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Preliminary investigation on the acoustic properties of absorbers made of recycled textile fibers

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ABSTRACT

In recent years, wastes reduction and their conversion into new resources are becoming a major requirement for our society. A considerable interest is focused on the use of recycled textile materials in building products and on their potential application as absorbing acoustic material. In developing innovative products it is not only important to recycle, but also to manufacture devices with recycled content. The challenge is the use of textile waste fibers and nontoxic binder to obtain composite materials with less social, economic and environmental impact. In this paper 100% merino wool wastes bounded with chitosan are investigated to obtain sound absorbing materials, particularly for the acoustic refurbishment of the open-office spaces. The use of chitosan instead of synthetic and plastic elements represents a valid solution to obtain bio-materials for optimizing buildings environmental sustainability. The acoustic performance of innovative composite materials were investigated. Measurements of normal incidence sound absorption coefficient were carried out by means of a standing wave tube, according to ISO standard 10534-2. Experimental results were very promising, showing absorption coefficient higher than 0.5 at frequencies above 500 Hz. This proved that it could be possible to produce sustainable alternative to traditional commercial synthetic products.

Keywords: Acoustical parameters, Textile waste, Sustainable composites

1. INTRODUCTION

The building sector has a significant impact on issues concerning both the consumption of natural resources and energy and the production of solid wastes which are difficult to dispose of (1). Therefore, the awareness of having to use materials with less social, economic and environmental impacts has been gaining more relevance in the construction and rehabilitation of buildings (2). The growing concern for environmental health has encouraged researchers and engineers to look for alternative materials developed from natural or recycled resources. As a consequence, agricultural and industrial wastes are becoming more attractive in the civil engineering and architectural applications, especially in the form of sustainable panels or mats (3).

The apparel industry can be considered of great relevance for the economy growth of every country in terms of trade, employment, investment and revenue; but it is also responsible for the production of an enormous quantity of wastes (4). A textile fabric can provoke pollution from the earliest manufacturing process (pre-consumer waste) to the end of its useful-life, particularly due the “throw away” culture (post-consumer waste) (5). Charity activities could be a solution able to minimize the impact of post-consumer wastes disposal, but innovative policies are needed for the recycling of pre-consumer textile wastes.

The reuse of discarded textile fibers as new raw materials for the production of innovative building composites could reduce the environmental impact caused by the construction industry and the textile industry, limiting the use of virgin resources and the need for landfill. Apart from the ecological advantages, many socio-economic benefits related to the “circular economy” are provided by transforming textile by-products in useful added-value goods (4).

Recently, several researchers carried out studies in order to use textile wastes to find an eco-compatible solution to noise pollution issue which increasingly affects the quality of human life (6). Trajković et al. (7) produced an insulating material encasing different fabric mixtures in 100% polypropylene non-woven structure. It was observed that the absorption coefficients were maximum in the range of 1000-2000 Hz and the noise reduction coefficient value was similar to that of others

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commercial building insulators. Binici et al. (8) compared sandwich-shaped chipboards including textile fibers with control chipboards and showed that the addition of fibers improved the sound insulation capacity. Tiuc et al. (9) investigated the effects of the addition of textile waste fibers on the noise reduction coefficient of rigid polyurethane foam.

The use of by-products to produce “green composites” has received more attention also considering that to obtain good thermal and acoustic performances it is only necessary to mix and keep the waste fibers together by means of binding solutions (10). The binders used in the building bio composites are often mainly based of epoxy and phenolic adhesive resins with an undesirable environmental impact. Binici et al. (11) studied innovative insulating panels obtained by mixing textile wastes and sunflower stalks with epoxy. Zou et al. (12) investigated the influence of epoxy plasticizer on the mechanical behaviour of cotton/PET wastes composites. Consequently, the development of natural and renewable binders able to make a sustainable end-of-life disposal of the construction products is actually the greatest challenge and the most important edge of the current research on adhesives.

The present study investigates the use of chitosan solution to bond 100% Merino wool waste fibers in order to produce innovative materials with good sound absorption properties. The choice to use only wool fibers mixed with an organic binder ensured an even more ecological recycling process that made the final product more sustainable. In fact, thanks to their high nitrogen content, natural fibers can decompose in about a year, resulting more biodegradable than the synthetic ones (13). In addition, chitosan is a biodegradable, non-toxic and non-water soluble polysaccharide obtained by industrial treatment of chitin from crustacean shells (14). Recently, chitosan has received wide attention in the area of biobased composites thanks to its good binding properties. El Hage et al. (15) carried out a research about new insulating and flame retardant materials from miscanthus and recycled textile fibers bonded by chitosan glue. Patel et al. (16) investigated the potential use of chitosan as wood adhesive.

The aim of the paper is the study of the sound absorbing behaviour of the innovative investigated materials by means the experimental measurements of their sound absorption coefficients. The experimental data where compared with those predicted by phenomenological and empirical theoretical models. The paper also focuses on the characterization of the non-acoustical parameters in order to better understand how they affect the acoustic behaviour of the composites under investigation.

2. METHODS

2.1 Sample preparation

Fabrics waste of 100% Merino wool produced during the garment cutting process by a local clothing company, were used to prepare the batting matrix of the innovative composite materials. The wool matrix (Figure 1a) was obtained by scouring and carding the fibers derived from a defibering process of the discarded fabrics.

a)  b) 

Figure 1 – Wool batting matrix (a) and woolen innovative composite materials (b)

A chitosan binder was used to mix and bond the textile fibers. The solution was prepared by dissolving 15 g of chitosan flakes into 1 dm^3 of water and by adding 0.005 dm^3 of acetic acid. The mixture was mechanically stirred for about 60 minutes at room temperature and room relative humidity.

Several cylindrical samples with different density values (ranging between 80 and 197 kg/m^{-3}) were obtained by following the molding method (Figure 1b). The fibers were soaked in the chitosan solution and, before placing them in the molds, the excess amount of binder was eliminated by squeezing the liquid excess. The same percentages of binder and fibrous matrix (60% and 40% respectively) were chosen in order to obtain materials in which textile fibers agglomerated quite homogeneously, entrapping air in the fibers network. Finally, samples were dried in an oven at 100° C, for one hour.

For each density value, six cylindrical specimens, 5 cm thick, were prepared. Three of them had a 10 cm diameter in order to measure sound absorption coefficients at low and mid frequencies and three had a 4 cm diameter to evaluate the sound absorption coefficients at high frequencies.

2.2 Non-acoustical parameters

Air flow resistance is a fundamental property for determining the sound absorbing behavior of porous materials. In the present work the procedure developed by Ingard and Dear (17), based on the acoustic waves, was taken into account. The measurement set up consisted of a 5 mm thick methacrylate tube, with a 4 cm inner diameter. The tube was divided in two parts; each of them had a length of 85 cm. At one end there was a 5 cm loudspeaker (Visaton FRS 5) with a frequency response spanning from 150 Hz to 20 kHz; at the other end there was a rigid termination made by 5 cm thick methacrylate. The tested samples were assembled between the two tubes. The flow resistance was deduced using the transfer function of the two microphones excited taking into account exponential sine sweep. All the processing was performed by a custom made Matlab® graphic user interface.

Porosity, as well as air flow resistance, plays a fundamental role among the parameters to be considered in sound absorbing material, therefore it was important to characterize it. ULTRAPYC 1200-e Quantachrome Helium gas Pycnometer was used to obtain the true density ρ_{true} of the materials, useful for determining their porosity values ε:

$$\varepsilon=1-(\rho_{bulk}/\rho_{true}) \tag{1}$$

where ρ_{bulk} is the bulk density value.

2.3 Acoustical parameters

Normal incidence absorption of woolen assemblies was measured according to the transfer function method described by ISO 10534-2:1998 (18). Two tubes with different diameters (10 cm, 4 cm) and a thickness of 5 mm were used for the test with the aim to consider the largest spectrum range. The tube with an internal diameter of 10 cm had a maximum measurable frequency of 2 kHz and it used two different microphone distances (6 cm and 20 cm, respectively referring to low frequency limit of 400 Hz and 50 Hz). The emitting end consisted of an 11 cm loudspeaker sealed into a wooden case and suitably isolated from the tube structure by an elastic and protective layer. The second tube, with a diameter of 4 cm, was the same used for the flow resistance measurement. In this case the microphone spacing was 3 cm, and the frequency covers a range between 200 Hz and 5 kHz. The receiving microphones were the same used in the previously described set up for the measurement of flow resistance. All the processing was performed by a Matlab® graphic user interface generating a 5 s linear sweep from 70 Hz to 3 kHz, used in combination with the largest tube, and from 500 Hz to 5 kHz considering the smallest tube.

2.4 Prediction models

The sound absorption coefficients measured in laboratory were compared with those estimated by theoretical prediction models. The empirical model proposed by Delany and Bazley (D&B) (19) and the phenomenological model suggested by Johnson, Champoux and Allard (JCA) (20-21) were chosen for the comparison. In both cases, the absorption coefficients of the investigated fibrous materials were obtained after determining the characteristic impedance Z_c and the wavenumber k as a function of frequency. The D&B theory was chosen because it remains a reference for fibrous materials similar to those under investigation which have high porosity values. According to the empirical model, the air flow resistivity σ is the only property required to calculate the parameter $X=(\rho_0 f)/\sigma$ (ρ_0 being air density and f being the frequency), needed to determine Z_c and k:

$$Z_c=\rho_0 c_0(1+0.057X^{-0.754}-j0.08X^{-0.732}) \tag{2}$$

$$k=\omega/c_0(1+0.0978X^{-0.700}-j0.189X^{-0.595}) \quad (3)$$

where c_0 is the speed of sound in air and ω is angular frequency.

Although the model proposed by Delany and Bazley may seem easier than other approaches, it could not guarantee an accurate result, since it does not take into account structural parameters of the material which instead influence the acoustic performance. Consequently, the Johnson-Champoux-Allard model was also selected. According to the phenomenological theory, the characteristic impedance and the wavenumber are expressed as a function of the dynamic bulk density ρ_e and the dynamic bulk modulus k_e:

$$Z_c=(\rho_0 k_0)^{1/2} \quad (4)$$

$$k=(\rho_e/k_e)^{1/2} \quad (5)$$

The computation of ρ_e and k_e involves the use of five macroscopic parameters including flow resistivity σ, porosity ε, tortuosity τ, viscous characteristic length Λ and thermal characteristic length Λ'. The two latter characteristic lengths describe the effects of viscosity and thermal dissipative forces inside the porous structure. Usually, $\Lambda \geq \Lambda'$ and in first approximation, $\Lambda'=2\Lambda$.

3. RESULTS

3.1 Non-acoustical parameters

This section shows the experimental results of the non-acoustical parameters in order to better understand their effects on acoustical absorption performance of the investigated fibrous composites. The value of air flow resistivity (i.e. the air flow resistance per unit thickness) was calculated because of its major relevance than air flow resistance for selecting or designing appropriate materials for noise control. The airflow resistivity is also an important property required in the most of theoretical models for predicting the acoustical behaviour of porous materials.

A summary of the results of porosity, air flow resistance and air flow resistivity by varying density values are shown in Table 1. All values are given as the mean of five different measurements with the error representing the standard deviation of the mean.

Table 1: Experimental non-acoustical parameters values of the investigated materials

Sample code	Density, kg/m^3	Porosity, -	Air flow resistance, Ns/m^3	Air flow resistivity, Ns/m^4
S1	80 ±1.0	0.94 ± 0.001	585 ± 35	11690 ± 2206
S2	122 ±1.2	0.91 ± 0.001	825 ± 98	16510 ± 2679
S3	145 ±1.6	0.89 ± 0.001	2300 ± 103	46005 ± 9067
S4	197 ±1.7	0.86 ± 0.002	3313 ± 310	66261 ± 7771

As it can be observed, although the porosity reduced with increasing density, all materials were characterized by a void fraction close to 90%. This was in agreement with the porosity values of felts and mineral fiber materials respectively ranging from 0.83 to 0.95 and from 0.92 to 0.99 (22). The air flow resistivity values also depended on the density values, increasing with the increase of density. However, all tested materials were below 100 kNs/m^4, which is the limit of a material for being considered as an impervious layer, according to del Rey et al. (23).

3.2 Acoustical parameters

Figure 2 plotted the absorption coefficients obtained from the experimental measurements. A comparison among all the investigated materials pointed out that the samples S1 and S2 showed a sound absorption coefficients trend in accordance with the acoustic behavior of mats with higher absorbent performance. This was due to their low air flow resistivity values (11690 Ns/m^4 for S1 and 16510 Ns/m^4 for S2) and their surface impedance values as close as possible to the wave impedance of the air, allowing sound wave to easily penetrate the material.

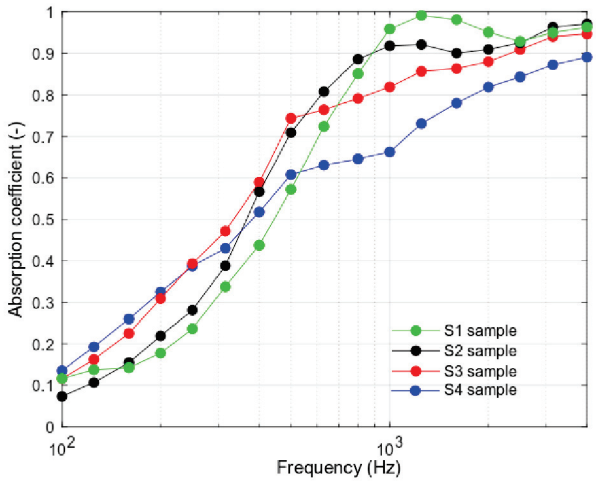


Figure 2 - Normal incidence absorption coefficients of the investigated materials

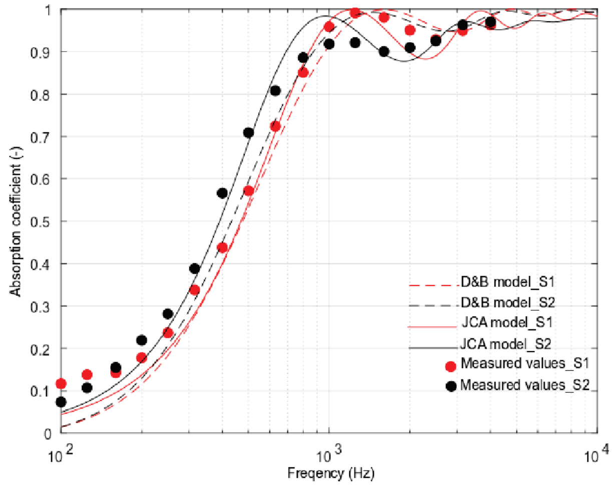
Thus, the application of S1 and S2 composites could be suitable for achieving high sound absorption especially in the medium and high frequency ranges. Although the sound absorption curves of the two samples were very similar up to 315 Hz, some differences in the location of the first peak could be noticed. For S1 sample, a first peak appeared at 1250 Hz, with α raising up to almost the unity; while for S2 sample, a first peak appeared at 1000 Hz, with α raising up to 0.92. A preliminary comparison was carried out with the expected position of the absorbing peak, as resulting from the quarter-wavelength rule, according to which the highest viscous losses are expected at the frequencies for which particle velocity is at a maximum on the sample surface. For a 5 cm sample the peak is expected at a frequency of 1700 Hz, but the location of the measured peaks shifted towards lower frequencies, probably because of the influence of the tortuosity of the materials and their air flow resistivity.

As it can be observed in Figure 2, the sound absorption capability of the S3 and S4 mix decreased in the mid and high frequency ranges and increased at low frequencies. At 1250 Hz α was around 0.86 for sample S3 and 0.73 for sample S4, against 0.99 for sample S1 and 0.92 for sample S2. This was because the high air flow resistivity values of the samples S3 and S4 (46005 Ns/m^4 and 66261 Ns/m^4, respectively) increased the viscous and thermal interaction inside the micro pores forming the material, but at the same time, the surface impedance also increased. Consequently, materials with a behaviour further from that of a perfect absorbent mats were obtained as a result.

As anticipated, the prediction of the sound absorption coefficients of the investigated materials was carried out by means of the Delany-Bazley and Johnson-Champoux-Allard models. The predicted results were compared with the measured data in order to determine, on one side, whether measured values were consistent with theoretical expectations, and, on the other, to subsequently use prediction formulae to optimize and design more efficient panels. Figure 3 shows the result of the comparison. The coefficients used to feed the D&B model, i.e. density and air flow resistance were derived from measured values (Table 3). The JCA equations were solved using some parameters, i.e. density, porosity and air flow resistance, previously measured and summarized in Table 3. The tortuosity values were estimated close to unity according to Willie et al. (24). The shape factor and the characteristic length ratio Λ'/Λ values were adjusted to get the best agreement between the measurement and the modeling values. Particularly, $\Lambda'/\Lambda=2$ and the shape factor was 2 for S1 and S4 samples, 3 for S2 sample and 0.8 for S3 sample.

As it can be observed in Figure 3(a), the experimental results were in agreement with the theoretical approaches, particularly with JCA model which allowed a more accurate estimated trend than D&B model. Taking into account sample S1, the phenomenological model perfectly predicted the first peak at around 1250 Hz. The estimated drop was almost aligned with the measured one at around 2500 Hz, although it was underestimated in absolute value. The first peak predicted by JCA model for S2 sample was also almost aligned with the measured one, although it was overestimated.

As confirmed by Figure 3(b), both selected models could be considered valid to predict the frequency responses of the samples S3 and S4, characterized by higher flow resistance values.

a) 

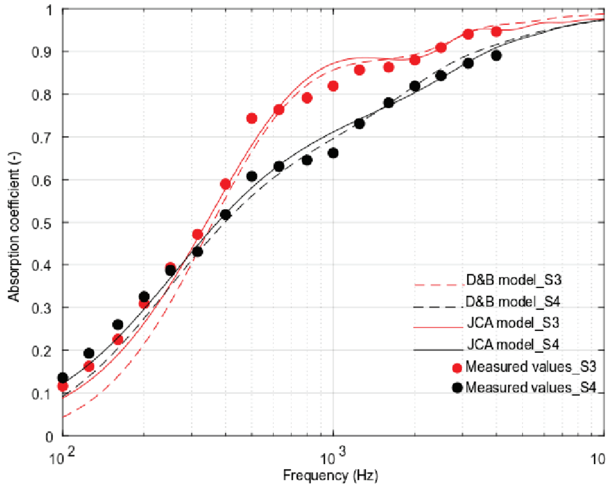
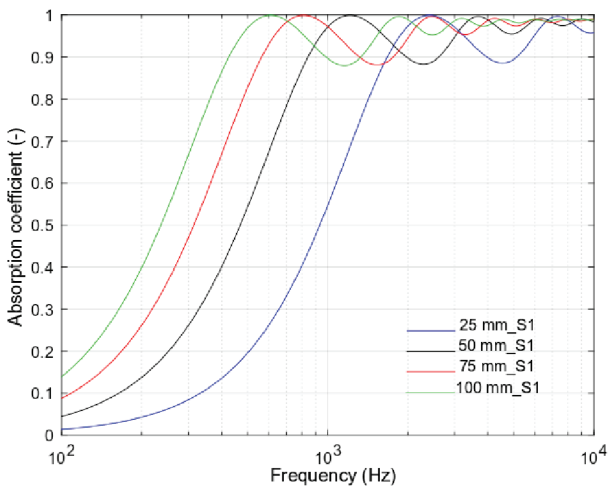
b) 

Figure 3 – Normal incidence absorption coefficients of S1, S2 samples (a) and of S3 and S4 samples (b)

Figure 3 shows that the two selected models estimated the sound absorption coefficients trend of the two denser materials (S3 and S4) almost with the same good accuracy. On the contrary, the JCA model performed better than the D&B model when applied to the absorption curves of the less dense materials (S1 and S2). This was probably due to the greater detail of the JCA model which took into account some additional structural parameters (i.e. the porosity and the tortuosity) which affected the acoustical behaviour of the less dense materials than the denser ones.

The effect of varying thickness on the sound absorption property of S1 and S2 samples, according to the prediction model proposed by Johnson, Champoux and Allard, was evaluated. The thickness of the fibrous materials is among the most influencing factor on their sound absorbing capacity (25). The phenomenological model was selected to predict the trend of the absorption curves when the thickness of the samples became 25 mm, 75 mm and 100 mm. JCA model was chosen because of its good agreement with the experimental data previously measured. As shown in Figure 4, the sound absorption coefficients increased in the low frequency range in accordance with the increase in thickness.

a) 

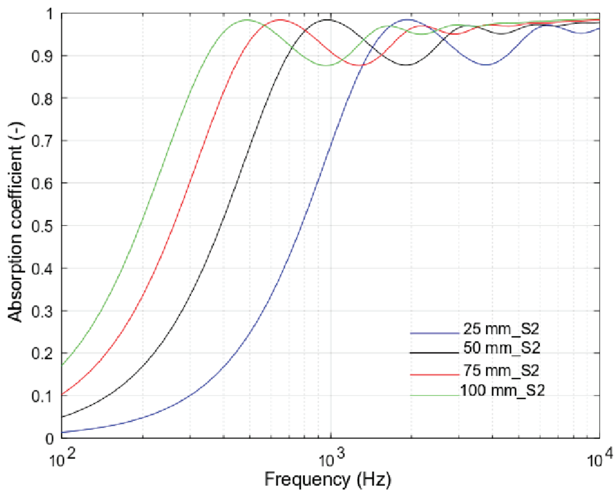
b) 

Figure 4 –Absorption coefficients as a function of different thickness of sample for S1 (a) and S2 (b) sample

Little variations can be observed could be seen for the sound absorption performance in the medium and high frequency ranges. So, after all, the increase of thickness improved the absorption capability of the materials at low frequencies, without altering the absorbent properties in the medium and high frequency ranges. For this reason, the increase of the thickness could be used as solution to compensate for the shortcomings of the porous structure for low frequency sound absorption. As confirmed by Figure 4, when the thickness was 100 mm, the first peak already appeared at around 630 Hz for S1 sample and at around 500 Hz for S2 sample, with an α close to unity. In the same situation, for S1 sample, α raised up to 0.7 at 315 Hz and up to 0.8 for S2 sample at the same frequency.

CONCLUSIONS

In this research work 100% wool recycled fibers were mixed using a chitosan binding solution in order to develop composites with good sound absorbing properties. Five kind of materials with different density values, but the same percentages of binders and fibers contents were produced. Non-acoustical parameters were measured in order to better understand how they affects the acoustic behaviour of the investigated mats. It was observed that samples with lower air flow resistivity values (S1 and S2) showed an acoustical behavior in full accordance with materials with good absorbent performance, offering a sustainable solution when great sound absorption in the mid and high frequency ranges was required. The samples characterized by higher resistivity values (S3 and S4), showed an improved low frequency performance compared with the more permeable samples, and a slightly reduced high frequency performance. All the results confirmed the promising application of the investigated textile composite materials in the noise reduction field, showing good absorption capacity at high or low frequencies, according to the requirement. The experimental data were also compared with those predicted by phenomenological and empirical theoretical models. It was concluded that the models suggested by Johnson, Champoux and Allard showed better agreement with the measured data than the theory proposed by Delany and Bazley. This was verified especially for materials with lower air flow resistivity values, whose acoustical behaviour was more affected by characteristic parameters of the porous structure. The effect of varying thickness on the sound absorption behaviour of S1 and S2 samples, according to the predicting model proposed by Johnson, Champoux and Allard, was evaluated. It was concluded that, as expected, an increase in thickness improved the absorption capability of the materials at low frequency sound. Further investigations are under way to analyze the effect of other binding solutions and different manufacturing processes.

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