Production of eco-sustainable insulating panels by recovering wood waste: fabrication and preliminary experimental characterization of thermal and acoustic properties

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Abstract. The work was developed in the ReScaLe - FiAer project framework, funded by the Fondazione Cassa di Risparmio di Perugia. It is focused on the identification and collection of multiple high quality wood waste from a local window manufacturer. Three types of wood were available, from different tree species (pine, oak, and mahogany) and sizes (pieces of wood, mixed coarse chips, and mixed fine chips). Preliminary analyses were performed in order to evaluate the properties of the raw material. For each type of wood, eco-sustainable panels (300x300 mm²) were assembled by gluing. Multiple tests were carried out in order to identify the optimal mixtures and to ensure a good mechanical resistance with the minimum adhesive use. Panels were assembled by using vinyl glue, easily available and cheap, and flour glue, with a lower environmental impact and safe for people's health. The thermal conductivity of the panels was measured by means of the Small Hot Box experimental apparatus: it varies in the 0.071-0.084 W/mK range, at an average temperature of 10°C, depending on the tree species and regardless of the type of adhesive used. Furthermore, 100-mm diameter cylindrical samples with two different thicknesses for each type of wood and glue were fabricated, in order to investigate their acoustic behaviour in an impedance tube. The use of flour glue improves the sound absorption and insulation performance of the samples.

1 Introduction

Climate change and global warming are becoming very important issues also in the building sector: carbon dioxide emissions in the atmosphere significantly increased during twentieth century, mainly due to energy use and anthropogenic activities. In this context an adequate knowledge of environmental issues is required. Both the correct energy management obtained through concrete actions that promote energy efficiency of buildings and a rational use of renewable sources are required as possible solutions [1]. Buildings manage by around 40% of energy consumption and 36% of CO₂ emissions in the EU [2]. The improvement of the energy performance of the building envelope and the reduction of the consumptions for

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heating and cooling, which can be achieved by introducing innovative eco-sustainable materials, could play a fundamental role in the control of global warming and climate change.

In this context, the thermal insulation properties of the opaque and glazing components are crucial in the building design step: the nearly zero energy buildings (NZEB) are the final aim to limit heat losses and to reduce energy consumptions for buildings air conditioning. Wood is one of the most promising secondary raw materials, in a circular economy perspective [3-5]: it can also be useful for creating compounds, biofuels, and chipboard panels [6]. It is one of the most resistant and long lasting natural organic materials and wood fibres have excellent thermal and acoustic insulation properties. Moreover, the wood fibre panels are fully compostable and they are characterized by thermal inertia and breathability, with a reduced environmental impact. Many research works available in the literature report the properties of wood as a waste in wood works. The addition of binder and glue is frequent in many processed wood products, in order to give shape stability, but it results in a significant increase of air flow resistivity and lower sound absorption. Nevertheless, acoustic measurements show very high sound absorption values, in particular above 500 Hz [7]. Zoltán Pásztori et al. [8] studied insulating panels composed of shredded bark of *Robinia Pseudoacacia*; it was found that the thermal conductivity of the panels is around 0.06 W/mK, which is similar to the value of other natural insulation materials. Furthermore, it was found that the formaldehyde emissions of finished boards are much lower than that of other wood-based panels. Another interesting research study deals with Life Cycle Assessment (LCA) of an innovative insulation panel based on eucalyptus bark fibres [9]. The eucalyptus bark panels, with densities in the 25-50 kg/m³ range, showed lower embodied energy and carbon emissions than traditional insulation materials (expanded polyurethane, polystyrene, glass fibres, and glass wool). Therefore, they could be an attractive insulation material for a more sustainable building sector. Many other research works confirmed that the use of discarded products of industrial and agricultural processes can be used as based materials for insulating panels. In [10] locally available by-products (rice husk, wheat husk, wood fibre, and textile waste fibre) were used to produce composites with a biodegradable poly(butylene adipate-co-terephthalate)/poly(lactic acid) (PBAT/PLA) blend binder by hot pressing. The density and thermal conductivity of the produced composites were in the 378–488 kg/m³ and 0.08–0.14 W/mK range, respectively. The lowest thermal conductivity (0.08 W/mK) was observed for the rice husk composite with a density of 378 kg/m³. The thermal insulation performance of bamboo- and wood-based shear walls in light-frame buildings was studied in [11]. All the results indicate that the thermal insulation performance of bamboo composites were slightly lower when compared with wood ones, both at the material and at shear wall levels.

In this context the ReScaLe – FiAer project (Produzione di pannelli isolanti eco – sostenibili mediante REcupero degli SCArti del LEgno derivanti dalla realizzazione di sistemi FInestrati innovativi a base di AERogel), funded by the Fondazione Cassa di Risparmio di Perugia, is focused on the reuse of multiple high quality wood waste collected at a local window manufacturer. The available wood, derived from the different processing phases, is of three different types for tree species (pine, oak, and mahogany) and for size (pieces of wood, mixed coarse chips, and mixed fine chips). Preliminary analyses were performed in order to evaluate the properties of the raw material; the many different samples were manufactured by assembling the different kinds of wood with both vinyl and flour glue. The thermal performance of the panels was carried out by means of the experimental apparatus called Small Hot Box. Finally, the acoustic performance was tested by means of an impedance tube (acoustic absorption coefficient and transmission loss).

2 Materials and methods

In Umbria region (central Italy), wood represents one of the most used materials for the production of the glazing system frames. Different types of high quality wood waste, deriving from different processing phases were provided by the FAIL Società Cooperativa (Marsciano, Italy) [12], partner of the project ReScaLe – FiAer, which operates in the window sector for many years. Scraps from the manufacture of pine window frame (about 70% of the total production of the company), mahogany, and oak with different sizes were collected. Three main typologies of waste wood were available: pieces of wood (average density 540 kg/m³, 740 kg/m³, 460 kg/m³ for pine P, oak O, and mahogany M, respectively), mixed coarse shavings (CS, mainly composed of pine) and mixed fine ones (FS, more homogeneous).

2.1 Raw material characterization

In order to evaluate the properties of the raw material, pieces of wood of each kind were chipped with a 1-mm sieve; moreover, the mixed chips (coarse and fine) were further grinded (250 µm sieve). Wood powder samples were characterized at University Perugia Biomass Research Centre (CRB) [13]: the results are reported in Table 1.

Table 1. Raw materials characterization.

Thermogravimetric analysis						
	P	O	M	CS	FS	
humidity [%]	8.2	6.0	9.2	8.0	8.5	
volatile matter [%]	74.5	74.7	71.8	76.2	75.6	
dry volatile matter [%]	81.2	79.2	79.1	82.8	82.7	
ash [%]	0.6	0.3	0.9	0.1	0.2	
dry ash [%]	0.7	0.3	1.0	0.1	0.2	
fixed carbon [%]	16.6	19.3	18.1	15.8	15.6	
dry fixed carbon [%]	18.1	20.5	19.9	17.2	17.1	
CHN analysis						
	P	O	M	CS	FS	-
carbon	0.7	0.2	0.3	0.1	0.1	
hydrogen	48.6	48.3	47.0	47.4	46.8	
nitrogen	7.4	6.9	7.2	7.8	7.7	-
Calorific value						
	P	O	M	CS	FS	
Higher Heating Value HHV [MJ/kg]	19.1	19.0	18.4	19.1	18.8	

The LECO TGA-701 apparatus was used for the thermogravimetric analysis and moisture, ash, and volatile substances contents and thermal stability curves were evaluated, according to ASTM E1131-08. Each sample (an amount of about 0.3 gr) was heated up from ambient temperature (about 25°C) to 900°C under air atmosphere, with a flow rate of 3.5 l/min and a heating rate of 20 °C/min. The samples were placed in ceramic crucibles positioned in a revolving carousel; the weight loss of the material depending on the temperature was measured by positioning each crucible above a balance [14–16]. Carbon, Hydrogen, and Nitrogen contents were measured by means of a LECO Truspec CHN elementary analyser [13]. An amount of about 0.1 gr of each sample was wrapped with a specific tin sheet and inserted in the instrument, in order to be tested according to EN-ISO 16948:2015 [17]. Moreover, the Higher Heating Value HHV of the biomass was measured by

means of a calorimeter LECO AC 350 [13] following the hyperbolic method, in compliance with EN ISO 18125 [18]. The sample (amount of about 0.7 gr), burned in a controlled environment, developed heat which was transmitted to the distilled water in which it is immersed. The temperature variation of the distilled water was measured by means of a thermometer with a precision of 0.0001°C.

Taking into account thermogravimetric analysis, no-relevant differences were found between the samples. A weight loss of about 10% up to 100 °C linked to the loss of humidity of the samples can be observed in the stability curves, regardless of tree species and particle sizes. The weight remains constant up to about 230 °C, a value beyond which the loss is considerable (up to about 30%). In the panels fabrications, especially when made with hot presses, it is therefore necessary to set 230 °C as the upper temperature limit. The carbon content in the raw material, related to HHV, is similar for the samples (47 % for mahogany and mixed fine shavings with a superior calorific value of 18.5 MJ/kg; 49% for pine with a superior calorific value of 19.1 MJ/kg), according to data available for different wood types (in the 48% - 52% range) [19].

2.2 Fabrication of eco-sustainable opaque panels: sample description

In order to fabricate the samples, wood pieces were firstly chipped using a hammer chipping machine model TRITO 25/66 (ISVE, Italy), available at University of Perugia, with a 30-mm sieve. Each type of wood (pine, oak, and mahogany) was subjected to three grinding steps, in order to obtain a homogeneous size (Figure 1 a).

Several preliminary investigations were carried out about the type of glue to be used to assemble the samples. As a choice, polyvinylacetate (PVA) glue Vin was considered, due to its availability, low cost, and low degree of toxicity. Moreover, it penetrates into the wood fibers, involving perfect gluing and elements with a resistance greater than that of the same piece of wood are obtained. However, in order to reduce the environmental impact, the flour glue (Flo, mixture of flour and water) was purposely prepared in the laboratory (Figure 1 b).

Fig. 1. Wood chipped (a); flour glue (b); identification of the optimal mixture (c) (d).

In order to obtain panels with good mechanical and compactness properties with the minimum amount of glue, more than 30 small samples were preliminarily assembled: an amount of wood chips (30 gr) was mixed with different percentages of both vinyl glue and water and flour glue (Fig. 1 c and d). At the beginning, mixtures consisting of 5% by weight of PVA glue and 5% of water were made, but the sample did not thicken. The amount of glue was gradually increased until the optimal mixture was identified: 50% of wood, 25% of vinyl glue, and 25% of water. Similar tests were conducted to assemble the samples with natural glue (flour and water), which was slightly worse in terms of resistance: it was necessary to add 60% by weight of glue in the mixture. According to the optimal identified mixtures (50% wood, 25% vinyl glue, and 25% water for samples with vinyl glue and 40% wood and 60% flour glue and water for panels with natural glue), panels were assembled for each tree species (pine, oak, and mahogany) and type of glue (vinyl and flour) by hand at room temperature. The mixture was inserted into moulds with different shapes and sizes, by using non-adhesive

paper on the walls, so that the mixture did not bond to the surfaces, and left to compact under weights for a few days. Each panel was then removed from the mould and it was kept in oven at 70 °C for 24 h, in order to remove exceeding water.

For the thermal characterization, samples of 300x300 mm² dimensions were fabricated. The main features of the samples are summarized in Table 2. The thicknesses of the panels were not very constant (0.034 – 0.045 m), due to the manual assembly. Among the samples with PVA glue, the oak one is characterized by the highest density (345.5 kg/m³), in compliance with the value of the raw material. This difference disappears with the use of natural glue, probably due to different boiling times and therefore thickening during its preparation.

100-mm diameter cylindrical samples were assembled for acoustic characterization, one for each type of wood and adhesive, with two different thicknesses (25-mm and 50-mm, very constant), for a total of 12 specimens. Also in this case, using flour glue the density differences between the woods (with the same thickness) are less marked, especially for the 50-mm thick (Table 2).

Table 2. Main characteristics of the examined samples for thermal and acoustic measurements.

Samples for thermal characterization (300x300 mm)					
sample	adhesive	acronym	thickness [m]	density [kg/m³]	picture
pine	vinyl glue	P_Vin	0.040	282.2	
	flour glue	P_Flo	0.035	325.2	
oak	vinyl glue	O_Vin	0.034	345.5	
	flour glue	O_Flo	0.036	333.5	
mahogany	vinyl glue	M_Vin	0.040	281.6	
	flour glue	M_Flo	0.045	345.7	
Samples for acoustic characterization (100-mm diameter)					
sample	adhesive	acronym	thickness [m]	density [kg/m³]	picture
pine	vinyl glue	P_Vin_25	0.025	243.4	
		P_Vin_50	0.050	262.2	
	flour glue	P_Flo_25	0.025	298.4	
		P_Flo_50	0.050	304.8	
oak	vinyl glue	O_Vin_25	0.025	271.8	
		O_Vin_50	0.050	292.4	
	flour glue	O_Flo_25	0.025	313.2	
		O_Flo_50	0.050	315.6	
mahogany	vinyl glue	M_Vin_25	0.025	238.6	
		M_Vin_50	0.050	256.8	
	flour glue	M_Flo_25	0.025	305.7	
		M_Flo_50	0.050	307.4	

2.3 Thermal characterization

The thermal performance was evaluated with an experimental apparatus designed and built at the Department of Engineering (University of Perugia), named Small Hot Box [20, 21]. It is composed of a very insulated hot chamber, placed in a room kept at constant temperature. A sandwich insulated panel closes the system and a square opening (0.3 x 0.3 m dimensions, for a total area of 0.09 m²) represents the central part designed for the sample location. The cold side of the system is the laboratory room, kept at constant temperature thanks to the HVAC system. The temperature difference between hot and cold side of the sample is kept at least equal to 20 °C. The thermal conductivity of the sample is obtained as the ratio between thermal flux and surface temperature difference, measured by a thermal flux meter installed in the central part of the sample and 4 thermo-resistances on each side, respectively.

The relative uncertainties (type B) $\dot{u}(\lambda)$ of the tests were also calculated in compliance with UNI CEI ENV 13005: 2000 [22].

2.4 Acoustic characterization

The sound absorption properties of the wood-based samples described in Table 2 were investigated in the 100 – 1600 Hz frequency range [24, 25]. The normal incidence absorption coefficient was measured by means of a Kundt's impedance tube, by using the Transfer Function method, according to ISO 10534-2 standard [23]. It is the absorbed part of the acoustic energy of a wave incident on the tested sample in a specific configuration with respect to the total incident energy; the not absorbed part is reflected back to the source side. The Transfer Function Method was used in order to evaluate the Transmission Loss (TL) properties of the panels. Four microphones were used to measure TL: two of them between the samples and the sound generator source and the other two on the back of the sample, in order to calculate the noise abatement.

3 Results and discussion

3.1 Thermal properties

The measured thermal properties and the standard uncertainties type B are reported in Table 3. At least two tests were carried out for each sample, setting the temperature values at 45 °C and 50 °C in the hot chamber. The hot and cold side temperature difference was kept in the 22.7 – 30.0 °C range. Each test was performed with the heat flow meter method for a duration of about 2 hours, during which the stationary conditions of temperature (hot and cold sides) and of the thermal flux were maintained. As expected, the thermal conductivity values increase when the temperature setting is higher (50 °C). The thermal performance depends on the type of wood and glue: thermal conductivity values vary between 0.080 W/mK for the mahogany panel with vinyl glue (thermal resistance equal to 0.50 m²K/W) and 0.92 W/mK for the oak one with flour glue (thermal resistance equal to 0.39 m²K/W). Natural glue tends to slightly worse thermal properties (+ 3.4% is the maximum thermal conductivity increase measured for the oak sample). The relative uncertainty values for some tests are in compliance with the measurement error of the apparatus (5 – 6 %): the conditions were very steady (hot and cold side surface temperatures and heat flux through the samples). However, very high values were obtained for some measurements; for oak samples the uncertainty of the test was up to 23%, probably due to a no-homogeneity of the material, by involving a difference of about 8 – 10 °C between top and bottom surface temperatures.

The experimental data were measured at an average temperature of the sample in the 33 – 35 °C range, due to the operation conditions allowed by the test facility. In order to compare the performance of the investigated panels to those of other wood-based ones available on the market or in the Literature (in general referred to 10 °C or 23 °C), the measured data were reported at the standard temperature of 10 °C, in compliance with ISO 10456 [26]. The mahogany panel is characterized by the best thermal performance, similar to the pine one (λ = 0.071 and 0.078 W/mK in the two tests), as shown in Table 3. The thermal conductivity of the oak panel is slightly higher (0.080 and 0.084 W/mK) than the other wood panels. λ -values are slightly higher than the ones measured by means of the hot plate method in Pásztorý et al. [8] on hot pressed black bark of Robinia Pseudoacacia panels with formaldehyde; they found a thermal conductivity of 0.065 W/mK. However, the obtained results are in agreement

with a previous study of the same author [27], in which λ -values in the 0.061 – 0.077 W/mK range were obtained for black locust, poplar, larch, spruce, and scots pine panels. The thermal properties of some commercial products are also in line with the ones measured for the eco-sustainable panels. An example are the mineralized wood wool panels with cement ($\lambda = 0.065$ W/mK) [28]. However, the thermal properties in general are also highly affected by the density, in addition to the type of wood and glue, the method of assembly, and the chip size. Glued chipboard panels (density of about 700 kg/m³) have a thermal conductivity of 0.16 W/mK, while much lower values (0.04 – 0.05 W/mK) are achieved with very light wood fiber panels (50 kg/m³) [29–30].

The eco – sustainable wooden panels studied in this work are characterized by thermal performance comparable also to those of other standard thermal insulation materials, such as expanded vermiculite (0.077 – 0.082 W/mK) [31].

Table 3. Thermal properties of the eco – sustainable panels.

sample	test [°C]	ΔT_s [°C]	ΔT_{air} [°C]	ϕ_{med} [W/m ²]	λ [W/mK]	R [m ² K/W]	$\dot{u}(\lambda)$ [%]	$\lambda_{@10^\circ C}$ [W/mK]
P_Vin (s=40 mm)	45	19.87	23.19	35.71	0.085	0.47	13	0.076 – 0.077
	50	20.55	28.48	43.87	0.085	0.47	14	
P_Flo (s=35 mm)	45	15.80	23.43	38.60	0.086	0.41	4	0.077
	50	18.89	27.57	47.04	0.087	0.40	4	
O_Vin (s=34 mm)	45	18.66	25.29	48.98	0.089	0.38	18	0.080 – 0.083
	50	22.38	30.02	61.09	0.093	0.37	19	
O_Flo (s=36 mm)	45	12.93	23.57	32.95	0.092	0.39	21	0.082 – 0.084
	50	15.52	24.38	41.10	0.095	0.38	23	
M_Vin (s=40 mm)	45	18.94	24.64	30.06	0.080	0.50	10	0.071 – 0.078
	50	18.43	25.16	40.34	0.088	0.46	12	
M_Flo (s=45 mm)	45	12.83	23.03	23.41	0.082	0.55	8	0.072 – 0.073
	50	16.92	22.73	30.87	0.082	0.55	9	

3.2 Acoustic absorption and insulation properties

The absorption coefficient (α) and the sound insulation properties (TL) trends at normal incidence (100 – 1600 Hz) for each sample are reported in Figure 2. As expected, when the thickness increases, the first peak of the absorption curve increases and it is moved to lower frequencies, according to [32], due to the higher tortuosity of the more thick sample. When considering the same thickness and glue, oak is characterized by the best absorption performance, with a peak value of about 0.9 (O_Vin_50). In order to better compare the acoustic properties of the panels, the Sound Absorption Average SAA index [33] is calculated as of the average absorption coefficient in the twelve 1/3 octave bands from 200 Hz to 1600 Hz (Tab. 4). When considering the same thickness, the flour glue improves the sound absorption performance, with a maximum increase for 25-mm oak (SAA rises from 0.13 with vinyl glue to 0.26 with flour glue). The differences between woods are less marked for the 50-mm thick samples, with both glue types. 50-mm flour glue samples, with lower density differences, are characterized by the same acoustic absorption properties (maximum difference between oak and mahogany with pine is about 8%). The absorption properties of the panels are better than the ones of 30-mm mineralized wood fiber panel studied in [7] (maximum α -value of 0.42 at 1600 Hz).

The oak samples (the most dense) have the best sound insulation properties. In general, the flour glue improves TL-values: the increase is limited in the 25-mm samples (about 1.5

dB), while it is about 2 – 3 dB in the 50-mm thick panels. The sound insulation performance of pine and mahogany with natural glue is similar ($TL = 2.5 - 5.5$ dB for the 25-mm thick samples and $TL = 4 - 7$ dB for the 50-mm ones); oak TL values are about 1.5 – 2.5 dB (25-mm) and 2 – 4 dB (50-mm) higher than pine and mahogany.

Fig. 2. Normal incidence absorption coefficient and Transmission Loss of the panels.

Table 4. Sound Absorption Average (*SAA*) index of the investigated panels.

Sample	SAA	Sample	SAA
P_Vin_25	0.08	P_Flo_25	0.14
P_Vin_50	0.25	P_Flo_50	0.41
M_Vin_25	0.11	M_Flo_25	0.19
M_Vin_50	0.30	M_Flo_50	0.44
O_Vin_25	0.13	O_Flo_25	0.26
O_Vin_50	0.36	O_Flo_50	0.44

4 Conclusions

The first part of the ReScaLe – FiAer project involves the reuse of waste wood deriving from the production process of an Umbrian windows company, in order to fabricate insulating panels. In the present work, the material is characterized taking into account different wood (pine, oak, and mahogany) and glue (vinyl and flour) types. The tests are carried out on the chipped row material, in order to evaluate the density, the thermogravimetric analysis, the Carbon, Hydrogen and Nitrogen contents, and Higher Heating Value. The thermal stability curves show a significant weight loss for temperatures above 230°C. The carbon content, linked to the Higher Heating Value, is similar for all the tested samples.

The wood shavings are used in order to fabricate samples both with vinyl and flour glue. After many attempts to create resistant panels with the minimum amount of glue, the optimal mixtures were identified: 50% of wood, 25% of vinyl, and 25% of water for the samples assembled with commercial glue, and 40% of wood and 60% of flour glue and water for the panels with natural glue. Square samples 300x300 mm² (thickness about 40 mm) and cylindrical ones with 100-mm diameter (25-mm and 50-mm thicknesses) were assembled in order to evaluate the thermal and acoustic properties, respectively. Thermal conductivity values in the 0.071–0.084 W/mK (at an average surface temperature of 10°C) were measured. The best performance are related to the mahogany samples, similar to pine ones, both with vinyl and flour glue. The uncertainty of measurements is limited for the pine and mahogany tests (in the 4 – 3% range), while it is high for the oak panels, probably due to an imperfect homogeneity of the samples involving high variable surface temperatures during the tests. Results are in agreement with the properties of similar commercial panels, with literature

values, and are quite similar to the ones of other standard insulation materials, such as expanded vermiculite. Furthermore, the samples are characterized by good sound absorption and insulation properties tested in an Impedance Tube. Oak panels, with lower densities, have the best performance which improve with increasing thickness. Increasing α - and TL-values are observed with flour glue (SAA equal to 0.44 for oak and mahogany 50 –mm panels and TL = 11 dB at 1600 Hz for oak 50-mm sample). Increasing the thickness of the samples, the differences between wood species are smaller in terms of sound absorption and insulation performance. It is important to notice that the type of glue does not influence the thermal results, while the use of flour glue tends to improve the acoustic properties: the use of natural glue will be therefore preferred in order to reduce the environmental impact of the panels.

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References

1. F. Pierobon, M. Zanetti, S. Grigolato, A. Sgarbossa, T. Anfodillo, R. Cavalli, Life cycle environmental impact of firewood production – a case study in Italy, *Appl. Ener.* **150**, 185–195 (2015)
2. <https://ec.europa.eu/energy/en/topics/energy-efficiency/buildings>
3. K. Mi Hyung and S. Han Byul, Analysis of the global warming potential for wood waste recycling systems, *Journal of Cleaner Production* **69**, 199–207 (2014)
4. E. Ratajczak, G. Bidzińska, A. Szostak, M. Herbec, *Resources of post-consumer wood waste originating from the construction sector in Poland*, *Resources, Conservation and Recycling* **97**, 93–99 (2015)
5. E. Cespirini, G. Resente, V. Causin, T. Urso, R. Cavalli, M. Zanetti, *Energy recovery of glued wood waste – A review*, *Fuel* **262**, 116520 (2020)
6. M. U. Hossain and C. S. Poon, Comparative LCA of wood waste management strategies generated from building construction activities, *Journal of Cleaner Production* **177**, 387–397 (2018)
7. U. Berardi and G. Iannace, Acoustic characterization of natural fibers for sound absorption applications, *Building and Environment* **92(II)**, 840–852 (2015)
8. Z. Pásztor, I. Ronyecz Mohácsiné, Z. Börcsök, *Investigation of thermal insulation panels made of black locust tree bark*, *Construction and Building Materials* **147**, 733–735 (2017)
9. Y. Casas-Ledon, K. Daza Salgado, J. Cea, L.E. Arteaga Perez, C. Fuentealba, *Life cycle assessment of innovative insulation panels based on eucalyptus bark fibers*, *Journal of Cleaner Production* **249**, 119356 (2020)
10. R. Muthuraj, C. Lacoste, P. Lacroix, A. Bergeret, Sustainable thermal insulation biocomposites from rice husk, wheat husk, wood fibers and textile waste fibers: Elaboration and performances evaluation, *Industrial Crops & Products* **135**, 238–245 (2019)
11. J.S. Wang, C. Demartino, Y. Xiao, Y.Y. Li, Thermal insulation performance of bamboo- and wood-based shear walls in light-frame buildings, *Energy & Buildings* **168**, 167–179 (2018)
12. FAIL Società Cooperativa, see <http://www.failgroup.it>

13. C. Buratti, I. Costarelli, F. Cotana, L. Crisostomi and F. Fantozzi, “The Biomass Research Center Laboratory for Biomass Characterization”, in *proceeding of the 14th European Biomass Conference and Exhibition* (Paris, 2005), Biomass for Energy, Industry and Climate Protection, pp. 1855-1858
14. UNI EN ISO 18134-1:2015. Solid biofuels - Determination of moisture content - Oven dry method - Part 1: Total moisture - Reference method
15. UNI EN ISO 18122:2016. Solid biofuels - Determination of ash content
16. UNI EN ISO 18123:2016. Solid biofuels - Determination of the content of volatile matter
17. UNI EN ISO 16948:2015. Solid biofuels - Determination of total content of carbon, hydrogen and nitrogen
18. UNI EN ISO 18125:2018. Solid biofuels - Determination of calorific value
19. <https://www.chimica-online.it/materiali/legno.htm>
20. C. Buratti, E. Belloni, L. Lunghi, M. Barbanera, Thermal Conductivity Measurements By Means of a new ‘Small Hot-Box’ Apparatus: Manufacturing, Calibration and Preliminary Experimental Tests on Different Materials, *International journal of thermophysics* 2016, 37–47
21. C. Buratti, E. Belloni, L. Lunghi, A. Borri, G. Castori, M. Corradi, Mechanical characterization and thermal conductivity measurements using of a new 'small hot-box' apparatus: innovative insulating reinforced coatings analysis, *Journal of Building Engineering* 7, 63–70 (2016)
22. UNI CEI ENV 13005, 2000. Guida all’espressione dell’incertezza di misura (in Italian)
23. ISO 10534-2. Acoustics – Determination of Sound Absorption Coefficient and Impedance in Impedance Tubes – Part 2: Transfer-Function Method, 2015
24. P. Ricciardi, F. Torchia, E. Belloni, E. Lascaro, C. Buratti, *Environmental characterisation of coffee chaff, a new recycled material for building applications*, *Construction and Building Materials* **147**, 185–193 (2017)
25. C. Buratti, F. Merli, E. Moretti, *Aerogel – based materials for building applications: influence of granule size on thermal and acoustic performance*, *Energy and Buildings* **152**, 472 – 482 (2017)
26. ISO 10456:2007. Building Materials and Products - Hygrothermal Properties - Tabulated Design Values and Procedures for Determining Declared and Design Thermal Values, ISO, Geneva, Switzerland
27. Z. Pásztor and I. Ronyecz, *The Thermal Insulation Capacity of Tree Bark*, *Acta Silv. Lign. Hung.* **9**, 111–117 (2013)
28. <https://www.celenit.com/it/celenit-n.php>
29. http://www.caseinpaglia.it/index.php?option=com_content&view=article&id=52&Itemid=63
30. https://unikore.it/phocadownload/userupload/f2201fa35c/Conduktivita_termica_peso_specifico.pdf
31. <https://www.casaenergetica.it/info/tecnologia/materiali/vermiculite.html>
32. P. Ricciardi, E. Belloni, F. Cotana, *Innovative panels with recycled materials: thermal and acoustic performance and Life Cycle Assessment*, *Appl. Energ.* **134**, 150 – 162 (2014)
33. ASTM C423-09A:2009. Standard Test Method for Sound Absorption and Sound Absorption Coefficients by the Reverberation Room Method, ASTM International, West Conshohocken, PA, USA