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Innovative Thermal Insulation Products for a Circular Economy

V Vasile[1], C Petcu[1], V Meiță[1] and M C Zaharia[1]

[1]National Institute for Research and Development in Constructions, Urbanism and Sustainable Spatial Development "URBAN-INCERC", 266 Pantelimon Road, 021652, Bucharest, Romania

vasile@incd.ro

Abstract. The depletion of non-renewable resources is followed by severe ecological and social impacts, and the heavily usage of raw, virgin resources leaves significant, long lasting footprints. In order to move into a more sustainable economic system, a recently more frequently discussed approach for overcoming the current linearity of product lifecycles is the concept of circular economy (CE). The transition to a more circular economy, where the value of products, materials and resources is maintained and circulated (by recycling activities) in the economy for as long as possible, is an essential contribution to the EU's efforts to develop a sustainable, low carbon, resource efficient and competitive economy. In this context, ecological solutions consisting of materials which helps carbon sequestration and necessitates small amounts of energy for production are becoming increasingly popular from buildings construction point of view, namely: the raw material is cheap and in large quantities; have low thermal conductivity; are from a renewable source. The paper presents an analysis of some innovative thermal insulating products made from renewable or recycled resources (recycled plastics, low quality wool, straw, cellulose), their thermal conductivities over a temperature interval and acoustics coefficients (α_s, α_w), the purpose being to inform the market in order to increase the present level of technical knowledge and to facilitate the implementation of high energy efficiency buildings with products from *recycled materials or using industrial by-products.*

1. Context

*The depletion of non-renewa*ble resources is followed by severe ecological and social impacts [1], and the heavily usage of raw, virgin resources leaves significant, long lasting footprints. Especially the use of fossil resources, both as fuel and in the form of plastics has long been criticized for pollution, climate change, threatening the wild life and future generations. New studies [2, 3] show that plastic waste and various additives can infiltrate ecosystems even more and deeply, by disintegration into smaller pieces of micrometre-sized plastic thus raising concerns related on the assimilation of these pollutants into the food chain, with unknown future impact due to the novelty of these substances for the organisms.

In this perspective the European Union (EU) is committed to developing a sustainable, competitive, secure and decarbonised energy system, by different means including the reduction in the greenhouse gas emissions and decarbonising the building stock (responsible for approximately 36 % of all CO_2 emissions in the EU) by 2050 [4], restricting single-use plastics as well as imposing their recycling. Following the EU Directives and regulations, the national legislation and building regulation codes are regularly updated in Member States (M.S.) and force improved regulations for buildings, waste management and other measures to increase energy efficiency, reduce pollution and increase the reutilisation of by-products into economy.

A recent technical report focusing the use of thermal insulating materials in buildings [5] shows the typical annual CO_2 savings from a selection of insulation applications. However, one of the present downsides of building high energy efficiency buildings resides in the vast amount of thermo insulating materials used for the building envelope, in order to achieve the required high thermal resistance. In addition to better designed materials and construction methods, thick layers of insulation, usually between of 10 ÷ 30 cm thick depending on the relevant legislation, construction element, designer and stakeholder determinations are common in all new buildings and the majority of renovation. Materials like polystyrene (EPS), polyisocyanurate (PIR) or polyurethane (PUR) foams, as well as mineral wool (MW) are already integrated in existing, proved technologies for thermal insulation but they could have a negative impact on environment in the building decommissioning or due to a high level of embodied energy in the production phase.

One way to securely reuse by-products and reduce greenhouse gases release could be to incorporate these materials into building products, thus achieving a significant long sequestration of waste and of the embedded carbon dioxide. In this article we focus on the utilisation of organic materials as straw, cellulose, plastic from recycled sources, low-quality wool as thermal insulating building products, thus avoiding the pollution of soil and water with low biodegradable matters and of the air with greenhouses gases as CO_2, methane etc. from the disposal of straw or textile materials (either by burning or by natural decay).

2. Materials and methods

A recent study [6] shows that insulating natural raw materials have gained a small (4–6%), but growing market share in Europe in the last fifteen years. It also stresses that this consumer acceptance is based on the fulfilment of regulatory requirements, i.e. conformity with recently published European standards and/or the issue of European Technical Approvals (ETA). In the following we are focusing mostly thermal insulating properties of the tested products, also showing some acoustic properties of phono-absorption, especially for new organic materials such as low-quality wool from Romania, studied in the last year.

The primary function of thermal insulating products is to save energy and any product will save more energy across its lifetime than it requires for its manufacture [7]. However, in the present context we consider that special attention should be accorded to insulation which embed little energy in production and a high percent of by-products. Therefore, in the following we present as an excerpt from an extensive research focusing more materials, densities and production technologies, some relevant properties for a selection from such products:

- Cellulose (figure 1) as a by-product of different industries, which could be used as a bulk insulation product, e.g. for different cavities. Particularly for this research, a by-product consisting in fine shredded thin paper and cellulose acetate, originating from the tobacco industry, was used;
- Semi-rigid boards (figure 2), consisting of compressed raw vegetable material, mainly agricultural waste from Triticale family, manufactured by compressing dry, selected long straws to a density around 125 kg/m^3 then applying on both board sides fiberglass with the aim of secure the ensemble and to facilitate the plaster application, afterwards fasten the resulting boards by sewing them with polyester fibre yarn;
- Mats (blankets) produced using fibres from recycled plastic bottles (figure 3) using a thermal bonded nonwoven technology. The material used for this product is mainly the polyester made by recycling recipients from polyethylene terephthalate (PET) which are first transformed into fibres then carded and mixed with a variable proportion of thermoplastic fibres which confer the final product different properties, based on the fibres proportion and the temperature / pressure the fibre batt was exposed;

- Mats (blankets) made from low quality wool (80% by mass) (figure 4), originating from non-demanding native races of sheep, resilient to diseases and harsh weather but providing inferior long thick medullated fibres without the required crimp and elasticity, thus integrating into economy wool fibres with characteristics which make them unsuitable for other (traditional) industries i.e. textile industry.

In order to determine the thermal resistance of analysed materials, the guarded hot plate method (GHP) was used. Thermal conductivity tests were performed in a guarded hot plate apparatus ANTER UNITHERM 6000 with thermal conductivity range between 0.02 ÷ 2 W/mK and sample thickness up to 75 mm. Specimen dimensions are (300 × 300) mm and the cellulose, being a bulk material, was tested in a PUR frame which is not affecting the results as it is positioned away from the measuring zone, in the thermal guard area. The measuring method is known to specialists, previous described in the scientific literature [8] and it is according to the specifications of EN 12667 [9]. All specimens were previously conditioned at constant mass in an oven ventilated with air taken at 23 ± 2 °C and heated at 70 °C. After reaching constant mass, the specimens were put into a thin plastic bag, to avoid humidity transfer from the ambient during the test.

Figure 1. Bulk cellulose in a testing frame

Figure 2. Straw board

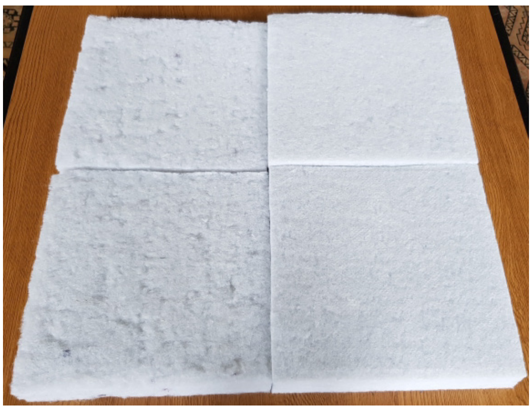

Figure 3. Products made from recycled plastics

Figure 4. Wool mat above a layer of virgin low quality wool (with thick, brittle fibres)

From acoustical point of view, for new organic materials, more specific for four types of products made of low-quality wool from Romania, there were made researches consist of measurements in reverberation room for determine the absorption coefficient, and analysis the results obtain for sound absorption.

The determined acoustic coefficients, the test methodology, the method of assembling the samples in the reverberation room of the Acoustics Laboratory building at INCD URBAN-INCERC – the INCERC Bucharest Branch, and the results obtained by measurements and by calculation estimation and graphical presentation, were in accordance with the standards in force, namely: absorption coefficients acoustics in diffuse field, "α_s" (%), determined according to EN ISO 354 [10] and the acoustic absorption coefficients for evaluation, "α_w", calculated according to EN ISO 11654 [11]. The samples are blankets made from low quality wool (70% by mass) with the following relevant characteristics:

- Product P6 with a density of 18 kg/m^3, thickness 5,5 cm;
- Product P7 with a density of 30 kg/m^3, thickness 4 cm;
- Product P10 with a density of 16 kg/m^3, thickness 10 cm;
- Product P11 with a density of 36 kg/m^3, thickness 4 cm.

For each sample the surface was between 10 ÷ 12 m^2 in accordance with the recommendations of the measurement standard. Samples were placed on the floor of the reverberation room.

3. Results and discussions

Thermal conductivity of materials under real conditions will be distinct from the laboratory results, mainly due to the different temperature and humidity of these materials in an actual building envelope, as well as differences between materials preparation in the laboratory and their installation in building construction. For frequently used construction materials the EN ISO 10456 [13] provides procedures for determining declared and design thermal values.

At this time [13] do not provide coefficients to calculate thermal conductivity of the tested products at different ambient conditions, so the results were analysed and processed to suggest conversion coefficients for temperature (Figure 5) and to be compatible with equation (1), used in [13] for correlating thermal conductivity at a given temperature T_2 with already known thermal conductivity at a certain temperature T_1:

$$\lambda_2 = \lambda_1 \cdot e^{f_T \cdot (T_2 - T_1)} \tag{1}$$

where λ_2 is the thermal conductivity for temperature T_2, λ_1 is the thermal conductivity determined at temperature T_1. For simplicity, in this paper λ_1 was considered λ_{10} i.e. the thermal conductivity at $T_1 = 10$ °C, which is usually the declared value of thermal conductivity.

Thermal conductivity as function of mean specimen temperature are presented in Figure 5 as test results with equations compatible with [13].

From the Figure 5 it is obvious that cellulose is compacting very well, with few and insignificant air gaps, as its exponential coefficient is extremely low and it has a relatively small gradient with temperature. However, the thermal conductivity value is higher than the wool product with a similar density (45 kg/m^3), as the heat flows through paper flakes with higher section than wool fibres. Another issue is that wool products with different densities have distinct thermal conductivities and equation coefficients. The thermal conductivity is lower for the product with density value of 65 kg/m^3, and it also have a smaller gradient with temperature as the fibres are more compact leaving minor air gaps.

For comparison with some existing construction materials, thermal conductivity of tested materials is shown in the Figure 6 along with usual insulation products, for which values and calculation methods from [13] were used. From this perspective, comparing the results obtained for the tested products and the thermal conductivity of some materials already in use, it is obviously that the tested products demonstrate very good thermo insulating properties, at least in dry condition.

Acoustic results are presented below in the figures 7 ÷ 10 as acoustic absorption coefficients calculated for a 1 m^2 sample and table 1 summarizes the results of α_w (as defined by EN ISO 11654), obtained for the samples tested in the reverberation room.

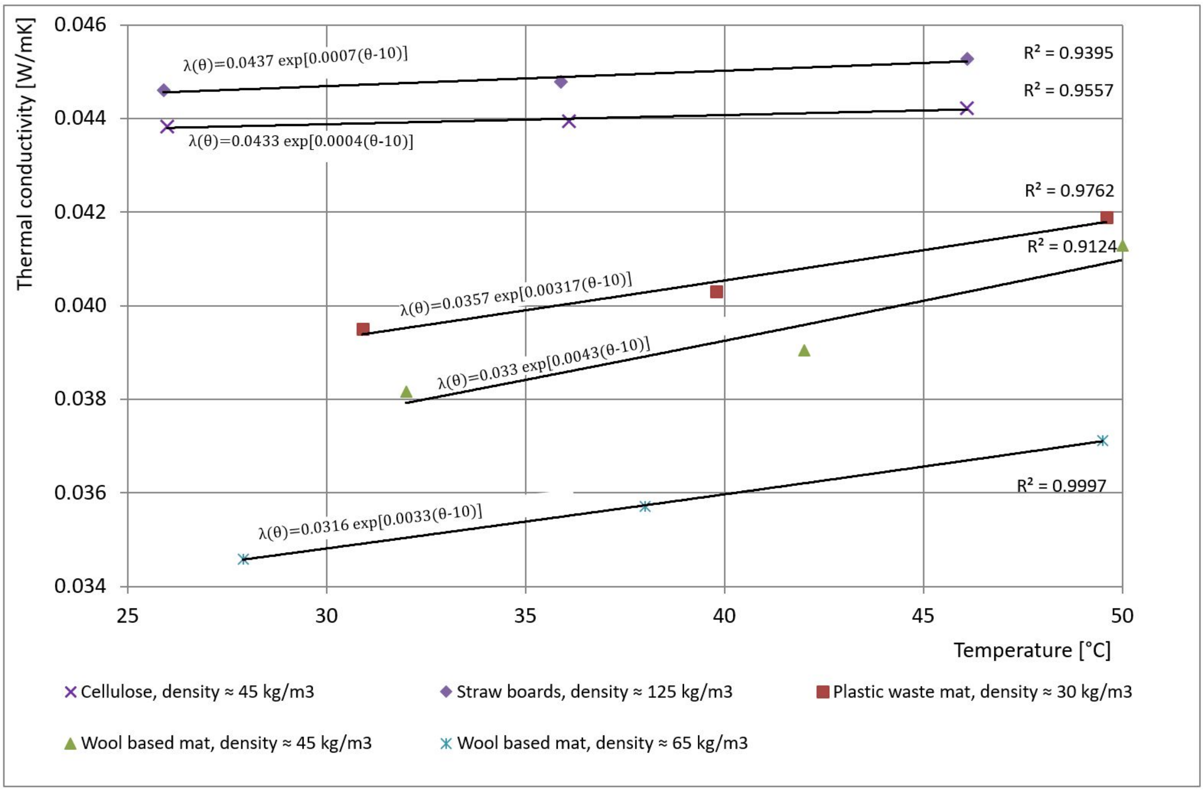

Figure 5. Test results, correlations and exponential equations as required by EN ISO 10456

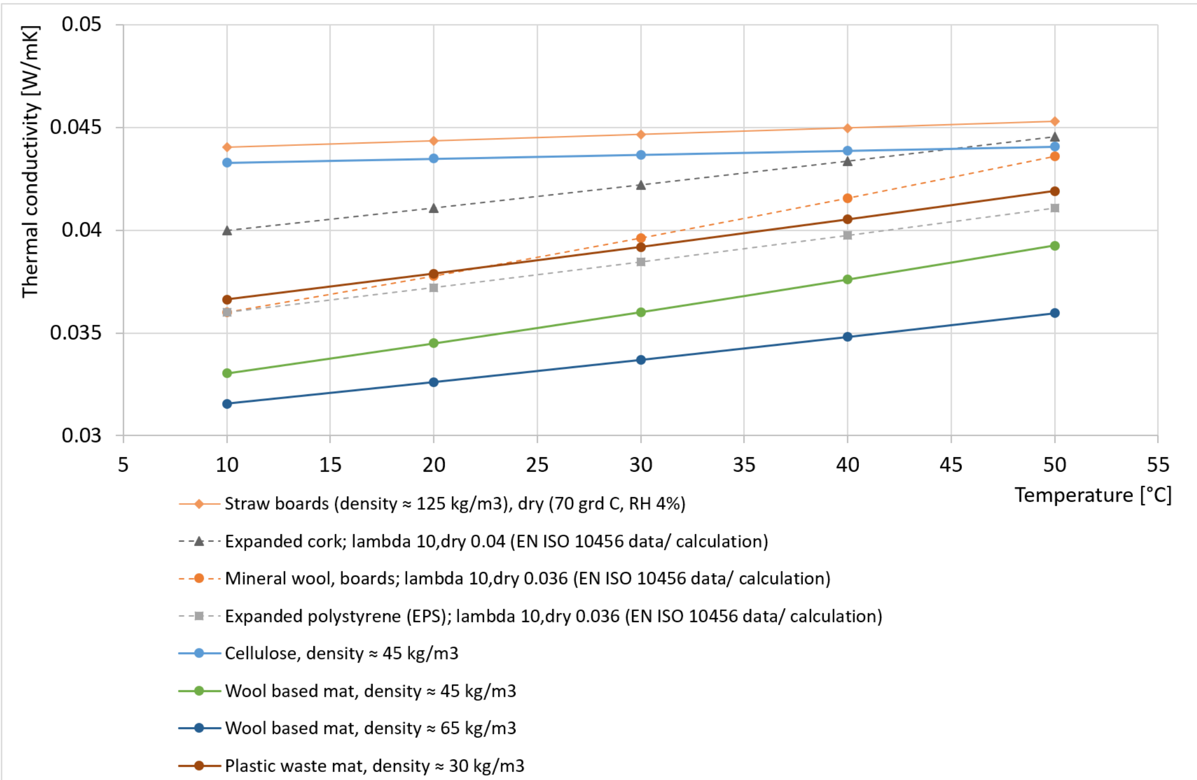

Figure 6. Analysis between test results and values obtained using data from EN ISO 10456, for existing insulation materials (represented with dash lines)

Table 1. Results of α_w, obtained for the samples tested in the reverberation room

Sample	α_w coefficient	Acoustic absorption class
Sample P6	$\alpha_w = 0,65$ (H)	C
Sample P7	$\alpha_w = 0,65$ (H)	C
Sample P10	$\alpha_w = 0,85$	B
Sample P11	$\alpha_w = 0,75$ (H)	C

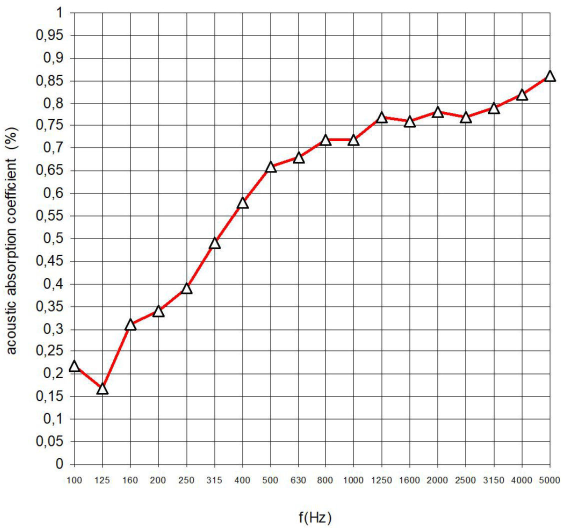

Figure 7. Acoustic absorption coefficients α_s (%), obtained in conformity with EN ISO 354, for sample P6

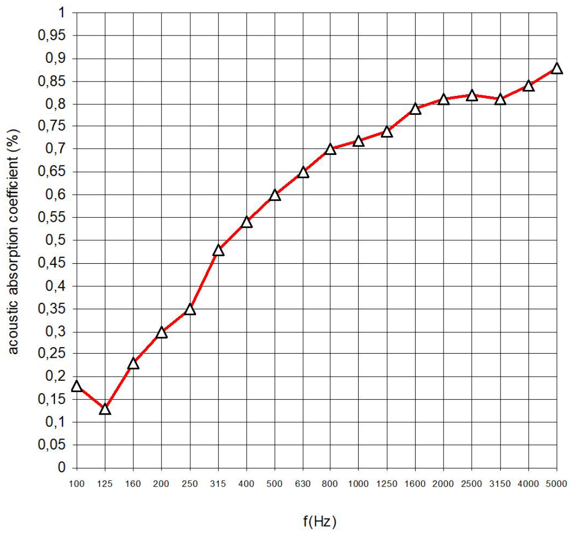

Figure 8. Acoustic absorption coefficients α_s (%), obtained in conformity with EN ISO 354, for sample P7

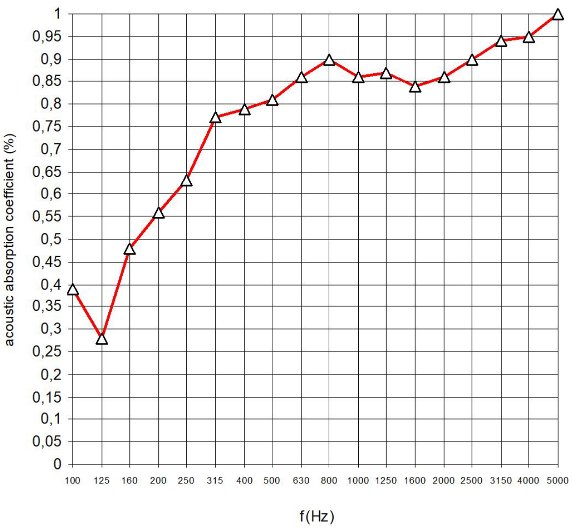

Figure 9. Acoustic absorption coefficients α_s (%), obtained in conformity with EN ISO 354, for sample P10

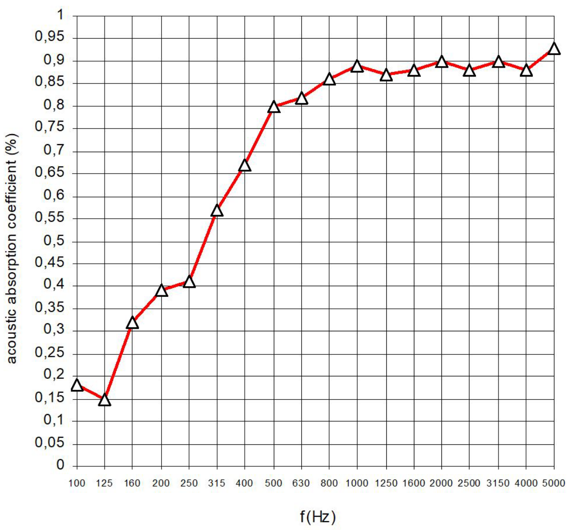

Figure 10. Acoustic absorption coefficients α_s (%), obtained in conformity with EN ISO 354, for sample P11

4. Conclusions

In this paper, the thermal conductivity of products made from waste such as cellulose, straw, recycled plastics and low-quality wool were investigated, as they are a few of the materials relevant for a circular economy. Our study, focusing thermal insulating and phono-absorption properties of the tested products, concludes that it is possible to obtain useful construction materials from recycled materials or using industrial by-products.

Thermal characteristics of the analysed products greatly depend on density, both in respect with thermal conductivity and its values in a temperature range. In the presented interval, a higher density translated in a lower conductivity and a more stable characteristic at temperature variations. The thermal conductivity of lower densities specimens fluctuates more with the temperature, as convection increase greatly.

Tested samples provided good thermal insulation characteristics, comparable with existing insulation materials (Figure 6). Further research is needed to facilitate a widespread use of these materials in construction technologies, in particular related to the characterization of specific heat (as crucial for the evaluation of thermal dynamic properties and for dynamic simulations) and to the investigation of fire resistance, water vapor diffusion and humidity influence on thermal and acoustic characteristics, fungal resistance, behaviour in the event of moist conditions.

Acknowledgments

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