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The development history and prospects of biomass-based insulation materials for buildings

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ABSTRACT

Thermal insulations have begun to play an increasing important role in realizing building energy saving in the past years. Thermal insulations made of biomasses like agro-residues, forest residues, etc., are developing very fast recently, although their research and development history is relatively short. In order to help researchers to achieve a global viewpoint of the research on this topic and to improve the research and application progress, a systematic review is presented in this study. After review and screening, 144 original research journal papers were selected as samples and analyzed to investigate the following topics: Historical development of bio-insulations from 1974 up to April 2016, from viewpoint of number of papers published and corresponding journals; Geo-graphical distribution of researchers, according to country and continent categories; Kinds of biomasses under research including agro-residues, forestry residues, economic plants, etc.; Analysis methodologies and research scale of bio-insulations; Common types, manufacturing methods and properties of bio-insulation; Experimental equipment, software, and corresponding standards. Moreover, the shortcomings of the current research are discussed in details. Finally, some suggestions are presented, including: a scientific plan on bio-insulation research; selection of suitable types; traditional and innovative treatments for improving specific properties; the required properties testing order; scientific presentation of research results. This study can help to achieve a more precise comprehension about bio-insulations research status, find suitable experimental equipment for effectively testing various properties, adopt innovative ways to improve specific properties, avoid making mistakes during the research and provide a better expression of the research results. Furthermore, this study can stimulate the research and application of bio-insulations to get a great-leap-forward development in the near future, especially in the fabricated building field.

1. Background and introduction

Nowadays, industry, transportation and buildings are the three major social energy consumers. In particular, with the increasing demand of indoor thermal comfort, more and more energy is consumed in the building sector by the energy systems providing heating, ventilation, and air conditioning services. The improvement of the thermal insulatio n of buildings is one of the most effective ways to get energy savings, through the reduction of heat or cold losses through envelopes. However, many traditional construction materials do not have good thermal insulation properties. So, many kinds of extra thermal insulation materials, like solid boards (panels), solid bucks, particles, sandwiches, coils are being used in many parts of the buildings, such as in the exterior walls, roofs, floors and exterior doors. These materials can be applied not only in traditional buildings but also in fabricated buildings.

The common insulations can be classified into four categories depending on the raw material: (1) from rocks and slags, such as rock-wool, glass-wool, expanded perlite, glass beads, vermiculite, cinder, ceramic products, etc.; (2) from petrochemical and coal chemical intermediate products, such as Polystyrene, Polyurethane, Polyethylene, etc.; (3) from plants, including agricultural waste, forestry waste and industrial plants fiber waste, such as straws, rice husk, waste papers, wood shavings, cotton, corn crops, etc.; (4) from metals, such as metal reflection film, hard metal visor, radiation plate, etc., the applications of which are still limited because they can only be applied in roofs and they are much more expensive than other thermal insulation materials.

Jelle [1] summarized the state of traditional thermal building insula-

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tion materials focusing on their properties and requirements. The considered insulations included mineral wool, expanded polystyrene, extruded polystyrene, polyurethane, vacuum insulation panels, gas insulation panel, aerogels, and further possibilities like vacuum insulation materials, nano-insulation materials and dynamic insulations. He pointed out that thermal insulation materials must satisfy several requirements related to thermal conductivity, mechanical strength, building site adaptability and cut-ability, fire protection, fumes emission during fire, robustness, climate ageing durability, resistance towards freezing/thawing, water resistance, costs and environmental impact.

With the development of society and people's ecological awareness, a sustainable and healthy indoor environment is increasingly attracting the attention of the public. Thermal insulations for buildings face humans directly, being always applied as the inner or outer coatings. Thus, their environmental performance is drawing a lot of attention not only in the production process but also during their lifetime. As for thermal insulations made of rocks (e.g., rock wool, perlite, vermiculite, etc.), they generally do not have a satisfying environmental performance because various pollutants (CO_x, NO_x, SO_x, volatile organic compounds and particulate matters) are emitted during their energy intensive production process. Moreover, most of the existing insulating materials are not renewable (e.g., those derived from petrochemical products). Thus, renewable, environment-friendly, low cost, and high thermal resistance insulation materials are highly demanded.

Recently, there is an increasing interest in thermal insulations from biomasses, often named "bio-based insulations" or "bio-insulations" [2–6]. Agricultural straws, such as wheat, corn or rice straws, in raw form (e.g., straw bales) have been used as building insulation materials for a long time due to their hollow structure, low cost, low density and low thermal conductivity. Up to now, bio-based insulations have a much wider definition, which include biological materials, such as hemp [7–12], flax [13–18], cotton stalks [19–21], etc. In particular, Sossoni E et al. [7] carried out an experimental research on an innovative hemp-based composite, whereas Freivalde L et al. [8] paid attention to the fire resistance of hemp fiber insulations. Hajj N E et al. [15] developed a new green composite using only flax fiber material for thermal insulation and sound absorption using flax-tows, therefore adding value to the less noble part of the flax plant. Segovia C et al. [16] evaluated the mold growth in a hybrid bio-insulation made of tannin-resin and flax fiber. Xiao-yan Zhou et al. [19] developed a binder-less fiberboard made of cotton stalk fibers with no chemical additives using high frequency hot-pressing.

Also forest residues, such as cork [22,23], wood fibers/shavings/chips [24–29] have been used for bio-insulation. For instance, Taoukil D et al. [24] showed that the thermal insulation performance can be improved by adding wood chips into a new kind of sand mortars. Kawasaki T et al. [28] produced a sandwich panel based on wood, which can be used either on the surface of the wall or as the wall and floor itself.

In addition, many kinds of straws [4,30–36] have been considered. Thomson A et al. [32] presented findings from an on-going experimental study monitoring modern straw bale construction and investigated the degradation behavior of wheat straw cyclically exposed to high humidity levels. Holzhueter K et al. [36] carried out the first investigation in Japan to monitor the interstitial hydrothermal environment of a straw bale wall at various depths and heights. As for rice husk [37–39], Palumbo M et al. [37] evaluated, by the help of a thermogravimetric analysis, the thermal degradation and fire behavior of six thermal insulation materials made up by such crop by-product and two kinds of natural binders.

In the meantime, the types and manufacturing methods of bio-insulations have broadened out, so that much more advanced properties can be obtained, which is leading to a rapid acceleration of bio-insulation applications. Moreover, in many developing countries (like China, India, Brazil, Russia) the rapid growth of agricultural production combined with the decreasing consumption of biomass for housing heating (where biomass has often been substituted by natural gas or liquefied petroleum gas) are making large amounts of biomass available, which need to find a proper utilization. Thus, the utilization of biomass as insulation material becomes a very interesting option both to avoid in situ burning and to save energy that would otherwise be wasted.

As a matter of fact, the R & D (research and development) on bio-insulations for buildings with advanced technology has a very short history. According to the authors' investigation on this topic, most of the research was carried out after 1998. Anyhow, it has been developing very fast in the last 15 years, having attracted the interest of researchers from various countries. Accordingly, in this paper, all the related research on bio-insulations will be taken into account, but only some representative researches are shown here due to space limitations. Zhou et al. [19] carried out a research on a new environmental-friendly thermal insulation board made of cotton stalk by a hot-pressing manufacturing method. The results showed that this bio-insulation board can get thermal conductivity values ranging from 0.0585 to 0.0518 W/m. K with a density of 150–450 kg/m^3, which is close to that of the expanded perlite and vermiculite within the same density range. La Rosa et al. [22] manufactured and tested an eco-sandwich material containing cork, flax fibers and bio-based epoxy resin as natural materials. The results showed that the use of the eco-sandwich in buildings can lead to many advantages among which the good thermal insulation property and the lighter weight. Binici et al. [31] developed a mixture of corn stalk particles and epoxy as insulation material. The results showed that this insulation material can satisfy the criteria of the Turkish Standard (TS805EN601) and can be used commercially. Asdrubali et al. [40] presented the multipurpose experimental thermo-acoustic characterization of common reed-based building panels. The experimental results showed that the thermal conductivity is around 0.05 W/m. K, which is comparable to many common commercialized materials. Moreover, a significant sound insulation performance can be obtained with longitudinal stalk layout. Pennec et al. [41] investigated the thermal conductivity of a compaction of sunflower pith particles with a combined finite-discrete element method and obtained a difference between numerical results and experimental data of less than 1%. Chikhi et al. [42] analyzed the effect of date palm fibers addition on thermal conductivity, water absorption and mechanical properties of gypsum based materials. The results showed that the addition of date palm fibers can improve thermal performance as well as compressive and flexural strength. Much more current research status can be found in Sections 2–7.

The development history of bio-insulations dates back to 1974 but the rapid development period began only in 1998 and particularly after 2003. Up to now, only few review works on this topic were carried out, despite the large production of specific original research work. After investigation, there are only five papers that can be considered as reviews in this field and are discussed in the following. Nevertheless, a comprehensive and global view on current bio-insulations research cannot be learnt from them. In 2015 Francesco Asdurbali et al. [43] reviewed unconventional sustainable building insulation materials and summarized the common required properties of these materials (including natural and recycled materials). The state of the art of unconventional building insulation materials (including reeds, bagasse, corn, date palm, durian, rice and so on) with a special focus on density, thermal conductivity and biomass yields was presented. Moreover, the comparison of unconventional and conventional insulations from the view point of thermal performance, resistance to fire and water/moisture resistance factor, acoustic performance and LCA performance was also discussed. However, the information about current research methodologies, detailed manufacturing and testing processes was not mentioned at all. In 2016 Hurtado et al. [44] reviewed the research status of cellulose fiber insulations focusing on manufacturing, installation and thermal performance. Moreover, the various properties of cellulose fiber insulation like density and setting(lay-out), thermal properties, moisture properties, air infiltration, fire properties, fungal development, and life cycle analysis were also discussed. However, the research object in that review was limited to cellulose fiber of recycled paper and the attention was mainly focused on thermal performance, while disregarding other equally important properties like the mechanical requirements. In 2013 Madurwar et al. [45] reviewed the application potential of agricultural waste for sustainable construction