Acoustic properties of agroforestry waste orange pruning fibers reinforced polypropylene composites as an alternative to laminated gypsum boards.

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Abstract

The present paper investigates the acoustic properties of natural fiber reinforced composites. Fibers from orange tree pruning were obtained and subject to different treatments in order to obtain mechanical, thermomechanical and chemi-thermomechanical pulps. These pulps were used as reinforcement for a polypropylene matrix. The obtained composite materials were submitted to acoustical tests in an impedance tubes device. The transmission losses obtained against the fiber content were obtained and discussed. Latter it was researched the influence of the fiber treatments on the soundproof characteristics. A numerical method was used to preview the acoustic insulation of the materials against the sound frequency. Finally the results were compared with that of the most usual lightweight soundproof solutions.

Keywords: Soundproofing, Natural fiber composites, Agroforestry recycling

1 Introduction

Noise is considered one of the worldwide biggest polluters [1, 2]. In the 90's, the World Health Organization (WHO) provided worrying data about that kind of pollution in the United States: about 40% of the population were exposed to road traffic noise with an equivalent sound pressure level exceeding 55 dB(A) daytime and 20% were exposed to levels exceeding 65 dB(A). More than 30% were exposed at night to equivalent sound pressure levels exceeding 55 dB(A) which is disturbing to sleep. In the recent decades, the society progressed significantly, from industrial, technological and social points of view. Most of the actions made by the human beings in relation with the industry, the use of new technologies, or in their day to day interactions with the environment are a cause of noise. Therefore, noise pollution remains a matter to be resolved. The effects on the health due to noise exposure are well known [3]. Most health effects are of a sensorial kind as stress, leading to high blood pressure, coronary heart disease, stroke, and other. In most cases the diagnosis is not immediate, aggravating the situation further. Sound insulation is one of the techniques used to reduce the effects of noise in the cited cases. However, the problem is not completely solved and needs further research to find new materials capable of improving the performance of the conventional solutions [4-6] In the case of buildings, the most used solutions are light materials as the laminated gypsum boards. Construction materials as lightweight aggregate concrete have been researched and its acoustic properties have been characterized [7], but, to the best knowledge of the authors, the proposed agroforestry waste reinforced composites have been not studied.

On the other hand, there is a need for new and innovative materials capable to satisfy new requirements as lightness, sustainability and cost efficiency [8-11]… Composite materials are a very active research field, and the source of many engineering solutions. As an example, natural fiber reinforced composites provide a way to recover and add value to agro-forestry wastes, avoiding its incineration and the resulting generation of CO_2. For this research, the use of orange tree pruning as reinforcement for composite materials can reduce the need for burning, provide low cost alternatives to wood fibers, and extend the value chain for the agricultural industry [12].

The main advantages of using lignocellulosic fibers, instead of mineral fibers, as reinforcement of polyolefin matrices are; their high specific mechanical properties, good aspect ratios, low equipment abrasion during preparation and manufacturing, high availability, low density, and comparatively low cost per volume basis [13]. The last of the potential advantages is clear, as orange tree pruning are agro-forestry wastes with any value. Moreover, the composite materials reinforced with natural fibers, as orange tree pruning, could be considered almost 100% recyclable, as recovering energy by incineration is possible.

In many of the States of the European Union the basic quality soundproofing levels that all the buildings and installations must achieve are regulated. Hence, all the proposed solutions must be adapted to these regulations. The norms include materials and procedures to correctly obtain the targets, as well as the tests to be performed, to prove the quality of the results. While some of the regulations are informative, some others are mandatory, setting bounds for the insulation, limit values for the reverberation time and installation vibrations. The energy savings must be also noted, having in account the guidelines to obtain buildings with an envelope that limits the energy demands to obtain a correct thermal comfort. Moreover, Directive 89/106/CEE-construction products, and Regulation UE n. 305/2011, that is applicable from July 2013 and must be developed by the member countries, adds in one of the annexes the regard to the use of sustainable and natural resources. The annex establishes that new building works must be designed, build and demolished in a way that the use of natural resources is sustainable and ensure: a) the reuse and recycling of all the materials after the building is demolished, b) the durability of the building and c) the use of raw materials and secondary materials must be compatible from an environmental point of view. In that context it is possible to propose real sound-proofing solutions, based on the studied composite materials, with application to new building works and to building rehabilitations.

In this work, mechanical pulp (MP), thermomechanical pulp (TMP), and chemi-thermomechanical pulp (CTMP) from orange tree pruning were used to prepare composite materials, formulated with a 20 to a 50 wt% of MP, TMP, and CTMP as reinforcement of a polypropylene (PP) matrix. The acoustic properties, against aerial noise, of single layer soundproof elements made with the formulated composites are tested and discussed. The objective of the research is finding the influence of the percentage of reinforcement on the acoustic properties of the composite materials. It was also researched the influence of the chemical treatments on such properties. The researched materials showed themselves light and feasible solutions for soundproofing against aerial noise, and a clear alternative to the conventionally used laminated gypsum boards.

2 Materials and methods

2.1 Materials

The composites were prepared using polypropylene (PP) homopolymer (Isplen PP099 G2M) with an average melt flow rate (230 ºC; 2.16kg) of 55 g per 10 min and a density of 0.905 g/cm3, kindly provided by Repsol-YPF (Tarragona, Spain). Polypropylene functionalized with maleic anhydride (MAH-PP) (Epolene G3015) with an acid number of 15 mg KOH/g and Mn of 24800 Da was acquired from Eastman Chemical Products (San Roque, Spain). Biomass from orange tree pruning fibers (OPF) obtained from seasonal tree pruning was supplied by Mas Clara de Domeny (Girona, catalonia, Spain). Other reactants were used: Diethyleneglycol dimethyl ether (diglyme) was supplied by Clariant and was used as dispersing agent. Decahydronaphthalene (decalin) (190 ºC boiling point, 97% purity) supplied by

Fisher Scientific was used to dissolve the PP matrix in the fiber extraction from composites process. The reactants that were used for fiber treatment are summarized as follows: sodium hydroxide (Merck KGaA, Darmstadt, Germany), antraquinone (Badische Anilin & Soda Fabric AG, Germany) used without any further purification. Pes-Na (polyethene sodium sulfonate) is an anionic polyelectrolyte. Poly-DADMAC (polydimethyl diallyl ammonium chloride) is a cationic polyelectrolyte. Pes-Na 0.001N and Poly-Dadmac 0.001N were supplied by BTG Instruments GmbH (Germany).

2.2 Preparation of orange tree pruning derivatives

All the biomass from orange tree pruning was submitted to a crushing and classification process. Some OPF samples were submitted to a defibering process under cold aqueous conditions in a Sprout-Waldron equipment to obtain mechanical pulp (MP) with a higher aspect ratio. This process gave almost 100% yield with respect to the starting material [14, 15]. Another OPF sample was submitted to a thermo-mechanical process (vaporization followed by defibering). The OPF were heated to 160 ºC for 30 min, and the obtained pulp was rinsed with water and then passed through Sprout-Waldron equipment, resulting in thermo-mechanical pulp (TMP) with an increased reactant surface, and around 95% yield. For OPF chemi-thermomechanical fibers, the OPF were submitted to a sodium/ hydroxide/antraquinone (AQ) cooking process (5% NaOH: 0.1% AQ) in a liquid to fiber ratio of 4:1, working at 160 ºC for 20 min. Afterwards, the slurry was washed and shredded in Sprout-Waldron equipment, giving around 90% yield.

2.3 Compounding

Composite materials comprising 30 to 50 wt% PP/OPF with and without coupling agent were obtained. The materials were prepared in a Brabender® plastograph internal mixing machine. The working parameters were 80 rpm for OPF during 10 min at a temperature of 180 ºC. In the case of the coupled composites, the MAH-PP was added to the plastograph with the PP pellets. The resulting blends were ground with a knives mill, dried, and stored at 80 ºC for at least 24 h before processing. Materials with 30 to 50 wt% MP from OPF where prepared and will be referred in the text as MP a%, were a% is the OPF content. Similarly composite materials with a 30 wt% of TMP and CTMP from OPF were obtained.

2.4 Composite processing

The samples for the tensile test were produced with a steel mould in an injection-molding machine (Meteor 40, Mateu & Solé). Ten test specimens from each obtained composite blend were used for the experiment. The processing temperatures were 175, 175, and 190 ºC (the machine has three heating areas), the last corresponding to the injection nozzle. First and second pressures were 120 and 37.5 kgf/cm2, respectively. Standard composite specimen samples (approx. 160 x 13.3 x 3.2 mm) were obtained and used to measure the tensile properties in agreement with ASTM D638.

2.5 Mechanical characterization

Prior to the mechanical testing, the specimens were stored in a Dycometal conditioning chamber at 23 ºC and 50% relative humidity for 48 h, in agreement with the ASTM D638 standard. Afterwards, composites were assayed in a Universal testing machine (InstronTM 1122), fitted with a 5 kN load cell and operating at a rate of 2 mm/min. Tensile properties were analyzed by means of dog-bone specimens, according to the ASTM D638 standard. The Young's modulus was obtained with an extensometer. Results were obtained from the average of at least 5 samples.

2.6 Acoustic characterization

The acoustic characterization of the materials is a fast growing research line, mainly due to the expanding services that many companies are required to provide. Some examples are the textile, paper and composite materials industries.

One of the main acoustic parameters to characterize is the specific flow resistance of the composite materials. There are international norms that provide guidance to measure that parameter (ISO 9053:1991), and as an alternative there are also widely accepted experimental procedures [16]. The procedure is based on measurements in an impedance tube, as one of the methods to measure the absorption coefficient at normal incidence, described by the cited norm [17], a parameter of high interest to acoustically characterize the materials as absorbent. However there are no standard procedures to estimate the transmission losses in materials or panels from the impedance tubes. Nonetheless there are some authors that based their measurements of the transmission losses, and their acoustic characterization of the materials, from impedance tubes tests [18-22].

In the Polytechnic School of Gandia, a new method to measure the transmission losses (TL), based on impedance tubes, was developed and used for that research. The design and development was based on the available literature.

The device is based in two impedance tubes used to measure the transmission losses (Fig.1).

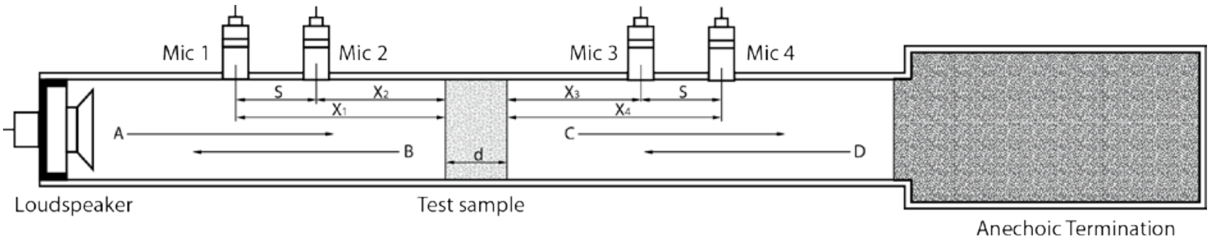


Figure 1: Diagram of the device used to meassure the transmission losses

The loudspeaker, placed at the end of the tube, generates plane waves. The path followed by these plane waves inside the tube are referenced in figure 1 as A, B, C and D the microphones, two placed in the tube between the loudspeaker and the sample, and two placed at the rear end, between the sample and an anechoic termination. The device represents the description of the transference matrix that represents the incident and reflected waves from the upper and lower pats of the sample. If the matrix coefficients are known it is possible to obtain the *TL* from eq.1:

$$TL = 20\log_{10}\left|\frac{e^{jks} - H_{12}}{e^{jks} - H_{34}}\right| - 20\log_{10}\left|H_t\right| \qquad (1)$$

Where S is the distance between the microphones, H_{12} and H_{34} represent the transference function between the microphones 1 and 2 (preceding the sample), and 3 and 4 (subsequent to the sample) respectively, defined by eq.2:

$$H_{i,i+1} = P_{i+1}/P_i \qquad (2)$$

Were P_i is the complex acoustic pressure at point i, and is measured by the microphones.

The relation between the auto spectrums, H_t is defined by the eq.3:

$$H_t = \sqrt{\left|S_d / S_u\right|} \tag{3}$$

Where S_u is the auto spectrum preceding the sample and S_d is the auto spectrum subsequent to the sample, that are obtained by applying Eq 4 and 5.

$$S_d = P_3 \cdot P_4^* \tag{4}$$

$$S_u = P_1 \cdot P_2^* \tag{5}$$

Where P_2^* and P_4^* are the complex conjugates of the complex acoustic pressure at points 2 and 4.

There are some particularities that define the test facility designed at the Polytechnic School of Gandia. The tube preceding the sample measures 1315mm, and the section subsequent to the sample measures 1233mm. Both tubes have a 40mm interior diameter. The distances X_1 and X_2 were 120 and 80 mm, respectively, and X3 and X4 120 and 80 mm subtracting the sample thickness. The prototype allows for tree different distances between the microphones, while the standard mechanisms allow only two. The distance between the microphones determines the spectrum of frequencies to measure, as it must be ensured a plane propagation wave in the tube (ISO, 1998). In that work, a 32mm distance was used to perform all the measures.

2.7 Prediction of the acoustic insulation

There are a lot of models to predict the acoustic insulation, both for aerial and impact sounds [23-27]. Many models used to describe the airborne insulation are based on the coupling effect between the acoustic impedances of the layers of a composite to obtain the global isolation of all the layers. The result is the index of sound reduction (R) or the Transmission Loss (TL) (ISO 10140-2, 2010) (ASTM E90-09), that could be expressed as a function of the frequency or as a global value.

3 Results and discussion

Table 1 shows the main mechanical properties of the composites, used to perform the acoustic insulation calculations. A 15mm gypsum board has a 10 to 12km/m^2 mass, being slightly lighter than the proposed composite materials.

All the tested composite materials showed airflow resistance values higher than 1000 kpas/m^2. The airflow resistance is the resistance experienced by air as it passes through a material. This property is directly related to the capacity of the material to absorb o reflect sound energy. The high values for the airflow resistance shown by the researched composites imply that such materials act as a sound impervious layer.

Material	Young's Modulus E (GPa)	Thickness (mm)	Mass (kg/m^2)	Critical Frequency (Hz)
MP 20%	2.8	15	14.8	2372
MP 30%	3.7	15	14.8	-
MP 40%	4.3	15	14.8	-
MP 50%	5.1	15	14.8	-
TMP 30%	3.1	15	14.8	2600
CTMP 30%	2.9	15	14.8	2687

Table 1: Main characteristics of the tested specimens

The materials showed a slightly toasted color as the amount of reinforcement was increased (Figure 2). Likewise, the microphotography, of the fracture zone shows the good interface between the fibers and the matrix. The material is compact and not porous, as the matrix totally wets the fibers.

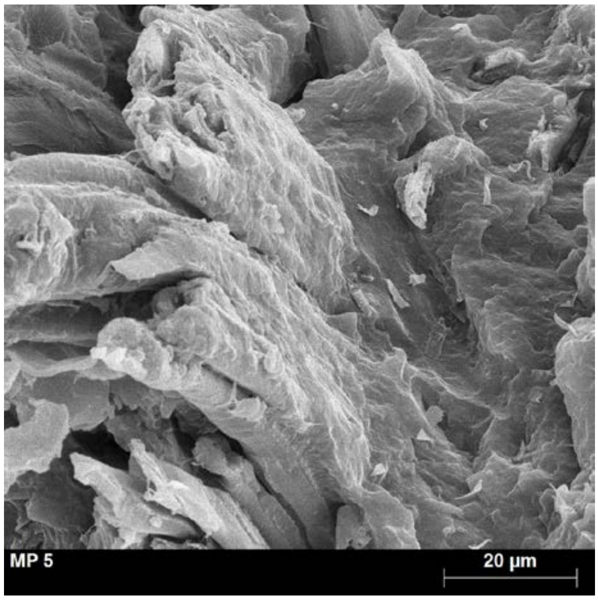


Figure 2: Visual appearance of the composites and microphotography of the fracture zone in a tensile strength specimen.

Figure 3 shows the Transmission Loss measured in the tested 20 to 50 wt% MP composite materials.

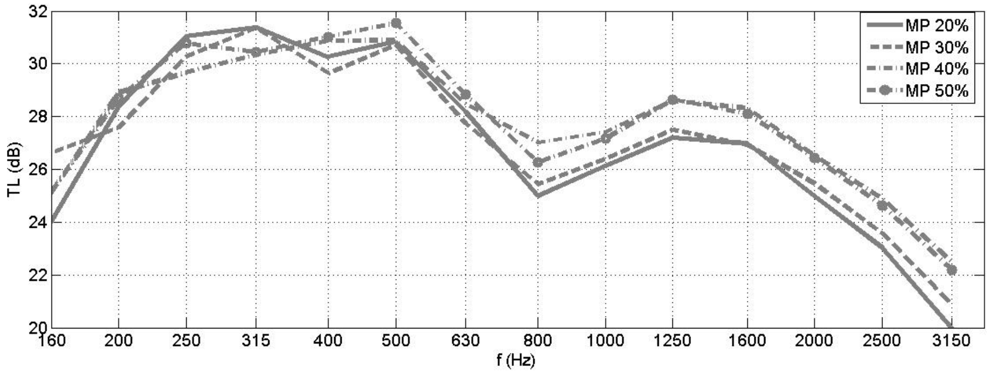


Figure 3: Transmission loss against the frequency for the 20 to 50% mechanical pulp polypropylene reinforced composite materials

Figure 4 shows the transmission loss or insulation versus the frequency. All the values were obtained under incidence normal conditions. The test were performed in the impedance tube defined in the methods section

The results are similar for the 20 to 50 wt% MP from OPF composite materials. Nevertheless, in the case of higher sound frequencies, the composite materials with 40 to 50 wt% of MP from OPF showed higher values of sound insulation. In the case of mid to low frequencies, the values are similar for all the tested composite materials. That range of mid to low frequencies are the most interesting to have in account as are the most difficult to attenuate. Having that in account it was decided to continue the test with the composite materials with 30wt% OPF contents. Consequently, MP 30%, TMP 30% and CTMP 30% composite materials were prepared ant tested. Figure 3 compares the Transmission Loss measured for the 30 wt% MP, TMP and CTMP composite materials.

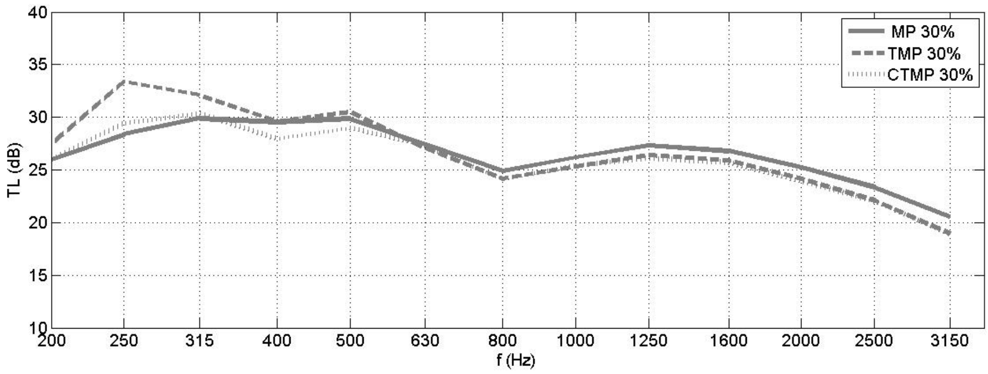
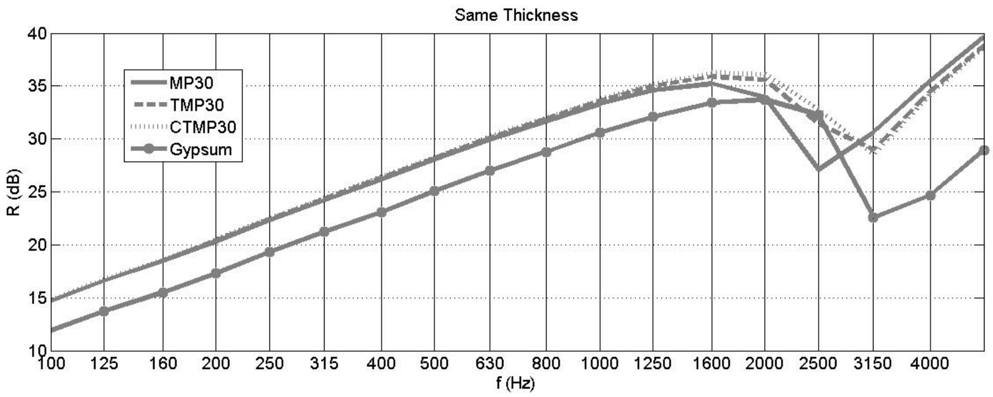


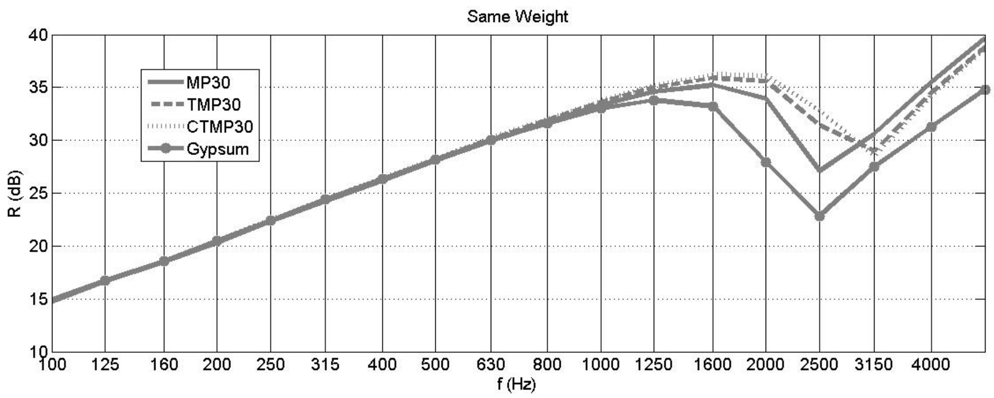
Figure 4: Transmission loss against the frequency for the 30% mechanical, thermomechanical and chemi-thermomechanical pulp polypropylene reinforced composite materials

In the case of the tested materials, the value of the transmission loses (TL) are very similar, regardless of the fiber treatment. Only the TMP 30% showed higher values for some frequencies.

Figures 5a and 5b show the value of the index of sound reduction that are the result of the numeric simulation. The calculations were made for the 30 wt% MP, TMP and CTMP composite materials, and were compared with that of a lightweight common insulation material (laminated gypsum boards). Two different simulations were made, one supposing a constant thickness for all the samples (fig. 3b), and the other presuming that the mass of all the samples was the same (fig. 4b).



a)



b)

Figure 5: Numeric simulations of the index of sound reduction for the 30% mechanical, thermomechanical and chemi-thermomechanical pulp polypropylene reinforced composite materials, compared with laminated gypsum boards.

The thikness was presumed to be of 13 mm and the mass of 13.1 kg/m^2.

The values for the Transmission Loss or insulation shown in figure 4 were obtained under difuse field conditions. The numerical methods that allow obtaining the values require an integration limit angle [28]. The influence of the limit angle on the precision of the computed values is an issue of current interest. The limit angle that was used to obtain the values shown in figure 4a and 4b was 78º. It was found that all the tested materials showed a sharp decrease of the insulation property between 2000Hz and 3000Hz. These values match the critical frequency, obtained from the mechanical characterization (Table 1).

The weighted airborne sound insulation values are compared in figure 6.

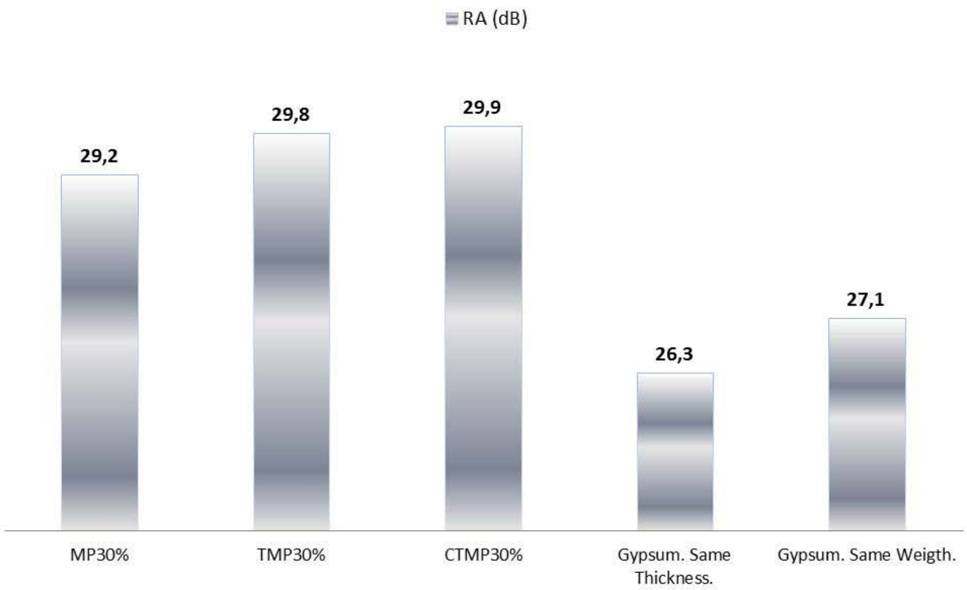


Figure 6: Acoustic insulation, global values comparison

The global values of the evolution show that all the tested composite materials had higher sound attenuation index that that of the commonly used insulation materials. The values are 3dB higher in the case of the same thickness specimens, and 2dB higher for the case of same mass specimens.

4 Conclusions

In this work, orange tree pruning fibers reinforced polypropylene composites are presented as airborne insulation solutions. The study presents the behavior of the acoustic properties ofsuch composites against aerial sound. Their mechanical properties, together with their relative lightness and their soundproofing properties, show similarities to that of the impermeable layers, like the laminated gypsum boards, commonly used by builders.

The influence of the reinforcement contents against the acoustic properties was investigated. Reinforcement contents between 20 to 50% were tested. Likewise, it was investigated the incidence of the fiber treatments in the acoustic properties. While such treatments showed some impact on the mechanical properties, only showed a slight incidence on the acoustic ones.

Moreover, the obtained insulation properties of the composites are compared with that of the laminated gypsum boards, commonly used as lightweight solution for building. The values were compares by frequencies and by weighted. To obtain this values, a mathematical prediction model was used. The model allowed obtaining the sound reduction index (*R*) in the diffuse field, understood as random incidence.

The tests developed by using an impedance tube, to investigate the impact of the reinforcement content, showed that by increasing the percentage of reinforcing fibers, the insulation could increase by 2dB. The Transmission Loss increased significantly with reinforcement percentages higher that the 20%, mostly for the medium and high frequencies. It was found that for reinforcement contents higher than the 40 to 50% the soundproofing remained saturated

Composites reinforced with a 30% of MP, TMP and CTMP fibers were submitted to test in the impedance tube. The results showed that the fibers treatment had little influence in the sound insulation properties.

Predictive models were used to compare the acoustic properties of the composites with that of the laminated gypsum boards. Regardless of considering equal mass or equal thickness samples, the soundproofing properties, against aerial sound, of the orange tree pruning fibers reinforced composites were always superior to that of the laminated gypsum boards. Similarly, when comparing the weighted value, the composites showed properties from 2 to 3dB higher than that of the laminated gypsum boards.

The mechanical properties of the composite materials, together with the obtained sound insulation properties, make those materials due to be used as light insulation solutions. The application this new material is especially interesting for buildings, but it is possible to use such materials in other fields, as cars or product design.

It will be necessary to perform a lifecycle assessment to study the environmental impact of the agroforestry waste reinforced PP as light insulation solutions, in comparison with laminated gypsum boards, to find if its recyclability compensates the energy need to obtain the raw materials.

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