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Towards Energy-Efficient and Sustainable Insulation Materials

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***Abstract*— During the last several decades, thermal insulation materials underwent considerable technological evolution owing to the needs of our civilisation, which drive the improvement of existing materials or the search for new ones that will satisfy the growing needs of the construction industry in terms of their quality and quantity. The innovations related to thermal insulation materials presented in this paper concern mainly the search for high-performance insulation materials but also the development of materials that will use natural resources in a sustainable manner.**

Keywords—thermal insulation, sustainable development, recycling

I. Introduction

The progress of civilisation constantly necessitates improving existing materials or the search for new ones that will satisfy the growing needs of the construction industry in terms of their quality or quantity.

The requirements for construction products stem from the basic requirements [1, 2] for buildings, and therefore all materials used in construction, including those used to insulate buildings from external factors, must meet the requirement concerning the "sustainable use of natural resources". According to this requirement, buildings should be designed, constructed and, after their useful life has ended, demolished in such a manner that the use of natural resources is sustainable and ensures the durability of buildings as well as the use of environmentally friendly raw materials and recycled materials.

Thermal insulation materials are used since they enable energy savings and ensure thermal insulation properties of building envelope elements, thus fulfilling the sixth basic requirement for buildings [1, 2].

When analysing development directions for thermal insulation materials and construction products and deciding which of those can be referred to as modern and innovative, it should be recalled that in addition to desirable characteristics, modern materials should also meet the criterion of low energy consumption during their manufacturing process. At the same time, these materials should make it possible to reduce the amount of energy consumed when the building is in use without compromising the safety and comfort of its occupants.

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Given the ever-increasing demand for energy and declining reserves of non-renewable resources, sustainable development principles must be observed as well.

In the Technology Roadmap: Energy Efficient Building Envelopes document by the International Energy Agency [3], priority areas for research and innovation in the construction sector for the next 10 years have been identified. The authors' intention was to provide guidance for the development of energy-efficient construction materials. Technology Roadmap… focuses primarily on areas where the largest savings with respect to embodied energy are envisaged and which also make it possible to reduce the amount of energy consumed during building operation most effectively.

Legislators have recognised the need to seek energy savings as well as to reduce the consumption of natural resources in the process of manufacturing construction materials and have imposed the obligation to recycle construction and demolition waste. Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste assumes that by 2020 we will effectively recycle 70% (by weight) of waste originating from construction materials. Materials that can be recycled include thermal insulation materials such as expanded polystyrene (EPS) and extruded polystyrene (XPS), polyurethane foam or mineral wool. The polystyrene granulate obtained by recycling used thermal insulation is increasingly used in the production of new thermal insulation products or is included in mortars and heat-insulating mineral plasters after being crushed.

The need to recycle petroleum-based thermal insulation materials (XPS, EPS) is also due to their important disadvantage – their rates of biodegradation are so slow that they can be treated as non-biodegradable materials when compared to the average human lifespan. As a consequence, landfills are full of polystyrene packaging and thermal insulation materials that constitute demolition waste.

II. In search of biodegradable thermal insulation materials

The pressing need to limit our dependence on non-renewable resources is becoming an increasingly important factor for construction material technologies as well as in other areas. In these circumstances, the natural direction for development is the search for materials that would present an alternative to the Earth's depleted resources. A fitting quote from Mark Twain is: "Buy land, they're not making it anymore".

Researchers who are trying to make progress in this area have already been successful in producing thermal insulation materials from renewable sources of plant origin; at the same time, they are looking for effective recycling methods for non-biodegradable plastics.

Currently, we have non-petroleum-based plastics, so-called biopolymers that are based on compostable materials and produced from renewable substances such as potato starch, sugars produced from corn, cellulose, etc. These materials include biopolypropylene (bio-PP), biopolyethylene (bio-PE), polyhydroxyalkanoates (PHAs) and cellulose acetate (CA) [4]. The biopolymer market is growing rapidly; according to Bio-Based Society forecasts, it will reach 12 million tonnes/year by 2020 [5].

Most polymers derived from biomass can be processed using the standard technologies applicable to plastics, so that they also can be foamed. Foamed polymers obtained from biomass are already used in construction. An example of a foamed thermal insulation material is polylactide (PLA), which is made from cornmeal. It is a polymer belonging to the aliphatic polyesters group, which, when foamed with carbon dioxide, gains the porous texture that is desirable from the point of view of thermal insulation materials [6, 7, 8]. This material has a thermal conductivity coefficient comparable to non-biodegradable expanded polystyrene (λ = 35 mW/m K).

Biodegradable thermal insulation materials are already being implemented on an industrial scale. But how do we deal with the polystyrene waste that is already in landfills? Researchers from Stanford University and from the Chinese Beihang University are working on a solution that uses the digestive enzymes of mealworm beetle larvae (Tenebrio molitor [9]) in the form of a substance that decomposes polystyrene [10]. Feeding exclusively on styrofoam, mealworm larvae convert it into carbon dioxide and biological waste. The next few years will show whether the 2015 paper published in Enviromental Sciences and Technology [10] proves to be a breakthrough and helps solve the problem of millions of tonnes of these materials that take up landfills and litter beaches [11].

III. Renaissance of thermal insulation materials of plant and animal origin

The difficulties involved in the biodegradation of plastic thermal insulation materials highlight the opportunities offered by the use of thermal insulation materials of plant origin. When left in the natural environment after their useful life has expired, these are subject to composting. i.e. organic recycling, which involves the decomposition of organic matter by microorganisms – aerobic or anaerobic bacteria, nematodes and fungi. This natural method of disposing of, and recycling, organic waste is based on substance transformation and decomposition under appropriate temperature and humidity conditions.

Thermal insulation based on organic matter has been used for millennia. Reed, wood chips, moss, hay and straw were already known as materials suitable for insulating log houses hundreds of years ago. In the 20th century, they were superseded by moisture-resistant plastics and fire-resistant mineral-based materials, but now they are making a comeback in the new form of recycled paper and wood processing waste or even recycled denim and cotton [12].

Sheep’s wool, which is a natural, renewable and durable material, also has favourable thermal insulation properties. Sheep’s wool insulation is safe and does not cause eye, skin or lung irritation. Wool is an excellent example of a renewable material; additionally, it can be regenerated and reused or left to naturally biodegrade. Wool’s favourable thermal insulation properties result from the porous internal structure of wool fibres (the external layer encloses thin-walled cells filled with air, which form the core of the fibres) as well as from the crimping of these fibres, which endows them with natural fluffiness. All these factors result in a large amount of air being trapped between wool fibres, and air is a good insulator.

In addition, it should be noted that sheep’s wool production requires approximately 14 times less energy than producing glass wool insulation [13], which results in sheep’s wool thermal insulation products having one of the lowest environmental impact indicators according to the British Thermal Insulation Manufacturers and Suppliers Association [14].

Natural cork has a similarly low environmental impact; it is the undisputed leader among thermal insulation materials of plant origin, since it has proved superior to other products in this category. This material is obtained from cork oak (Quercus suber) by skilfully harvesting its bark approximately every 10 years (Fig. 1). Harvesting the regrowing layer of dead oak bark is an excellent example of sustainable approach to natural resources and of respect for nature.

Figure 1. Cork oak (photo: I. Hager);

Other examples of thermal insulation materials that are based on the lignin and cellulose present in wood industry waste, cannabis and straw from annual crops are lignocellulosic panel boards and foams. The production of traditional particleboards and flakeboards requires the use of organic resins that serve as a matrix, making the product stiff and hydrophobic [15]. The lightweight and porous structure of lignocellulose foam does not require the use of synthetic binders [16]. These foams have bulk densities ranging from 40 to 280 kg/m3. For these prototype materials, stress at 10% relative deformation ranges from 20 kPa to 190 kPa. Inventors of these materials from the Fraunhofer Institute report that their thermal conductivity amounts to 40 mW/m K at a density of 40 kg/m3 [16]. A successful attempt to produce a natural composite with good thermal insulation properties that would also be completely biodegradable resulted in an innovative material with a natural polymer matrix based on chitin and inclusions consisting of organic waste from the wood or food industries (Fig. 2a). The matrix, which has been grown from mycelium (Fig. 2b), is a high-density amorphous polymer that can be used in applications hitherto reserved for synthetic plastics. This natural polymer in the form of mycelium is grown on pasteurised organic waste from local agricultural or wood industries. The waste provided as the nutrient for the mycelium may include rice husks, wood shavings, flax, hemp or coconut fibres. This promotes the regional production of construction materials in accordance with the principles of sustainable development. Organic waste is a nutrient for the mycelium and subsequently forms an inclusion in the natural bio-composite produced [17].

The technology of “growing” thermal insulation materials on the basis of mycelium and organic waste has already been patented and implemented by a team of young researchers from the Ecovative company [17, 18]. In this manner, the team produces thermal insulation panels with varying densities (LD, MD, HD) (Fig. 2c) and with thermal conductivity coefficients similar to that of styrofoam. The cultured composite material fills the mould, growing under controlled temperature and humidity conditions. After the growth stage has been completed, the finished product is dried, killing the mycelium and fixing the shape of the product.

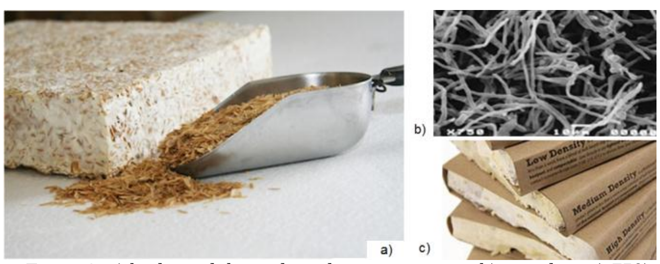

Figure 2. a) biological thermal insulation composite; b) mycelium (x750); c) ECOVATIVE LD, MD, HD thermal insulation panels [18].

IV. High-performance thermal insulation materials and products

In the latest version of the Directive on the energy performance of buildings, Article 9 introduces the concept of “nearly zero-energy buildings” (nZEB) [19] as a requirement for public buildings from 2019 and for all new buildings from 2021. In the directive, a nearly zero-energy building is defined as a “building that has a very high energy performance”. In order to reach that target, it will be necessary to increase the thickness of the thermal insulation layer, which will result in the higher consumption of thermal insulation materials.

Conventional thermal insulation materials such as mineral wool, expanded polystyrene (EPS) and extruded polystyrene (XPS) or polyurethane-polyisocyanurate (PUR-PIR) foams require significant thickness in order to achieve the desired effect of a very low heat transfer coefficient.

Thus a natural direction for developing this group of construction materials is the search for high-performance thermal insulation solutions for which the thermal conductivity coefficient will be significantly lower and the thickness of the thermal insulation layer that provides comparable thermal resistance can be reduced.

High-performance materials, which enable the construction of thinner building envelope elements, will make it possible to save not only energy but also money owing to the increase in usable floor area of buildings, which translates into tangible financial benefits in the case of commercial facilities.

The use of high-performance thermal insulation materials in building envelope elements will also minimise the impact of the construction industry on the environment by reducing the buildings’ energy demand as well as cutting the emission of pollutants into the atmosphere since less fossil fuels will be burned in order to heat buildings.

In the past decades, many innovative construction products have been brought to the construction market that have ever better thermal insulation properties. These include aerogels, VIPs (vacuum insulation panels) and GFPs (gas-filled panels). Their characteristics are described below.

Aerogel is obtained by extracting water from silica gel and then replacing it with carbon dioxide. It is hardly a new material, since it was first described by Kistler [20] in the early 1930s.

The aerogels currently produced exhibit a thermal conductivity coefficient of 17 mW/m K [21, 22]. Owing to their porous structure, aerogels are now considered to be the world’s lightest solids. The lightest among them are carbon aerogels with densities of 0.16–0.18 mg/cm3. To date, silica aerogels with densities ranging from 1.9 to 3 mg/cm3 have been used in construction industry. These have open pores with diameters ranging from 10 to 100 nm. Owing to the Knudsen effect, the thermal conductivity of these materials may be lower than that of dry standing air (λ = 28 mW/m K) [21, 22]. Drawbacks of aerogels include their fragility and still high price resulting from their costly production process. However, their undeniable advantage is their resistance to high temperatures. They remain stable up to the melting point of silica, i.e. about 1200°C.

Silica aerogels are translucent and have the ability to disperse light. Owing to these characteristics, they are used in high-performance glazing for office buildings, public buildings, gyms and swimming pools [24]. Aerogels can also be used in the form of granules or as fibres from which blankets and panels are formed [23].

Multi-chamber polycarbonate panels filled with aerogels are used on roofs and façades to better utilise natural light with minimal heat loss. Owing to their translucence (90% at 1 cm thickness) and ability to diffuse light, they can be used to reduce glare and direct sunlight, thereby improving lighting conditions and increasing comfort for building occupants [24].

Another important direction in the development of thermal insulation materials are attempts to use gases with lower heat conductivities than air. In these applications, carbon dioxide (14 mW/m K) and noble gases such as argon, which is already used for glazing (16 mW/m K), krypton (8.8 mW/m K) and xenon (5.1 mW/m K) are the best choices [25]. Multi-chamber gas-filled panels are products in which aluminum foil or aluminum-coated PET membranes are filled with a gas with low thermal conductivity [27]. These enable savings already at the stage of transporting light membranes to the construction site to be filled with gas there. In terms of their thermal conductivity coefficient, the insulation properties of these panels are similar to those of the gas inside them.

Vacuum undoubtedly provides the most effective thermal insulation. The idea to use vacuum as a thermal insulator was first brought forward by James Dewar who designed the flask named after him in 1892. This solution was used in the production of vacuum insulation panels (VIPs), which are successfully used in the construction industry, mainly in Germany and Switzerland. These panels are used both for upgrading the thermal efficiency of existing buildings and in new buildings.

A vacuum insulation panel consists of a sealed aluminum foil or aluminum coated PET membrane and a core. The latter plays an important role in this type of insulation because it determines the product's shape and mechanical properties. The core is made of fibreglass, polyurethane foam or pyrogenic silica in the form of a powder and/or aerogel, i.e. of open porous materials, so that when air is vacated from the panel, it is also removed from the pores while the shape of the element remains unchanged [26].

The use of vacuum virtually eliminates heat transfer by conduction and convection, which results in thermal conductivity an order of magnitude lower than for traditional insulation materials (4 mW/mK). Advantages of vacuum insulation panels also include the possibility of considerably reducing the thickness of the thermal insulation layer. A VIP just 2.5 cm thick is required to achieve thermal resistance comparable to a 24 cm mineral wool layer (λ = 38 mW/mK). The technology was originally developed for the refrigeration industry, and this insulation type was first used in the construction industry in the 1990s.

Unfortunately, vacuum insulation panels are still expensive compared to traditional insulation, and they must be installed by well-trained teams. It is not possible to change their shape during on-site assembly and thus assembly plan has to be carefully prepared before ordering the material. The obvious disadvantage of VIPs is the partial loss of their thermal insulation properties if the membrane is pierced as well as the gradual deterioration of their characteristics resulting from air diffusion and the gradual equalisation of pressure with their surroundings.

Researchers at the Fraunhofer Institute have developed an air-tight multi-layer membrane for use in vacuum insulation panels, which consists of five layers: two layers of polyethylene (PE) and polyethylene terephthalate (PET) and three layers of aluminum foil, one of which is covered with a thin film of Ormocer – a hybrid material in which organic and inorganic structures coexist on a molecular scale. Owing to the new multi-layered structure and the organically modified ceramic coating, vacuum in VIPs can now be maintained for much longer – up to several decades [29].

V. Conclusion

The construction industry bears its share of responsibility for managing natural resources, which requires a continuous effort to reduce the consumption of non-renewable resources and to use recycled materials. It must also strive to ensure the economic viability of the solutions proposed and to improve the quality of thermal insulation products by setting the right requirements.

Social concerns about the environmental impact of construction materials have been reflected in increased interest in, and demand for, sustainable thermal insulation materials. These concerns have also been responded to by innovation – increasing the number of bioproducts and materials based on renewable resources. Public awareness of the environmental impact of the construction industry drives interest in thermal insulation materials made of cork, sheep's wool or cotton, and also in insulation products that incorporate rice husks or wood industry waste.

Innovation related to high-performance insulation materials is among the challenges of the 21st century. In the search for materials with lower thermal conductivity coefficients, new products have been developed that utilise noble gases (GFPs) as well as the excellent thermal insulation properties of vacuum (VIPs). The aerogel technology is developing steadily as well in order to find alternative, less-energy intensive production methods.

In conclusion, to borrow the terminology used to evaluate the popularity of information and communication technologies (Gartner's Hype Cycle [30]), each technology, including those that involve the production of new innovative insulation materials, goes through certain development stages and faces evolving market expectations. These phases are similar for all technologies, although their durations may be very different. Some technologies never reach the "plateau of productivity" stage, e.g. they become obsolete before they reach maturity (Fig. 3).

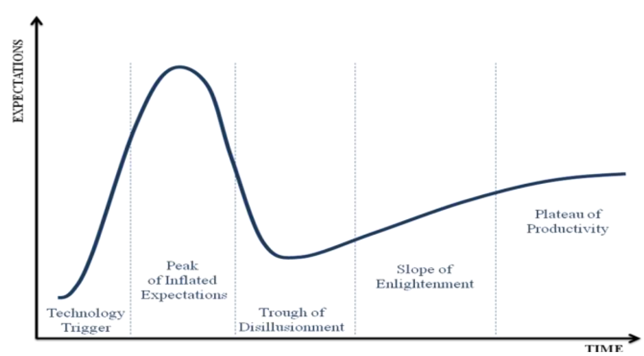

Figure 3. Emerging technology popularity cycle (Gartner's hype cycle), based on [42]

Similar trends can be observed with respect to the technologies related to other construction materials and products. The coming years will tell which of the solutions discussed here will successfully climb out of the "trough of disappointment" and negotiate the "slope of enlightenment" to finally reach the "plateau of productivity".

If, however, we do not wish our children's generation to meet the same fate as the Easter Islanders who precipitated the fall of their civilisation by foolishly overexploiting natural resources and causing the deforestation of their island, we must continue to make efforts to reduce our dependence on non-renewable resources. Thus we should focus on enabling sustainable material solutions for the construction industry of the future to reach the "plateau of productivity".

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