MDF + asphalt cloth + 3 reed panels	39 (-1; -5)

The panels were characterized thermally and acoustically. The measured parameters are shown in Table 3. The acoustic insulation tests were carried out in the horizontal transmission chambers of the Acoustics and Vibrations Laboratory as indicated in the EN ISO 140-3 [12] and the results of the global index R_w (C; C_{tr}) were calculated according to EN ISO 717-1 [13]. The results of acoustic insulation measurements indicate that reed panels can also be used as interior partitions (traditional architecture, similar to that used in traditional architecture in northern areas), or outdoors in facades, roofs and acoustic barriers. In this case, by itself or in combination with other products derived from wood (to increase its mechanical resistance and decrease the air and water permeability of the panel). Isolation tests were carried out in which the reed panels were combined with medium density boards, observing for some combinations a notable improvement of the R_w index, with comparable and/or superior values to those which have more traditional characteristics, such as the double hollow brick partition with gypsum plaster whose index is R_w (C; C_{tr}) = 39 (0; -2). Although reed can not be expected to match or exceed the characteristics of resistance and technical specifications of traditional building materials, it could, for example, be focused on rural or low-income housing where demand is lesser. In addition, it is easily adaptable to different climates and altitudes. Among its advantages are its rapid growth, minimal care required for its development and its high resistance/weight ratio that results in a very accessible and promising material.

2.4 Materials from fique and coconut fibers

In recent years, natural fibers have been considered valid raw materials for producing sound absorbing panels alternative to traditional synthetic ones [14, 15]. We have investigated the possibilities of materials produced from natural fibers of fique and coconut [16]. Coconut fiber, called seed fibre is obtained as a residue of the fibers of the coconut shell. Fique fiber is a strong and relatively flexible fiber from the leaves. Fique short fibers were used, which are the byproduct of the manufacture of cordage and packaging from long fibers. The fibers can be woven to produce a fabric or meshed to produce a nonwoven material. Because of its lower cost, non-wovens that can be manufactured manually or mechanically by means of a punching machine were chosen. The resultant samples were fibrous materials whose diameter tends to be larger than the diameter of synthetic fibers and have more irregular shapes and diameters compared to synthetic fibers. Figure 4 shows a photo of manufactured samples.

***Figure 4**. Manufactured samples (upstream): non-woven sample of fique, sample of non-woven and sample in which both types of fibers, fique and coconut are combined.*

It has been seen that if the density is the same, the acoustic and thermal properties of the non-wovens are very similar regardless of whether they are made only of fique, only of coconut or of a mixture of both types of fibers. The difference is found in the mechanical properties and in the final color of the sample, achieving a finishing tone or another depending on the proportion of fibers used. For thicknesses between 1.5-2.5 cm the acoustic properties were very similar for surface densities or grammages of the nonwoven between 0.7 and 1.3 kg/m^2. The thermal conductivity, however, increased from 0.037 W/K·m for the non-woven fabric of lower density to a value of 0.07 W/K·m for the sample with the highest density. The values of thermal conductivity as a function of grammage are indicated in Table 4. From these previous studies, non-wovens whose densities oscillated between 0.6-0.7 kg/m^2 due to the combination of their acoustic and thermal properties were chosen as more appropriate samples.

***Table 4.*.** *Values of thermal conductivity at 24ºC depending on the weight of the manufactured samples*

Density (kg/m^2)	**Thermal conductivity (W/K·m)**
0,7	0,037
0,85	0,044
1	0,052
1,2	0,066
1,5	0,078

Table 5 summarizes the acoustic and thermal properties of non-woven samples of fique, coconut and fique-coconut with a grammage of approximately 0.7 kg/m^2. For this grammage the values of the thermal conductivity are comparable to those of a mineral wool. These fibers have good sound absorption coefficients at medium and high frequencies. Moreover, by increasing the material thickness, it is possible to obtain significant sound absorption also at low frequencies. The values of the NRC coefficient for thickness samples of 2.5 and 5 cm thickness are shown in Table V. The value of the sound absorption coefficient for this maximum (α_M) and its frequency (f_M) have also been included for each sample.

Table 5. *Non-woven properties of fique, coconut and fique-coconut manufactured with grammages around 0,7 kg/m^2.*

Sample	**Thermal Conductivity (W/m·K)**	**NRC (2,5 cm)**	**NRC (5 cm)**	**α_M**	**f_M (Hz)**
Fique	0,037	0,60	0,70	0,95	2300
Coconut	0,041	0,55	0,65	0,88	2500
Fique-Coconut	0,040	0,55	0,65	0,92	2500

The manufactured non-woven materials have acoustic and thermal properties comparable to a glass wool or rock wool. Therefore, these non-woven materials could be used to reduce the reverberation time in enclosures and for airborne sound insulation as components of a multilayer system. Due to its low mechanical resistance, as with a mineral wool, it is advisable to combine them with a perforated panel or board that provides a rigid, durable and good-looking surface and at the same time improves the acoustic behavior of the structure, especially at low frequencies. Manufactured non-woven material could also be used as a floor covering or as part of a floating floor to reduce vibrations and reduce impact noise. The parameter that indicates the suitability of a material to act as an acoustic damper is its dynamic rigidity. The procedure for the measurement of dynamic stiffness is described in EN ISO 29052-1: 1994 [17]. Table 6 shows the measured dynamic stiffness values for the three types of manufactured non-woven materials they are 1.5 and 2.5 cm thick. The values of the three non-woven materials are similar since the grammages and the morphology of the fibers are also similar. In technical documents and catalogs, a dynamic stiffness value between 5 and 20 MN/m^3 [18] is recommended, depending on the thickness, for products intended to be used to reduce the impact noise in a floating floor.

Table 6. *Measured values for dynamic stiffness for the three types of manufactured fabrics and two thicknesses, 1.5 and 2.5 cm.*

Non-woven fiber	**Thickness (cm)**	**Dynamic stiffness (MN/m^3)**
Fique	1,5	8,7
	2,5	1,4
Coconut	1,5	7,2
	2,5	1,7
Fique-Coconut	1,5	9,1
	2,5	2,3

3. CONCLUSIONS

The building sector is mainly dominated by thermo-acoustic insulating materials such as mineral wool, extruded and expanded polystyrene, but the rush towards more environmentally friendly buildings offers opportunities for the development of sustainable materials. The introduction of the concept of "sustainability" in the building sector gradually led to the production of products made from natural or recycled material. Nevertheless, researchers have questioned the real sustainability of natural fibers, in regard to the toxicity of the chemical products used for their cultivation or for the material transformation in building products.In general, the use of these products is not widespread due to their social demand being relatively recent and their respective development difficulties in a conservative sector. A way to start considering these materials would be by introducing them into Building Regulations as specific recommendations to increase the use of ecological materials in new construction, allowing a reduction of construction taxes.

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