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NATURE-BASED THERMAL INSULATION MATERIALS FROM RENEWABLE RESOURCES – A STATE-OF-THE-ART REVIEW

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Abstract

In the 21st century, global climate change and the high level of fossil energy consumption have introduced changes affecting all sectors of the economy, including the building industry. Reducing energy consumption has become an important task for engineers because 30% of the total energy consumption is used for heating our buildings. Recycling the huge amount of industrial and agricultural by-products has also become urgent because due to their CO2 emissions, their combustion is not a state-of-the-art alternative. Besides rediscovering some long-known, nature-based insulating materials, there are also several research projects that have resulted in new products. In the last century it was relatively easy to review this product range, but nowadays there are so many kinds of nature-based thermal insulating products, there is a need for systematization, and more in-depth knowledge about them is required. The purpose of this paper is to develop a new systematization of nature-based thermal insulation materials, summarize the main knowledge about them, and indicate the direction of recent research and development.

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Key words

- Nature-Based,
- Thermal Insulation Material,
- Energy Efficiency,
- Renewable.

1 INTRODUCTION

At the turn of the 21st century, predictions of global warming and climate change have motivated the European Union to call on their member states to take legal and economic measures to reduce fossil fuel consumption. In 2014, a new EU climate and energy framework was initiated, which tightened targets for 2020. The accepted energy goals for 2030 are to have a 40% reduction in CO_2 emissions (compared to 1990 levels) with 27% of the energy consumed coming from renewables and a 27% increase in energy efficiency (Knopf et al., 2015).

At the same time the market for thermal insulation materials has also changed. Traditional thermal insulation materials (e.g., polystyrene and mineral wool products) still command an extensive market share. In addition, high-performance thermal insulation materials have also appeared that had not been previously used in the building industry (e.g., aerogels, VIPs). Meanwhile, various kinds of nature-based thermal insulation materials have been rediscovered, because their production requires less use of fossil fuels than artificial materials. The need to recycle industrial and agricultural waste has also become extremely urgent. The reprocessing of building industrial waste (e.g., thermal insulation materials) is often extremely difficult, because some products (e.g., plastic foams) naturally decompose very slowly, while others cannot decompose at all (e.g., mineral wool). Moreover; during the decomposition of some waste, toxics might be released from their raw materials or from their binders and adhesives. It can therefore be concluded that sustainable development cannot be guaranteed by only using artificial materials (Ljungberg, 2007).

Germany has the most relevant thermal insulation materials market in the European Union; therefore, an overview of its market composition and time trends perfectly represents the market processes and forecasts concerning this region. The proportion of artificial materials began to decrease around the year 2000. At the same time the proportion of nature-based materials started to increase from 1% to 6% in 2004 and in 2014 to 11% (**Tab. 1** and **Fig. 1**). In light of a 50% share of mineral wool products (MW) and 38% share of plastic foams (27% expanded polystyrene foam (EPS); 6% extruded polystyrene foam (XPS); 5% polyurenthane foam (PUR), an 11% share of nature-based materials might be seen as insignificant, but taking into account the rate and speed of growth (from 1% to 11% over 15 years), it can still be considered as a significant change. The reason for this phenomenon is the recently increasing demand for using nature-based thermal insulation materials that comes from the spread of environmentally conscious engineering. The raw materials of nature-based thermal insulation are organic and contain large amounts of CO_2 extracted from the air (Danner, 2008; Wieland, 2010; Mandl et al., 2001).

Tab. 1 *Market trends of thermal insulation materials in Germany (Danner, 2008; Wieland, 2010; Mandl et al., 2001)*

Material	Market share					
	1989	1994	1999	2004	2010	2014
MW	59%	60%	58%	54%	53%	50%
EPS	32%	31%	28%	28%	27%	27%
XPS	3%	3%	4%	6%	6%	6%
PUR	5%	4%	4%	5%	5%	5%
Other	-	1%	1%	1%	1%	1%
Natural	1%	1%	5%	6%	8%	11%

Looking at the market composition of nature-based thermal insulation materials in Germany, the share of cellulose insulation is the largest (32%), followed by thermal insulating fiberboard (products with a typically 200-400 kg/m^3 density) (28%), and wood wool products (20%). Hemp and flax fiber-based materials account for 9%, sheep wool insulation amounts to 4%, and the remaining 7% includes other materials (**Fig. 2**) (Danner, 2008; Wieland, 2010).

If the above materials are installed in buildings instead of materials that produce combustion, which also results in CO_2 emissions, the CO_2 concentration in the air could be significantly reduced. In addition, it can also be observed that recent developments are aimed at reducing energy needed for the production of nature-based thermal insulation materials in order to make them more competitive versus traditional artificial materials.

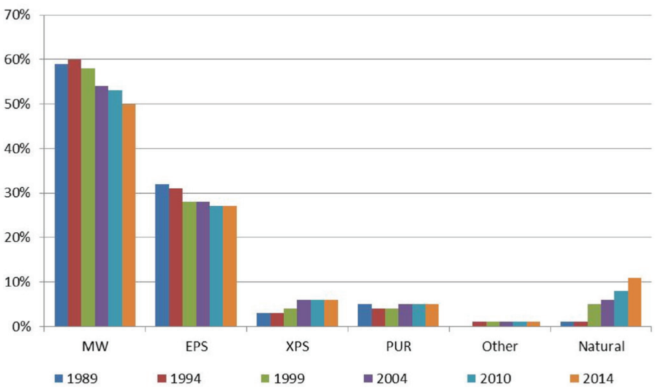

Fig. 1 *Market trends of thermal insulation materials in Germany (Danner, 2008; Wieland, 2010; Mandl et al., 2001)*

2 BRIEF HISTORY

Prehistoric peoples built temporary dwellings from the same materials that they used for clothing. The most common materials were animal skins, fur, wool and plant-related products such as reed, flax or straw, but their lifespan was limited. Later, because of a more settled lifestyle and the development of agriculture, they needed more durable materials for housing, such as stone, wood and earth (Bynum, 2001).

The industrial revolution in the 18th-19th centuries brought about significant innovations in building technology and building physics that also had a deep impact on the development of thermal insulation materials (Déry, 2010).

By the end of the 19th century, the methods for planning and constructing buildings had developed and changed dramatically over a relatively short period. New building materials emerged (cast-iron, glass structures, concrete, steel), and structural systems were planned not in empirical ways but on calculative methods. The main problem was caused by the unusual thermal expansion of these new materials. To avoid cracks and their resulting damage, it became obvious that these structures needed extra thermal protection. Furthermore, the thermal insulation capacity of the cast-iron, concrete and steel constructions was much lower than a thick wall made of adobe or brick, thereby resulting in greater heat loss and higher heating demands. By the turn of the 20th century, it was clear that flat roofs made of reinforced concrete and light frame structures made of steel and wood also needed extra thermal protection. Rising energy consumption and the relatively high costs of fossil fuel (coal and crude oil) during a worldwide economic crisis (the "Long Depression", 1873-1896) forced thermal power plants to reduce heat losses from steam engines, heating equipment, chimneys, and also the building structures around them. The above-described crisis and light frame construction were some of the reasons why industrial architecture started to utilize thermal insulation materials (Tomlow, 2007; Bozsaky, 2010).

One focus of the developing technologies and innovations was to improve human comfort in buildings. It was evident that the task soon became how to keep heat inside, with the role of thermal insulation becoming significant in residential buildings. Heating and ventilation equipment exhibited extraordinary developments in the 1880s and their calibration became necessary. The calculation of the heat losses and heat gains of buildings became a key problem for mechanical

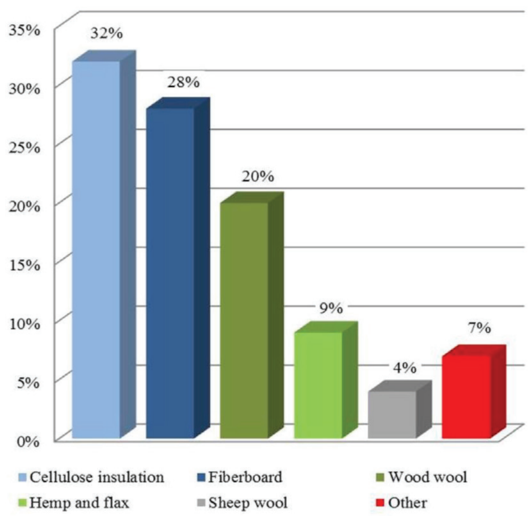

Fig. 2 *Distribution of nature-based thermal insulation materials in Germany* (Danner, 2008; Wieland, 2010)

engineers with the first theories on thermal insulation and building physics appearing at the same time (Tomlow, 2007).

Since the middle of the 19th century, thermal insulation products have been developed that originally had natural origins. However, artificial materials in the 19th century, mineral wool products, and in the first half of the 20th century, plastic foams also appeared at the same time. They almost completely displaced nature-based materials because their production costs were low until the first oil crisis, and they did not have durability and flammability problems (Bynum, 2001).

Nowadays there is a wide range of nature-based thermal insulation materials that are manufactured from renewable resources in the building industry, but most designers have only limited information about their properties and possibilities of application. Moreover, only a limited number of standards and regulations have been published, thereby leading to considerable mistrust.

The diversity of nature-based materials means a necessity exists to systematize them as well as extend general engineering knowledge about them. When taking a look at the wide range of available nature-based products, it could be concluded that designers and engineers have rediscovered quite a few forgotten materials. Lots of new products that were previously completely unknown in construction or used in another economic sector (e.g., agriculture) have also been marketed. In addition, numerous research and development projects are also being undertaken in order to introduce new nature-based products to the market for thermal insulation materials.

Based on this study, which is supported by the literature and market research, it has been concluded that nature-based thermal insulation materials can be grouped as:

– rediscovered materials,
– recently introduced materials and
– materials in an experimental stage.

3 REDISCOVERED MATERIALS

The group of rediscovered materials consists of nature-based thermal insulation materials that were formerly used as building insulation products. These materials had become forgotten since the increased use of artificial materials, but they were rediscovered owing to the increased popularity of eco-conscious architecture at the turn of the 21st century.

3.1 Cork

Cork was previously used by ancient Romans for wall and roof insulation (Bynum, 2001). The first modern wall-insulating cork products were produced in the 1870s (Déry, 2010). Today, the waste materials of the cork industry are generally used for the production of insulating boards. During production peeled cork bark is milled under high pressure and at high temperatures. After sorting, the raw materials are put into steel forms; during autoclaving, the cork granulate expands and becomes a homogeneous block with the help of its own natural resin and without any additives. The blocks are cooled down, and then they are sawed with heated metal threads. Subsequently, the cork boards are passed through a straightening bank before packaging (Gil, 2015). Cork insulation has excellent thermal and sound insulating qualities as well as good vapor and air permeability. It is waterproof, water repellent (due to its wax content), and frost-proof (Asdrubali et al. 2012). Cork burns slowly and with difficulty; it is long-lasting and dimensionally stable. It is resistant to UV radiation, molds, bacteria, insects and rodents; moreover, it is environmentally friendly and recyclable. Cork is suitable for the thermal and sound insulation of acoustic floating floors, pitched roofs (over or between rafters), facades, building plinths, flat roofs, terraces and green roofs (Pfundstein, 2007).

3.2 Wood Wool

Wood fiber production was patented in the 19th century, but the first wood wool product for the building industry was manufactured by Heraklith in 1908 (Bynum, 2001, Déry, 2010). It is composed of wood (pine or poplar), cement or magnesite (the binding material), water, and a small amount of saline. During production wood logs are sawed into a cross-sectional shape, and then they are planed into fibers 0.2-0.8 mm thick, 3-5 mm wide, and 60-100 mm long. To prevent mold the fibers are dried to a 12% moisture content and then submerged into saline. After this treatment, wood wool is put in a mixing machine where a binder is added. This mixture is put in steel molds in three layers; it is then compressed under high pressure. The almost finished boards are stored at a specified temperature and humidity until the binder cures. The final step is cutting them down to size. Along with its relatively good thermal insulation, its sound-insulating quality is excellent. Wood wool has good vapor permeability and a high mechanical strength. It is not very flammable and is resistant to rodents and mold; its surface is easy to plaster. Wood wool products are used to create sound-insulating structures (e.g., partition walls, soundproofing and sound-absorbing coverings) and the thermal insulation of facades, floors, pitched roofs, and false ceilings. It can be used as snap-in formwork to eliminate thermal bridges in lintels, balconies, pillars, etc. There are three types of wood wool products, i.e., homogeneous boards, inhomogeneous (combined with expanded polystyrene or mineral wool) boards, and additional system elements (e.g., corner or shutter elements) (Pfundstein, 2007; Balázs 1994).

3.3 Fiberboard

Fiberboard production developed as a side branch of the paper industry. The first products were made of unreliable materials, but the steam explosion process developed by William Mason in 1924 and the steam-pressurized refining process developed by Arne Asplund in 1931 brought about a breakthrough. A disadvantage of both processes is that they have high water consumption, which was the main reason for patenting a dry process in 1955; however, it uses a lot of electricity (Winkler, 1999).

Fiberboard is made from wood chips from which fibers are extracted using either a wet or dry process. After an adhesive is added, the next steps are mat formation and heat pressing. This procedure is suitable for adjusting the bulk density of the end product (thermal insulation fiberboards have a bulk density of 200-400 kg/m^3). The last steps are conditioning, edge-finishing, and grinding (Winkler, 1999). Low-density fiberboard is recyclable and has good thermal and sound insulation. Fiberboard has low water absorption as well as resistance to vapor permeation. Fiberboard is preferred for insulating attic spaces and pitched roofs (over and between rafters), as well as for filling partition walls and other soundproofing structures. There is also a loose, in-blown form of wood fiber insulation, which has a lower density (32-45 kg/m^3) and a lower rate of thermal conductivity (λ = 0.038 W/mK) than insulating board. Similarly to cellulose insulation, it is implemented with a high-pressure insufflating machine (Pfundstein, 2007; Winkler, 1999).

3.4 Particleboard

The first artificial board made from wood was patented in 1887. Mass production was begun in 1932 after the invention of layered particleboard by M. Himmelheber. Its production was far cheaper and more efficient because Himmelheber mainly used by-products and waste material from the wood industry as raw material. The modern technology for its manufacture was developed by F. Fahrni in the 1940s; since then it has not changed significantly. The first step of its production is grinding, which is followed by drying and classification. Then comes the binding (artificial resin) and set formation in one or more layers, depending on the end product. After a heat-pressing process, the final steps are cutting and edge and surface finishing (Hadnagy, 1983; Rowell et al., 1996). Low-density products are good for thermal insulation, but their quality is lower than wood wool and fiberboard. The main advantages of particleboard are their low shrinkage rate, high mechanical strength, and nearly isotropic behavior (Pfundstein, 2007; Novák, 2002). Because of their relatively high thermal conductivity, particleboard is rarely used as a self-contained thermal insulating layer. It is usually used as a support surface in insulating sandwich panels or combined insulating boards. Particleboard is often combined with plastic foam for insulating attic floors and attic spaces (Pfundstein, 2007).

3.5 Reed

Reed was widely used in temperate and cold climates for roofing since the early Middle Ages. The thermal-insulating ability of dry, hollow reed stalks was well-known, so insulating products made from reed were already manufactured in the 19th century. Because of their high water absorption, they were usually treated with bitumen. In order to protect reed products from insects, mold and fire, insulating plates with a two-sided asbestos covering (Celotex) were developed in the 1920s (Bynum, 2001; Déry, 2010; Manohar et al., 2006). The production of reed boards begins by binding them into sheaves after removing seeds and leaves from the reed stalks. Thereafter, the reed stalks are pressed between wire pairs which are tied together with wire clips. In addition to their good thermal and sound insulation ability, reed board is easy to plaster. In addition, it does not contain any chemicals or binding materials. Reed boards that use anchors are suitable for insulating facades. They can be used on a roof (over and above rafters) or as floor insulation. For fire safety and protection against rodents and insects, the use of 4-10 cm loam plastering or clay luting is necessary (Pfundstein, 2007).

3.6 Straw Bales

The development of baling machines in the second half of the 19th century strongly contributed to the birth of straw bale architecture. The first straw bale houses were built in Nebraska (USA) in the 1880s, where there were no available building materials except large quantities of straw bales as agricultural by-products (Novák, 2002; Minke and Krick, 2012; Novák, 2008). Nowadays, due to the increased interest in eco-architecture, straw bale construction has spread all over the world. Its raw material is a pressed straw bale that is tied together with polypropylene, metal or hemp threads. Protection against rodents and insects is provided by two-sided adobe plaster and dense metal netting placed on the upper and lower planes of a wall (Novák, 2002; Minke and Krick, 2012; Novák, 2008). It is not flammable due to its high density, i.e., there is not enough oxygen in compressed straw bales for burning. The surface of high-density straw bales has been charred in experiments; the charring results in a layer that prevents oxygen from entering the bale. Fire resistance can be improved by two-sided loam plastering (Móder et al., 2010). Straw bales should overlap according to the rules of brick bonding. In order to maintain stability, the bales are knitted with peanut sticks or reinforcing bars. The mechanical stability of a straw bale structure is often ensured by a wood frame structure, where straw bales are the in-fill insulation of wall and stab structures (Pfundstein, 2007; Novák, 2002; Minke and Krick, 2012; Novák, 2008).

3.7 Flax and Hemp Insulation

The raw material of flax insulation is the flax stalk, which has been used for making clothes and rope since prehistoric times. The first insulating products made from flax were developed in the United States in the 1910s under the trademarks of Flaxlinum and Fibroleft (Bynum, 2001). Hemp is also an important raw material from the textile industry, but hemp fiber is stronger and more flexible than flax. During its production the fibers are glued with natural adhesives (e.g., potato starch). Waste products from the textile industry and synthetic fibers are often added to flax products. Borax and boric acid are used to prevent flammability and improve resistance against pests (Pfundstein, 2007; Novák, 2008; Briga-Sá et al., 2013; Zach et al., 2013; Kymäläinen and Sjönberg, 2008). Hemp and flax products are available in rolls and boards. They are used for insulating pitched roofs (between rafters), wood slab structures (between beams), attic spaces and also for in-fill insulation of lightweight wood or steel structures. In addition, lightweight concrete bricks that also contain hemp fiber have appeared on the building material market in the 2000s. Experiments are being run to increase the tensile strength of concrete containing hemp fiber reinforcement; however, the durability of hemp fiber in concrete is still questionable. Research has been conducted on the durability of hemp-based thermal insulation using hydrophobic additives (Novák, 2008; Briga-Sá et al., 2013; Zach et al., 2013; Kymäläinen and Sjönberg, 2008, Korjenic et al., 2011).

3.8 Cotton

Cotton fibers are mainly used by the textile industry; moreover, their availability is very limited in Europe. Therefore, 80-90% of cotton-based thermal and sound insulation materials are produced from textile waste (e.g., jeans). During its manufacture cotton fibers are combed and loosened (carding), mechanically stabilized, and treated with a small amount of additive (3-8% boric acid) to improve its fire resistance and mold-proofing. What is advantageous is that it is a renewable raw material that has good vapor permeability; moreover, its manufacture involves low energy consumption (Novák, 2008; Briga-Sá et al., 2013). It is also recyclable and compostable. It does not contain any food source for rodents and insects, so there is no need for protection against them. Its main disadvantage is high water absorption; therefore, cotton insulation is not permitted for insulating structures in direct contact with moisture (e.g., facades). There are insulating blankets, felts, and strips made of cotton, but it can also be used as in-blown insulation similar to cellulose. It is primarily used for insulating attic spaces, attic floors, and pitched roofs (between rafters) (Pfundstein, 2007). Recent experiments have been conducted with compressed thermal insulation boards made from cotton. Depending on the pressure used during manufacture, these products have a wide range of mechanical strength and a relatively high insulating quality (λ=0.0585-0.0815 W/mK) (Zhou et al., 2010).

4 RECENTLY-INTRODUCED MATERIALS

A group of recently-introduced materials consists of nature-based thermal insulation products that have previously been well-known, but with other means of application. The spread of eco-conscious architecture has promoted the manufacture of thermal insulating products from these materials, thereby introducing new alternative nature-based thermal insulating products to the building industry.

4.1 Cellulose Insulation

Loose-fill and in-blown cellulose insulation was invented in Scandinavia in the 1920s; they are used as in-fill insulation of wood structures (Novák, 2008). The use of cellulose insulation was limited to this region for a long time and has only spread further over recent decades. Cellulose insulation is recycled newspaper which has been classified and has had contaminants (e.g., paper clips) removed. The cleaned material enters a rough and then a fine grinding mill. After this procedure, admixtures (borax, magnesium sulfate) are added to the fine-flaked material in order to provide protection against fire, mold, insects, and rodents (Novák, 2008; Vėjelis et al. 2006). Finally, the mixture is poured into plastic bags. Cellulose insulation is able to fill even the smallest hollows and can form a continuous insulating layer. Because it is recycled raw material, its production requires less energy. Its implementation is waste free, simple, and rapid. In the form of loose filling or insulating pellets, it can be used as non-load-bearing floor insulation. Cellulose insulation can be blown through a pipe onto a surface or into a hollow using a special insufflating machine. This technology is suitable for insulating facades, floors, pitched roofs (between rafters), and the core insulation of lightweight structures (Pfundstein, 2007; Novák, 2008; Vėjelis et al. 2006).

4.2 Sheep Wool

Although animal skins were used for clothing in prehistoric times, sheep wool insulation is a product of modern architecture (Bynum, 2001). These insulating products are made of pure sheep wool that has been cleaned and usually strengthened with polyester fibers. Just like other nature-based materials, sheep wool is also impregnated with borax. Wool fibers are fine, smooth, stretchable, strong, and flexible (Dénes et al., 2017). Moreover; wool fibers are curly, which improves their thermal insulation abilities. Sheep wool is recyclable, rot-proof and ignites at a relatively high temperature (580-600 °C). Sheep wool insulation is very rarely used due to its high price. In the building industry there are felts, blankets, and sealing strips made of sheep wool. It is suitable for insulating pitched roofs (between rafters) and attic spaces or even facades (Pfundstein, 2007; Novák, 2008).

4.3 Coconut fiber

Coconut fiber is the protective layer on a coconut shell. It can be removed by soaking the coconut in fresh or salty water; during the soaking the coconut shell rots away and the more resistant coconut fiber survives (Bozsaky, 2017). Afterwards the fiber is washed, dried and combed; then coconut fiber blankets can be produced. It is suitable for indoor, outdoor and core insulation. It is long-lasting, waterproof, and flexible. Coconut fiber has high tensile strength. Its cost and low fire resistance (despite additives) are its main disadvantages (Pfundstein, 2007; Novák, 2008; Panyakaew and Fotios, 2011; Manohar, 2012; Manohar et al., 2006).

4.4 Seagrass

The dry, hollow stalks of seagrass (Zostera marina) and Neptune grass (Posidonia oceanica) have the same insulating quality as reed or straw. In the autumn, when the plant dies, waves wash the leaves to the shore; they roll into brown balls of various densities and sizes. These seagrass balls are seen as pollution on coasts and beaches, and it is extremely hard to remove and dispose of them (Carmona et al., 2018).

In 1893, S. Cabot developed the so-called Cabot-Quilt, which was the first insulating product made from seagrass with a two-sided paper or asbestos covering. Because of its beneficial material properties, this product remained on the market until the 1940s (Bynum, 2001).

Thermal insulation products made of seagrass and Neptune grass have a high degree of resistance to fire, moisture and pests (mold, insects, rodents). Neptuntherm is the best-known seagrass product today; it was developed by R. Meier (Bozsaky, 2017). In loose-fill form or insufflated, it can be used as in-fill insulation (similar to cellulose insulation). There are also insulating blankets, which are suitable for facades, walls, slabs (between beams) and pitched roof (between rafters) insulation (Carmona et al., 2018; Pfundstein, 2007).

5 MATERIALS IN AN EXPERIMENTAL STAGE

At the beginning of the 21st century, the spread of eco-architecture inspired the development of new and unusual thermal insulation materials as well as the appearance of rediscovered and recently introduced thermal insulation materials. Most of them are in experimental stages so they cannot be found on the thermal insulation materials market. Nevertheless, it is expected that they could be more widespread over incoming decades.

Cornstalks and corncobs are available in large quantities as agricultural waste. These products are usually burnt as biomass because the opportunities for their utilization are much more limited than straw bales. In the 1920s, corn-based insulation board was used in the USA, and there were attempts to improve insulating boards made from cornstalks in the 1950s in Czechoslovakia (Pinto et al., 2016). Nowadays, there are experiments to produce insulation products made from corncobs and formaldehyde binder with high mechanical strength but a relatively poor thermal insulating quality ($\lambda = 0.096$ W/mK) (Panyakaew and Fotios, 2008). An insulating product made of a special mixture of shredded cornstalks and synthetic resin was also patented in Hungary in 2008. This mixture was put into steel molds, compressed with a defined force, and dried out, thereby forming solid blocks similar to straw bales. The research results showed high thermal and sound insulation qualities ($\lambda = 0.0455\text{-}0.0555$ W/mK, $s' = 4.8\text{-}17.7$ MN/m^3). The resistance of cornstalk blocks to fire, moisture, and pests might be resolved with some additives similarly to other nature-based materials; however, its production has not yet begun (Bozsaky 2012).

Researchers in Japan have conducted experiments to develop thermal insulating products made from bamboo fiber. A steam explosion process was applied to extract fibers from bamboo stems (similarly to fiberboard production). After mixing the fibers with synthetic resin, rigid insulating boards were produced using a heat press. Depending on its density, the thermal conductivity of this product ranged from 0.08 to 0.34 W/mK (Takagi et al., 2007).

As an alternative thermal insulation material, insulating blankets have been developed from palm leaves in Morocco (North Africa). Palm leaves are nutrient-poor, so they are unsuitable for feeding animals; therefore, they are usually burnt as biomass. To produce insulating blankets from palm leaves, the first step is to extract fiber from the leaves. The palm fibers are cleaned (washed) and dried; natural adhesive is added. Palm fiber blankets have been manufactured with a thermal conductivity of 0.041 W/mK (Oushabi et al., 2015). Researchers from North Africa and the Middle East have attempted to create thermal insulating masonry elements from a mixture of palm fibers and lime. Its material properties are very similar to the elements of hemp concrete (λ =0.18W/mK) (Belakroum, et al., 2015).

It should also be mentioned that efforts in some countries have been made to introduce special thermal insulation products made from kenaf fiber (also called Deccan hemp or Java jute), rice stalks, and pineapple leaves (Ardente et al., 2008; Asdrubali et al., 2015). There have also been attempts to create thermal insulating products with sunflower stalk additives (Evon et al., 2015).

6 CONCLUSIONS

The excessive consumption of fossil fuels has encouraged mankind to make as many industrial products from renewable sources as possible. It can also be observed in the building industry, where this trend is most likely to be found in the thermal insulation material market. At the start of the 21st century, significant changes occurred that resulted in an increased market share for nature-based thermal insulation materials. Although some of these materials have been known for a long time, many durable but artificial materials had almost completely supplanted them for decades. According to recent experience, strong developments and improvements in manufacturing technology, durability, reliability, standards, material quality, resistance against pests, fire, and moisture, nature-based products are becoming more and more competitive (e.g., straw bales, fiberboard, cellulose insulation). In addition, new and previously unused and unknown thermal insulating products with renewable raw materials have also appeared. They often utilize agricultural or industrial by-products (hemp fiber, flax fiber, cotton, seagrass). Additional research and development is being conducted to create newer products that increase the utilization of agricultural waste (e.g., palm fiber, cornstalks and sunflower stalks).

The quantity and market share of nature-based thermal insulation materials has increased so much in recent decades that a need for the further classification of nature-based materials according to their novel aspects has occurred. On the basis of recent studies and reviewing the long evolutionary history of nature-based thermal insulation materials, the following groups can be made:

– rediscovered materials (cork, wood wool, low-density fiberboard and particleboard, reeds, straw bales, flax, hemp),
– recently introduced materials (sheep wool, cellulose insulation, cotton, coconut fiber, seagrass), and
– materials in experimental stages (cornstalks, corncobs, palm fibers, kenaf fibers, sunflower stalks).

The quality of the thermal insulation of the above materials is very close to the same properties of traditional artificial materials (**Tab. 2**). Their resistance to fire, heat, moisture, and pests has been a key issue for a long time, but today there are many methods to improve their safety and resilience. Production technology is continuously being upgraded to provide an even more reliable and constant quality of these materials. The research on product development of thermal insulation materials makes it possible to introduce more and more new products to the market. The distrust of nature-based thermal insulation materials with renewable origins can also be relieved. Their advancement can be further enhanced by introducing knowledge about nature-based thermal insulation materials into the education of construction industry specialists (e.g., civil engineers and architects).

When examining the market for currently used nature-based thermal insulation materials, the proportion of rediscovered materials is 57% (fiberboard 28%, wood wool 20%, hemp and flax 9%). The proportion of recently introduced materials is 43%, especially cellulose insulation (32%). It should also be added that, when considering current trends, it is expected that these percentages may change in the coming decades.

Tab. 2 *Thermal conductivity of nature-based thermal insulation materials*

Materials	**Thermal conductivity (W/mK)**
Rediscovered materials	
Cork	0.037-0.060
Wood wool	0.070-0.090
Fiberboard	0.040-0.090
Particleboard	0.055-0.100
Reeds	0.042-0.060
Straw bales	0.038-0.072
Flax	0.037-0.045
Hemp	0.039-0.050
Recently introduced materials	
Cellulose insulation	0.045-0.055
Cotton	0.040-0.050
Sheep wool	0.035-0.040
Coconut fiber	0.040-0.050
Seagrass	0.040-0.045
Materials in experimental stage	
Cornstalk block	0.045-0.055
Corncob board	0.096
Bamboo fibers	0.080-0.340
Palm fibers	0.041
Kenaf fibers	0.039
Sunflower stalks	0.064-0.085

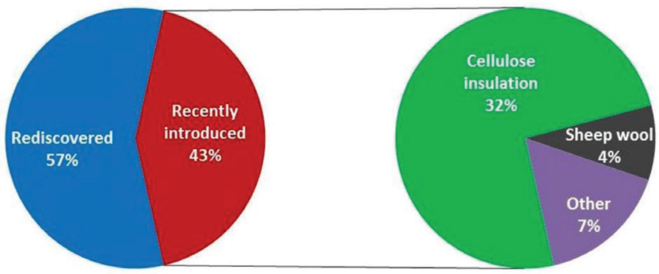

Fig. 3 *Market distribution of nature-based thermal insulation materials in Germany (Danner, 2008; Wieland, 2010)*

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