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The research of physical – mechanical characteristics of ecological thermal insulation

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1. Introduction

One of the most developing industrial brands in the world is the manufacturing of ecological and eco-friendly building materials. Ecological and eco-friendly materials are manufactured from secondary processing refuse or from shifting reservoir without the supplement adverse to health or environment. The manufacture of this type materials is related to environment protection, greenhouse effect decrease and energy saving. Materials should have small thermal conduction and adequate strength characteristics in order to be used in building enclosures in which different short-term and long-term loads act and which could compete with nonecological contemporary effective thermal insulations.

Ecological organic thermal insulation slab is manufactured using secondary raw materials or cardboard and synthetic fiber polyolefin as a binding material [1]. In order to determine thermodynamical and mechanical characteristics of formed materials, the samples of material with different amount of binder, different structure, different densities and using 3 different granulometric composition cardboard milling refuse were prepared.

2. Experimental part

2.1. The research of thermal conduction

The heat release is a very complicated physical process because it depends on hydrodynamical and thermal processes. The heat amount that body surface gets or releases during a time unit while enacted by mass stream is proportional to the difference of temperatures of the body surface and mass stream. Newton described this law by using the following equation

$$Q = kS\Delta T \tag{1}$$

here S is surface area, m^2; ΔT is the difference of mass stream and surface temperatures. If mass stream temperature is higher than surface temperature, so $\Delta T = T - T_s$, here T and T_s are the average temperatures of mass stream and surface [2].

Thermal conduction coefficient is a complicated function of many variables. Thermal conduction coefficient can be determined notionally or during the experiment. In the first case it is calculated from differential equations, which describe hydrodynamical and thermal processes. These processes happen when mass stream affects the surface. However, these equations are complicated, many assumptions are made while resolving them. That is why the results are not always correct. In the second case it is determined from experimental research of thermal transfer.

In order to determine thermal conduction coefficient we have used a constant thermal flow method. Thermal conduction coefficient λ is determined while measuring thermal flow and the difference of temperature when sample geometry is known. The experiments were carried out in average 10°C temperature, using (300×300 mm) samples, which were (40-50 mm) thick. Prior to the experiment the samples were kept at least for 6 hours in 23 ± 5°C temperature and 50 ± 5% relative air humidity environment. The prepared samples were put in the thermal conduction determination device and were squeezed with 50 Pa load. When thermal flow and temperatures in both sides of the samples are steady, the experiment is complete. Experiment lasts for 2 – 3 hours.

The Fox 304 device (manufacturer – Laser Company, USA) was used to measure thermal conduction. The device is computerised, final experimental results are computed by program LaserComp.

2.1.1. The research of binder, density and structure impact on material thermal conduction

The values of binder, thermal conduction, density and granulometric composition that were measured during the experiment are given in Table 1.

Table 1
The data of samples prepared for thermal conduction

Sample party	Sample Nr.	Sample granulometry	The amount of binder, %	Density, kg/m^3	Thermal conduction coefficient, W/(mK)
1	1	Non-bolted	10	101	0.0464
	2		10	117	0.0486
	3		10	123	0.0485
2	4		5	84.2	0.0473
	5		5	94.2	0.0473
	6		5	111	0.0481
3	7	1.5 mm	5	78.6	0.0449
	8		5	84.2	0.0454
	9		5	92.4	0.0470
4	10	5.0 mm	5	84.5	0.0471
	11		5	91.9	0.0473
	12		5	103	0.0480

As it can be seen from the data given in Table 1, average density of the samples varied from 78.6 kg/m^3 to 123 kg/m^3. The biggest density have the samples prepared using milled nonbolted cardboard, the amount of binder was 10% from milled cardboard amount. The smallest density had the samples prepared using 5% binder amount and fine (1.5 mm) and rough (5.0 mm) milled cardboard fraction.

As results from the Table 1 show, the amount of binder influence sample density. The sample density with bigger binder amount is about 10% bigger. When binder amount in all the samples is constant, that is 5%, the biggest influence on thermal conduction makes granulometric composition. The smallest thermal conductivity have the samples prepared using milled cardboard, which was bolted through 1.5 mm bolter. All values of all the samples are given in Fig. 1.

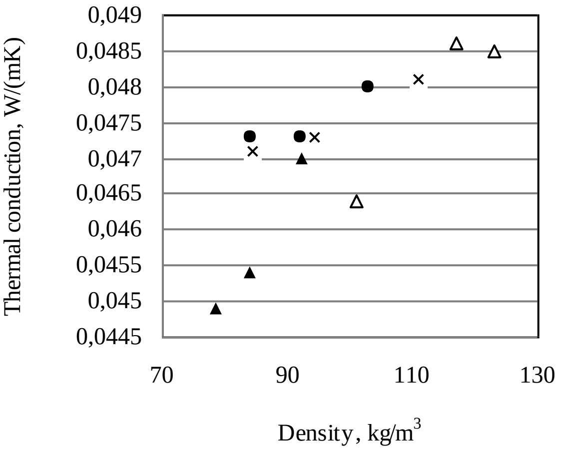

Fig. 1 The relation of thermal conduction and sample density, points are the numbers of parties: Δ - *1*; ● - *2*; ▲ - *3; x - 4*

As it can be seen from Fig. 1, the results of samples are chaotically scattered. It shows that thermal conduction is influenced by several parameters.

In Fig. 2 the reliance of thermal conduction from two parameters – density and the amount of binder are shown.

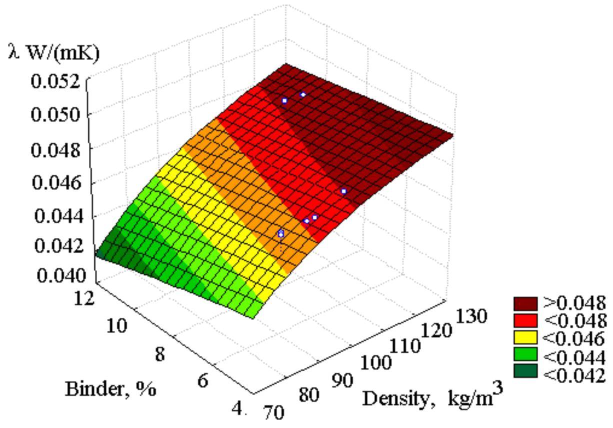

Fig. 2 Thermal conduction reliance from density and amount of binder

According to experimental data thermal conduction reliance from density and amount of the binder is described by the empirical equation

$$\lambda = \frac{0.0540 + \rho^{-1.304}}{-0.466\, exp^{(-(0.0317\, Z))}} \tag{2}$$

with coefficient of determination $R^2 = 0.74589$ and average standard deviation $S = 0.00067463$; here Z is amount of the binder in % from milled cardboard mass [3].

Determination coefficient shows if there is a stochastic relation between y and all analysed factors. Determination coefficient is equal to the square of correlation coefficient and it shows how many percent of the analysed factor values are explained by the regression equation.

Whereas three parameters – density, amount of binder and milled cardboard granulometry were changed, we got empirical thermal conduction reliance from all three parameters.

Thermal conduction reliance on density, amount of binder and granulometric composition

$$\lambda = \frac{-0.9890 + \rho^{0.00834}}{\left(1 - \left(0.00220\, exp^{(-(-0.0503\, Z)+(0.0255\, G))}\right)\right)} \tag{3}$$

with average standard deviation $S = 0.02692$ and determination coefficient $R^2 = 0.7434$, here G is milled cardboard granulometry, mm [3].

As we can see from Table 1, the smallest thermal conduction have the samples with smallest density. As it is known from traditional materials research, in small density materials convection proceeds intensively – heat is freely transported between separate thermal insulation elements – in fibrous materials between separate fibres, in foam – between separate granules and etc. When a particular density in the material structure is reached, big cavities deplete, accordingly depletes convection. When the material density is enhanced further on, thermal conduction increases again because of the bigger thermal conduction through solid material carcass [3]. Thanks to the binder we get products of this density while forming ecological material. Because heat transfer during the convection is small, that is why in all cases when density is enhanced thermal conduction encreases because of the heat transfer through solid material carcass. Thermal conduction in this material encreases as well because of the bigger amount of contacts between separate elements and better contact between them.

In all cases granulometric composition of milled cardboard refuse used for samples had an impact to thermal conduction. First of all, cardboard granulometric composition decided density of the samples. The smallest thermal conduction and density had the samples prepared using the smallest granulmetric cardboard grist – 1.5 mm and smaller. Meanwhile the samples, prepared using nonbolted and bolted through 5 mm bolter cardboard grist, were almost identical in density as well as in thermal conduction. Fine fraction samples distinguished in more homogenous structure and smaller cavities between separate elements. Smaller cardboard fraction was more ruffle, that is why we got smaller sample density.

However, we could not decrease granulometry and sample density more, because the samples are formed from two elements – filler, which consists of cardboard grist and binder, which consists of polypropylene refuse.

When smaller fraction is used and it is tried to bind it with polyolefin binder, the smallest parts of cardboard begin to carbonize because the smallest elements get hot quickly and polyolefin does not reach the melting temperature.

The impact of the binder on thermal conduction and sample density is significant. Comparing prepared sample with 5% and 10% of the binder, it can be observed almost 20% sample density enhancement with the bigger binder amount. When 10% the of binder is used, polypropylene not only binds separate cardboard particles, but also it‘s separate fibres melt and thicken. Samples prepared with the amount lower than 5% of the binder were weak and they hardly kept their form, that is why they were not used in further research.

2.2. The research of strength indicators

The most important strenght indicators of thermal insulation materials are: compression stress by 10% deformation, stress parallel to the sample surface and compressibility [4]. For compression research there were 3 samples with different amount of the binder and different granulometry prepared. Sample measurements were 100×100×40 mm. The samples were measured and weighed, then they were put on raft of compression device. The sample was laid on the centre of upper moving board and it was pressed with constant 0.1 *d* speed per minute and not bigger than 25% declination (here *d* – sample thickness in mm). The accuracy of strenght scan – 0.1 N.

In order to determine if a material has sufficient force by stretching in order it could withstand loads which form while transporting and installing it, a research of parallel with surface strenght by stretching σ_t according to standard LST EN 1608 is exercised. The product is presuposed to be appropriate for usage in enclosuring constructions if it withstands the stress load equal to half bigger mass of the product [5]. Three samples with different amount of the binder and cardboard granulometry were prepared, their measurements were 240×100×40 mm. Prepared sample is fixed in stretch device and it is stretched with constant 10×(1±10%) mm/min speed, untill it collapses. The biggest stress force is recorded.

Parallel with surface stress is calculated according to the formula

$$\sigma_{mt=}\frac{F_m}{d\,b} \qquad (4)$$

here F_m is the highest stress force, kN; *d* is sample thickness, m; *b* is sample width, m [5].

Compression research is performed in order to choose floor payload for floating floor construction. Prepared sample, 100×100×40 mm, is put in computerized press on the centre of moving board. It is pressed with constant speed according to the set pressing scheme [6].

Hounsfield HQ10 (England) universal experiment device was used for research.

2.2.1. Determination of compression stress by 10% deformation

For compression stress evaluation the samples with different amount of the binder and different cardboard granulometry composition were prepared. Results of the research are presented in Table 2.

Table 2

Data of samples prepared for compression experiment

Sample party	Sample Nr.	Granulometric composition	Amount of binder, %	Density, kg/m^3	Compression stress, kPa
1	1	Nonbolted	5	97.0	2.42
	2			105	2.50
	3			93.9	2.71
2	4	Nonbolted	7,5	102	3.54
	5			105	5.62
	6			102	4.60
3	7	Nonbolted	10	103	4.81
	8			107	4.31
	9			107	7.09
4	10	1.5	5	84.9	0.571
	11			85.1	0.622
	12			79.7	0.519
5	13	5.0	5	102	1.58
	14			104	2.34
	15			99.8	1.61

Most often strenght indicators of thermal insulation materials are asociated with density of the material [7]. In Fig. 3 compression dependance of materials on density is presented.

In Fig. 3 the items of each party are indicated by different signs. Even samples of the same composition (granulometry and amount of binder) have a big range of results. The smallest dispersion of the results is noticed in the samples were 1.5 mm granulometry cardboard particles and 5% of the binder is used. It is possible to state that thanks to small cardboard particles the raw materials are mixed better and more homogenuous structure of a sample is obtained. As we can see from Table 2, if the amount of the binder is upgraded two times, that is from 5% to 10%, the compression stress also upgrades about two times. However, the bigger amount of the binder spreads not so good in formed item and other characteristics of the material worsen as well.

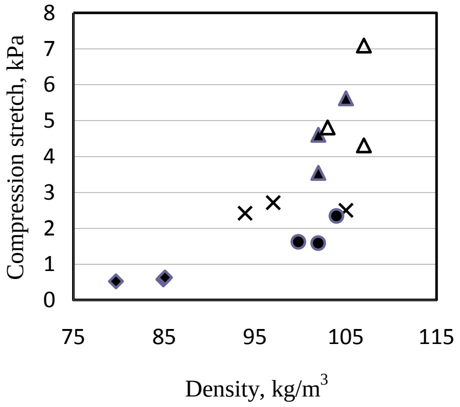

Fig. 3 Compression stress relation with amount of binder; points – the parties of items: x - *1;* ▲ - *2;* Δ - *3;* ♦ - *4;* ● - *5*

As for many other building materials the granulometric composition of cardboard influence compression stress a lot [8]. As the data analysis shows, the samples with the same amount of the binder but with different granulometry have compression stress that can differ four times or more. The biggest force have the samples prepared with nonbolted cardboard, that is from different sizes of particles, that spread evenly in matrix of the item and form more contact zones that enable items to stand the load. The samples, made with 5 mm fraction cardboard have more than two times smaller force. In this case the binder fills big spaces between fill parts, so the binding material spreads worser in all matrix of sample and because of that there is less contact zones supporting separate particles.

A very small compression stress is obtained by using 1.5 mm fraction fills. Although the binder spreads evenly in sample matrix, but the big part of cardboard particles does not contact with each other. The particles are just hanging on the binder. Because of that a smaller density of the samples than with other fractions is got and there is a lot of free space for separate cardboard particles to move. In this case the compression stress of polyolefin fibres affected not only by compression but also by bending and extension stretches, but not the cardboard particles, is determined. In order to determine the influence of separate indicators to compression stress the dependance of compression stress on density and amount of the binder was assessed, Fig. 4.

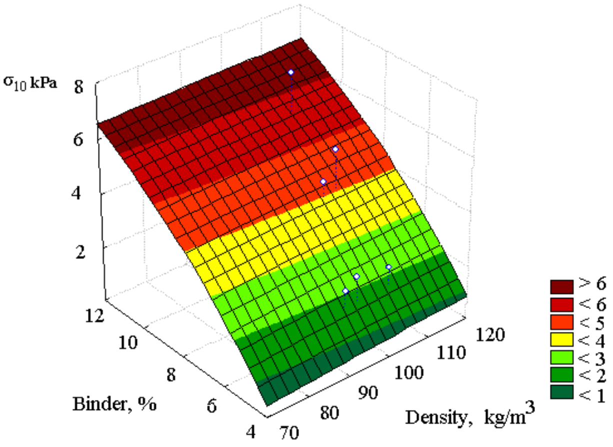

Fig. 4 Dependance of compression stress on density and amount of the binder

According to experimental data empirical dependance of compression stress from the amount of the binder is described by the following formula

$$\sigma_{10} = \frac{11.13 + \rho^{-0.0817}}{-0.0431\, exp^{(-(-0.106\, Z))}} \tag{5}$$

with average standard deviation $S = 1.130688$ and coefficient of determination $R^2 = 0.73262$.

Compression stress dependance on density, amount of the binder and granulometric composition is described by the regression equation

$$\sigma_{10} = \frac{-18.0 + \rho^{0.661}}{\left(1 - \left(0.00127\, exp^{(-(-0.406\, Z) + (10.94\, G))}\right)\right)} \tag{6}$$

with average standard deviation $S = 1.056226$ and coefficient of determination $R^2 = 0.82185$ [4, 7].

2.2.2. The determination of stress parallel with sample surface

The research results of stress parallel with sample surface are given in Table 3.

Comparing samples with the same granulometry (with nonbolted cardboard particles) but with different amount of the binder a big difference of results is observed. Two times bigger amount of the binder exaggerates compression stress almost three times. The exact comparison is disturbed by big dispersion of the results. The discrete results of the samples prepared with 5% of the binder differ more than four times, with 10% of the binder – more than two times, with 7.5% of the binder – only 15%. These results show that amount of the binder does not influence dispersion of the results. Dispersion of the results is influenced by mixture of raw materials, regime of temperature and different fraction amount of cardboard particles. Using nonbolted cardboard particles different fraction amount stays changeable and depends on bolting time, structure of initial raw materials, composition, thickness, humidity and etc.

Table 3

Data of samples prepared for extension research

Sample party	Sample Nr.	Granulometric composition	Amount of binder, %	Density, kg/m^3	Stress, kPa
1	1	Nonbolted	5	89.4	19.1
	2			87.0	4.26
	3			88.7	11.65
2	4	Nonbolted	7.5	90.5	26.2
	5			90.5	30.7
	6			90.7	27.4
3	7	Nonbolted	10	90.7	17.5
	8			93.2	41.5
	9			92.9	32.4
4	10	1.5 mm	5	77.7	1.33
	11			81.4	1.15
	12			80.2	1.40
5	13	5.0 mm	5	99.8	20.3
	14			101	19.9
	15			97.8	14.3

The results of samples with the same amount of the binder but with different granulometry also differ a lot. The highest strenght have the samples prepared from 5 mm fraction cardboard. This shows that bigger cardboard fraction binds better with the binder. Furthermore, the binder coats cardboard particles with thicker layer. Hereby bigger amount of polypropylene fibres contact with separate cardboard particles. When smaller fraction is used – 1.5 mm, a very small stress is obtained. It shows that separate polypropylene fibres do not stipulate proper fastening of cardboard fibres. Moreover, as it was mentioned in previous chapters, smaller cardboard particles are „roughened“ more, in that way the initial structure of cardboard is destroyed. This is approved by small density of the material. Comparing densities of the samples prepared of 1.5 mm and 5.0 fractions, in all cases density of the samples prepared of 1.5 mm fraction is by 20% lower than in the samples, prepared of 5.0 mm fraction.

According to research results stress dependance on two indicators – density and amount of the binder is shown in Fig. 5.

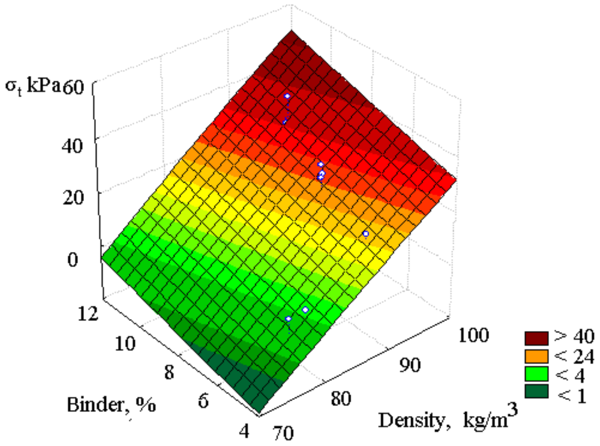

Fig. 5 Stress dependance on density and the amount of binder

According to experimental data we got empirical dependance between stress and amount of the binder

$$\sigma_t = \frac{-205 + \rho^{-0.673}}{0.975\, exp^{(-0.0967\, Z)}} \qquad (7)$$

with average standard deviation $S = 2.633303$ and coefficient of determination $R^2 = 0.82060$.

Stress dependance on density, amount of the binder and granulometric composition is presented by the regressive equation:

$$\sigma_t = \frac{-116 + \rho^{1.085}}{\left(1 - \left(0.00843\, exp^{(-(-0.228\, Z) + (21.83\, G))}\right)\right)} \qquad (8)$$

with average standard deviation $S = 2.82327$ and coefficient of determination $R^2 = 0.79259$ [5, 7].

2.2.3. Determination of compressibility

The results of compressibility research of prepared samples are given in Table 4.

Table 4

Data of samples prepared for compressibility research

Sample party	Sample Nr.	Granulometric composition	Amount of binder, %	Density kg/m^3	Compressibility, mm
1	1	Nonbolted	5	97.0	11.1
	2			97.8	11.1
	3			99.4	10.6
2	4	Nonbolted	7.5	90.4	9.76
	5			90.2	9.98
	6			90.5	8.48
3	7	Nonbolted	10	91.4	8.48
	8			91.8	8.77
	9			92.2	8.32
4	10	1.5 mm	5	81.4	18.7
	11			79.8	17.8
	12			79.9	17.6
5	13	5.0 mm	5	105	11.1
	14			102	11.8
	15			101	10.9

While executing compressibility research the samples were treated in different periods of time and with different values of compression loads [6]. However, the bigger inluence for the samples had the duration of load. Additionally, the results are presented not in stress values, but in shift depletion after the load was removed in Fig 6.

As we can see from the data, presented in Table 4, the biggest influence on compressibility of the material has amount of the binder. Sample compressibility is lower with bigger amount of the binder, it means that the sample recovers its form better after the load is removed. It is conditioned by bigger numbers of connections between the binder and cardboard fibres.

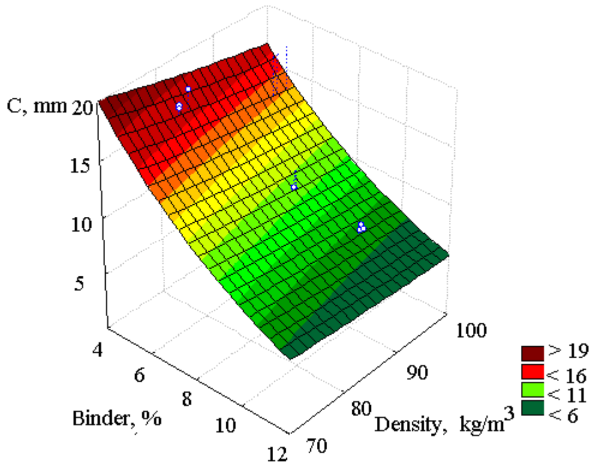

Fig. 6 Compressibility dependance from sample density and amount of the binder

According to experimental data we got empirical dependance between compressibility and amount of the binder

$$C = \frac{0.798 + \rho^{-0.552}}{0.00272\, exp^{(-(-0.140\, Z))}} \qquad (9)$$

with average standard deviation $S = 1.654157$ and coefficient of determination $R^2 = 0.98584$.

Stress dependance on density, amount of the binder and granulometric composition is presented by the regressive equation

$$C = \frac{-2.59 + \rho^{0.520}}{\left(1 - \left(0.515\, exp^{((-0.188\, Z) - (0.641\, G))}\right)\right)} \qquad (10)$$

with average standard deviation $S = 0.766202$ and coefficient of determination $R^2 = 0.98584$.

3. Conclusions

1. During the new generation thermal and mechanical experiment it was established that the biggest density have the samples prepared with nonbolted milled cardboard and amount of the binder is 10% from shredded cardboard amount are also increased.

2. When amount of the binder is increased, density of the material and the value of thermal conduction coefficient.

3. The granulometric composition of cardboard decided the density of the samples. The lowest thermal

conduction and density had the samples with the smallest granulometric cardboard fibres – 1.5 mm and smaller.

4. During the mechanical and thermodynamical characteristics research it was determined that to form ecological thermal insulation slab 5% amount of the binder is sufficient.

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EKOLOGIŠKOS TERMOIZOLIACIJOS FIZINIŲ – MECHANINIŲ SAVYBIŲ TYRIMAI

Reziumė

Straipsnyje aprašomi organinių termoizoliacinių plokščių, pagamintų iš kartono atliekų ir sintetinės rišamosios medžiagos, termodinaminiai ir mechaniniai tyrimai. Tam tikslui buvo naudoti bandiniai su skirtingu rišamosios medžiagos kiekiu, skirtingo tankio ir skirtinga termoizoliacinės medžiagos granuliometrija. Tyrimais nustatyta, kad ir termoizoliacinės medžiagos granuliometrinė sudėtis, ir rišamosios medžiagos kiekis turi įtakos gaminių tankiui. Tankis visais atvejais turi įtakos šilumos laidumo koeficiento kitimui. Mažiausiu šilumos laidumu pasižymi bandiniai, kuriems paruošti buvo naudotas maltas kartonas, išsijotas per 1.5 mm sietą. Mechaninių charakteristikų tyrimais nustatyta, kad geriausias stiprumo savybes turi didesnio tanko bandiniai su didesniu rišamosios medžiagos kiekiu.

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THE RESEARCH OF PHYSICAL – MECHANICAL CHARACTERISTICS OF ECOLOGICAL THERMAL INSULATION

Summary

In this article the thermodynamical and mechanical research of organic thermal insulation slabs prepared from cardboard refuse and synthetical binding material is presented. For this aim the samples with different amount of binding material, different density and different thermal insulation material granulometry were used. During the research it was established that granulometric composition of thermal insulation material and amount of the binder influence density of the samples. In all cases density influences the alternation of thermal conduction coefficient. The lowest thermal conduction have the samples prepared from milled cardboard, bolted through 1.5 mm bolter. During the research of mechanical characteristics it was determined that the best strength characteristics have the samples prepared with bigger amount of the binder and higher density.

Keywords: insulation characteristics, insulation material, natural stock fiber, insulation slabs.

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