UDC 691:035.267

THE USAGE OF HEAT INSULATING MATERIAL FROM FLAX NOILS IN LOW-RISE RESIDENTIAL BUILDINGS

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Abstract

Based on complex experiments, an assessment was made of the use of flax noils as a fibrous structure-forming material for thermal insulation boards. The article presents information on the selection and ratio of thermal insulation components based on flax noils. The indices of sorption humidity at a relative air humidity of 40–97 % and the vapor permeability coefficients of insulation materials made of noils are determined. The issues of resistance of thermal insulation materials to fungus are considered. The results of full-scale tests of a wall enclosure with a ventilated insulation system, an external wall with a wooden frame system and an attic floor structure of residential buildings in operation, including insulation materials based on flax noils and fibres as thermal insulation, are presented. Based on the obtained data, the values of thermal transfer resistance of the enclosing structures under study are calculated. Based on the test results, it was determined that the wall enclosing structures containing flax noils thermal insulation boards provide a heat transfer resistance of 3,24−4,55 (m2·°C)/W at an air temperature of –22 °C and –23 °C. At an air temperature of –17 °C, the thermal resistance of the attic floor with insulation based on flax noils is 6,27 (m2·°C)/W. It was found that the heat transfer resistances of the experimental enclosing structures with flax noils thermal insulation materials exceed the indicators of the walls and attic floor structure, including flax fiber thermal insulation, by 11−16 %. Based on the tests conducted, the effectiveness of thermal insulation boards made from noils was confirmed in comparison with insulation materials based on various plant materials, including flax fibres.

As a result of the research, the rational use of flax noils as a structure-forming component of thermal insulation for low-rise residential buildings was substantiated.

Keywords: heat insulating material, flax noils, sorption humidity, vapor permeability coefficient, thermal transfer resistance.

УТЕПЛИТЕЛЬ ИЗ ЛЬНЯНЫХ ОЧЕСОВ ДЛЯ ТЕПЛОИЗОЛЯЦИИ ЖИЛЫХ МАЛОЭТАЖНЫХ ЗДАНИЙ

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Реферат

На основании комплексных экспериментов проведена оценка использования льняных очесов в качестве волокнистого структурообразующего материала теплоизоляционных плит. Приведены сведения о подборе и соотношении компонентов тепловой изоляции на основе очесов льна. Установлены показатели сорбционной влажности при относительной влажности воздуха 40–97 % и коэффициенты паропроницаемости утеплителей из очесов. Изучен вопрос стойкости теплоизоляционных материалов к появлению грибка. Представлены результаты натурных испытаний стенового ограждении с вентилируемой системой утепления, наружной стены с деревянной каркасной системой и конструкции чердачного перекрытия эксплуатируемых жилых домов, включающих в качестве тепловой изоляции утеплители на основе льняных очесов и волокон. Основываясь на полученных данных, рассчитаны значения сопротивления теплопередаче исследуемых ограждающих конструкций. По итогам испытаний определено, что стеновые ограждающие конструкции, содержащие теплоизоляционные плиты из очесов, при температуре воздуха –22 °С и –23 °С обеспечивают сопротивление теплопередачи 3,24−4,55 (м2·К)/Вт. При температуре воздуха –17 °С термическое сопротивление чердачного перекрытия с утеплителями на основе очесов льна составляет 6,27 (м2·К)/Вт. Установлено, что сопротивления теплопередаче экспериментальных ограждающих конструкций с теплоизоляционными материалами из льняных очесов превышают показатели стен и конструкции чердачного перекрытия, включающих тепловую изоляцию на основе волокон льна, на 11−16 %. На основании проведенных испытаний подтверждена эффективность теплоизоляционных плит из очесов относительно утеплителей на основе различного растительного сырья, включая льняные волокна.

В результате исследований обосновано рациональное применение льняных очесов в качестве структурообразующего компонента тепловой изоляции для жилых малоэтажных зданий.

Ключевые слова: утеплитель, очесы льна, сорбционная влажность, коэффициент паропроницаемости, термическое сопротивление теплопередаче.

Introduction

Growing energy consumption costs for heating residential and public buildings stimulate the development and use of new efficient thermal insulation materials that help increase the thermal resistance of enclosing structures. In addition to improving thermal performance, modern insulation materials also have environmental requirements. It should be noted that manufacturers and suppliers of thermal insulation both in Belarus and in other countries are not always ready to meet customer requirements for the environmental safety of thermal insulation. One of the most appropriate solutions for the production of environmentally friendly thermal insulation materials is the use of secondary fibrous plant materials of agricultural origin. The demand for this area is confirmed by scientific research conducted in many countries on the development of insulation using plant materials [1−5].

In Belarus and the Russian Federation, the most well-known application of flax fibers is as a structure-forming material for thermal insulation boards. Polyester fibers are used as a binder for insulation materials of the «Akoterm Flax» trademark [6], and starch is used for thermal insulation materials of the «Ecoteplin» brand [7]. Thermal insulation boards have a thermal conductivity coefficient of 0,038 to 0,04 W/(m·K) with an average density of 30−34 kg/m^3 and are used to insulate enclosing structures of low-rise buildings. The disadvantages of thermal insulation made of flax fibers include high price and limited use due to the lack of rigidity of the material structure. It is also worth noting the low level of fire protection of «Akoterm Flax» thermal insulation boards, which belong to flammability group G4. To reduce the fire hazard of «Ecoteplin» thermal insulation materials, borax is added to the composition during the production of thermal insulation.

Research into the development of insulation materials based on industrial hemp and various binders such as polyester, polyalky fibers, and without a binder using a fire retardant is being conducted in various countries [8−10]. With a density of 35−90 kg/m^3, thermal insulation materials have a thermal conductivity coefficient of 0,037 to 0,04 W/(m·K). High cost and limitations in the area of application hinder the popularization of insulation materials based on hemp fibers.

Coconut fibers were used to produce thermal insulation boards based on secondary plant materials in Trinidad and Indonesia [11, 12]. The research results showed that the thermal insulation material has the following thermal engineering characteristics: average density of 30−115 kg/m^3 and thermal conductivity coefficient of 0,058–0,104 W/(m·K).

In Malaysia, the thermal insulation properties of thermal insulation made from oil palm bark fibers were studied [13, 14]. Samples of thermal insulation boards were made using only bark fiber. With an average density of 20 to 120 kg/m^3, the experimental compositions of thermal insulation boards provide a thermal conductivity coefficient in the range of 0,03–0,092 W/(m·K). Insulation materials based on a mixture of oil palm fibers and cellulose fibers were also obtained. Formaldehyde resin was used as a binder [15]. With the content of oil and cellulose fibers in a ratio of 1:1, the thermal conductivity coefficient of the thermal insulation boards at an average density of 250 kg/m^3 is 0,045 W/(m·K).

Cotton fibers were used as a structure-forming material for thermal insulation in a scientific paper [16]. The insulation is characterized by the following thermal performance indicators: average density of 150−450 kg/m^3 and thermal conductivity coefficient of 0,059−0,082 W/(m·K). Thermal insulation boards are intended for insulation of walls and attic floors.

Research by scientists from India is devoted to the production of thermal insulation materials from banana, pineapple and jute fibers [17]. Analysis of the obtained data allowed us to establish that the lowest values of the thermal conductivity coefficient were recorded with the following quantitative composition of the fiber components: banana – 60 %, pineapple – 32 % and jute 8 %. When banana fibers are used separately as a structure-forming material, the thermal conductivity coefficient of the insulation is 0,041–0,067 W/(m·K) with an average density varying from 20 to 120 kg/m^3 [18].

The search for alternative raw materials of agricultural origin for the production of thermal insulation boards is a relevant area for many countries around the world. With the correct selection of a binder, thermal insulation based on plant fibers should provide high thermal and operational properties. Comprehensive research on the production of thermal insulation boards based on plant fibers is carried out at the «Green Construction» laboratory at the Euphrosyne Polotskaya State University of Polotsk. Particular attention during testing is paid to the environmental safety of thermal insulation materials.

Methodology of experimental research

Samples of insulating materials made of flax noils or fibers were manufactured in accordance with a certain sequence of technological operations. The components were preliminarily dosed. To obtain a modified binder, lime was first added to the liquid sodium glass, and then gypsum was added. After each of the additive components was added, the binder was mixed. The mold was filled with fibrous structure-forming material uniformly and layer by layer throughout the entire volume. The binder was applied to each laid layer in turn, using a sprayer. Then, the samples of thermal insulation materials based on flax noils or fibers were kept in the mold for 6 hours at a temperature of 20±2 °C and stripped. Then the thermal insulation samples were dried for 4 hours at a temperature of 45–55 °C.

The average density of the samples was determined according to GOST 17177 «Building thermal insulation materials and products. Test methods» [19].

The thermal conductivity coefficient of the insulation materials was measured on sample slabs measuring 250×250×30 mm using the ITP-MG4 «250» device, in accordance with the requirements of Standards of the Republic of Belarus 1618 «Construction materials and products. Methods for determining thermal conductivity under steady-state thermal conditions» [20].

The determination of the water resistance of liquid glass modified with lime and gypsum was carried out according to the method given in the research paper [21].

The sorption moisture content of thermal insulation boards was determined according to Standards of the Republic of Belarus EN 12088 «Building thermal insulation products. Method for determining sorption moisture content» [22].

The vapor permeability of thermal insulation was studied in accordance with Standards of the Republic of Belarus EN 12086 «Building thermal insulation products. Method for determining vapor permeability» [23].

The thermophysical properties of thermal insulation boards under operating conditions were studied using the RTP-1-16T information and measuring complex. The ambient air temperature, on the surface and inside the materials under study were recorded using thermocouples, and heat flow indicators were measured using heat flow converters.

After full-scale tests, to study the humidity in thermal insulation materials, prism samples measuring 50×50 mm in cross-section were cut out along the thickness of the insulation. Then the prism sample was cut into fragments of the same thickness. Then each sample was weighed and placed in a drying cabinet. Upon reaching a constant mass, the fragments were weighed again. Humidity was determined by the change in the mass of the samples before and after drying.

Main points

Components of thermal insulation material. The initial stage of the research involved selecting a fibrous structure-forming material for producing thermal insulation boards based on secondary plant materials. Flax noils, flax fibers, jute, coconut, bamboo, nettle, cotton waste and oil palm bark fibers were considered as structure-forming materials. Liquid sodium glass was used as a binder. The thermal conductivity coefficient of the samples was determined at an average density of 50 kg/m^3 and the same component consumption. The tests showed that the samples based on flax noils and nettle fibers have the lowest thermal conductivity coefficient of 0,041 W/(m·K) among the samples studied. The thermal conductivity coefficient of the samples made of jute, bamboo and cotton waste fibers is 0,043 W/(m·K). The thermal conductivity of boards based on flax, oil palm bark and coconut fibers exceeds the thermal conductivity coefficient of materials made from noils and nettle fibers by 15−32 %.

At the next stage, polyvinyl acetate dispersion, starch and rosin were considered as alternative binders to liquid glass. The studies were conducted on Belarusian plant raw materials - flax noils, flax and nettle fibers. The results of the tests indicate that the thermal conductivity coefficient of the samples on liquid glass and rosin have almost identical values and are lower than that of the samples containing polyvinyl acetate dispersion and starch by an average of 10 %. It should be noted that there are difficulties in ensuring the required amount and uniform distribution of rosin in the structure of the material.

Liquid glass also has a disadvantage. When in contact with water, liquid glass dissolves. In the course of the conducted research on ensuring the durability of insulation materials when used in conditions of high humidity, the required amount of a two-component additive of lime and gypsum in a ratio of 1:1 was established to increase the water resistance of liquid glass. When introducing a modifying additive in an amount of 8−12 % of the binder mass, the water resistance of liquid glass is 93−97 %.

Due to the lack of agricultural crop areas and production lines for obtaining fibers from nettle stems in Belarus, as well as the existing significant difficulties with the distribution of rosin over the volume of thermal insulation, flax noils and modified liquid sodium glass were adopted as components of experimental compositions of thermal insulation boards.

Consumption of thermal insulation components. To determine the quantitative compositions of thermal insulation materials based on noils, providing a combination of the best thermal engineering characteristics, studies were carried out to establish the range of variation of the fibrous structure-forming material and modified binder. The lowest values of the thermal conductivity coefficient of 0,034−0,04 W/(m·K) were achieved with an average density of 60−100 kg/m^3. The consumption of thermal insulation board components is presented in Table 1.

https://doi.org/10.36773/1818-1112-2024-135-3-7-12

Table 1 – The consumption of thermal insulation board components from flax noils

The consumption of components per 1 m³, weight percentage		
structure-forming material	binding	modifying agent
0,86–0,92	0,08–0,14	0,08–0,12

Sorption moisture. Samples for determining sorption moisture were taken from thermal insulation based on flax noils with an average density of 70 kg/m³, providing a thermal conductivity coefficient of 0,035 W/(m·K). The quantitative composition of the insulation components per 1 m³ corresponded to the following values: flax noils − 60 kg/m³, liquid glass − 9 kg/m³, gypsum – 0,5 kg/m³ and lime – 0,5 kg/m³. Based on the data obtained, an isotherm of water vapor sorption of thermal insulation boards made of flax noils was constructed (Figure 1).

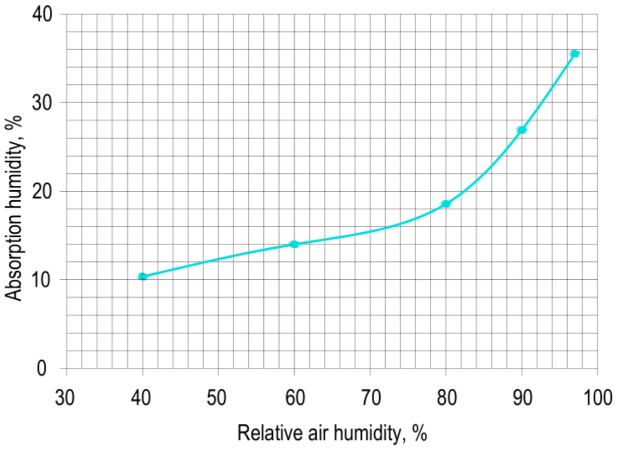


Figure 1 – Isotherm of water vapor sorption by flax noils

The conducted studies allowed us to establish that the sorption moisture content of the samples of thermal insulation materials based on flax noils at a relative air humidity of 40 % is 10,2 %. The value of the sorption moisture content of the samples at an air humidity of 60 % increases by 1,4 times. The maximum value of the sorption moisture content during storage of the samples at an air humidity of 80 % was recorded at 19,2 %. At a relative air humidity of 90 %, the sorption moisture content of the samples from flax noils reaches 26,5 %, and at an air humidity of 97 % it is 37,6 %.

For comparison, the sorption humidity values of the samples of flax fiber-based thermal insulation boards with identical quantitative composition with flax noils insulation were determined. The obtained experimental data indicate that at a relative air humidity of 40−90 %, the sorption humidity values of the samples of flax fiber-based thermal insulation practically coincide with those of noils materials. The sorption humidity value of the flax noils insulation at an air humidity of 97 % exceeds the value of flax fiber-based thermal insulation materials by 15 %. In comparison with liquid glass thermal insulation boards without a two-component additive, the introduction of lime and gypsum into the binder allows to reduce the sorption humidity values of the insulation by 20 % and 18 %, respectively, compared with samples made of noils or flax fibers.

In addition, an analysis of the sorption moisture values of the previously obtained and studied insulation materials based on plant raw materials and liquid glass was conducted. At a relative air humidity of 60−80 %, the sorption moisture of thermal insulation materials based on chopped straw, a mixture of straw and flax shives, eucalyptus fibers, coconut, jute, as well as a mixture of rice husks and straw is in the range from 8 to 24 % [24−27]. Based on these values, it can be concluded that the sorption moisture of thermal insulation based on flax noils has values close to those of insulation materials containing eucalyptus fibers, as well as a mixture of rice husks and straw. At the same time, the sorption moisture of thermal insulation materials made from noils is 24−42 % higher than the values of thermal insulation boards based on coconut and jute fibers, but 18−26 % lower than the values of thermal insulation made from a mixture of straw and flax shives, as well as chopped straw.

Simultaneously with the determination of the sorption humidity of the noils-based thermal insulation boards, the resistance of the samples to the appearance of fungal formations at a relative air humidity of 90–97 % was studied. Such conditions are as close as possible to the state of insulation soaking when the continuity of the protective coating of the roof or walls of the building is broken. After 200 days of keeping the samples in a desiccator at a relative air humidity of 90 %, there was no spot fungus on the surface of the materials. The formation of spot fungus on the surface of flax noils was recorded on the 135 th day when storing the samples in a desiccator with a relative air humidity of 97 %. It should be noted that when the samples are in a desiccator with an air humidity of 97 %, the time of the onset of spot fungus formation on the surface of noils coincides with the indicators of structure-forming materials made of flax fibers, straw, a mixture of straw and flax shives, and also significantly exceeds the value of thermal insulation based on a mixture of rice husks and straw. At a relative humidity of 90 % in the desiccator, the formation of spot fungus was not recorded on any samples.

Vapor permeability. The vapor permeability coefficient was determined on samples of flax noils measuring 110×110×50 mm. The quantitative composition, density and vapor permeability coefficient of the studied thermal insulation materials are presented in Table 2.

Table 2 – Composition, average density and vapor permeability coefficient of insulation materials made from flax noils

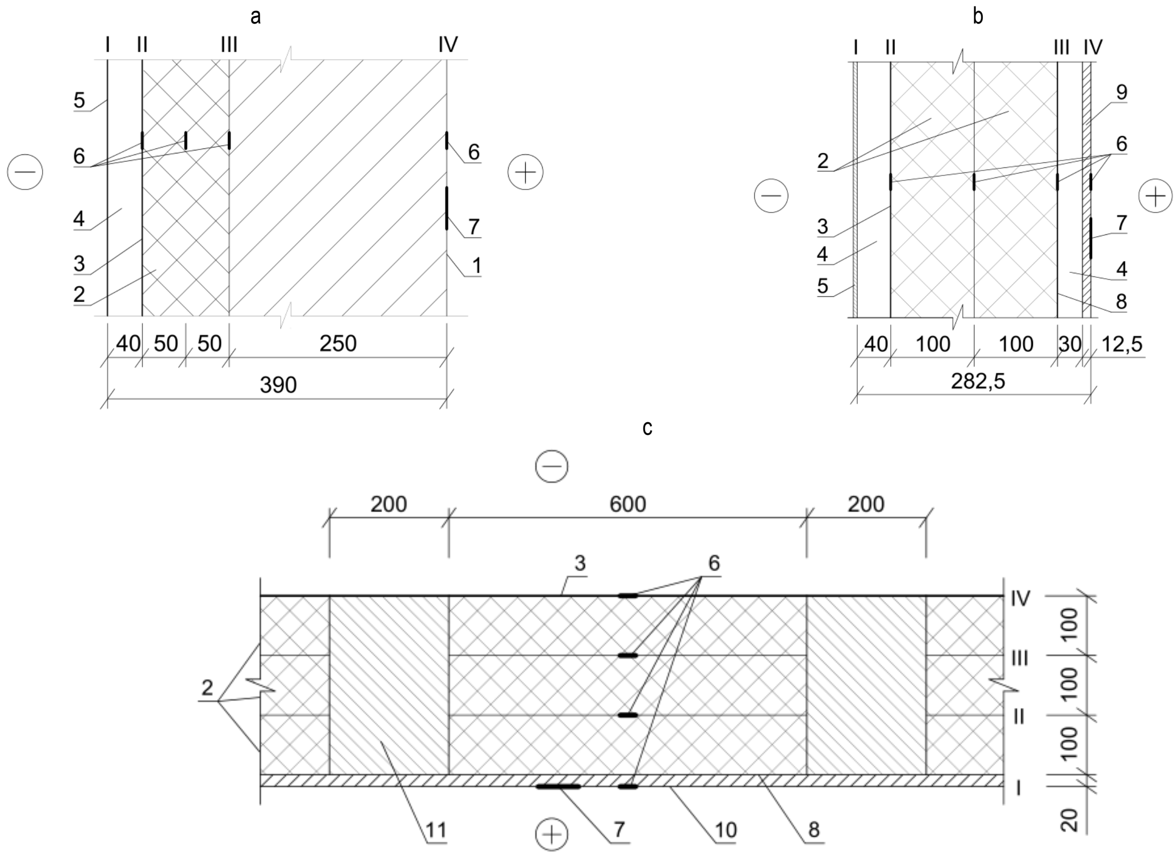
№ of sample	Consumption of components per 1 m³, kg				Average density, kg/m³	Vapor permeability coefficient, mg/(m·h·Pa)
	flax noils	liquid glass	lime	gypsum		
1	30	9	0,5	0,5	40	0,412
2	50	9	0,5	0,5	60	0,388
3	70	9	0,5	0,5	80	0,371
4	90	9	0,5	0,5	100	0,356
5	110	9	0,5	0,5	120	0,343

According to the data in Table 2, thermal insulation based on noils with an average density varying from 40 to 120 kg/m³ provides a vapor permeability coefficient within the range of 0,343−0,412 mg/(m·h·Pa). The established indicators of vapor permeability coefficients and sorption moisture of thermal insulation boards made of flax noils make it possible to calculate the humidity regime of enclosing structures of designed buildings.

A comparative analysis of the vapor permeability indices of samples based on plant waste has shown that the vapor permeability coefficients of thermal insulation materials containing flax noils are 5−10 % lower than the values of thermal insulation made from flax fibers and have values close to those of insulation materials based on chopped straw, as well as a mixture of straw and shives [24, 25]. The increase in the vapor permeability coefficients of thermal insulation boards made from mineral fibers relative to thermal insulation based on flax noils is 35−40 %.

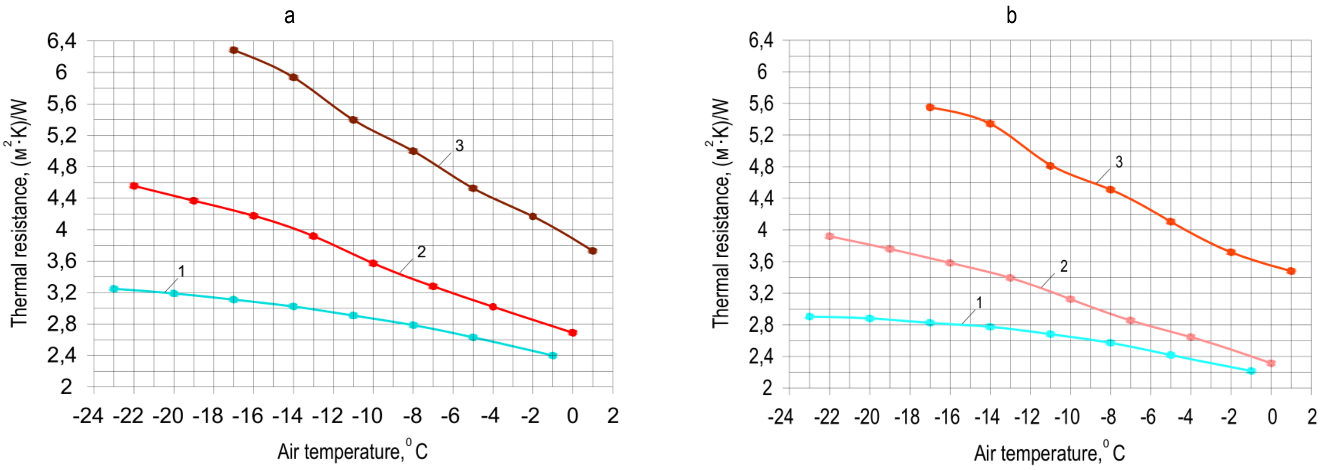
Full-scale tests of enclosing structures with insulation made of flax noils. In the autumn-spring periods of 2018−2024, full-scale tests of thermal insulation boards based on flax noils were carried out in enclosing structures of residential buildings in operation. Samples of insulation based on flax fibers were used for comparative tests. Observations of thermophysical processes occurring in enclosing structures containing insulation made of flax noils or fibers were carried out to confirm the effective operation of thermal insulation materials on plant raw materials. Samples based on flax noils or fibers were made in the form of slabs measuring 1200(1000)×500(600)×100 mm and used as thermal insulation in an external wall enclosure with a ventilated insulation system, an external wall with a wooden frame system and an attic floor of a one-story residential building. The average density of thermal insulation materials used for wall structures corresponded to 100 kg/m³, for an attic floor – 70 kg/m³. The schemes of the investigated enclosing structures with the location of thermocouples and heat flow sensors are shown in Figure 2.

Based on the obtained heat flow density values and temperature distribution across the thickness of the enclosing structures, the dependence of the thermal resistance of heat transfer of the studied wall structures and attic floor on the outside air temperature was determined (Figure 3). For the attic floor, the outside air temperature was taken to be the air temperature in the unheated attic. Full-scale tests for the specified structures were conducted in different time periods. For this reason, the thermal resistance values for each enclosing structure are specified for its own temperature range.



I, II, III, IV – boundaries of enclosure layers
1 – solid ceramic brick; 2 – insulation; 3 – water and wind protection membrane; 4 – air gap; 5 – facade metal cassette; 6 – thermocouple; 7 – heat flow sensor; 8 – vapor barrier; 9 – plasterboard; 10 – edged board of ceiling sheathing; 11 – wooden floor beam

Figure 2 – Layout of thermocouples and heat flow sensors by section:
a – external wall with ventilated insulation system; b – house walls with wooden frame system; c – attic floor structures



1 – external wall with ventilated insulation system; 2 – house wall with wooden frame system; 3 – attic floor structure

Figure 3 – Dependence of thermal resistance of enclosing structures with insulation made of flax noils (a) and fibers (b) on the temperature of the outside air (air in an unheated attic)

The dependencies presented in Figure 3 allowed us to establish that the wall enclosure with a ventilated insulation system containing flax noils insulation boards at an outside air temperature of –1 °C has a thermal resistance of heat transfer equal to 2,4 (m^2·K)/W, which is 9 % higher than the value of wall 1 with flax fiber-based materials. When the air temperature drops to –23 °C, the value of thermal resistance of enclosing structure 1 with flax noils insulation increases by 35 % to 3,24 (m^2·K)/W and is 11 % higher than the value of wall enclosure 1 with flax fiber-based insulation.

A similar dependence was established for the external enclosing structure of a house with a wooden frame system. The thermal resistance of wall 2 with flax noils insulation materials at an air temperature of 0 °C is 2,68 (m^2·K)/W, which is 16 % higher than the value of enclosing structure 2 with flax fiber-based insulation boards. The thermal resistance index of wall structure 2 containing noils insulation materials increases by 1,7 times to 4,55 (m^2·K)/W when the temperature drops to –22 °C, and is 17 % higher than the value of enclosing structure 2 including flax fiber-based insulation boards.

https://doi.org/10.36773/1818-1112-2024-135-3-7-12

The significant difference in the thermal resistance values of wall 1 and wall 2, containing slabs based on flax noils and fibers, is due to the increase in the thickness of the thermal insulation by 2 times from 100 mm (wall 1) to 200 mm (wall 2).

At the air temperature in the attic space of +1 °C, the thermal resistance to heat transfer of the attic floor with thermal insulation materials based on noils is 3.53 (m^2·K)/W, which is 8 % higher than the value of the attic floor with insulation made of flax fibers. A decrease in the temperature in the attic space to –17 °C leads to an increase in the thermal resistance of the attic floor with thermal insulation based on flax noils to 6.27 (m^2·K)/W, which is 13 % higher than the value of the insulated attic floor with flax fiber slabs.

The increase in the thermal resistance of heat transfer of experimental enclosing structures with slabs based on flax noils at low negative air temperatures is from 35 % to 78 %, which confirms the effective operation of thermal insulation made from flax noils in the winter period.

The increase in thermal resistance to heat transfer in the studied structures using heat-insulating boards based on noils compared to the use of insulation made of flax fibers is achieved due to the multidirectional arrangement of elementary fibers in the structure of the material, which prevents convective air transfer as a result of a decrease in the size of thin air layers of irregular shape and their partial localization in the form of individual closed microvoids.

After completion of the full-scale tests in the spring, the average values of the humidity of the thermal insulation materials were determined. Analysis of the obtained results allowed us to establish that the average humidity values of the flax noils-based thermal insulation boards after operation in the winter period are within the range of 12 % to 16 % and are 14–15 % lower than the humidity values of the flax fiber thermal insulation. The established humidity values of the insulation materials also determine the higher thermal performance of the flax noils-based insulation compared to the flax fiber thermal insulation boards obtained during full-scale tests.

Conclusion

According to the research results, it was established that the best values of thermal conductivity coefficients of 0,036−0,04 W/(m·K) can be achieved by using flax noils as a structure-forming material and an average density of insulating boards of 60−100 kg/m^3.

The analysis of the study of sorption humidity of insulation made of flax noils showed that at a relative air humidity of 60−80 %, the sorption humidity of thermal insulation based on tow is 14–19 %, which is a fairly low figure for thermal insulation based on plant materials. The formation of fungus on materials made of flax noils is possible only with long-term constant exposure to conditions with a relative air humidity of 97 %. However, such operating conditions are excluded with the correct maintenance of protective coatings of thermal insulation.

With an average density of 40 to 120 kg/m^3, the vapor permeability coefficient of insulation materials based on flax noils is within the range of 0,34−0,41 mg/(m·h·Pa). The obtained indicators of water vapor sorption and vapor permeability coefficients allow calculating the humidity regime of building enclosing structures using flax noils boards.

The use of flax noils thermal insulation during field tests in enclosing structures of residential buildings in operation made it possible to establish that the structures of a wall with a ventilated insulation system and a wall of a house with a wooden frame system that includes noils-based thermal insulation boards at an outside air temperature of –22°C and –23°C have a thermal resistance to heat transfer of 3,24 and 4,55 (m^2·K)/W, respectively, which exceeds the values of wall enclosures with flax fiber insulation by 11−16 %. The structure of an attic floor with noils-based thermal insulation boards at a minimum temperature in the attic space of –17 °C provides a thermal resistance to heat transfer of 6,27 (m^2·K)/W, which is 13 % higher than the value of a floor with flax fiber insulation. The obtained indicators indicate that the experimental slabs provide high thermal insulation properties in the winter period.

As a result of the tests, the efficiency of using noils insulation boards in enclosing structures of low-rise residential buildings in operation was confirmed.

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Material received 08/09/2024, approved 17/10/2024, accepted for publication 17/10/2024