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A review of unconventional sustainable building insulation materials

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ABSTRACT

Building insulation is commonly realized using materials obtained from petrochemicals (mainly polystyrene) or from natural sources processed with high energy consumptions (glass and rock wools). These materials cause significant detrimental effects on the environment mainly due to the production stage, i.e. use of non-renewable materials and fossil energy consumption, and to the disposal stage, i.e. problems in reusing or recycling the products at the end of their lives. The introduction of the concept of "sustainability" in building design process encouraged researches aimed at developing thermal and acoustic insulating materials using natural or recycled materials. Some of them, such as kenaf or wood fiber, are already commercialized but their diffusion could be further improved since their performance is similar to the synthetic ones. Others are currently under study and their development is only at an early stage. The goal of the paper is to report a state of the art of building insulation products made of natural or recycled materials that are not or scarcely commercialized. Comparative analyses were carried out considering in particular thermal characteristics in terms of thermal conductivity, specific heat and density. Data on the acoustic performance of the materials were also reported. Life Cycle Assessment data were finally collected, in order to put in evidence the environmental advantages of these materials. Particular attention was paid to researches focused to exploit local materials and even industrial byproducts, since these approaches respectively limit transportation and disposal impacts.

1. Introduction

One of the most important challenges of future buildings is the reduction of energy consumptions in all their life phases, from construction to demolition. The United Nation Environment Program [1] estimates that buildings consume about 40% of the world global energy, 25% of the global water, 40% of the global resources; buildings are also responsible of about 1/3 of greenhouse gas emissions of the whole planet. Similar values were observed by studies performed by the U.S. Department of Energy [2] and by the European Commission [3]. In Europe, this situation fostered the definition of several environmental policies: the most important ones are the Energy Performance of Building Directive (EPBD, [4]) and the Energy Efficiency Directive (EED, [5]). European Commission estimated that these actions will contribute to reduce the energy demand for heating and cooling purposes by 8% in 2020, 12% in 2030 and 17% in 2050 compared to 2005 data. Fig. 1 reports the trend of the European energy demand in the residential sector from 2000 to 2050 (data over 2013 are estimations) [6]. Strategies for the

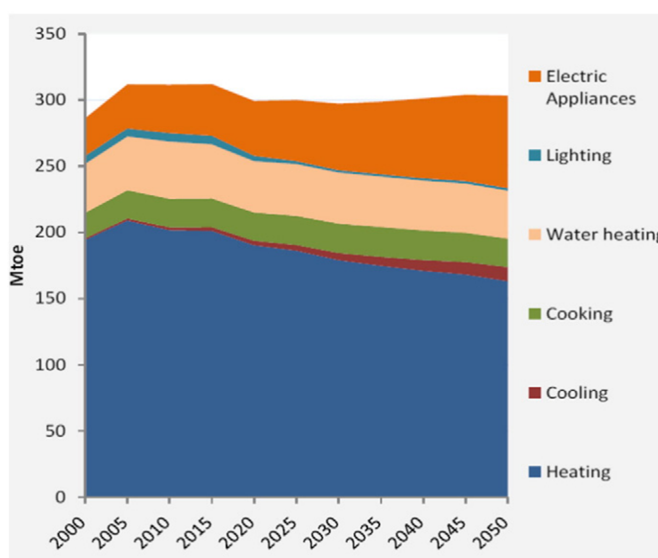

Fig. 1. Trend of the European energy demand in the residential sector by energy use [6].

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reduction of heating and cooling demands are focused not only on improving appliance efficiency or modifying citizen life styles, but also on enhancing the insulation properties of building envelopes. The latter action could play a decisive role since it can lead to significant improvements with a low pay-back time [7–10]. The importance of increasing the thermal performance in the building sector was also highlighted by a comparative analysis about energy production and consumption estimations. The study evidences that in 2035 about the 75% of energy production will be produced from fossil fuels. In order to reduce adverse environmental impacts the most interesting strategy is represented by investments aimed at increasing energy efficiency in the building sector, since about four-fifth of its potential was estimated to be unexploited in 2012 [11]. Using efficient insulation materials is also important to reduce the impact of urban noise; about 65% of European citizens are estimated to be exposed to noise levels for which adverse effect on health can be expected [12]. A detailed analysis of these impacts on citizens is reported in [13]. Unfortunately the use of natural or recycled materials for these purposes is not particularly widespread: a 2012 analysis reports that in 2011 mineral wool (52% of the market share) and plastics (41%) prevailed in the world thermal insulating materials market [14]. Their use can cause environmental issues due to the consumption of non-renewable materials and to the disposal phases of end-of-life products, in particular for plastics. The introduction of the concept of "sustainability" in the building sector gradually led to the production of insulation products made of natural or recycled material; some of them are already present in the market while others are still at an early stage of production or study. These approaches could be particularly important and useful in developing countries, which do not have well-defined recycling policies and are affected by disposal issues due to large quantities of agricultural and industrial by-products. However actions aimed at reducing the environmental impacts of the building sector should not only be addressed at enhancing thermal insulation properties of buildings envelopes, but also at a better energy optimization at an urban level; for instance the importance of teleheating systems, cogenerative smart grids and high energy efficiency technological systems was proven in detail by recent studies [15,16].

The main goal of the paper is to report a state of the art of innovative thermal and also acoustical insulating materials realized using natural and/or recycled materials whose development is only at an early stage or whose sales are still limited. After a brief description of each material taken into account, the study reports the parameters which are usually requested by building designers for the characterization of thermal insulation materials (density, thermal conductivity, specific heat) and acoustic materials (sound absorption and sound insulation properties). A brief analysis about fire and vapor resistance and sustainability of each material is finally reported.

2. Thermal, acoustic and environmental properties

2.1. Thermal insulation

Thermal insulation systems and materials aim at reducing the transmission of heat flow. The thermal insulation performance of single or combined homogeneous materials is usually evaluated respectively through thermal conductivity and thermal transmittance. Thermal conductivity λ defines the steady state heat flow passing through a unit area of a homogeneous material, 1 m thick, induced by a 1 K difference of temperature on its faces. It is expressed in W/mK and it is measured in compliance with EN 12664 (low thermal resistance) [17], EN 12667 (high thermal resistance) [18], EN 12939 (thick products of high and medium thermal resistance) [19] or also ASTM C518 [20]. A material is usually considered as a thermal insulator if its conductivity is lower than 0.07 W/mK.

Thermal transmittance, also known as U-Value, is the steady state heat flow passing through a unit surface area induced by a 1 K difference of temperature and it takes into account also convective and radiative heat transfers. It is expressed in W/m^2K and it is measured with the hot-box method [21–24]. Thermal transmittance can also be estimated with the ISO 6946 calculation method [25], but several comparative studies demonstrated that the calculated U-values are usually lower than the measured ones [26,27]. Thermal conductivity and transmittance are used to define the insulation properties in steady state; for the unsteady the most used parameter is the thermal diffusivity D, that allows to compare the ability of materials to conduct and store thermal energy. It is given by the ratio of thermal conductivity and the product of density and specific heat. It is expressed in m^2/s and it is measured in compliance with ISO 22007-1 [30]. The specific heat defines a material's ability to store energy: it is the heat required by 1 kg of material to modify its temperature of 1 K and it is expressed in J/kgK. A material characterized by a high value of specific heat can provide low diffusivity values even with low density. Insulators characterized by thermal conductivity under 0.05 W/mK and specific heat over 1.4 kJ/kgK can be considered very performing even in unsteady state conditions.

The importance of the evaluation of thermal performance in buildings using approaches more accurate than the steady state one was proved also in [28]. The study reports the outcomes of an analysis carried out comparing building energy consumptions using the more accurate semi-stationary and dynamic methodologies calibrated through in situ measurements. The most reliable results were obtained using the dynamic methodology, thanks to a better estimation of solar gains. The importance of a proper evaluation of thermal inertia using dynamic approaches was deeply discussed also in [29].

Another parameter that deeply affects buildings thermal performances is the albedo of the roof that is measured in compliance with ASTM E1918 [31]. Albedo is defined as the component of solar radiation reflected from an object back into space. A recent study has also studied the potential of using spaceborne data to locate areas where this parameter should be increased using more reflective surfaces [32]. This approach can be used in urban plans to tackle heating issues in buildings.

2.2. Acoustic properties

Airborne sound insulation is expressed by the weighted sound reduction index R_w, as defined by EN ISO 717-1 [33]. The sound reduction index defines the ability of a structure (wall, roof, window, etc.) to prevent the passage of sound through itself and it is expressed in dB. The higher the sound reduction index, the higher the sound insulation of the structure. Sound insulation properties of a sample are evaluated through phonometric measures performed in compliance with ISO 10140 [34]. The R_w is calculated on real-sized samples, such as windows, doors, partitions etc. The ability of a sample to limit the transmission of sound can be evaluated for small sized samples by means of an impedance tube and it is expressed as Transmission Loss TL [35]. The ability of materials and systems to dissipate the incident acoustic energy is assessed by the sound absorption coefficient α. It is defined as the ratio between the absorbed and the incident sound power. The sound power absorbed by a material is usually evaluated by Eq. (1).

$$W_a = W_i - W_r - W_t \quad (1)$$

$$\alpha = \frac{W_a}{W_i} \quad (2)$$

where: W_i is the incident sound power, W_r the sound power reflected by the analyzed material, W_t the sound power that passes through the material and W_a is the absorbed sound power.

This parameter can be measured for small samples using an impedance tube in compliance with ISO 10534-2 [36] or, for bigger samples (at least 10 m^2), in a reverberation room as defined by ISO 354 [37] or by ASTM C423-09a [38]. These two methods define two different kinds of absorption coefficients, respectively for normal incidence and random incidence of sound. Sound absorption properties could be also