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Thermal Conductivity Coefficient Research On Mineral Wool After Partial Immersion in Water and Drying to Constant Mass

Thermal Conductivity Coefficient Research On Mineral Wool After Partial Immersion in Water and Drying to Constant Mass

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Abstract. This work concerns the thermal conductivity coefficient of mineral wool. Thermal conductivity coefficient is the basic parameter characterizing thermal insulation materials. Its value depends on various parameters. One of such parameters is the moisture content of the material. The value of the thermal conductivity coefficient rises as the water content of the material increases. The thermal conductivity coefficient of damp mineral wool can be found in various publications. The purpose of this work was to check whether the thermal conductivity coefficient of mineral wool changes after subjecting the material into water at specific time intervals and after drying to a constant mass. The scope of the study included measuring the thermal conductivity coefficient of mineral wool in three processes: before immersion in water, at the time of removal from water and after drying again. The measurements were made at an average temperature of 10˚C and a temperature difference of 20 K sample thickness. Fourteen test specimens with a density in the range (74÷127) kg/m^3 were tested. Due to the type of mineral wool, the samples were divided into four groups. Test specimens 30, 40 and 50 mm thick were immersed in water to a depth of 10 mm for 1, 7, 14 and 28 days. After this time, the samples were dried to a constant mass and the thermal conductivity coefficient was measured. According to the obtained research results and statistical tests, it was found that the influence of water and redrying on the thermal conductivity coefficient of the mineral wool is insignificant. The largest difference between the initial value of thermal conductivity coefficient and the coefficient value after immersion in water and drying of the same sample was 0.9% and was less than the uncertainty of measurement (3%).

1. Introduction

The function of thermal insulating products for building applications is to limit thermal conductivity between the insulated object and the environment. The basic parameter characterizing thermal insulation materials is the thermal conductivity coefficient λ. Its value depends on the temperature, density, type of pores, the type of gas contained in the cells and the moisture content. Before the product is put on the market, initial type tests are carried out. The thermal conductivity coefficient measurement was carried out on new samples previously stored under laboratory conditions. Depending on the usage of the material (thermal insulating products in building applications or building equipment and industrial installations), the test is carried out at one temperature or for a larger temperature range. On the basis of the obtained test results, the manufacturer determine the declared value of thermal conductivity coefficient.

One of the materials used for thermal insulation is mineral wool. The common raw material for the production of mineral wool is basalt [1]. The mineral wool as a fibrous material is characterized by a low density in the range of 10 to 230 kg/m^3. It is also an anisotropic material. Thermal conductivity coefficient of fibrous materials is different for fibers arranged perpendicularly and parallel to the direction of the heat flow [2] .

Thermal insulation is usually properly protected against weather conditions. For example, the thermal insulation of building partitions can be protected by the use of plaster, facing or roofing. During the exploitation of the object, the protective layer may be damaged and the insulation can be exposed to unfavorable effects (e.g. water). Water has a thermal conductivity coefficient that is about twenty times greater than air. Its deep penetration into the material causes displacement of air, which results in an increase in the insulation's thermal conductivity coefficient. Manufacturers of mineral wool insulation often use hydrophobic admixtures to protect the material against water. These admixtures cause the water molecules to be repelled from the fibers and the absorption of the material decreases [3].

Research on the influence of moisture content on the thermal conductivity coefficient of mineral wool has been presented in many works. They analyzed the effect of absorption on the thermal conductivity [3, 4, 5, 6, 7]. Most of the research was conducted on new products. Others such as [8] conducted research on 25 years old glass wool insulation.

The purpose of this work was to verify whether the value of thermal conductivity coefficient of mineral wool after water absorption in selected periods of time and after drying to constant mass will change. The scope of the research included determination of absorption by partial immersion samples placed in water for 1, 7, 14 and 28 days and measurement of thermal conductivity coefficient for dry, damp and dry again samples. Absorption tests carried out in this study simulate the effect of precipitation on the insulation for a certain period of time (e.g. during assembly or during exploitation) when the protective layer is damaged.

2. Experiments

The experiment was carried out on fourteen test specimens. Each sample consisted of two square boards with sides of 500 mm cut out of one sheet of mineral wool. Four types of mineral wool were used for the tests, which were marked with the letters A, B, C and D. An example of a test specimen from each type is shown in figure 1.

Figure 1. View of one selected sample for each group of mineral wool (from left: A, B, C, D group)

Each sample was marked with a symbol (e.g. A-1). The letter indicated a group of samples of the same material, while the number was their ordinal number.

A group consisted of test specimens of the same material with a density in the range (118÷127) kg/m^3, B group with density (74÷77) kg/m^3, C group with density (103÷105) kg/m^3, D group with density (89÷91) kg/m^3 (see table 1). The samples kept the original thickness of the product. In A group, the nominal thickness of the sample was 30 mm, in B group - 40 mm, in C and D groups - 50 mm.

Table 1. Basic parameters of test specimens

sample name	length	width	thickness	density
[-]	[m]	[m]	[m]	[kg/m^3]
A-1	0.500	0.501	0.031	122
A-2	0.500	0.500	0.032	117
A-3	0.499	0.500	0.031	121
A-4	0.499	0.499	0.031	120
A-5	0.499	0.500	0.031	118
A-6	0.499	0.500	0.031	119
A-7	0.500	0.500	0.030	127
B-8	0.497	0.497	0.040	74
B-9	0.498	0.498	0.040	77
C-10	0.500	0.498	0.048	103
C-11	0.499	0.499	0.049	105
D-12	0.501	0.501	0.049	90
D-13	0.500	0.500	0.050	89
D-14	0.500	0.501	0.050	91

The study included four stages: measurement of thermal conductivity coefficient of test specimens after conditioning in laboratory conditions, saturating specimens with water, measurement of thermal conductivity coefficient of wet samples and measurement of thermal conductivity coefficient of dried samples to constant mass. The tests were carried out on samples of mineral wool with different density. Each mineral wool of which the test specimens were cut out was a hydrophobic material as determined by a simple test. The test consisted of checking the reaction of water in direct contact with the surface of the material. It has been observed that the water drops retain their shape during contact with the material and do not soak into the material.

2.1. Stage I - measurement of the thermal conductivity coefficient of samples after conditioning

Measurements of the thermal conductivity coefficient were made on samples taken from new boards previously stored in laboratory conditions. The detailed parameters of the samples are presented in table 1. Before starting the measurements, the samples were conditioned in the chamber for 72h at 23°C and 50% relative humidity. Then the samples were stored in the laboratory room, where the temperature and relative humidity were kept at a level of (23±2)°C and (30±5)%. After conditioning the samples were measured and weighed, then the thermal conductivity coefficient was measured in steady-state conditions (the temperature field does not change over time [9]). The measurements were made in a device with a guarded hot plate. It's is a two-sample device in which two almost identical samples are placed between the heating and the cooling plates. It generates an unidirectional, constant and homogeneous heat flow within the samples. The thermal conductivity coefficient was carried out at an average temperature of 10°C with a temperature difference of 20 K on the thickness of the specimen. After measurement the samples were reweighed. The obtained thermal conductivity coefficients for stage I will be marked with the symbol λ_{dry} in the further part of the article.

2.2. *Stage - II - subjecting the samples to water*

Subsequently, each test specimen was partially immersed in water to have its bottom surface (10 ± 2) mm below the water level. Before immersion, the samples were weighed with an accuracy of 0.1 g. The immersion period was different. Samples were kept in water for 1 day, 7 days , 14 days or 28 days. After a prescribed time, the specimens were removed from the water and drained for (10 ± 0.5) min by placing them vertically in a mesh, inclined at 45°. After that, the samples were weighed again. On the basis of the obtained results, the water absorption W_p was calculated using the expression (1),

$$W_p=\frac{m_n-m_0}{A_p}, \quad \frac{kg}{m^2} \tag{1}$$

where m_n is the mass of the test specimen after partial immersion, in kilograms, for period of n time (for one day n=1, for 7 days n=7, for 14 days n=14 and for 28 days n=28), m_0 is the mass of test specimen before partial immersion, in kilograms and A_p is the bottom surface area of test specimen, in square meters.

The water absorption test was carried out according to the methods described in standards [10] and [11], whereby the water absorption by partial immersion of thermal insulation products, including mineral wool products, in the short term (24 hrs) and in the long term (28 days) respectively is determined. For the purpose of this work, the test procedure has been slightly modified. Formula (1) was adopted on the basis of standard [10], with the symbol m_{24} given in this standard was replaced by the symbol m_n . In contrast to the mentioned methods test samples had a size (500 × 500) mm and they were weighed after 1 day immersion in water and after 7, 14 and 28 days. Samples marked with symbols from A-1 to A-4 were submerged in water for 1 day, samples from A-5 to A-7 for 7 days , samples B-8, B-9 and C-10, C-11 for 14 days , samples from D-12 to D-14 for 28 days.

Apart from the water absorption, the moisture content of the samples was also determined at the moment of their removal from the water. The percentage of the water content in the material was determined by the formula (2) for moisture W taken from the literature [1],

$$W=\frac{m_w-m_s}{m_s}\times 100,\ \% \tag{2}$$

where in the studied cases mass of the wet test specimen $m_w=m_n$ and mass of the dry test specimen $m_s=m_0$.

2.3. *Stage - III - measurement of the thermal conductivity coefficient of samples after water absorption*

Directly after removing the samples from the water and weighing them, the thermal conductivity coefficient was measured again. The study was conducted similarly to the first stage, except that the samples were wrapped in plastic film to prevent evaporation of absorbed water. In order to check whether the film has a significant impact on the results, additional tests were carried out. Thermal conductivity coefficient of the sample was measured several times in two cases: with and without foil. The film caused an increase in the coefficient by 0.8%. This difference was taken into account in further calculations. The thermal conductivity coefficient for wet test specimens determined directly after stage II was marked with λ_{wet} .

2.4. *Stage IV - measurement of the thermal conductivity coefficient of samples after drying to constant mass*

After testing the damp samples, they were dried at a temperature of (23±2)°C and relative humidity (30±5)% . The samples were dried to constant mass, i.e., until the difference between the last two measurements was less than 0.05%. The mass measurement for the example test specimen is shown in figure 2.

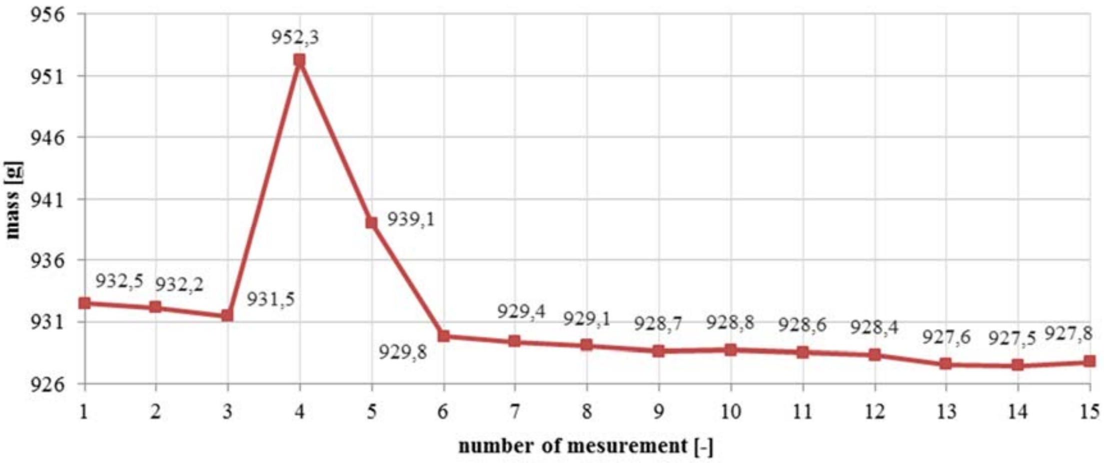

Figure 2. Mass of A-2 specimen depending on number of measurement

Measurements from 1 to 3 were made before the sample was immersed in water, and measurements from 4 to end were taken at the time of removing the sample from the water and before the thermal conductivity coefficient was examined. The 5th mass measurement was made after thermal conductivity test. The remaining mass measurements were made on samples which were dried at a temperature of (23 ± 2) ° C and relative humidity (30 ± 5)%. On the basis of measurement no. 6 (figure 2.) it can be concluded that after just two days of drying, the mass of the sample was 99.7% of the initial mass. It was noticed that the sample after redrying was smaller than at the beginning of the test. Drying to constant mass of sample A-2 lasted for 14 days, and the difference between the last two measurements was 0. 03%.

After establishing a constant mass, the thermal conductivity coefficient was measured under the same conditions as in stage I. The thermal conductivity coefficient results obtained in stage IV were marked with the general symbol $\lambda_{(a)dry}$.

3. Results and discussion

Table 2. presents the results of testing the water absorption by partial immersion. The greatest absorbability W_p=0.57 $\frac{kg}{m^2}$ had the C-11 sample immersed in water for a period of 14 days. Water content in this specimen was 11%. Considering the mean values, the samples immersed in water for 24 hours had the lowest absorption. The lowest water absorption W_p=0.08 $\frac{kg}{m^2}$ was observed for samples A-2 and A-3 immersed for 1 day. The same result was obtained for sample A-7, which was immersed for 7 days. W_p results for group C were on average 61 % higher than for group B, after the same immersion time (14 days). This was due to differences in the type, structure and density of the material in samples of groups B and C. Specimens from group D, although being the longest time immersed in water (for 28 days), had a W_p similar to that of samples A-5 and A-6 immersed for 7 days. The differences between water absorption by partial immersion after 7, 14 and 28 days were negligible, except results for samples A-7 and D-14. After rejecting these results, it can be assumed that the average water absorption after 7, 14, 28 days was W_p=0.21 $\frac{kg}{m^2}$.

The thermal conductivity coefficients performance in all stages of study were presented in table 3.

In case of most samples (except for B-9 and A-7) the value of $\lambda_{(a)dry}$ coefficient after redrying increased by a certain value in the range (0.1÷0.9) %.

Table 2. Water absorption and moisture of samples after partial immersion

sample name	immersion period time n	water absorption by partial immersion Wp	moisture W	density
[-]	[days]	[kg/m^2]	[%]	[kg/m^3]
A-1	1	0.10	3	122
A-2	1	0.08	2	117
A-3	1	0.08	2	121
A-4	1	0.15	4	120
A-5	7	0.22	6	118
A-6	7	0.21	6	119
A-7	7	0.08	2	127
B-8	14	0.18	6	74
B-9	14	0.19	6	77
C-10	14	0.40	8	103
C-11	14	0.57	11	105
D-12	28	0.23	5	90
D-13	28	0.21	5	89
D-14	28	0.33	7	91

Table 3. Thermal conductivity coefficient of the samples in all studied cases

sample name	thermal conductivity			immersion period time	$\frac{\lambda_{(a)dry}-\lambda_{dry}}{\lambda_{(a)dry}}\times100$	$\frac{\lambda_{wet}-\lambda_{dry}}{\lambda_{wet}}\times100$
	λ_{dry}	λ_{wet}	$\lambda_{(a)dry}$	n		
[-]		[W/(mK)]		[days]	[%]	[%]
A-1	0.0326	0.0329	0.0328	1	0.6	0.9
A-2	0.0321	0.0321	0.0322	1	0.4	0.0
A-3	0.0324	0.0320	0.0325	1	0.3	-1.1
A-4	0.0325	0.0327	0.0326	1	0.3	0.8
A-5	0.0321	0.0327	0.0323	7	0.5	1.7
A-6	0.0322	0.0326	0.0322	7	0.2	1.2
A-7	0.0321	0.0323	0.0321	7	0.0	0.6
B-8	0.0344	0.0350	0.0344	14	0.1	1.9
B-9	0.0345	0.0349	0.0344	14	-0.2	1.3
C-10	0.0336	0.0349	0.0338	14	0.7	3.7
C-11	0.0338	0.0352	0.0341	14	0.8	3.9
D-12	0.0330	0.0338	0.0333	28	0.9	2.5
D-13	0.0332	0.0338	0.0333	28	0.3	1.6
D-14	0.0335	0.0341	0.0337	28	0.7	1.9

The biggest percentage difference between $\lambda_{(a)dry}$ and λ_{dry} was obtained for specimen D-12 (0.9%). It can be noted that the difference between $\lambda_{(a)dry}$ and λ_{dry} increases with the increasing difference between λ_{wet} and λ_{dry} (table 3.).

Statistical tests have been carried out to check whether there is a statistically significant difference between the initial value of the thermal conductivity coefficient of mineral wool and the value of the thermal conductivity coefficient of mineral wool treated with water and dried again. In the case of a group of samples immersed for 1 day in water, the Student's *t*-test was applied. The use of this test was possible because the results λ_{dry} and $\lambda_{(a)dry}$ had a normal distribution (proved by the Lillieforst test). For the remaining groups, due to the distribution of results other than normal, the Mann-Whitney *U* test was performed. The results of statistical tests are presented in table 4.

Table 4. Statistical test results (Student's *t*-test, Mann-Whitney *U* test)

	λ_{dry} [W/(mK)]	$\lambda_{(a)dry}$ [W/(mK)]	immersion period time [days]	test name
mean (A-1÷A-4)	0.0324	0.0325	1	Student's *t*-test
variance	0.00000004	0.00000006		
samples sizes	4	4		
df (degrees of freedom of the test)	6			
t Stat (value of the statistic test)	-0.8184			
p-value of the test	0.444			
two-sided test (critical value)	2.44			
mean (A-5÷A-7)	0.0321	0.0322	7	Mann-Whitney *U* test
p-value of the test	0.700			
mean (B-8÷B-9)	0.0344	0.0344	14	Mann-Whitney *U* test
p-value of the test	1.000			
mean (C-10÷C-11)	0.0337	0.0339	14	Mann-Whitney *U* test
p-value of the test	0.333			
mean (D-12÷D-14)	0.0332	0.0334	28	Mann-Whitney *U* test
p-value of the test	0.400			

For all analyzed groups, the p-value is higher than the assumed significance level $\alpha=0.05$. This means that the difference between the initial values of the thermal conductivity coefficient and the values of the thermal conduction coefficient of the same samples after immersion in water and drying is not statistically significant.

The Kruskal-Wallis test was performed to check if the immersion time of the test specimens in water influences on the difference between λ_{dry} and $\lambda_{(a)dry}$. As hypothesis H_0, there was no statistically significant influence of immersion time in water on the difference between the thermal conductivity coefficient values. The alternative hypothesis H_1 was the statement that the immersion time has a statistically significant effect on the difference in the thermal conductivity coefficient value. The test results are presented in table 5. Since the test probability of p-value equal to 0.392 is higher than the assumed significance level of $\alpha=0.05$ and the value of χ^2 = 3 does not fall into the critical area $[7.815, \infty)$ of χ^2 distribution with three degrees of freedom at $\alpha=0.05$, there are no grounds to reject the H_0 hypothesis.

Table 5. Kruskal-Wallis test for various times of immersion in water

	mean $\frac{\lambda_{(a)dry}-\lambda_{dry}}{\lambda_{(a)dry}}*100$ [%]	immersion period time [days]
	0.4	1
	0.2	7
	0.3	14
	0.6	28
df (degrees of freedom of the test)	3	
χ^2(value of the test statistic)	3	
p-value of the test	0.392	

The Kruskal-Wallis test was also subject to the difference between λ_{dry} and $\lambda_{(a)dry}$ values due to the density of the tested specimens. As hypothesis H_0 , there was no statistically significant influence on sample density on the difference between the thermal conductivity coefficient values. The alternative hypothesis H_1 was the statement that the material density has a statistically significant influence on the difference between the thermal conductivity coefficient values. The test results are presented in table 6 . Since probability test parity p-value = 0.392 is greater than the assumed level of significance $\alpha=0.05$, and the statistic value $\chi^2= 3$ does not fall in the critical area $[7.815,\infty)$ distribution χ^2 with 3 degrees of freedom at $\alpha=0.05$, there is no reason to reject the H_0 hypothesis .

Table 6. Kruskal-Wallis test for different densities

	mean $\frac{\lambda_{(a)dry}-\lambda_{dry}}{\lambda_{(a)dry}}*100$ [%]	mean density [kg/m^3]
	0.3	121
	-0.1	76
	0.7	104
	0.6	90
df (degrees of freedom of the test)	3	
χ^2(value of the test statistic)	3	
p-value of the test	0.392	

4. Conclusions

As part of this work, the influence of water on the thermal conductivity coefficient of mineral wool was investigated. Based on the obtained research results and conducted analyses, it was found that:

- the difference between the initial value of thermal conductivity coefficient of mineral wool samples and the value of thermal conductivity coefficient of the same samples which were immersed in water and dried to constant mass is statistically insignificant as confirmed by the statistical tests and is less than the uncertainty of measurement (3%).

-the time of immersion in water and density of mineral wool specimens have no significant impact on the difference between the initial value of the thermal conductivity coefficient and the value of the thermal conductivity coefficient of the samples immersed in water and dried to constant mass.

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