

Physical properties of insulation materials based on straw and flax boon

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Abstract. Performance evaluation of environmentally friendly thermal insulation materials based on crushed straw and flax boon was determined by studying the physical parameters of thermal insulation in a climatic chamber and full-scale tests in buildings. In the climatic chamber at an air temperature of $-20\text{ }^{\circ}\text{C}$, depending on the insulation moisture content, the thermal conductivity of the flax boon and straw slabs is $0.058 - 0.072\text{ W}/(\text{m}\cdot^{\circ}\text{C})$, which is 27 - 31% lower than that of straw slabs equal to $0.08 - 0.105\text{ W}/(\text{m}\cdot^{\circ}\text{C})$. With a relative air humidity of 50 - 95%, the moisture content of the flax boon and straw slabs varies within the range of 14 - 18.1% or less by 24% of the values of the crushed straw insulation. Under operating conditions, the thermal conductivity of the attic floor structure with flax boon and straw slabs corresponds to $0.07\text{ W}/(\text{m}\cdot^{\circ}\text{C})$ at an air temperature of -20°C and is 22% less than the similar indicator of flooring with straw slabs equal to $0.09\text{ W}/(\text{m}\cdot^{\circ}\text{C})$. A lower thermal conductivity of the floor structure with the use of flax boon and straw slabs provides an increase in temperature amplitude by 5 - 5.8 $^{\circ}\text{C}$ compared with the use of straw slabs. The results of studies in the climatic chamber and full-scale tests have confirmed the most effective operation of the flax boon and straw slabs as a thermal insulation material, which reduces energy consumption and, consequently, reduces financial costs for heating buildings.

1. Introduction

Traditional thermal insulation materials are obtained from polystyrene (polystyrene foam slabs) or natural mineral raw materials with high energy costs (glass and rock wools) [1]. A significant reserve for thermal insulation materials production in various regions of the world is plant raw materials. By origin, two main sources of plant materials can be distinguished as a structure-forming material for thermal insulation manufacture. The first source includes garden waste, and the second source is natural plant materials.

In recent years, the growing interest of the scientific community and industry is caused by experimental studies on hemp, straw, coconut, corn, sunflower, and wood to obtain thermal insulation [2].

A number of researchers [3-9] note that plant materials, such as hemp, cork waste, wood fibers, flax fiber and noils, rice husk, cotton fiber waste, can successfully compete with expanded polystyrene and rock wools in terms of thermal insulation properties.

Cereal straw is the most common structure-forming raw material used to produce thermal insulation materials in the form of straw blocks, Ecocon panels, Stramit slabs [10-12]. The greatest effect on the insulating properties can be achieved when using structure-forming compositions from a



mixture of crushed straw and other raw materials of different fractions and microstructures. As an example, thermal insulation slabs based on mixtures of sphagnum moss and straw, crushed straw and faux fur waste, crushed straw and reed, crushed and chopped buckwheat straw of different fractions can be mentioned [13-15].

A significant disadvantage, which very often limits the use of plant-based insulation in constructions, is high water absorption or high sorption of water vapors from the air by the thermal insulation material. In their works, a number of scientists [16-20] studied hydrothermal characteristics of thermal insulation materials based on buckwheat, wheat and rye straw, flax shove, flax fibers, hemp fibers, rice husk, wood fibers. Reduction of water absorption or sorption of water vapors by thermal insulation is possible by chemical treatment of the material [21] or by creation of a waterproof shell of the binder [22].

For this reason, in order to predict the stable effective operation of thermal insulation materials in building structures, it is necessary to conduct studies to determine the physical characteristics of thermal insulation under conditions of varying temperatures and relative humidity.

The thermal insulation material obtained by the authors of this article from a mixture of flax boon and straw requires the study of the main thermophysical characteristics as in work [23] before industrial production.

The aim of the research is to confirm the effective operation of an environmentally friendly thermal insulation material based on a structure-forming composition from a mixture of crushed straw and flax boon.

To assess the insulation effectiveness, it is necessary to carry out studies of the material physical parameters in the climatic chamber and full-scale tests under the conditions of building operation.

2. Methods

2.1. Determination of thermophysical properties of thermal insulation slabs in a climatic chamber.

The dimensions of the experimental insulation slabs were taken from the condition of filling the aperture between the warm and cold compartments of the climatic chamber and are 300 × 400 mm with a sample thickness of 100 mm. The efficiency of insulation in the climatic chamber was evaluated by physical indicators when modeling various temperature and humidity operating conditions. At a given relative humidity in the cold compartment of the chamber under conditions of variable thermal effects, the temperature change was determined along the cross-section of the samples and heat fluxes density. At the preliminary stage of testing, samples were kept in the climatic chamber for 3 weeks under certain temperature and humidity conditions (Table 1).

Table 1. Temperature and humidity conditions in the climatic chamber

Sample No.	The composition of the insulation slab filler	Air temperature in the chamber compartments, °C	Relative humidity in the chamber, %	
			warm compartment	cold compartment
1	Straw	18	50 - 60	50 - 60
2	Flax boon and straw	18	50 - 60	50 - 60
3	Straw	18	50 - 60	90 - 95
4	Flax boon and straw	18	50 - 60	90 - 95

From the conditions given in table 1, it follows that by the beginning of the main stage of the experiment samples 3, 4 had higher moisture content in comparison with samples 1, 2.

During the main stage of testing in the warm section of the climatic chamber, the designed indoor air parameters for a residential building were maintained as following: air temperature $t_a = 18$ °C and relative humidity $\varphi = 50 - 60\%$ according to the requirements.

In the cold compartment of the climate chamber, the air temperature (outdoor temperature) changed over time in the following sequence: 1) $t_o = 10^\circ\text{C}$; 2) $t_o = 5^\circ\text{C}$; 3) $t_o = 0^\circ\text{C}$; 4) $t_o = -5^\circ\text{C}$; 5) $t_o = -10^\circ\text{C}$; 6) $t_o = -15^\circ\text{C}$; 7) $t_o = -20^\circ\text{C}$. At each temperature t_o value, the samples were kept for 120 hours. After a 3-week stay of the samples in the chamber, as the initial temperature distribution, a stationary state in the studied region corresponding to $t_o = 10^\circ\text{C}$ and $t_a = 18^\circ\text{C}$ was accepted. To determine the temperature values along the sample cross-section, the thermal insulation slab was conventionally divided into 4 zones of 25 mm each. The values of temperatures and heat fluxes densities were fixed by the information-measuring complex RTP-1-16T in every 1.5 minutes.

2.2. Full-scale tests of insulation on the attic floor of a residential building.

At the next stage of research, straw and a mixture of straw with flax boon slabs were placed on the attic floor of a residential building. Thermal insulation slabs were laid between the wooden balks of the attic floor (Figure 1).

The design of the space between the balks on the attic floor includes a trim board for the ceiling hem, a vapor barrier, thermal insulation slabs based on straw (floor 1) and based on a mixture of straw with flax boon (floor 2). The cross-sectional diagram of the attic floor structure is shown in Figure 2.



Figure 1. Thermal insulations labs in the attic floor

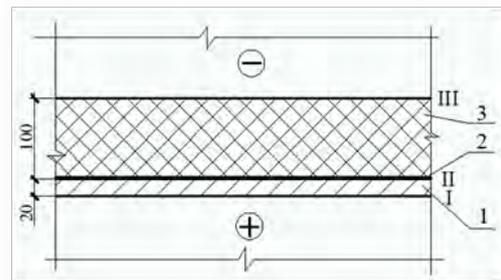


Figure 2. Scheme of space between attic floor balks: 1 layer – edged board of ceiling boarding; 2 layer – vapour barrier; 3 layer - thermal insulation slab; I, II, III - fence layer boundaries

To fix the temperature and heat fluxes by the information-measuring complex RTP-1-16T, thermocouples and heat fluxes sensors were installed in the attic floor structure (Figure 3).



Figure 3. Location of the heat flux sensor and thermocouples on the attic floor ceiling

The moisture indicators of straw and shove and straw slabs samples in the climate chamber and on the attic floor are determined in accordance with norms.

3. Results and Discussions

3.1. Physical indicators of thermal insulation slabs in the climatic chamber.

The studies carried out and discussed below are a continuation of the experimental work on obtaining effective thermal insulation slabs based on a flax boon and straw mixture. The scientific publication [23] presents the results of studies to determine the strength at 10% strain, average density, thermal conductivity, moisture sorption, the influence of moisture content on the thermal conductivity in laboratory conditions.

According to the obtained characteristics, it was established that the best mechanical and thermophysical indicators were peculiar to the thermal insulation slab, having the following composition per 1 m³: crushed rye straw – 81 kg; flax boon – 54 kg; modified liquid glass – 95 kg. The average thermal insulation slabs density in the dry state is 230 kg/m³. Slabs were made from a mixture of straw with flax boon at a straw flow rate of 0.6 mass proportion.

To predict the effective work of the insulation under operating conditions, it is necessary to conduct tests in the climatic chamber, simulating the temperature and moisture content conditions of the material in winter and carry out full-scale tests with the laying of insulation slabs in the external structures of the buildings in operation.

The tests in the climatic chamber were carried out on straw and a mixture of straw with flax boon compositions with changes in moisture content (Table 1). For samples 1 and 3 the thermal conductivity in a completely dry state is 0.056 W/(m²·°C), and for samples 2 and 4 it is 0.047 W/(m²·°C). Based on the research data in the climatic chamber, temperature distributions over the thickness of the samples were obtained in the form of temperature drop lines (Figures 4 - 7).

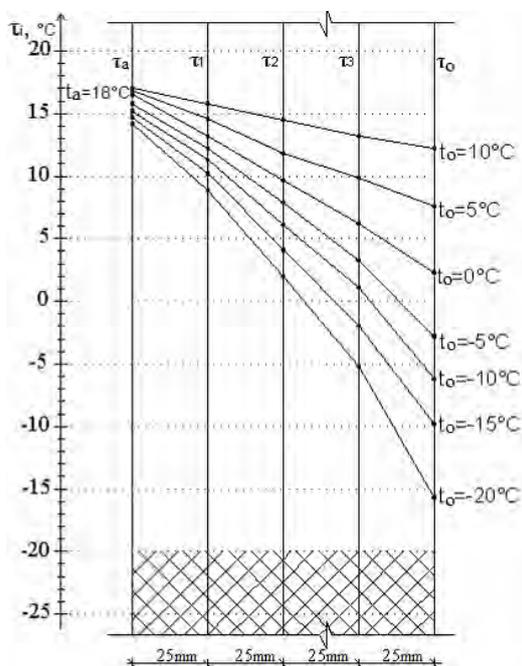


Figure 4. Temperature distribution over the thickness of the straw slab (sample 1)

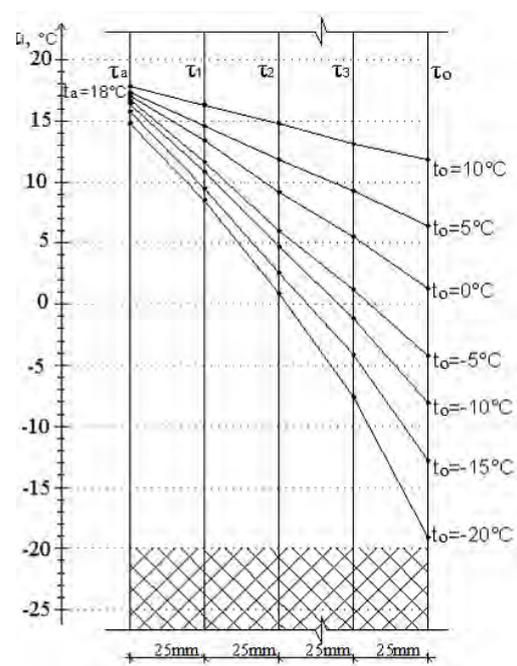


Figure 5. Temperature distribution over the thickness of the flax boon and straw slab (sample 2)

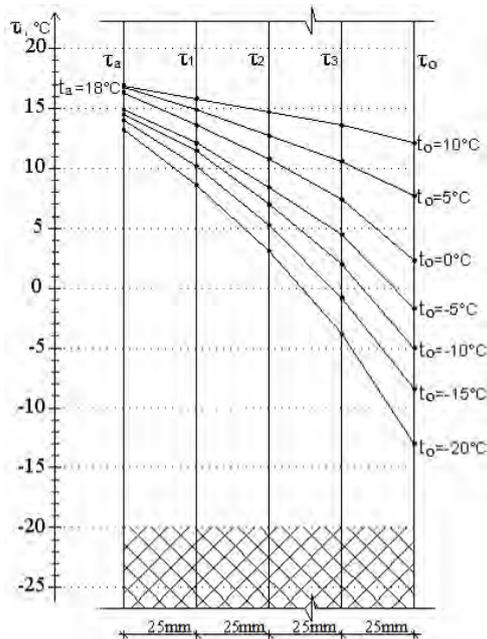


Figure 6. Temperature distribution over the thickness of the straw slab (sample 3)

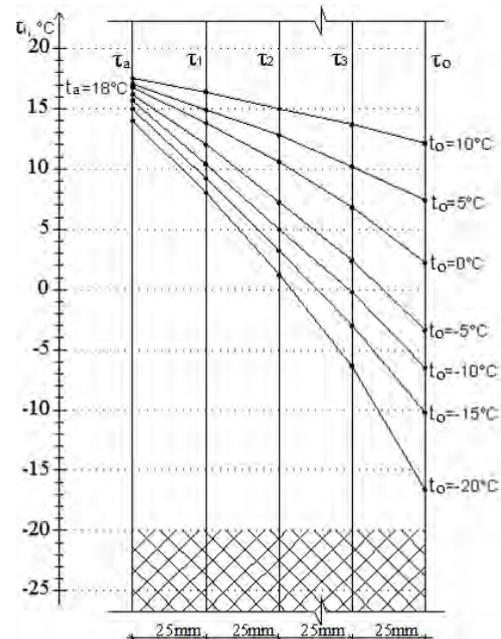


Figure 7. Temperature distribution over the thickness of the flax boon and straw slab (sample 4)

Using the obtained dependences, the thermal conductivity and thermal resistance to heat transfer of the samples were determined at specified temperatures in the cold compartment of the chamber. The results of experimental and calculated data are presented in table 2.

Table 2. Thermo-technical characteristics of thermal insulating slabs according to the results of the experiment

Outdoor temperature, °C	Heat flux density, W/m ²				Thermal resistance to heat transfer, (m ² ·°C)/W				Thermal conductivity, W/(m·°C)			
	sample 1	sample 2	sample 3	sample 4	sample 1	sample 2	sample 3	sample 4	sample 1	sample 2	sample 3	sample 4
+10	5.6	5.7	6.2	6.05	0.9	1.05	0.77	0.89	0.111	0.095	0.13	0.112
+5	11.3	8.9	11.6	10.5	0.92	1.23	0.79	0.94	0.109	0.081	0.127	0.107
0	14.6	12.4	15.1	14.6	0.97	1.27	0.83	1.0	0.103	0.079	0.121	0.1
-5	18.6	16.2	19.6	18.0	1.0	1.29	0.85	1.09	0.1	0.077	0.118	0.092
-10	20.1	16.9	22.2	19.1	1.06	1.45	0.88	1.16	0.094	0.069	0.114	0.086
-15	21.6	18.0	24.6	19.9	1.14	1.59	0.91	1.27	0.088	0.063	0.110	0.079
-20	23.9	19.7	27.5	22.2	1.25	1.72	0.95	1.38	0.08	0.058	0.105	0.072

The analysis of the obtained results shows that as the air temperature in the cold compartment decreases, the heat flux density and thermal resistance of the material increases and the thermal conductivity decreases.

The efficiency of the thermal insulation material in terms of thermal resistance of sample 2 as compared to sample 1 is 38% at the temperature of $t_o = -20$ °C, and of sample 4 as compared to sample 3 is 45% at the same air temperature. The heat flux density of sample 2 is 18% less than that of sample 1,

and of sample 4 is 19% less than that of sample 3 at an air temperature in the cold compartment of the chamber equal to a $t_0 = -20\text{ }^\circ\text{C}$.

When comparing the same composition of the samples, we can see that the heat flux density value of sample 4 is 13% higher than that of sample 2, and the value of the heat flux density of sample 3 exceeds that of sample 1 by 15%. Thermal conductivity of sample 1 decreases with a 28% drop in temperature and of sample 2 with a 39% drop in temperature. For samples 3 and 4, the thermal conductivity values are reduced by 19% and 36% respectively.

From a comparison of the thermal conductivity indicators of straw slabs, it follows that at air temperature $t_0 = 10\text{ }^\circ\text{C}$ the thermal conductivity coefficient of sample 3 exceeds the thermal conductivity of sample 1 by 17%, and at $t_0 = -20\text{ }^\circ\text{C}$ by 31%. For flax boon and straw slabs, a similar dependence is traced, but with less intensity. Thus, the thermal conductivity of sample 4 increases by 18% relative to the value of sample 2 at $t_0 = 10\text{ }^\circ\text{C}$ and by 24% at a minimum temperature $t_0 = -20\text{ }^\circ\text{C}$.

At the maximum positive air temperature in the cold compartment of the chamber $t_0 = 10\text{ }^\circ\text{C}$, the thermal conductivity of sample 2 was 14% less than the thermal conductivity of sample 1. For moister slabs, the thermal conductivity of sample 4 is 13% less than that of sample 3. The thermal conductivity of sample 2 is 28% less than that of sample 1 at air temperature of $t_0 = -20\text{ }^\circ\text{C}$.

At the end of the experiment, the moisture content indicators of the samples were determined in the climatic chamber. The change in moisture content over the thickness of the material is shown in Figure 8. The moisture indicators at a thickness of 100 mm correspond to the surfaces of the samples from the warm compartment of the chamber.

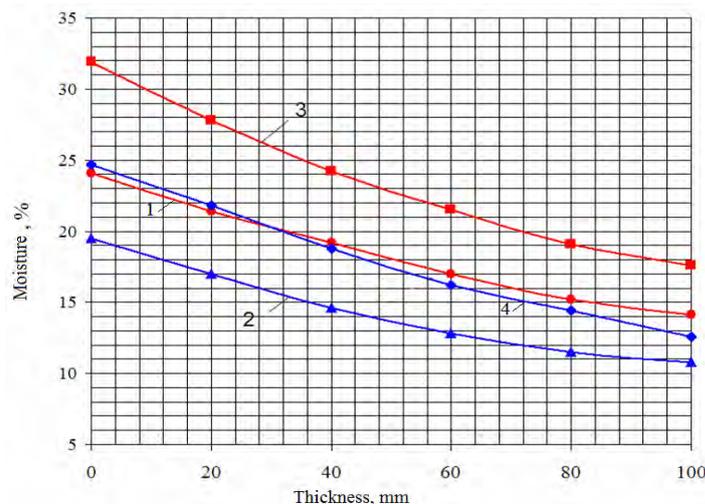


Figure 8. Moisture distribution over the thickness of insulating slabs after tests in climatic chamber: 1 – straw slab (sample 1); 2 – flax boon and straw slab (sample 2); 3 – straw slab (sample 3); 4 – flax boon and straw slab (sample 4)

From the obtained dependences it follows that the average moisture percentage value of sample 1 based on straw is 18.5% and exceeds by 28% the moisture content of sample 2 based on a mixture of flax boon and straw, equal to 14%. For pre-wetted slabs, the average moisture content of sample 3 is 23.7%, which is 31% more than the moisture content of sample 4, equal to 18.1%.

When comparing thermal insulating slabs of the same composition, it was found that the average moisture percentage of sample 1 is 22% lower than that of sample 3, while the average moisture content of sample 2 is 20% less than that of sample 4.

On the warm side of the chamber there was an increase in moisture content of samples 1 and 3 compared to the moisture content of samples 2 and 4 by 25% and 17%, respectively. The same dependence was traced from the side of the cold compartment of the chamber. Excess of moisture

content of samples 1 and 3 over moisture content values of samples 2 and 4 is 32% and 27%, respectively.

Based on the obtained thermophysical indicators, it was found that the most effective experimental thermal insulation materials operate at temperatures below $-5\text{ }^{\circ}\text{C}$. Under conditions of high moisture content, flax boon and straw slabs have higher thermal and technical characteristics compared to straw insulation.

3.2. Operational characteristics of insulation during full-scale tests on the attic floor.

As an example, we considered the time period from March 8 to March 31, 2018, equal to 23 days, with the most typical low night and high daytime outdoor temperatures. The temperature values were taken as the average values of the temperature readings during the day, from 23.00 to 7.00 (night hours) and from 11.00 to 15.00 (daytime hours). Figure 9 shows the temperature distribution as daily average values in the section of the attic floor for insulation based on crushed straw and a mixture of flax boon and straw.

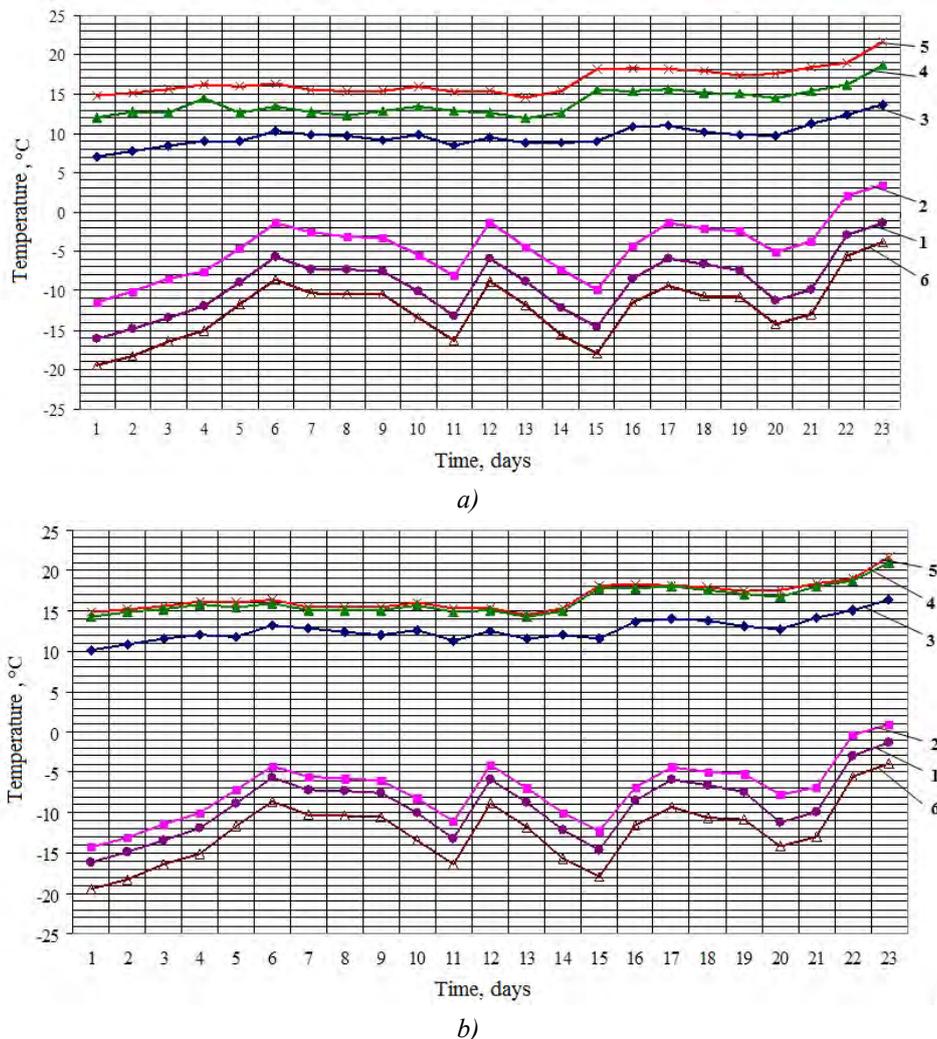


Figure 9. Temperature distribution over the thickness of attic floor for the period of 23 days (night hours): a –flooring with insulation based on crushed straw; b – flooring with insulation based on a mixture of flax boon and straw; 1 - air temperature in the attic, $^{\circ}\text{C}$; 2 - slab temperature at border-line III, $^{\circ}\text{C}$; 3 - slab temperature at border-line II, $^{\circ}\text{C}$; 4 - temperature of the material of the 1st layer at border-line I, $^{\circ}\text{C}$; 5 - air temperature in the living room, $^{\circ}\text{C}$; 6 - outdoor air temperature, $^{\circ}\text{C}$

Table 3 shows the average temperature values distribution in the living room, in the section of the attic floor, as well as the outdoor temperature and in the attic for the considered time periods.

Table 3. Average temperatures

Indicator	Measurement period					
	flooring 1			flooring 2		
	23 days	night hours 23 days	daytime hours 23 days	23 days	night hours 23 days	daytime hours 23 days
Outdoor temperature, °C	-7.7	-12.3	-1.1	-7.7	-12.3	-1.1
Attic air temperature, °C	-4.9	-9.2	1.9	-4.9	-9.2	1.9
Residential air temperature, °C	18.9	16.7	21.8	18.9	16.7	21.8
Slab temperature at border-line I, °C	16.6	13.9	19.6	18.3	16.3	20.4
Slab temperature at border-line II, °C	11.5	9.7	14.4	13.8	12.7	15.7
Slab temperature at border-line III, °C	-0.9	-4.4	4.5	-3.1	-7.2	3.3

From the presented data it follows that for attic flooring 1, the average temperature of the inner surface at border-line I for 23 days is 1.7 °C lower than for composition 2. At night, this difference is 2.4 °C, and in the daytime it is only 0.8 °C.

The average temperature of the thermal insulating material at border-line II of flooring 1 is 2.3 °C less than the value of insulation of flooring 2 over a period of 23 days. Over the same period of time, the temperature of the thermal insulating straw slab at border-line III turned out to be 2.2 °C higher than the temperature of the flax boon and straw slab.

When comparing the average temperature indicators for night hours, it was found that for straw slabs the temperature at border-line II is lower by 3 °C than for flax boon and straw slabs, and at border-line III this indicator for a straw-based insulation is 2.8 °C higher than the temperature of the material based on a mixture of straw with flax boon.

During daytime hours, changes in average temperatures of thermal insulating materials of both compositions are similar to changes in temperatures over 23 days at night, but they are less significant. Thus, for flooring 1, the temperature at border-line II is lower by 1.3 °C, and at border-line III it is 1.2 °C higher than for flooring 2.

The amplitude of average temperature values on the surfaces of flooring 1 straw slabs is 16 °C, in the coldest days, and in the warmest days it is 10 °C. For flax boon and straw slabs, the amplitudes of temperatures are 21 °C and 15 °C, respectively, which exceeds the values of floor insulation 1 by 31% during the coldest days and by 50% during the warmest days.

Of the 23 days considered, the coldest is the first day, and the warmest is the nineteenth. At night hours of the first day, the temperature difference on the surfaces of the insulating material based on straw is 18.6 °C, which is 24% lower than for a material based on a mixture of straw with flax boon equal to 24.4 °C. In the daytime, the temperature amplitude of the insulation 2 is fixed at 12.9 °C and exceeds the value of flooring 1 by 21%, equal to 10.7 °C.

On the nineteenth day, at night, the temperature difference between the surfaces of straw slabs is 12.2 °C, and that of flax boon and straw slabs is 18.3 °C, which exceeds the value of floor insulation 1 by 50%. For daytime hours, the amplitude of the temperature of straw slabs surfaces equals to 8.2 °C and is less by 25% than the indicator of flax boon and straw slabs corresponding to 10.9 °C. It is necessary to note more effective operation of floor insulation 1 and 2 at night colder hours, as compared to the daytime period.

Based on the obtained heat flux densities values, the thermal conductivity of the attic floor structure are determined. Figure 10 shows the dependences of the thermal conductivity on air temperature in an unheated attic.

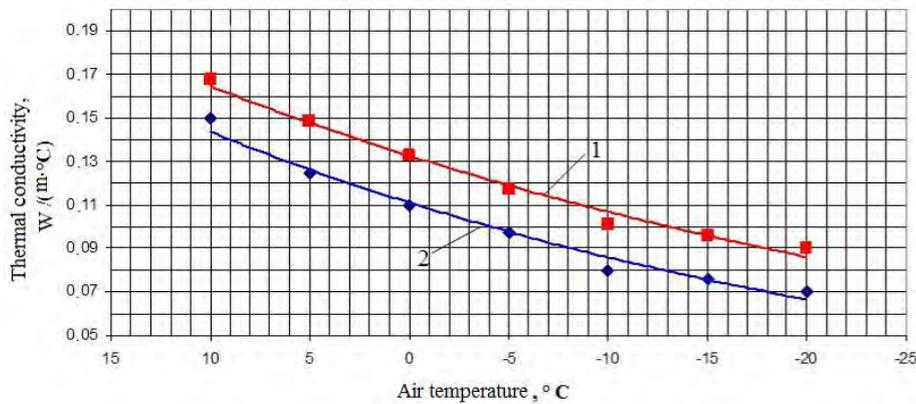


Figure 10. Dependence of the thermal conductivity of the attic floor structure from the air temperature in the unheated attic: 1 – straw slabs flooring; 2 – flax boon and straw slabs flooring

It follows from the graph presented that the value of the thermal conductivity of the attic floor structure 2 with flax boon and straw slabs is 0.07 W/(m·°C) at air temperature -20 °C and 22% less than the similar value of the structure 1 with straw slabs which is 0.09 W/(m·°C). At air temperature of 0 °C, the floor structure 2 thermal conductivity is lower by 17% than the thermal conductivity of the floor structure 1. With an increase in air temperature, the thermal conductivity of attic floors 1 and 2 further increases. Thus, at air temperature in the attic of +10 °C, the thermal conductivity of the floor with straw-based insulation equal to 0.17 W/(m·°C) exceeds the value of the thermal conductivity of the floor with flax boon and straw slabs equal to 0.15 W/(m·°C) by 13%.

Analyzing the data obtained, we can conclude that in all periods of measurements, both for the coldest and for the warmest days, the temperature amplitudes of the surfaces of flax boon and straw slabs are greater than the similar indicators of straw slabs. This is ensured by lower thermal conductivity and determines the best thermal insulating ability of insulation based on a mixture of straw and flax boon.

The distribution of moisture over the thickness of straw and a mixture of straw and flax boon slabs on the attic floor is similar to the indicators of insulation installed in a ventilated insulation system and is considered in [23].

Straw and a mixture of straw and flax boon slabs have been on the attic floor for 3 years. In the process of ongoing monitoring, damage, deformation, or changes in the geometric dimensions of thermal insulation slabs were not recorded.

4. Conclusions

1. Studies of the thermo-technical parameters of straw and a mixture of straw and flax boon slabs in the climatic chamber have shown that thermal insulation materials most efficiently operate at temperatures below -5 °C. In a climatic chamber at an air temperature of -20 °C, depending on the moisture content of the insulation, the thermal conductivity of the flax boon and straw slabs is 0.058 - 0.072 W/(m·°C), which is 27 - 31% lower than that of straw slabs equal to 0.08 - 0.105 W/(m·°C). With a relative air humidity of 50 - 95%, the moisture content of the flax boon and straw slabs varies from 14% to 18.1% and is less by 24% of the crushed straw insulation value.

Regardless of air humidity in the cold compartment of the climate chamber, as well as insulation moisture content at a temperature of -20 °C, the efficiency of slabs made of a mixture of straw and flax boon relatively straw slabs is 15 - 45% higher in terms of basic thermal characteristics.

2. Under operating conditions during full-scale tests, the thermal conductivity of the attic floor structure with flax boon and straw slabs is $0.07 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$ at an air temperature of -20°C and is 22% less than the similar indicator of straw slabs flooring equal to $0.09 \text{ W}/(\text{m}\cdot^{\circ}\text{C})$. An increase in the temperature amplitude by $5 - 5.8^{\circ}\text{C}$ in the structure of flax boon and straw slabs flooring compared to the use of straw slabs is achieved both due to the microstructure of the aggregate components, as well as due to the correctly selected ratio of the components, which provides a structure "frame in the frame" of the flax boon and straw insulation. The achieved increase in temperature amplitude allows us to reduce energy consumption, and, consequently, reduce the financial costs for heating buildings.
3. The results of studies in the climatic chamber and full-scale tests have confirmed the effective operation of flax boon and straw slabs as a thermal insulation material. Thermal insulation slabs based on a mixture of straw and flax boon, taking into account the environmental cleanliness of the components and low combustibility, can compete with polystyrene and mineral wool slabs.

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