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EXPLORING THE POTENTIAL OF RECYCLED TEXTILE PANELS TO IMPROVE SOUND INSULATION IN BUILDINGS

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ABSTRACT

Saving natural resources thanks to the use of recycled components and the growing interest towards improvement of indoor comfort conditions of the building occupants are stimulating the scientific community to investigate several sustainable building strategies. In this sense, the improvement of the sound insulation of buildings in combination with the use of more sustainable options is fostered by many regulations and, in particular, by the so called "Minimum Environmental Criteria". The present work investigates the sound insulation behaviour of nonwoven materials made from textile waste following an airlaying industrial process. Several panels with different density and thickness were evaluated according to the damping properties (i.e. total dynamic stiffness and the average loss factor). The results achieved allowed to hypothesize the employment of the tested materials in various fields. AlphaCell® software was used to model the expected sound insulating behaviour of different assemblies including the tested materials in combination with other building structures. The tested components were proposed to be used in air gaps of vertical walls, or as elastic layers in horizontal structures, applied to new building constructions or existing ones, showing an interesting potential for improvement of both airborne and impact sound insulation performance.

Keywords: sound insulation, textile waste, prediction.

1. INTRODUCTION

Noise pollution is one of the key concerns in building design because of its effects on both human health and environment quality [1]. In fact, according to some findings of the World Health Organisation, noise is the second largest environmental cause of health problems, having effects on hearing impairment, cardio-vascular and sleep disturbances, negative social behaviour and annoyance reactions [2]. At the same time, the increasing demand for sustainable building materials, is inciting researchers to seek novel solutions able to provide good properties for noise control applications [3]. Therefore, many studies [4-6] have been published to investigate the performances of innovative products (mainly fibrous) produced from recycled wastes and considered as green materials.

The fast-fashion has provoked the production of a huge amount of textile waste likely to grow over time and which is normally discarded in landfills [7]. The use of textile residues as raw materials for building components could be considered an alternative solution to landfills disposal, by recovering their economic value [8]. Furthermore, this could limit the environmental impacts associated with the consumption of virgin resources by construction sector [9].

The most part of existing studies on acoustic performances of green building materials concerns the material scale investigations, focusing on their absorption properties [10-12]. However, there is a need to consider the wall scale in order to also model their sound insulation performances for practical applications [13].

The TMM (Transfer Matrix Method) [14] is considered the most suitable method for modelling the sound insulation behaviour of poroelastic materials. In fact, this method enables to account for the characteristics of every layer of the samples, with various possible behaviours, and to apply finite size effects [15].

The present work aims at investigating the sound insulation behaviours of nonwovens materials produced from textile waste and bicomponent fibers, following an airlaying

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industrial production process. The possibility of using the studied materials in combination with existing building structures to improve their noise control behavior was explored. The acoustic behaviour of the investigated materials was modeled following the TMM implemented in the AlphaCell® software.

2. METHODS

2.1 Material properties

The investigated materials were innovative nonwoven panels produced from Textile Waste (TW) fibers. An industrial airlaying process using a man-made fiber as binder was followed. A Copolyester/polyester (Co PET/PET) sheath-core bi-component fiber was chosen as thermally bondable material in a percentage of 15%. In this way it was possible to exploit both the low melting temperature (i.e. 100 °C) of the copolyester and the structural integrity of the polyester ensured by its higher melting temperature. Three types of panels (i.e. TW-68, TW-96 and TW-134) differing in density and thickness values were produced (Fig.1).

Figure 1. Picture of the investigated panels.

Tab. 1 outlines the most important properties of the studied materials, useful to evaluate their sound insulation behaviour. An extensive explanation of the experimental measurement of the reported parameters lays beyond the scope of this paper, thus more details can be read in the previously published research study [16].

Table 1. Overview of the most useful properties of the tested materials: density ρ, thickness d and air flow resistivity σ.

Sample ID	ρ [Kg/m^3]	d [m]	σ [kN·s/m^4]
TW-68	68	0.04	17.4
TW-96	96	0.05	31.7
TW-134	134	0.025	95.5

2.2 Sound insulating characterization

The dynamic stiffness s' was experimentally determined in order to characterize the damping behaviour of the tested materials. The resonant method [17] was followed, also considering the contribution of the air stiffness. Three samples (20 × 20 cm) for each type of material were tested measuring the resonant frequency of the fundamental vertical vibration of the mass-spring system formed by the load plate and the resilient material under test. The sample was placed between a steel inertial base plate and a steel load plate of 7.9 kg on which an accelerometer (DJB Instruments Type A/120/V) and a shaker (Signal force/Data Physics) were positioned. The accelerometer measured the vibration obtained when the shaker excited the sample with a logarithmic sweep of 30 s, spanning from 5 to 300 Hz. The output signal from the accelerometer was analyzed with a custom MATLAB® script. All measurements were analyzed with a frequency resolution of 0.2 Hz.

Once the dynamic stiffness was known, the E-modulus and the loss factor η were obtained. The E-modulus was computed according to [18], multiplying the dynamic stiffness by the thickness of the samples. The loss factor parameter was obtained following the Half-Power Point Method [19], analyzing the frequency response function at resonant peak.

Tab. 2 shows the results of the dynamic stiffness, the E-modulus and the loss factor of the tested materials.

Table 2. Sound insulating properties of the tested materials.

Sample ID	TW-68	TW-96	TW-134
s' [MN/m^3]	5.82	4.97	8.51
η [-]	0.22	0.24	0.27
E [MN/m^2]	0.23	0.25	0.21
c [mm]	33.49	14.78	4.91

The compressibility c of the nonwovens was also evaluated following the [20]. An INSTRON 5869 machine was used to test the samples under pressure, evaluating the variation of the thickness value d after applying static load of 250 Pa, 2 kPa and 50 kPa. Three thickness values, respectively named as d_L, d_F and d_B, were obtained. Each load was applied for 120 s. Three samples for each type of material were tested. Compressibility was expressed as the difference between d_B and d_L.

As it can be seen in Tab. 2, the compressibility of TW-68 and TW-96 samples was higher than that exhibited by TW-134. Thus, the TW-134 nonwoven was able to recover the lost thickness after load cycles more than the other two materials, resulting to be more suitable to be used as resilient underlayer in a floating floor structure.

2.3 Application to real-world scenarios

In order to examine the practical applications of the investigated materials, they were incorporated in wall assemblies or in a floating floor and their influence on the overall acoustic insulating performance of the studied structures were investigated.

The analysis considered an untreated (reference) wall (Fig. 2(a)) and two wall solutions in which extra layers were added (Fig. 2(b-c)). The reference wall consisted of clay bricks (6 × 12 × 25 cm) finished with mortar and 1.5 cm thick gypsum plaster on both sides. The first improved solution was a single-leaf wall in which the layer of the textile material was added on the internal side of the reference wall (i.e. single-leaf_68 and single-leaf_96, respectively with TW_68 and TW_96 nonwoven panels). The second solution was a double-leaf wall in which the insulating nonwoven was interposed between two layers of clay bricks respectively 6 cm and 12 cm thick (double-leaf_68 and double-leaf_96 respectively with TW_68 and TW_96 nonwoven panels).

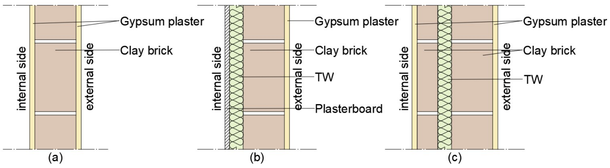

Figure 2. Configurations of wall structures simulated to compare the sound insulation ability of a reference wall (a) with that of single-leaf (b) and double-leaf (c) walls involving the addition of TW-68 and TW-96 layers.

The possibility of using the textile material as resilient underlayer in a floating floor structure was also investigated. A solid concrete floor consisting of a 14 cm thick dense concrete slab, a walking surface of 5 cm thick concrete screed and PVC floor tiles was chosen as reference structure. A textile nonwoven layer was added between the dense concrete slab and the walking surface to obtain the floating configuration (Fig.3).

The sound insulating materials were used considering their real thickness reported in Tab. 1, in order to characterize them starting from the experimental measurements results previously discussed [16].

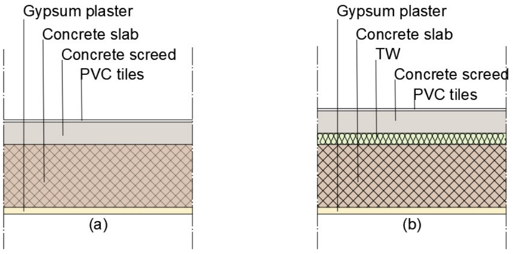

Figure 3. Configurations of floor structures simulated to compare the sound insulation ability of a reference floor (a) with that of a floating floor involving the addition of TW-134 layer (b).

2.4 Calculation method

The transfer matrix method (TMM) implemented in the software AlphaCell® was used to calculate the sound insulation performance of the studied structures [21]. This method computes the response of planar multi-layer systems assumed to be of infinite extent in the lateral directions while the structure is excited by a plane wave. The wave field in each layer is decomposed into forward and backward waves and boundary conditions are applied at each layer interfaces. The principle of the TMM is to consider a vector whose components depend on the position and on the problem to investigate (e.g. in acoustics the pair pressure and particle velocity is typically used), while the transfer matrix of a layer provides the linear relations between the values of the components on each side of the layer. Iterative application of the method allows to compute even the most complex structures.

The following procedure was applied in the present case:

- All layers were considered as porous materials having an elastic frame;
- The elastic behaviour was considered isotropic, thus it was described by four parameters: density ρ, loss factor η, Young's modulus E and Poisson's ratio υ;
- The porous behaviour of TW materials was described by JCA model [22, 23] using five parameters previously determined [16]: porosity, air flow resistivity, tortuosity, characteristic viscous and thermal lengths;
- A finite dimension of the structures (assumed to be 12 m^2 which might be valid for both the wall and the floor of a standard room) was considered in order to take into account the diffraction effect related to the lateral dimensions;

- A diffuse sound field with angles of incidences varying between 0◦ and 82◦ (i.e. between normal incidence and nearly grazing incidence) was considered.

Tab. 3 outlines the four parameters used to describe the elastic behaviour of layers of all studied structures. As previously anticipated, the parameters reported for TW layers were determined in laboratory or computed from experimental measurements, except for the Poisson's ratio. In fact, being the TW samples mostly made of fibers assumed to be parallel to the material plane, υ was assumed to be zero and frequency independent. The parameters reported for the other materials were taken from technical datasheets or from software material libraries.

Table 3. Input materials properties to simulate the acoustic insulating behaviour of the studied structures: density ρ, loss factor η, modulus of elasticity E, Poisson's ratio υ.

Layer	ρ [Kg/m^3]	η [-]	E [MN/m^2]	υ [-]
Plaster	1700	0.01	2500	0.20
Clay brick	1500	0.01	14000	0.20
Plasterboard	800	0.05	3200	0.30
Slab	2321	*	35000	0.23
Screed	1400	0.01	2500	0.20
PVC tiles	1000	0.20	210	0.30
TW-68	68	0.22	0.23	0
TW-96	96	0.24	0.25	0
TW-134	134	0.27	0.21	0

*The loss factor of concrete slab was considered frequency dependent.

The sound reduction index R (also known as sound transmission loss TL) of the walls and the normalized impact sound pressure level L_n were computed by AlphaCell® software. Furthermore, the weighted sound reduction index R_w reported together with the adaptation terms C and C_{tr} was chosen to assess the airborne noise insulation properties of each wall solution [24]. The impact sound pressure level together with the adaptation term C_I was chosen to evaluate the impact sound insulation of the floating floor solution [25].

3. RESULTS

Fig. 4 shows the transmission loss changes with frequency when TW materials were added to reference wall structure. The addition of TW materials led to increased R values over the entire frequency range (except for the first three bands when single leaf was considered), showing higher sound insulating properties for both the single-leaf and the double-leaf walls.

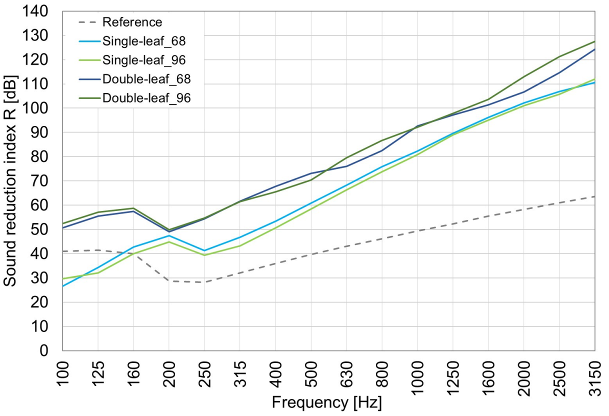

Figure 4. Comparison between sound reduction index R_w of the reference wall and single-leaf and double-leaf configurations.

Tab.3 summarizes the single-number sound transmission index R_w and the relevant adaptation terms C and C_{tr}. As expected, R_w of the single-leaf and double-leaf walls was higher than that of the reference structure. This was due to the damping effect involved by the addition of the TW layer. In fact, the fibrous layer behaved as a spring in mass-spring-mass system that start improving R from the resonance frequency on and, given the large amount of air that the fibrous layer incorporates, the resonance frequency could be predicted to be low. However, R_w obtained for the double-leaf solutions was higher than those for the single-leaf ones. In fact, the mass-spring-mass system obtained interposing the elastic TW cavity between two massive brick layers was more efficient to attenuate the transmission of the acoustic energy.

Table 3. Sound reduction index R_w together with the adaptation terms C and C_{tr} for all the studied wall structures.

Wall structure	R_w (C;C_{tr}) [dB]
Reference	43 (-1;-4)
Single-leaf_68	61 (-3;-10)
Single-leaf_96	60 (-3;-9)
Double-leaf_68	71 (-4;-9)
Double-leaf_96	71 (-3;-8)

Fig. 5 shows the decrease in the L_n value of the floating floor structure when the resilient layer TW was added. In fact, the mass-spring-mass system formed by the slab-resilient layer-walking surface system allowed to reduce the generated impact sound pressure level over the entire frequency range.

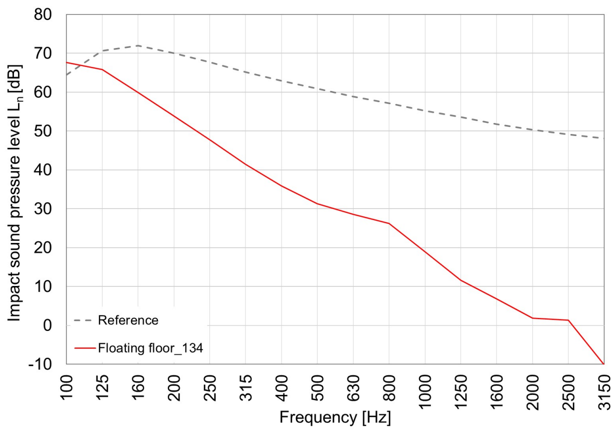

Figure 5. Comparison between impact sound pressure level $L_{n,w}$ with and without the damping layer

The single-number impact sound pressure level $L_{n,w}$ reported together with the adaptation term C_I is shown in Tab. 4. $L_{n,w}$ obtained for the floating floor solution was lower than that computed for the reference floor, confirming the positive damping role played by the TW material.

Table 4. Impact sound pressure level $L_{n,w}$ together with the adaptation term C_I for the studied floor structures.

Floor structure	$L_{n,w}$ (C_I) [dB]
Reference	62 (-0.5)
Floating floor_134	50 (-3)

The obtained results show that a fibrous material can be used not only as sound insulator, but it could work very well also as structural damping [26]. In fact, as demonstrated by Lai and Bolton [27] when layers of fibrous material are placed on panels, the panel motion can be effectively reduced. This is due to the viscoelastic interaction of fibrous medium and the near-field acoustical motion generated by the panel vibration.

4. CONCLUSIONS

Several textile waste panels differing in density and thickness values were developed following an industrial airstream production process. The sound insulating properties of the studied materials were investigated through the experimental measurement of their damping properties (i.e. a total dynamic stiffness and the average loss factor). The results of the laboratory tests were used to carried out simulations of the sound control behaviour of the TW panels. In fact, the transfer matrix method implemented with AlphaCell® software was used to investigate the effect of adding TW layers in different wall and floor assemblies. The increase of the sound reduction index of the wall structures including TW panels proved the positive effect of the investigated materials on the airborne sound insulation performance. In the same way, the reduction of the normalized impact sound pressure level of the floating floor including the TW layer confirmed their damping properties.

5. ACKNOWLEDGMENTS

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