Applied Mechanics and Materials
ISSN: 1662-7482, Vol. 887, pp 90-97
doi:10.4028/www.scientific.net/AMM.887.90
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Submitted: 2017-06-21
Revised: 2017-08-28
Accepted: 2017-08-31
Online: 2019-01-25

Sustainable Materials with Potential Application as Core Materials in Vacuum Insulations

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Keywords: Core materials, vacuum insulation panels, organic fibers, thermal conductivity, thermal insulation, heat transfer.

Abstract. The paper focuses on the various uses of several types of textile fibers (mainly by-products) in the development of modern insulation materials with a high value added. These materials bear several specific advantages over conventional insulations, which enable, among others, easier installation. Some of the newly developed insulations can also be used as core insulations in the manufacture of vacuum insulation panels (VIP). In the context of the research, the study of behavior of thermal insulating materials based on organic polymeric and natural fibers (including fibers from recycled textiles) was conducted. The experimental materials were used to study their physical and mechanical properties and their behavior under reduced pressure (up to vacuum) to evaluation their possible use in the field of VIP as core insulations. Researches have shown that developed insulation based on alternative base can have very good potential in the VIP area and compete with the standard core insulations based on glass fibers of SiO_2.

Introduction

Requirements for the minimum energy demands of buildings are constantly becoming stricter. It is the reason why high quality insulation materials are being used. One possibility is the application of vacuum insulation panels, which have extreme low values of thermal conductivity at low thickness. On the grounds of this fact the vacuum insulation panels can be a very good solution for the insulating of historical buildings with intricate facades or buildings where it is not possible to apply thicker insulation materials. The first patent for vacuum insulation, no. 516377, was granted by the German Reichspatentamt to O. Hemman/Sterchamolwerke, Dortmund in 1930 [1]. It had a porous material in its core and the cover was made of rubber. Other patents were no. 236788 by H. M. Strong and F. P. Bundy from 1951 and no. 2700633 granted by the US Patent Office in 1955 to H. P. Bovenkerk/GE, New York. This patent was based on a glass fiber kernel, welded into steel foil [1]. Patent no. 3151365 from 1964 was the first to describe nanostructured kernels, granted to inventors P.E. Glaser, A.G. Emslie and W.A. Salmon/Arthur D. Little, Cambridge. Further developments in VIP-technology were pursued by L'Aire Liquid [2] and Brown Boveri & Cie (BBC) in Heidelberg [3, 4]. The first commercial use of vacuum insulation panels was in 1970. These materials were developed for the insulation of fridges, freezers and refrigeration boxes. In 1999 vacuum insulation panels were approved in the USA for use in Civil Engineering as thermal insulation materials [5].

Many researchers concerned themselves with the topic of vacuum insulations and their production and applications; they are scientists from Sweden, Switzerland, Germany, Denmark, Slovenian, Greece, Canada, China, Korea and other states. In many countries vacuum insulations were implemented as insulation materials in buildings. They were tested for heat and moisture transport in building structures [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. These investigations concluded that vacuum insulation panels show 5-10 times bigger thermal resistance in comparison with traditional insulation materials, such as mineral wool or, expanded polystyrene.

These materials have some disadvantages, such as a high purchasing price and the necessity to be tailored to the given construction. It is necessary to train workers who will manipulate with these materials and install them onto the structure. Other disadvantage is the sensitivity on quality of vacuum inside them, which can reduce the resulting thermal insulation properties of the structures over time. It is also important not to forget about water impermeability of vacuum insulation panels. In a structure, these materials act as a vapor barrier that could entrap moisture in the structure on the interior side of the vacuum insulation panels. Many studies have proven that vacuum insulation panels did not increase the moisture content of the wall after retrofitting [7].

Fumed and precipitated silica, open-cell polyurethane, and several types of fiberglass are commonly used as core materials of vacuum insulation panels. Some research results published in specialist journals show that natural fibers (plant, animal) can be successfully used for the production of the core materials of VIPs [17]. The advantage of these fibers is the fact that they are porous and are often made up of bundles of very fine fibers (with a thickness in the order of microns), which need only be separated, adjusted lengthwise and combined back into mats of optimum bulk density. The advantage of these isolation materials is the relatively low energy consumption during their production, as well as the use of renewable resources of secondary raw materials, when the source of fibers is the by-products from agricultural production, waste textiles, etc. Studies carried out on these types of insulation materials at normal pressure show that in order to achieve the best thermal insulation properties, it is necessary to use fibers with very small thickness [18]. Therefore, cotton fibers with a low primary fiber thickness of about 10 microns, depending on the type of cotton and growth time, appear to be particularly advantageous [19]. However, if the core of vacuum insulation panels is made from an organic insulation, it is important to vacuum-seal it in a non-vapor permeable foil. This is to prevent moisture from degrading the properties, contamination of the insulation and possible biotic attack. It is not necessary to improve the natural fibers for their use in vacuum insulation, which markedly simplifies manufacturing, reduces price and energy consumption, compared to conventional thermal insulators produced from natural fibers. After vacuum-sealing, the thermal conductivity is significantly reduced. This is a very new area of application of these green fibrous materials and there is only a minimal amount of knowledge available. The aim of research being performed at the Brno University of Technology is to find suitable alternative core materials based on natural fibers, which are easily recyclable and do not burden the environment.

Description of the Test Samples and Methodology of the Carried Experiment

The trend of achieving sustainable development in the area of new, eco-friendly materials remains topical for many experts concerned with developing new materials applicable worldwide in civil engineering as well as elsewhere. Our research team has for many years been developing non-traditional materials that meet the current requirements. These materials are made with organic fibers – waste natural fibers produced by agriculture or waste industrial (locally produced) fibers. Their thermal and acoustic insulation properties are very close to those of conventional insulation materials (expanded polystyrene, extruded polystyrene, mineral wool, polyurethane foam), which are still finding broad use in the Czech Republic despite their harmful impact on the environment.

Test samples made with natural and secondary fibers were designed as part of the experiment. Potentially suitable raw materials were selected based on literary surveys and preliminary measurements after which prototype test samples were produced. Their bulk density ranged from 100 to 200 kg.m^{-3}, which are potentially suitable for selection of vacuum insulation panels.

Flax fibers, cotton fibers, recycled polyester fibers and primary pure polyester fibers with high fineness (0.9 dTex) were chosen for the production of the test samples.

Specifically, they were:

1. Flax fibers processed only by a basic technology of defibration during harvesting. Their average fiber thickness was 130 µm (see in figure 1).
2. Recycled cotton fibers with an average fiber thickness of 20 µm.
3. Recycled blend of cotton:polyester (50:50) fibers with an average fiber thickness of 26 µm.
4. Fibers made from a mixture of recycled cotton and polyester with an average fiber thickness of 21 µm.
5. Primary polyester fibers with an average fiber thickness of 10 µm.

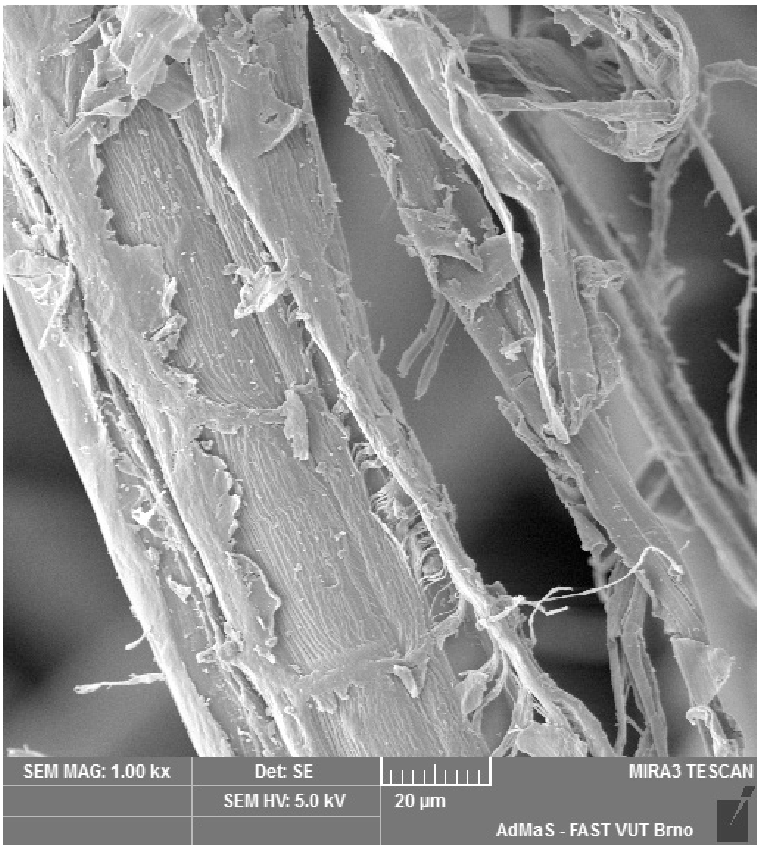

Fig. 1 REM picture – detail of flax fiber

From the above raw materials, test samples were made by the air-lay method, using 15% of binder bicomponent fibers. After production, the test samples with the dimensions of 200 mm x 200 mm were cut from mats.

Linear dimensions were determined according to EN 822 [20] / EN 12085 [21], thickness according to EN 823 [22] and bulk density according to EN 1602 [23] on the newly designed insulations. Determination of thermal conductivity was made in dependence on pressure using a FOX 200 vacuum instrument according to EN 12667 [24] and ISO 8301 [25]. The measurements were made in a standard way at an average temperature of 10 °C and a temperature gradient of 10 °C. Thermal conductivity measurements were performed at normal atmospheric pressure, followed by vacuum and at 1 mbar. Selected samples were also measured in dependence on the mean temperature at a constant temperature gradient of 10 °C (see Fig. 2).

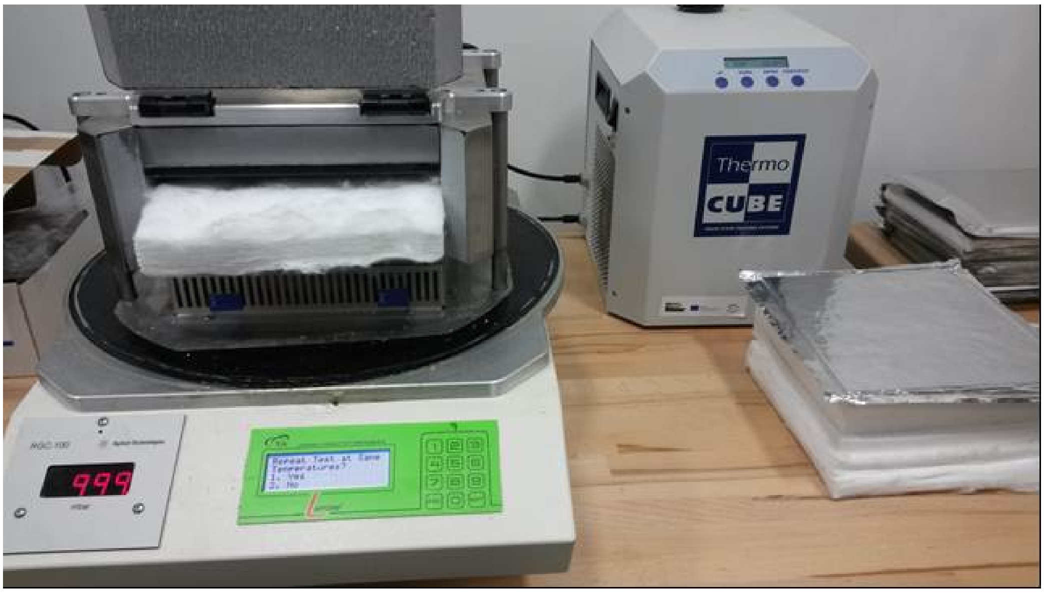

Fig. 2 FOX 200 Vacuum

Measurement Results

The test specimens were conditioned under laboratory conditions and then dried at 105 °C to constant mass. Their linear dimensions, thickness and density were measured. The results are shown in Table 1 below.

Table 1 Physical properties of the test samples

Sample n.	Composition	Thickness [mm]	Bulk density [kg.m^{-3}]
1	Flax oleiferous	23.92	92.44
2	Cotton	20.08	119.75
3	Cotton+PES	9.16	190.00
4	PES - recyclated	21.70	108.02
5	PES - primary	12.80	198.93

Next, the determination of the thermal conductivity coefficient was performed according to EN 12667 by the plate method at a mean temperature of + 10 °C and a temperature gradient of 10 °C at normal pressure. The results are shown in Table 2 below.

Table 2 Results of the determination of thermal conductivity at normal pressure

Sample n.	Composition	Thickness [mm]	Thermal conductivity [W.m^{-1}·K^{-1}]
1	Flax oleiferous	23.92	0.0352
2	Cotton	20.08	0.0373
3	Cotton+PES	9.16	0.0402
4	PES - recyclated	21.70	0.0360
5	PES - primary	12.80	0.0333

As can be seen from the results, the bulk density of the test samples ranged from 92.44 to 198.93 kg.m^{-3} and thermal conductivity between 0.0333 W.m^{-1}.K^{-1} and 0.0402 W.m^{-1}.K^{-1}. The best overall values were obtained in sample No. 5 made of primary polyester fibers with a fiber thickness of 10 µm. As is visible from the results, samples 1–4 showed that with increasing bulk density degradation of the thermal insulation properties came. The lowest thermal conductivity was discovered in sample 5, which was due to significantly higher fiber fineness.

The next test was measuring thermal conductivity. It was determined under reduced pressure (1 mBar) and under vacuum. Measurements were made at an average temperature of + 10 °C and a temperature gradient of 10 °C. The results are shown in Table 3 below.

Table 3 Results of the determination of thermal conductivity at lower pressure

Sample n.	Composition	Thermal conductivity [$W.m^{-1}.K^{-1}$]	
		1 mBar	Vacuum
1	Flax oleiferous	0.0223	0.0078
2	Cotton	0.0163	0.0051
3	Cotton+PES	0.0145	0.0041
4	PES - recyclated	0.0236	0.0058
5	PES - primary	0.0093	0.0019

As the above results indicate, in terms of the behavior of the materials under reduced pressure, the fiber thickness is key property. An extreme reduction in thermal conductivity was achieved in all samples under vacuum. The best values were obtained in sample 5 made from primary polyester fibres. In addition, sample 3, which was made from a mixture of recycled polyester and cotton fibers, showed very good results. Figure 3 below shows the dependence of thermal conductivity on samples in vacuum depending on fiber thickness.

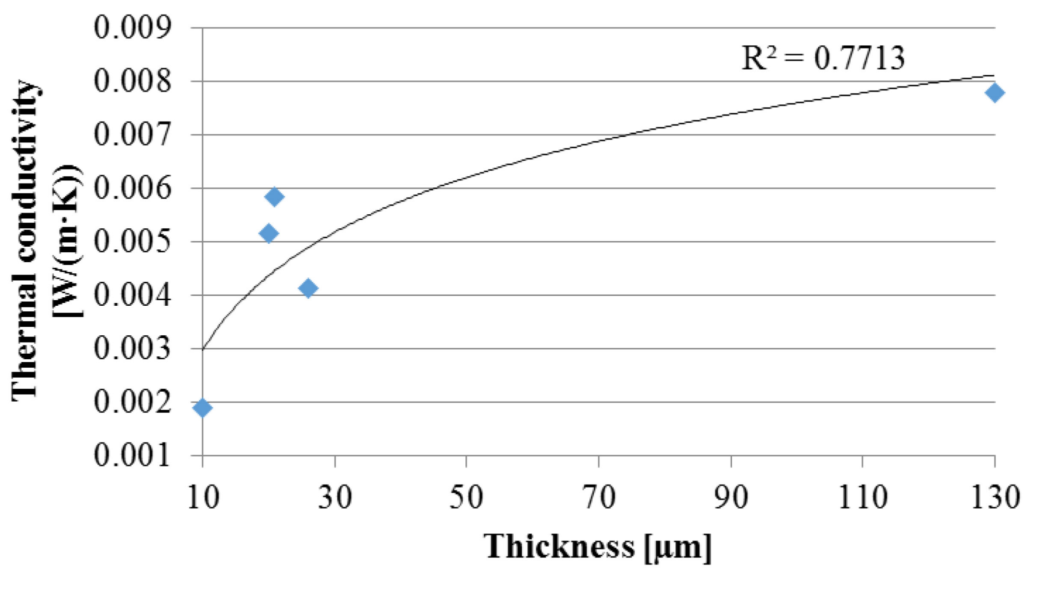

Fig. 3 Dependence of thermal insulation properties in test samples under vacuum on fiber thickness

From the point of view of the usability of the fibrous insulations for vacuum insulating panels, the dependence of the thermal conductivity on the pressure, or rather its value at slightly increased pressure is crucial. As a reference value, thermal conductivity is usually measured at a pressure of 1 mBar. There are very large differences between the values of thermal conductivity in each test specimens. In all cases, the thermal insulation properties were worse compared to the values measured in vacuum. The best values were again found in samples No. 5 and 3. Sample No. 5 further underwent a determination of thermal conductivity in vacuum. The results are shown in Fig 4. below.

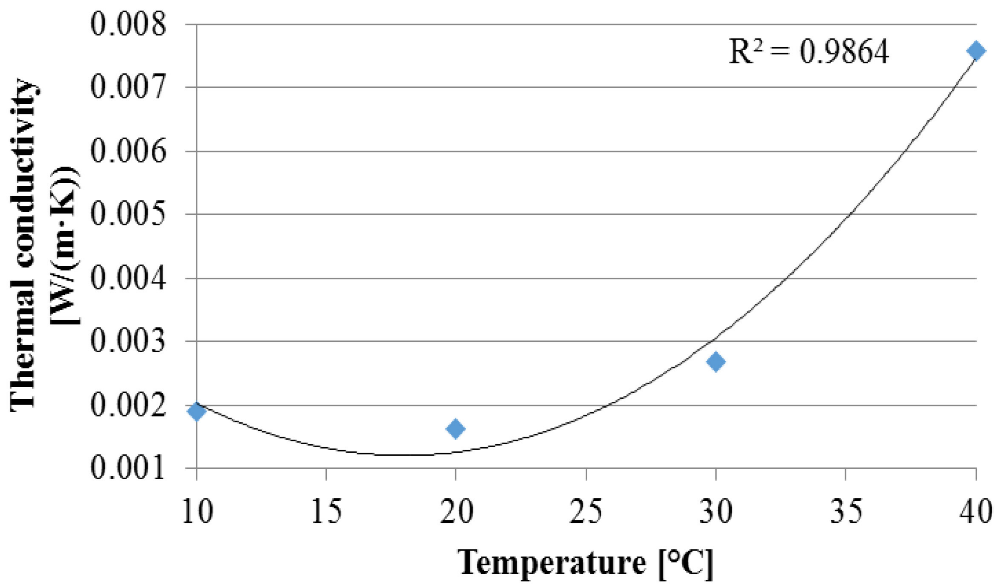

Fig. 4 Dependence of thermal insulation properties in test sample 5 under vacuum on temperature

As can be seen from the obtained values of thermal conductivity, the insulation exhibits the best values at an average temperature of +20 °C. When the temperature rises above +30 °C, is the thermal insulation properties see a significant degradation.

Conclusion

The aim of the research was to verify the possibility of using environmentally friendly insulating materials based on natural or waste fibers for use as core materials in vacuum insulating panels. Previous research has shown that these non-traditional insulation materials can be used for this purpose thanks to their porosity. Five types of materials based on both natural and waste fibers were tested in this study. These materials mainly tested for thermal insulation properties in dependence on pressure (vacuum, 1 mBar, normal pressure).

The obtained data shows that sample 5 from the five materials tested exhibited the best thermal insulation properties under reduced pressure. This sample was made with primary polyester fibers. The thermal conductivity of this sample at a pressure of 1 mBar was 0.093 $W.m^{-1}.K^{-1}$ and in vacuum was 0.0019 $W.m^{-1}.K^{-1}$ This sample was also subjected to a study of the dependence of thermal insulation properties in vacuum. It was found that the best thermal insulation properties are at 20 °C. Beyond this point there is a significant deterioration of thermal conductivity.

Very good results of thermal conductivity under pressure were also found in sample 3, which was made of 50:50 cotton and polyester fibers.

In conclusion, the thickness and the character of the feedstock fibers themselves have a significant influence on the thermal insulation properties in dependence on pressure, as demonstrated by the values presented in this paper. The finer the fibers, the better the thermal insulation properties of core material in which the fibers may be used (Fig 5.).

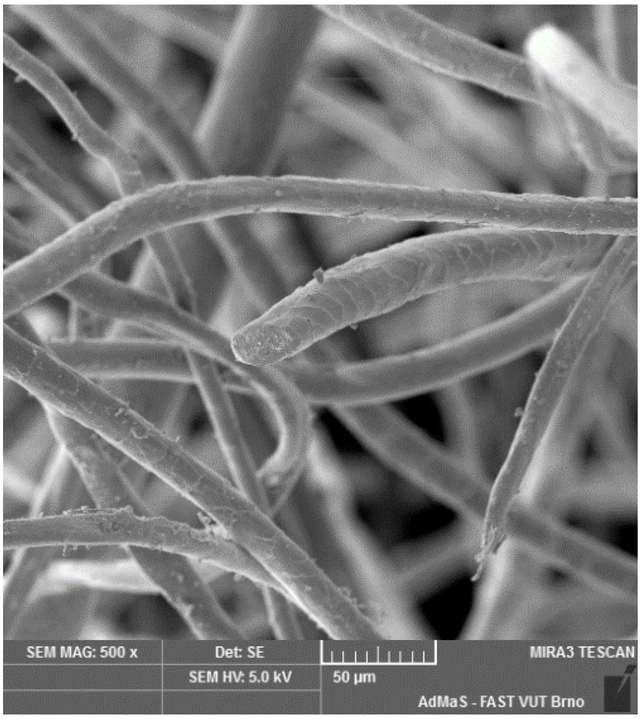

Fig. 5 REM picture – detail of structure if insulation based on textile (cotton) fibers

Acknowledgements

This paper was elaborated with the financial support of the project GA 17-00243S "Study of the behavior of insulating materials under extremely low pressure".

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[23] EN 1602 Thermal insulating products for building applications. Determination of the apparent density

[24] EN 12667 Thermal performance of building materials and products. Determination of thermal resistance by means of guarded hot plate and heat flow meter methods. Products of high and medium thermal resistance

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