UDC 691:620.1

Semko V., PhD, Senior Researcher, doctoral candidate
Leshchenko M., post-graduate
Rud A., student
Poltava National Technical Yuri Kondratyuk University

EXPERIMENTAL STUDY OF VARIABILITY OF THERMAL CONDUCTIVITY OF INSULATION MATERIALS

Those buildings and thermal isolation materials like foam polystyrene and mineral wool, plasterboard sheets and OSB, and also polystyrene concrete are used for effective thermal isolation of building envelopes in light steel thin-walled structures building technology. Results of experimental studies of effective thermal these thermal insulation materials are shown. The results of previous research were confirmed, namely: thermal conductivity coefficient of thermal isolation materials can be shown in shape of normally distributed random variables. Results of experimental studies have been shown that standard value of thermal conductivity coefficient is located in limits from 0,0009 W/mK – for foam polystyrene with density ρ = 25 kg/m^3 to 0,0351 W/mK – for polystyrene concrete B5 with density ρ = 1107 kg/m^3. The coefficient of variation in the range from 1,79% – for polystyrene concrete B5 with density 1292 kg/m^3 to 10,57% – for polystyrene concrete B5 with density ρ = 1107 kg/m^3.

Keywords: *thermal conductivity coefficient, statistical properties, distribution laws.*

Семко В.О., к.т.н., с.н.с., докторант
Лещенко М.В., аспірантка
Рудь А.Г., студент
Полтавський національний технічний університет імені Юрія Кондратюка

ЕКСПЕРИМЕНТАЛЬНІ ДОСЛІДЖЕННЯ МІНЛИВОСТІ КОЕФІЦІЄНТА ТЕПЛОПРОВІДНОСТІ ТЕПЛОІЗОЛЯЦІЙНИХ МАТЕРІАЛІВ

Відомо, що в технології будівництва ЛСТК для ефективної теплоізоляції огороджувальних конструкцій найчастіше використовуються такі будівельні та теплоізоляційні матеріали: пінополістирольні та мінераловатні плити, листи гіпсокартону та OSB, а також полістиролбетон. Наведено результати експериментальних досліджень ефективної теплопровідності цих теплоізоляційних матеріалів. Підтверджено результати попередніх досліджень, а саме: коефіцієнти теплопровідності теплоізоляційних матеріалів можна подати у формі нормально розподілених випадкових величин. Виявлено, що результати експериментальних досліджень показали, що значення стандарту коефіцієнта теплопровідності знаходиться в межах від 0,0009 Вт/(м·К) – для пінополістиролу густиною ρ = 25 кг/м^3 до 0,0351 Вт/(м·К) – для полістиролбетону Б5 густиною ρ = 1107 кг/м^3; коефіцієнт варіації знаходиться в діапазоні від 1,79% – для полістиролбетону Б6 густиною 1292 кг/м^3 до 10,57% – для полістиролбетону Б5 густиною 1107 кг/м^3.

Ключові слова: *коефіцієнт теплопровідності, статистичні характеристики, закони розподілу.*

Introduction. Development of energy saving and energy efficiency is one of the most important factors of economic growth in Ukraine. Order of Cabinet of Ministers of Ukraine «About National Action Plan on energy efficiency for the period 2020» was issued in November 2015. The results of the past years have shown that 60% of total primary energy supply provided through internal resources at the beginning of the second millennium. Today the structure of total primary energy supply doesn't correspond to the resource potential of Ukraine. Dynamics of final energy consumption was influenced by the same factors as indicators of overall energy supply and wasn't characterized by pronounced unsustainable trends. Although that the performance of primary energy and final energy intensity have decreased rapidly in Ukraine, they are at a much higher level compared to the EU member states for today. The improvement of building norms and standards (especially provision of annual increase in the number of newly constructed buildings with close to zero energy consumption) is one of the items in energy efficiency measures for the household sector. Therefore, energy-independent building is becoming more popular at the last time. Energy-independent buildings are usually built low-rise skeletonized type.

Those buildings and thermal isolation materials like foam polystyrene and mineral wool, plasterboard sheets and OSB, and also polystyrene concrete are used for effective heat insolation of building envelopes in light steel thin-walled structures building technology. Therefore, research of effective thermal conductivity (thermal conductivity coefficient) of this materials is rather topical issue.

Review of recent research and publications sources and selection the general problem hadn't resolved before. In Ukraine, the study of the thermal reliability and temperature effects on building structures have been engaged G. G. Farenyuk, V. A. Pashinsky, N. V. Pushkar, A. M. Karyuk [1, 2]. A method for evaluating the thermal reliability of building envelope for their thermal insulating properties was given in one of the works [2]. The method is based on determining the probability of building envelope thermal failures.

The study of thermal insulation probability properties of materials have been presented in the work of V. V. Shulgin and A. M. Karyuk [3], where thermal conductivity coefficients was calculated by results of testing several tens experimental samples of materials and was given in shape random variables with normal distribution. Statistical properties have shown that thermal conductivity coefficient of thermal isolation materials is increased with its increasing of density. For instance: thermal conductivity coefficients for mineral wool with density 50 and 115 kg/m^3 are 0,0047 and 0,0040 W/mK in accordance. Herewith similar experimental and numerical studies were provided by foreign scientists [4, 5]. Comparing the results for the same type of mineral wool 40 and 100 kg/m^3 standard is 0,00046 and 0,00050 W/mK in accordance, that on the order of less than the aforementioned data. So the question remains as to compliance the values of the statistical characteristics of the thermal conductivity of insulating materials.

The goal of the paper was to research the variability of thermal conductivity coefficient of thermal isolation materials which the most common use in light steel thin-walled structures technology and to compare them with the previous research.

The main material and results. One of the components of the thermal reliability of wall construction – is the quality of the materials from which it is composed. It is known that the degree of thermal conductivity of insulation material is characterized by a value of its thermal conductivity coefficient λ, W/mK. Thermal conductivity coefficient is equal to the amount of heat which is transferred per unit time through unit surface area of the material at a single gradient of temperature. Availability of pores in the insulation materials can't be considered them as a continuous medium. So use of Fourier law for such materials is conditional to some extent. Thermal conductivity coefficient of porous material is conditional too. Therefore, the accuracy of calculation of this value is advisable to determine by using statistical methods [6].

The thermal isolation materials which the most common use in light steel thin-walled structures technology were taken for experimental studies. Namely: polystyrene, mineral wool, gypsum plasterboard, OSB-plate, and a different density polystyrene concrete. General properties of thermal insulation materials are shown in Table 1 and Table 2.

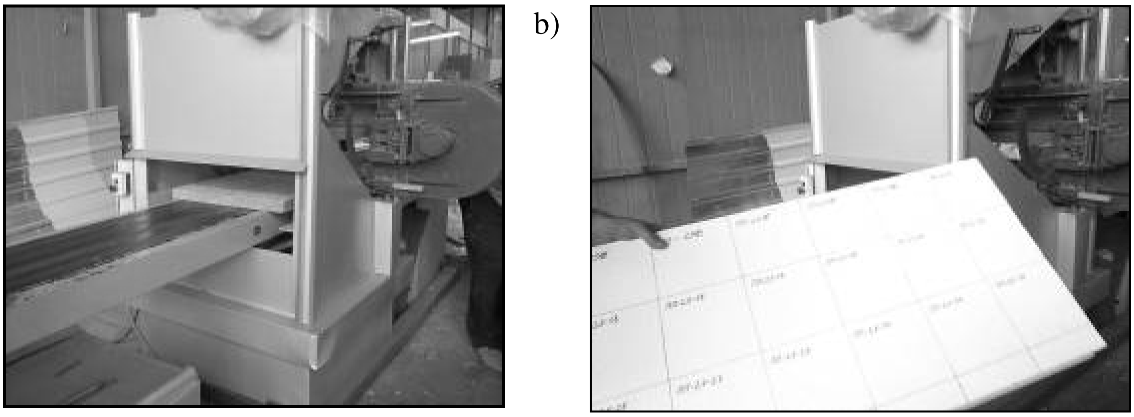
Table 1 – General properties of thermal insulation materials

Thermal insulation material	Specific weight of material (expected), kg/m^3	Thermal conductivity (expected), W/mK	Sheet dimensions, mm	Sheet thickness, mm
Foam polystyrene (FP)	25	0,038	1000×600	50
Mineral wool (MW)	135	0,037	1000×600	50
Gypsum plasterboard (GPB)	800	0,21	2500×1200	12,5
Oriented strand board (OSB)	600	0,13	2500×1250	10

The number of samples necessary to determine the effective thermal conductivity (thermal conductivity coefficient) or thermal resistance and sampling procedure were provided in the standard for a particular material or product [7, 8]. Thermal resistance identified in five samples if there isn’t mentioned the number of samples in the standard for a particular material or product [9].

The samples were made in the shape of a cuboid, the biggest facets of which are in the shape of a square with the size 150×150 mm according to the specifications of the device. The thickness of the sample was 10 ... 25 mm. Initially cut was made along the sheet on the tape machine for cutting mineral wool through the thickness for the materials such as foam polystyrene and mineral wool (Pic. 1). And then it was sawn in experimental samples.

a) b)



Picture 1 – Production experimental samples:
a) mineral wool; b) foam polystyrene

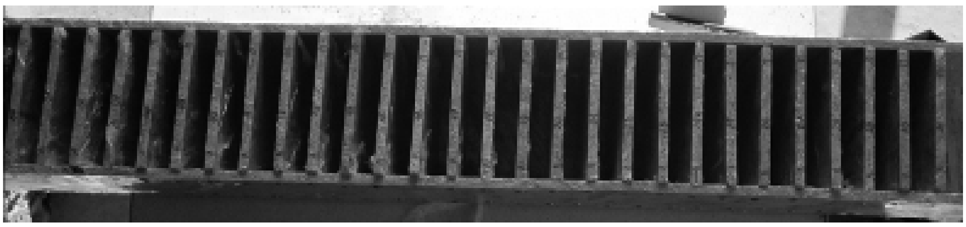
Since today there is no specification documents about regulation of physical values of polystyrene concrete in Ukraine, the effective thermal conductivity of polystyrene concrete with different projected density were asked to determine as part of experimental studies.

Production of polystyrene concrete (PSC) was making in laboratory of Department of Technology building constrictions, products and materials Poltava National Technical Yuri Kondratyuk University. The composition of concrete mix were: bonding substance – Portland cement M500, fill material – granulated foaming polystyrol (GFP), not «hard» water and liquid air entraining agent – saponified wood resin (SWR). The composition of concrete mix, calculation of expenses 1m^3 of materials was made according to the data of previous research [10] and Table 2. Determination of real density of polystyrene concrete was obtained experimentally. The results of the thermal conductivity coefficient of PSC in depending on the density are shown in [11].

Table 2 – The composition of concrete mix adopted for the production of PSC experimental samples

The composition of PSC	Expenses of materials for 1 m^3 polystyrene concrete at density (projected), kg/m^3					
	B1(200)	B2(400)	B3(600)	B4(800)	B5(1000)	B6(1200)
Portland cement M500, kg	165	290	412	563	500	650
Sand, kg	—	—	—	—	420	420
GFP, m^3	1,05	1,00	0,95	0,95	0,95	0,9
SWR, kg	1	0,8	0,6	0,6	0,6	0,6
Water, l	95	110	120	140	160	170

Collapsible formwork of the sheet OSB was designed (Pic. 2) with the size of cells 150×150×25 mm, which was covered with a polyethylene film to produce PSB-plates experimental samples. Stacking of concrete mix was conducted by hand with a trowel, and then with rodding. At the end the mix was alimenting at project mark. The samples were in the laboratory room at temperature +18±2 ºC and relative humidity 70–75 %. The samples were covered with a layer of wet fabrics for seven days. Then they were strip and kept in the laboratory until they gained project strength of concrete.

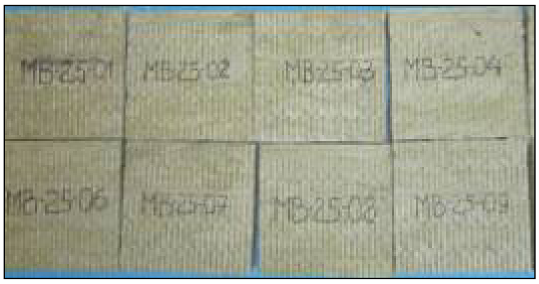


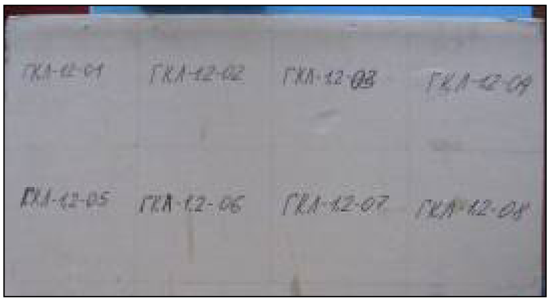
Picture 2 – Formwork for making PSC-plates experimental samples

General view of the experimental samples before the test is shown in Pic. 3.

Determination of the thermal conductivity of thermal insulation materials is performed using the device for measuring a thermal conductivity and thermal resistance of building and insulation materials – ИТС-1 (Pic. 4).

The device is designed in accordance with DSTU B V.2.7-105-2000 [9] and uses the stationary thermal stream. Essence of the method is to create a steady thermal stream that passes through the specified thickness flat sample and directed perpendicular to the front (major) sides of the sample, measuring the density of thermal stream, temperature of facial opposite sides and thickness of the sample.

a)  b) 

c) 

d) 

Picture 3 – General view of the experimental samples:
a) foam polystyrene; b) mineral wool; c) plasterboard; d) polystyrene concrete

Temperature and relative air humidity in the room, in which the test was conducted must be according (295±5) K and (50±10) %.

The device consists of measuring cell (heat protection sheeting, heater and refrigerator) and electronic unit placed in the same enclosure. There are a keyboard and a graphical indicator on the front panel of the device. Switches, the fuse cord mains supply outlet and a connector for measuring cell heater are located on the back of the front wall.

The operating principle of device is based on creating a steady thermal stream passing through the studied flat sample. Thermal conductivity of the sample λ is calculated by thermal stream, temperature of opposite sides of the sample and its thickness (1):

$$\lambda = \frac{d \cdot q}{\Delta T}, \qquad (1)$$

where d – thickness of the sample;

q – density of the thermal stream which passed through the sample;

ΔT – the temperature difference between the opposite sides of the sample.

The experimental sample has to have shape of a cuboid which facial sides are a square with the size 150 × 150 mm. The thickness of the sample must be within 10 ... 25 mm.

Facets of the sample which contact with working surfaces of the device panels must be flat and parallel. Deviations hard sides of facial sample against parallelism mustn't exceed 0,5 mm. Hard samples with different thickness and deviation from flatness were polished. The thickness of the samples was measured with beam trammel with a pointing error no more than 0,1 mm in the four corners in the distance (50,0 ± 5,0) mm from the top corner and the middle of each side. Arithmetic average of all measurement results was taken like the thickness sample.

The sample is inserted into the ИТС-1 measuring cell of the device between the heater and refrigerator and pressed by fixing screw with the necessary efforts at carrying out the measurement. Device conducted three basic measurements, and then recorded the result.

General view of the measuring ИТС-1 device and the process of measuring the effective thermal conductivity of thermal insulation materials presented in Pic. 4.

a)

b)

Picture 4 – Determination of thermal conductivity:
a) the measuring ИТС-1 device; b) process of sample installation

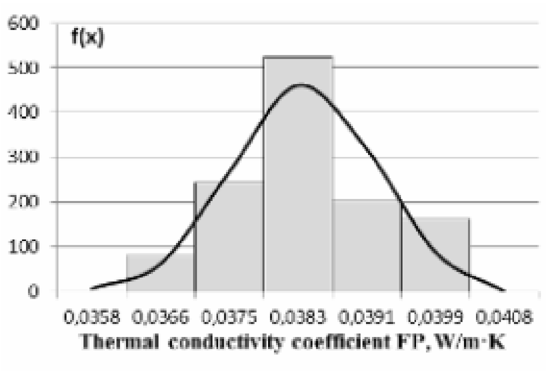
Value of thermal conductivity of all thermal experimental insulation materials was accepted to obtain reliable estimates of statistical properties and laws of distribution. Statistical analysis of the data fetching of thermal conductivity coefficient is executed in MS Excel using built-in statistical functions that implement the processing method and formulas given in [6]. The average values, standards and coefficients of variation were identified for each fetching and also constructed distribution histogram.

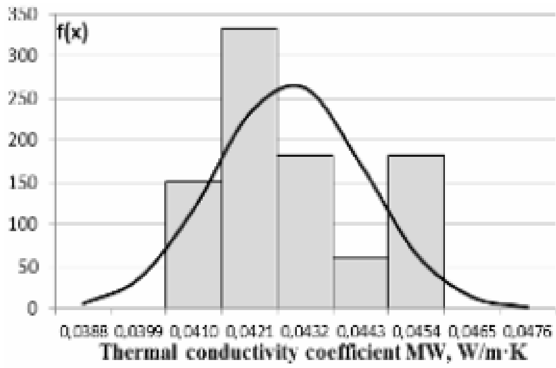
Results of statistical functions of thermal conductivity coefficient of foam polystyrene and mineral plates, plasterboard and OSB sheets and polystyrene concrete experimental samples of different density (the actual value of density are indicated) is given in Table 3.

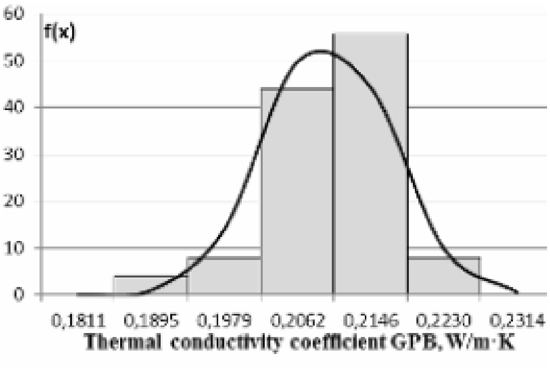
Table 3 – Statistical properties of thermal conductivity coefficient

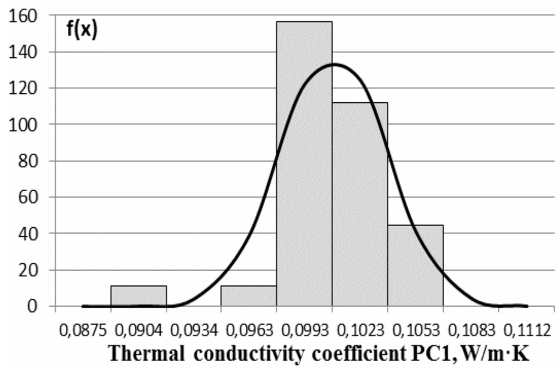
Type of thermal insulation material	Number of samples N	Arithmetic average value M, W/mK	Standard S, W/mK	Coefficient of variation V, %	Statistic of Pearson's criterion χ^2	Critical value χ^2_{cr}
Foam polystyrene, ρ=25 kg/m^3	30	0,0379	0,0009	2,27	0,956	5,99
Mineral wool, ρ=135 kg/m^3	30	0,0423	0,0015	3,52	0,473	5,99
Plasterboard, ρ=800 kg/m^3	30	0,2055	0,0071	3,46	1,758	5,99
OSB, ρ=600 kg/m^3	5	0,0989	0,0037	3,74	1,4	3,84
B1, ρ=309 kg/m^3	30	0,0994	0,0028	2,83	1,219	7,82
B2, ρ=605 kg/m^3	5	0,1563	0,0053	3,38	0,64	3,84
B3, ρ=808 kg/m^3	6	0,1980	0,0071	3,59	1,4	3,84
B4, ρ=875 kg/m^3	30	0,2760	0,0115	4,16	1,616	5,99
B5, ρ=1107 kg/m^3	5	0,3324	0,0351	10,57	1,4	3,84
B6, ρ=1292 kg/m^3	5	0,3764	0,0067	1,79	1,4	3,84

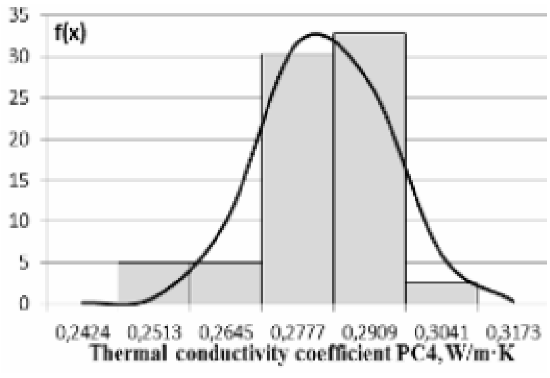
A common effect of many random factors causes fact that the physical and mechanical properties of insulating materials can be described by normal distribution in most cases that represents the boundary distribution of amount of many random variables. The histograms of distribution of thermal conductivity coefficient (n = 30) presented in Pic. 5 and have a symmetrical similar hills character, which is positioned like density of normal distribution. The results of the testing of this hypothesis by the Pearson's criterion of coherence are shown in Table 3. There is statistical significance of the criterion χ^2 in depending on the number of freedom degrees k and the significance level α for each of tested fetching specified. The significance level α determines the likelihood of rejection of the correct hypothesis and it's assumed equal α=0,05. Number of freedom degrees k equals the number of intervals in the histogram of distribution L, reduced on the amount of options of the selected theoretical distribution law and a further per unit – for normal $k=L - 3$.

a)


b)


c)


d)


e)


Picture 5 – Distributions of thermal conductivity coefficient:
a) foam polystyrene;
b) mineral wool;
c) plasterboard sheet;
d) polystyrene concrete ρ=309 kg/m³;
e) polystyrene concrete ρ=875 kg/m³

The received statistical value of fetching $\chi^2 \leq \chi_{cr}^2$ confirms that the normal distribution law doesn't contrary to experimental data and could be used for description of probability of thermal conductivity coefficient of foam polystyrene and mineral plates, plasterboard and OSB sheets and polystyrene concrete experimental samples with different density.

The results of experimental studies have shown that the value of the standard of thermal conductivity coefficient of the most common use in light steel thin-walled structures technology thermal isolation materials is located in limits from 0,0009 W/mK – for foam polystyrene with density ρ=25 kg/m^3 to 0,0351 W/mK – for polystyrene concrete B5 with density ρ = 1107 kg/m^3. The coefficient of variation is located in limits from 1,79% – for polystyrene concrete B6 with density 1292 kg/m^3 to 10,57% – for polystyrene concrete B5 with density ρ = 1107 kg/m^3.

Consequently, conducted research allows the following **conclusions:**

1. The results of previous Ukrainian researches were confirmed in study, namely: the thermal conductivity coefficient of the most common use in light steel thin-walled structures technology thermal isolation materials can be submitted in the form of normally distributed random variables.
2. The received statistical properties of thermal conductivity coefficient of thermal isolation materials the most match with the results obtained in foreign researches.
3. The received statistical properties of thermal isolation materials can be used for determine the probability of thermal rejection of light steel thin-walled envelopes structures.

References

1. Пашинський В. А. Температурні впливи на огороджувальні конструкції будівель: монографія / В. А. Пашинський, Н. В. Пушкар, А. М. Карюк. – О. : ОДАБА, 2012. – 180 с.

2. Пашинський В. А. Оцінка імовірності виникнення теплових відмов конструкцій / В. А. Пашинський, Г. Г. Фаренюк // Строительство, материаловедение, машиностроение: сб. науч. тр. – Дн-к : ПГАСА, 2010. – Вып. 56. – С. 567 – 571.

3. Шульгін В. В. Імовірнісне подання технічних характеристик теплоізоляційних матеріалів / В. В. Шульгін, А. М. Карюк // Збірник наукових праць. Серія: Галузеве машинобудування, будівництво. – П. : ПолтНТУ, 2013. – № 4 (39). Т.2 – С. 257 – 262.

4. Stankevičius V. The Effect of stochastically dependent physical parameters on the materials' thermal receptivity coefficient / V. Stankevičius, L. Kairys // Materials Science (Medžiagotyra), 2005. – Vol. 11, No. 2. – P. 188 – 192.

5. Uncertainty in the thermal conductivity of insulation materials / F. Domínguez-Muñoz, B. Anderson, J.M. Cejudo-López, A. Carrillo-Andrés // Building Simulation. Eleventh International IBPSA Conference Glasgow, Scotland, July 27 – 30, 2009. – P. 1008 – 1013.

6. Лычев А. С. Надежность строительных конструкций: учеб. пособие / А. С. Лычев. – М. : Издательство Ассоциации строительных вузов, 2008. – 184 с.

7. ДСТУ Б В.2.7-8-94. Плити пінополістирольні. Технічні умови. – К., 1994. – 22 с.

8. ДСТУ Б В.2.7-167:2008. Вироби теплоізоляційні з мінеральної вати на синтетичному в'яжучому. Загальні технічні умови. – К., 2000. – 22 с.

9. ДСТУ Б В.2.7-105-2000. Матеріали і вироби будівельні. Метод визначення теплопровідності і термічного опору при стаціонарному тепловому режимі. – К. : Держбуд України, 2001. – 25 с.

10. Семко О. В. Легкий бетон для заповнення порожнин сталевих тонкостінних конструкцій / О. В. Семко, Д. М. Лазарєв, Ю. О. Авраменко // Будівельні конструкції. Науково-технічні проблеми сучасного залізобетону: міжвід. наук.-техн. зб. – К. : ДП НДБІК, 2011. – Вип. 74. – С. 659 – 666.

11. Лещенко М. В. Теплотехнические свойства стеновых ограждающих конструкций из стальных тонкостенных профилей и полистиролбетона / М. В. Лещенко, В. О. Семко // Инженерно-строительный журнал. – 2015. – № 8. – С. 44 – 55.

Надійшла до редакції 17.03.2016