CHEMICAL ENGINEERING TRANSACTIONS

VOL. 114, 2024

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Petar S. Varbanov, Min Zeng, Yee Van Fan, Xuechao Wang

ISBN 979-12-81206-12-0; **ISSN** 2283-9216

DOI: 10.3303/CET24114141

Innovative Thermal Insulations from Cornstalk and Cereal Straw for Sustainable Architecture

David Bozsaky

Széchenyi István University, faculty of Architecture, Civil Engeering and Transport Siences, Department of Architecture and Building Construction, H-9026 Győr (Hungary), Egyetem tér 1
bozsaky@ga.sze.hu

Nowadays, architects are increasingly prioritising sustainability, leading to the rise in the popularity of construction products made from renewable raw materials. Using thermal insulation materials has become crucial to ensure the energy-efficient operation of buildings. In the building materials market, especially in the field of thermal insulation products, there is a growing interest in products made from natural, renewable raw materials. This is because their use can reduce the energy consumption of buildings but also the CO_2 emissions of the construction industry. There is an urgent need to utilise various industrial and agricultural by-products. In Hungary, a large amount of cereal straw and cornstalks are not used or are burned, which increases CO_2 emissions. Using them as a construction product would be an excellent alternative solution for reducing the greenhouse gas emissions of the construction industry. In recent years, there have been two attempts to produce building insulation materials from cornstalks and cereal straws. As part of comprehensive research, a laboratory qualification test of both products was carried out. Based on the evaluation of the results, both thermal insulation products seem promising. Their material properties support their applicability in building construction, although some limitations should be considered. This paper aims to present the two experimental products mentioned above, analyse their material properties, and evaluate their applicability in the construction industry.

1. Introduction

In the 21st century, there has been a significant shift towards technologies that utilise renewable energy sources and raw materials, driven by the excessive consumption of non-renewable energy sources and the resulting increase in harmful emissions (Chel and Kaushik, 2018). This claim towards energy and environmentally conscious thinking has permeated various aspects of life, including the construction industry (Kumdokrub and You, 2023). With the construction industry responsible for 36 % of the European Union's total energy consumption and 37 % of greenhouse gas emissions, there is a significant potential for energy savings – as reported concerning current status (UNEP, 2022) and trends (Lamb et al., 2021). The emphasis on thermal insulation has grown in importance, as its application can lead to substantial reductions in the energy required for heating buildings, which accounts for 70 % of household energy consumption according to statistical data (MEKH, 2021).

In the context of sustainability, the life cycle assessment of buildings has gained increasing importance. This assessment includes evaluating the energy needed for the production and installation of materials, as well as the potential for reuse, recycling, or disposal at the end of their life cycle (Pargana et al., 2014). Currently, over 90 % of thermal insulation materials are made from non-renewable sources, requiring significant fossil energy consumption during production (CMI, 2020). However, in the spirit of environmentally conscious architectural design, exploring renewable raw materials is worthwhile (Zach et al., 2013).

Regrettably, it is evident from current trends that designers, investors, and contractors tend to favour traditional artificial insulation materials. This is due to a combination of factors, including the lack of public awareness about alternative solutions, the relatively higher prices of materials (e.g., hemp, wool), and a general lack of trust stemming from unreliable technical literature and regulation in this area (Čuláková et al., 2012).

Paper Received: 13 April 2024; Revised: 1 August 2024; Accepted: 19 November 2024
Please cite this article as: Bozsaky D., 2024, Innovative Thermal Insulations from Cornstalk and Cereal Straw for Sustainable Architecture, Chemical Engineering Transactions, 114, 841-846 DOI:10.3303/CET24114141

2. Straw quilt and cornstalk insulation block

The utilization of agricultural by-products from agriculture in the building industry has major importance from environmental and economic points of view (Defo et al., 2024). The thermal insulating ability of natural materials was recognized very early. Around the second half of the 19th century, the first materials installed specifically for thermal insulation were also obtained from nature (Bynum, 2001) and also discussed from historical perspective (Déry, 2000). Throughout history, materials like straw have been used in construction, from adding straw fragments to clay to building thatched roofs. In the United States, straw bale construction was invented in the 1880s (Minke and Krick, 2012), and pressed straw boards were first patented in 1923 by S. N. Chayeff. The first insulation board designed specifically for thermal insulation was developed in 1935 by T. W. Dieden and brought to market by T. J. Mosesson in 1945 under the name Stramit (Neuberger and Kic, 2021).

In Hungary, approximately 60 % of cereal straw is harvested by domestic farms, with the remaining 40 % being either burned in the stubble or ploughed back into the soil. The majority of the harvested cereal straw (50-55 %) is utilized as animal bedding and stable manure, while a smaller portion (25-30 %) is used for making mushroom compost. Around 15-25 % of the straw is burned as biomass (Gyuricza, 2014). The benefit of using cereal straw is its cost-effectiveness as an agricultural by-product, its renewable nature, its proximity to easy access (resulting in low transport costs), and its abundant availability, with Hungary producing an average of 7.5 Mt/y (Tóth et at., 2007).

The straw quilt was patented in Hungary in 2020. The completed straw quilts measure 50×100 cm and are mounted using white linen or brown jute fibre. Production involves the use of a special machine capable of automatically cutting, compressing, and sewing the straw. The straw is loaded into the machine via a tray, where it is cut to size and then sewn together with the mounting using a high-performance sewing machine, resulting in a compact end product (Bozsaky and Ábrahám-Horváth, 2023).

Corn stalks and cobs are a significant agricultural waste, with Hungary producing 10-12 Mt annually. Currently, only 6-7 % of the corn stalks are harvested, mainly for use as fodder, while the rest is either ploughed into the ground (which is not ideal for the soil in large quantities) or burned as biomass – discussed in the work on energy crops (Gyuricza, 2014) and waste utilisation (Kálmán, 2008). In the construction industry, corn stalks have historically been used for thermal insulation in Central and Eastern European folk architecture. Maizewood, the first building industry product made from corn stalks, was patented by O. R. Sweeney in 1929 (Finlay, 1990). While there have been various attempts to create construction products from corn stalks throughout the 20th century, they were either quickly discontinued or remained at the patent level. In 2008, a corn stalk block similar to a straw bale was patented in Hungary. This insulating block is made by chopping up the raw material (plant fibre), mixing it dry, adding a bonding agent (glue), placing the mixture in a mould, pressing it to the desired size, and finally drying it. The main advantage of this block is that its raw material is cheap, readily available in large quantities, environmentally friendly, easily shaped, and recyclable (Bozsaky, 2017).

3. Laboratory tests

The qualification tests for the experimental products were carried out at the Laboratory of Building Materials and Building Physics of István Széchenyi University. The goal was to compare their material properties with other known thermal insulation materials and to assess their potential uses and limitations. The manufacturers supplied the necessary test specimens, including 21 pieces of 20x20 cm, 3 pieces of 15x30 cm, 6 pieces of 30x30 cm, and 5 production-size samples (50x100 cm) for the straw quilt tests, as well as 8 pieces of 30x30 cm and 12 pieces of 20x20 cm samples for the cornstalk block tests. The tests involved determining the volume density, dimensional stability, water absorption, compressive strength, and bending strength of the materials (results in Table 1.).

3.1 Bulk density

The (EN 1602, 2013) standard test was conducted on both 20x20 and 30x30 cm samples in their natural and air-dried (dried to constant weight) states. However, due to significant measurement deviations on smaller samples, only the data from the 30x30 cm samples for straw quilts can be considered relevant. The results indicate that the average bulk density of the straw quilt in its natural state is 103.45 kg/m^3 and 86.52 kg/m^3 in its air-dry state. The cornstalk block, on the other hand, exhibited a much higher bulk density, measuring 199.66 kg/m^3 and 165.39 kg/m^3.

3.2 Dimensional stability

There are two methods for determining the dimensional stability of thermal insulation products. According to (EN 1603, 2013), measurements were taken on samples of the production size, which was 100x50x50 cm for straw carpets and 30x30 cm for corn stalks. The results indicated that the length of the straw quilt samples decreased by 0.02 % (0.2 mm), their width by 0.08 % (0.4 mm), and their thickness by 0.20 % (0.2 mm). The average volume change was 0.3 %, and the bulk density decreased by 0.33 % when considering the mass changes. Similar results were observed for the cornstalk insulation blocks, with a 0.08 % (0.31 mm) change in length, a 0.13 % (0.28 mm) change in width, a 0.49 % (0.32 mm) change in thickness, and a 0.60 % change in volume.

(EN 1604, 2013) is utilized to assess the dimensional stability of straw quilts and cornstalk blocks during storage under specific temperature and humidity conditions for a designated period. In the case of straw quilts, this involved storage in a drying cabinet for 48 h at a temperature of 70±2 °C and a relative humidity of 50±5 %. Measurements were conducted on samples of the production size (100x50x50 cm) for straw quilts, and 30x30 cm for corn blocks. The results indicated that the length, width, and thickness of the straw quilt decreased by 0.38 %, 1.27 %, and 2.71 %, resulting in a 3.8 % decrease in volume and a 6.4 % decrease in bulk density. For the cornstalk blocks, the measured dimensions also decreased, with the volume and bulk density decreasing by 5.84 % and the weight changing by 11.30 %.

3.3 Thermal conductivity

The tests were conducted according to (EN 12667, 2001) on 30x30 cm test specimens using a Taurus TCA 300 thermal conductivity measuring device. The tests were carried out in delivery conditions, natural moisture content (8.01 m/m % for straw quilt, and 8.80 m/m % for cornstalk blocks) and in an air-dry state. Based on the test results, it was determined that the thermal conductivity of the straw quilt at an average temperature of 10 °C is 0.0401 W/mK in the air-dry state and 0.0434 W/mK with natural moisture content. For cornstalk blocks, the values were 0.0511 W/mK and 0.0562 W/mK. Comparing these values to the air-dry condition, it can be concluded that the thermal insulation capacity of both products is close to, or even reaches, that of traditional and well-known materials such as polystyrene foam and mineral wool.

3.4 Water absorption

The water absorption of thermal insulation materials can be tested using either partial or full water immersion. The partial immersion test can be carried out following the (EN 1609, 2013) standard and can be conducted as a short-term (24 h) or long-term (28 days) test. However, the long-term water absorption test is only applicable to artificial materials that may be used in areas not protected from moisture. For natural materials with limited moisture resistance, such as straw quilts and cornstalk insulating blocks, the 28-day test appeared irrelevant, so only the short-term water absorption was determined. Test specimens measuring 20x20 cm were conditioned for 6 h under normal laboratory conditions (T = 23±2 °C, φ = 50±5 %) and then placed in a water tank with their bottom surface 10±2 mm below the water surface. The test conditions were the same as the conditions mentioned above. Based on the tests, the water absorption of straw quilts was 1.312 kg/m^2, which is similar to mineral wool and lower than most natural materials (e.g., hemp, wool, cellulose), although higher than cork. For cornstalk blocks, the water absorption was 4.82 kg/m^2, similar to values measured for similar natural, organic materials.

The full water immersion test was conducted according to the (EN 12087, 2013) standard. However, the 28-day test was not carried out, and water absorption was measured after 1 h, 24 h, and 5 days (120 h). During the test, the samples were submerged in water with their upper surface positioned 50±2 mm below the water surface. Before the test, the samples were conditioned for 6 h under standard laboratory conditions as per the standard requirements. The test was conducted at a water temperature of 23±2 °C. The weight measurements and water absorption results indicated that the straw quilt with lower bulk density absorbed more water, while the cornstalk block absorbed a higher volume percentage of water. The results also showed that water absorption was rapid, especially in the first hour. Over the next 3 h, water absorption for the straw quilt increased by 4.7 %, while the cornstalk blocks exhibited a significant increase of 60.24 %. Subsequently, the rate of water absorption slowed down. Over the next 23 h, the water absorption for the straw quilt decreased by 8.47 % and for the corn stalk samples by 14.43 %. In the following 4 days, the absorption decreased by 10.96 % and 16.06 % for the straw quilt and corn stalk samples. After 5 days (120 h), both materials were considered saturated.

3.5 Compression behavior

The failure of thermal insulation materials from compressive stress is, with a few exceptions, typically due to excessive compression. Therefore, the compressive stress corresponding to 10 % compression should be used instead of compressive strength. Testing was conducted on 20x20 cm test specimens according to the (EN 826, 2013) standard. The average compressive strength of the straw quilt with a lower bulk density is 27.23 kPa, while that of the cornstalk block with a higher bulk density is 88.86 kPa. Both materials have lower compressive strength than most commercially available materials. However, the compressive strength of the straw quilt is similar to that of mineral wool, and the cornstalk block even matches some plastic foam products. Based on these results, it is not advisable to install a straw quilt for step-resistant insulation or in cases where a high compressive strength class is required (e.g., above rafters, utilized flat roofs). The cornstalk block can be installed in situations with higher compressive strength requirements (e.g., facades, and floors).

3.6 Flexural strength

Method B of the (EN 12089, 2013) standard was suitable for assessing flexural strength using 15x30 cm specimens. Due to the material's extreme flexibility, several deviations from the protocol occurred. It was unnecessary to wait for bending failure, as the load increased until the specimen's deflection allowed the measuring device's edges to hold it. Both materials reached their load capacity before this deflection, allowing maximum flexural resistance calculation at smaller deflections. The straw quilt exhibited a low flexural strength of 1.077 kPa due to mounting continuity loss and seam damage during specimen creation, reducing bending resistance. Testing with production-sized specimens or ensuring mounting continuity in standard-sized specimens might be beneficial. The cornstalk block showed a much higher flexural strength of 246.80 kPa, comparable to thermal insulation products like polystyrene foam and cork, attributed to its bonding agent content and higher bulk density.

Table 1: Material properties of straw quilt and cornstalk insulation block

Material property	Straw quilt	Cornstalk insulation block
bulk density		
air dry	86,56 kg/m^3	165,39 kg/m^3
natural	103,45 kg/m^3	199,66 kg/m^3
dimensional stability (T = 23°C,φ = 50%)		
width	0.08 % (0.40 mm)	0.13 % (0.28 mm)
length	0.02 % (0.20 mm)	0.08 % (0.31 mm)
thickness	0.80 % (0.20 mm)	0.49 % (0.32 mm)
volume	0.30 %	0.60 %
mass	0.47 %	4.68 %
bulk density	0.33 %	4.18 %
dimensional stability (T = 70°C,φ = 50%)		
width	1.27 % (0.64 mm)	1.19 % (2.48 mm)
length	0.38 % (0.38 mm)	1.24 % (2.69 mm)
thickness	2.71 % (0.26 mm)	3.51 % (2.25 mm)
volume	3.80 %	5.84 %
mass	7.49 %	11.30 %
bulk density	6.40 %	5.84 %
water absorption		
partial immersion	1.312 kg/m^2	4.820 kg/m^2
full immersion		
1 h	250.12 m/m %; 27.09 V/V %	116.48 m/m %; 20.37 V/V %
3 h	261.95 m/m %; 27.21 V/V %	161.29 m/m %; 32.64 V/V %
24 h	284.13 m/m %; 27.68 V/V %	184.59 m/m %; 37.35 V/V %
120 h	315.27 m/m %; 31.68 V/V %	217.26 m/m %; 43.35 V/V %
compressive strength	27.23 kPa	88.86 kPa
flexural strength	1.077 kPa	246.80 kPa
thermal conductivity (air dry)		
10°C	0.0401 W/mK	0.0511 W/mK
20°C	0.0420 W/mK	0.0539 W/mK
30°C	0.0433 W/mK	0.0576 W/mK
thermal conductivity (natural)		
10°C	0.0434 W/mK	0.0562 W/mK
20°C	0.0470 W/mK	0.0609 W/mK
30°C	0.0518 W/mK	0.665 K

Summarizing the results, it can be concluded that qualification tests have demonstrated that straw quilt and cornstalk insulation blocks are on par with other commonly used construction thermal insulation materials (Table 2.). They offer versatile usability, but it is important to note their potential drawbacks. Both materials exhibit sufficiently low thermal conductivity, making them suitable for insulating facades, non-walkable attic floors, high roofs (e.g. between and under rafters), and subsequent thermal insulation. However, their water resistance is a crucial consideration, and it is recommended to install them in areas protected against moisture. The lower strength values of the straw quilt make it more suitable for use in areas with minimal mechanical impact, while the higher strength parameters of the cornstalk block enable a wider range of applications.

Table 2: Material properties of the traditional thermal insulation materials (Bozsaky, 2017)

Material	Bulk density (kg/m^3)	Water absorption (kg/m^2)	Water absorption (V/V %)	Compressive strength (kPa)	Flexural strength (kPa)	Thermal conductivity (W/mK)
rock wool	20-200	3.0	-	15-90	-	0.034-0.045
fiberglass	15-150	3.0	-	15-90	-	0.034-0.045
expanded polystyrene foam	10-30	-	1.0-5.0	30-300	50-150	0.031-0.040
extruded polystyrene foam	25-45	-	0.7	200-700	100-300	0.029-0.040
polyurethane foam	30-100	-	1.5-3.0	100-1,000	250-500	0.022-0.040
foam glass	115-220	-	0	500-2,000	450-500	0.038-0.060
cork	100-220	0.5	-	100-200	140-200	0.037-0.060
wood wool	350-600	5.0	-	150-200	300-1,000	0.050-0.090
straw bale	80-120	4.3	-	20-90	-	0.038-0.072
fibreboard	30-270	1.0-2.0	-	40-200	120-200	0.038-0.045
cellulose	30-80	15	30	2.5	-	0.035-0.045
cotton	20-60	12-13	-	-	-	0.036-0.054
sheep wool	25-30	12	33	-	-	0.035-0.054

4. Conclusions

The use of agricultural by-products in the construction industry has precedent, but the introduction of straw quilts and cornstalk blocks as innovative thermal insulation materials is a recent development. Initial tests, including thermal conductivity, and dimensional stability, have indicated that these materials meet or exceed key benchmarks in thermal and mechanical properties, performing comparably to natural alternatives like straw bales and hemp. Tests show that straw quilts and cornstalk blocks exhibit mechanical resilience close to that of commercially available rock wool, with compressive strength values within its parameters.

Scaling up the production of these natural insulation materials would require developing processes that optimize the energy and material efficiency of agricultural by-product treatment, such as removing residual lignin. Compared to plastic foams and mineral wools, straw and cornstalk-based insulations result in a lower carbon footprint, consuming approximately 30-50 % less energy in the production phase alone. Additionally, the life cycle of these materials, from sourcing to recycling, suggests that they are not only biodegradable but also potentially reusable in various construction scenarios, further reducing environmental impact.

It would be beneficial to subject straw quilt and cornstalk insulation blocks to a tensile strength test to verify their resistance to anticipated stresses. Future work should focus on testing fire resistance, as they are likely to fall into fire protection category E. While there are no regulations for testing resistance to insects and rodents, conclusions can be drawn based on experience gained in agricultural applications and straw bale construction, such as removing seeds and embedding a protective net in plaster for protection against pests. Acoustic and vapour technical tests would be essential in assessing their sound insulation ability and vapour diffusion properties. It is reasonable to expect positive results as with other natural materials (e.g. straw bales, hemp).

Developing a comprehensive technical guide for application, including structural solutions and design recommendations, will be essential for ensuring these materials are used effectively in construction. Given the environmental benefits, such as reduced production energy and waste, straw quilts and cornstalk blocks have significant potential to serve as sustainable alternatives to artificial insulation materials like polystyrene and rock wool. Their use supports circular economy principles by utilizing agricultural byproducts, contrasting with the higher ecological footprint and limited recyclability.

References

Bozsaky D., 2017, Thermal insulation material in building construction, Terc Kiadó, Budapest, Hungary, ISBN 978-615-5445-44-6 (in Hungarian).

Bozsaky D., Ábrahám-Horváth R., 2023, Laboratory Tests on Properties of Innovative Natural Thermal Insulation Material. Pollack Periodica, 18(2), 125–130, DOI: 10.1556/606.2022.00735.

Bynum R.T., 2001, Insulation Handbook. McGraw-Hill Education, New York, USA, ISBN 0-07-134872-7.

Chel A., Kaushik G., 2018, Renewable energy technologies for sustainable development of energy-efficient building. Alexandria Engineering Journal, 57(2), 655–669, DOI: 10.1016/j.aej.2017.02.027.

CMI, 2020, Coherent Market Insight. Thermal insulation materials market analysis. Seattle, Washington, USA, 1–120.

Čuláková M., Šenitková I., Paulíková A., 2012, Optimization of construction solutions for green building. Pollack Periodica, 7(3), 33–44, DOI: 10.1556/pollack.7.2012.3.4.

Defo N., Bistac S., Nicodème R., Sikamea T., Njeugna E., 2024, Investigation of Physico-Chemical Properties of AgroIndustrial By-Products, Chemical Engineering Transactions, 109, 55–60, DOI: 10.3303/CET24109010.

Déry A., 2000, Historical materials science. Terc Kiadó, Budapest, Hungary, ISBN 963-00-4183-9, (in Hungarian).

EN 826, 2013, Thermal insulating products for building applications. Determination of compression behaviour. European Committee for Standardization (CEN), Bruxelles, Belgium.

EN 1602:2013 Thermal insulating products for building applications. Determination of the apparent density, European Committee for Standardization (CEN), Bruxelles, Belgium

EN 1603, 2013, Thermal insulating products for building applications. Determination of dimensional stability under constant normal laboratory conditions (23 °C/ 50% relative humidity). European Committee for Standardization (CEN), Bruxelles, Belgium

EN 1604, 2013, Thermal insulating products for building applications. Determination of dimensional stability under specified temperature and humidity conditions. European Committee for Standardization (CEN), Bruxelles, Belgium.

EN 1609, 2013 Thermal insulating products for building applications. Determination of short-term water absorption by partial immersion. European Committee for Standardization (CEN), Bruxelles, Belgium.

EN 12087, 2013 Thermal insulating products for building applications. Determination of long-term water absorption by immersion. European Committee for Standardization (CEN), Bruxelles, Belgium.

EN 12089, 2013 Thermal insulating products for building applications. Determination of bending behaviour. European Committee for Standardization (CEN), Bruxelles, Belgium.

EN 12667, 2001, 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. European Committee for Standardization (CEN), Bruxelles, Belgium

Finlay M. R., 1990, The Industrial Utilization of Farm Products and By-Products – The USDA Regional Research Laboratories. Agricultural History, 64(2), 41–52.

Gyuricza Cs., 2014, Energy crops, biomass production and use. Szent István University Institute of Crop Production, Gödöllő, Hungary (in Hungarian).

MEKH, 2021, Hungarian Energy and Public Utility Regulatory Authority (MEKH) Annual Energy Statistics Report. Budapest, Hungary (in Hungarian).

Kálmán G., 2008, New opportunities for utilizing by-products generated from corn cultivation and processing. Ph. D. Thesis, Budapest University of Technology and Economics, Faculty of Chemical and Biological Engineering, 10-37, Budapest Hungary, (in Hungarian).

Kumdokrub T., You F., 2023, Cornell Campus Metabolism and Circular Economy: Energy, Food Waste, and Construction Materials, Chemical Engineering Transactions, 103, 85–90, DOI: 10.3303/CET23103015.

Lamb W. F., Wiedmann T., Pongratz J., Andrew R., Crippa M., Olivier J. G. J., Wiedenhofer D., Mattioli G., Al Khourdajie A., House J., 2021, A review of trends and drivers of greenhouse gas emissions by sector from 1990 to 2018. Environmental Research Letters, 16(7), 073005, 1–32, DOI: 10.1088/1748-9326/abee4e.

Minke G., Krick B., 2012, Straw bale construction. Cser Kiadó, Budapest, Hungary, ISBN 978-963-278-249-2 (in Hungarian).

Neuberger P., Kic P., 2021, A Century of Use of SOLOMIT Thermal Insulation Panels. Energies, 14(21), 7197, DOI: 10.3390/en14217197.

Pargana N., Pinheiro M. D., Silvestre J. D., Brito J., 2014, Comparative environmental life cycle assessment of thermal insulation materials of buildings. Energy and Buildings, 82, 466–481, DOI: 10.1016/j.enbuild.2014.05.057.

Tóth Z., Kismányoki T., Hermann T., 2007, Significance of crop rotation and consideration for teaching land qualification. Hungarian Academy of Sciences, Centre for Agricultural Research, Institute for Soil Sciences, Keszthely, Hungary, ISBN 978-963-87616-3-7 (in Hungarian).

UNEP, 2022, United Nations Environment Program. 2021 Global Status Report for Buildings and Construction - Towards a Zero-emission. UNEP, Nairobi, Kenya.

Zach J., Hroudová J., Brožovský J., Krejza Z., Gailius A., 2013, Development of Thermal Insulating Materials on Natural Base for Thermal Insulation Systems. Procedia Engineering, 57, 1288–1294, DOI: 10.1016/j.proeng.2013.04.162.