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Investigation of the Compressive Stress of the Layered-Structure Dual-Density Mineral Wool Slabs

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This paper provides with the experimental results obtained by determination the dependence of the compressive stress at the 10 % deformation of the layered-structure dual-density mineral wool slabs (or their parts) on their density, also the influence of the density of separate layers on the compressive stress of the whole product and different density layers of the dual-density structure mineral wool. The test results show that, while applying to the layered-structure dual-density specimen by the compressive load, firstly, the lower-density slab part (layer) deforms, and, after it reaches a certain limit of consistence, the higher-density layer slightly deforms, as well. The values of the compressive stress of the layered-structure dual-density stone wool slabs depend on the density, and the values of the compressive stress of the whole product depend more on the density of the layer having the lower-density and its compressive stress.

Keywords: mineral wool, stone wool, layered structure, dual density, compressive stress, deformation.

INTRODUCTION

During the last years, the demand for the effective thermal insulation materials has been growing fast, as, on a worldwide scale, there has been the start for the active concern about minimizing the pollution of atmosphere, saving the energy resources; so are greatly focused on the thermal insulation of the building envelopes. The materials must be selected according to their physical and mechanical properties, as well as by evaluating the economical aspects. To reach the level of the currently valid technical requirements, it is necessary to install the separate thermal insulating layer from the effective thermal insulating materials. The thermal insulation products from mineral wool [1] have been recently and widely used in the buildings envelopes and constructions.

Mineral wool is attributed to the fibrous composites, as it consists of the matrix (binder) and reinforced (fibres) phases [2, 3]. The fibrous insulating materials of such type have the peculiar anisotropic structure, and their properties in distinct directions are not the same [4, 5]. The material framework consists of the fibres of the different uneven length and thickness bonded with the mineral or organic binder agent. The adjusting of the fibrous structure (possibility to change the direction of the fibre arrangement) at the stage of the technological process of production determines the thermal, strength, deformation and exploitation properties in the rigid mineral wool products [6 – 8]. Therefore, the values such as the compressive stress, tensile strength and the point load depend on the fibre arrangement in the product structure, as well as condition the effectiveness and durability of the thermal insulation.

The conveyor technological lines being used most often for the production of the mineral wool products, when the successive technological processes form the integral and homogenous primary fibre web with the added binding agent and water repellent oil. Depending on the type of the technological line and fibre regulation possibilities, the thermal insulating mineral wool products of the chaotic structure (when the fibres are orientated randomly and in different directions unevenly), directional structure (of the fibres orientated in a certain order) and layered-structure (consisting of several layers of different density) could be produced.

It is known that the orientation of fibres direction in the product structure changes its strength properties. The products of the chaotic fibre orientation (where the direction of most fibres coincides with the major face) have the higher deformation ability and relative elasticity. Whereas, the products of the directional fibre orientation have the much higher compressive strength, as their structure consists of the fibres and their groups are oriented perpendicularly against the major face. The deformation of such products is considerably lower. With the increase in the compressive load, the product deformation increases, and when it reaches the critical limit (1.5 % – 5 % deformation), it yields [7 – 9].

The products of the layered (or mixed) structure consist of several (at least 2) parts of the different thickness and density. Mineral wool slabs consisting of two densities are so-called dual-density mineral wool slabs [10], as they consist of the layers of the higher and lower density (Fig. 1).

Direction of these layers in the product structure is perpendicular to the compressive load working direction and coincides with the direction of movement of the primary fibre web on the conveyor belt. The fibres in the layer of the higher-density are mainly oriented to a horizontal direction, and the slab part of lower-density consists of the fibres of the more chaotic orientation [10 – 12].

The development of the layered-structure dual-density slabs was conditioned by the constantly growing demand for the thermal insulating products of mineral wool, because they ensure good mechanical properties, for the thermal insulation of different constructions (flat roofs, floors). Part of the higher-density slabs is usually marked

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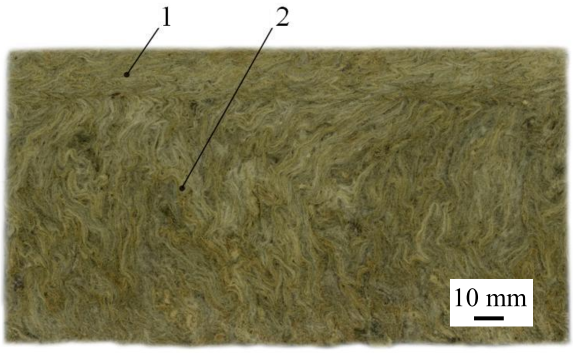

Fig. 1. Layered (mixed) structure dual-density stone wool products [10]: 1 – higher-density layer; 2 – lower-density layer

with an inscription or dash and must be installed with the marked side to the outside. Therefore, the upper – higher density slab part, which ensures itself in higher resistance to the concentrated compressive loads, becomes the main layer that distributes and transfers the loads from pressure. As a comparison, it is presented that, in order to produce the mineral wool product of the identical mechanical parameters, thus, when using the layered-structure production technology, it is possible to produce at least 10 kg/m^3 lower total density product, in comparison with the mono density product of the homogeneous structure [13]. Therefore, with the decrease in the nominal density of the products, it is possible to save the raw materials, optimize the operation of the technological line, increase the production capacity – by shortening the deadlines for the material supply. Furthermore, with the refusal of the multi-layer constructions (when the mineral wool slabs of the different mono density are laid separately), the labour expenditures will reduce and the work performance will accelerate. Thus, the regulation of the structure of the mineral wool slab and making layers during the primary fibre web formation allows producing the products of sufficient thermal, strength properties and optimum density suitable for the conditions of specific usage and operation.

The aim of these investigations is to determine dependences of the values of the compressive stress at 10 % deformation (σ_{10}) of the layered-structure dual-density mineral wool slabs on the density, by compressing the specimens of the different density and study the influence of the density of separate layers on the compressive stress of the dual-density structure mineral wool slabs.

TEST SPECIMENS AND METHOD

The dual-density stone wool slabs of 4 types (with different density and declared value of compressive stress) were selected for the tests.

Test specimens were as following:

1. MW-DM – 100 mm thick slabs (where higher-density layer $\rho = 200$ kg/m^3; the lower-density layer $\rho = 130$ kg/m^3; and the average density $\rho = 143$ kg/m^3); coefficient of thermal conductivity $\lambda_D \leq 0.040$ W/m·K; the declared value for compressive stress at 10 % deformation $\sigma_{10} \geq 50$ kPa;

2. MW-MM – 120 mm thick slabs (where higher-density layer $\rho = 180$ kg/m^3; the lower-density layer $\rho = 115$ kg/m^3; and the average density $\rho = 124$ kg/m^3); coefficient of thermal conductivity $\lambda_D \leq 0.039$ W/m·K; the declared value for compressive stress at 10 % deformation $\sigma_{10} \geq 40$ kPa;

3. MW-HR – 95 mm thick slabs (where higher-density layer $\rho = 180$ kg/m^3; the lower-density layer $\rho = 100$ kg/m^3; and the average density $\rho = 117$ kg/m^3); coefficient of thermal conductivity $\lambda_D \leq 0.038$ W/m·K; the declared value for compressive stress at 10 % deformation $\sigma_{10} \geq 30$ kPa;

4. MW-HF – 80 mm thick slabs (where higher-density layer $\rho = 140$ kg/m^3; the lower-density layer $\rho = 90$ kg/m^3; and the average density $\rho = 100$ kg/m^3); coefficient of thermal conductivity $\lambda_D \leq 0.037$ W/m·K; the declared value for compressive stress at 10 % deformation $\sigma_{10} \geq 20$ kPa.

For the measurements the computerized multi-purpose compression testing machine UTC 50 kN (manufacturer “Tram A/S”, Denmark) was used (Fig. 2).

Fig. 2. Testing machine for compression “UTC 50 kN”

The compressive stress and/or compressive strength of the mineral wool products were determined in accordance with the requirements of the harmonized standard [14]. From the above-mentioned slabs, the specimens in dimensions 200 mm × 200 mm have been squarely cut, the thickness of which is the original product thickness. The specimens’ surfaces were grinded with the sandpaper. The prepared specimens were compressed so that its compressive surface would be perpendicular to the compressive load direction, and the compression would occur on the vertical axis. The initial preload for specimen is 250 Pa ±10 Pa. The specimen is performed by increasing the compressive load with the constant 0.1 d/min. speed with the ±25 % deviation (here, d – the thickness of the specimens). The test continues at 10 % deformation until the specimen yields. The value of the compressive stress (σ_{10}) was determined according to the stress-strain curves.

RESULTS AND DISCUSSION

The layered-structure dual-density stone wool slabs used for the thermal insulation layers of the flat roofs were tested during the investigation. These slabs are used for the single-layer roof thermal insulation or the top layer of the multi-layer thermal insulation. European Organization for

Technical Approvals (EOTA) prepared and approved the guideline for ETAG [15], where the requirements for the thermal insulation layer in the flat roof systems are provided, when using the mechanically fastened flexible roof waterproofing membranes. According to [15] Clause 6.4.3.1, it is recommended that the compressibility (10 %) of the thermal insulation products used for the top layer of the flat roofs would, according to [14] be: $\sigma_{10} \geq 60$ kPa. This requirement applies to the mono density products or the top multi-layer or layered-structure products.

Different researches have already determined that the mechanical-strength parameters as well as deformation properties of most construction materials (including the thermal insulation materials) depend on density [16 – 18].

In order to determine σ_{10} values of the dual-density stone wool slabs (of the whole product and its separate constituent layers) and their dependences on density (ρ), the experimental measurements of density [19] and compressive stress [14] have been done, and the obtained results are given in Table 1. Analyzing the data obtained during tests, we may see that all specimens meet the declared values of the compressive stress, and the average density is often higher than nominal.

From Table 1, we can see that σ_{10} values in the first three cases depend on specimens ρ uneven. The ρ of higher-density layer of MW-DM type specimens was about 38 %, and the σ_{10} value was 41.8 % higher and respectively the ρ of lower-density layer was about 9.8 %, and the σ_{10} value was 3.8 % lower, in comparison with the average density of the whole product and its compressive stress. The ρ of higher-density layer for the MW-MM specimens was about 28 %, and the σ_{10} value was 58 % higher than for the ρ of lower-density layer – about 27 %, and the σ_{10} value was 17 % lower, in comparison with the average density of the whole product of that type and its compressive stress. MW-HR specimens distinguished themselves at most, as the ρ of higher-density layer was about 48 %, and the σ_{10} value was 106 % higher than the average density of the whole product and the compressive stress, but, the ρ of lower-density layer was 25.7 % lower that the density of the whole product, and the measured σ_{10} value is only 3.2 % lower than the average compressive stress of the whole product. However, the ρ value of the MW-HF higher-density layer was 38 % higher in comparison with the average density of the whole product, and the ρ of lower-density layer was respectively 18.4 % lower than the average density of the whole product – the values of the compressive stress differ fractionally (in just few per cent). So it could be explained by the fact that there was no very great difference among the values of the density and compressive stress of both layers of this slab and the whole product density. Also, after some the additional measurements of binder (phenol-formaldehyde resin) i. e. organic content [20], it became clear that the content of the binder in the lower-density layer amounts to 2.73 %, and, in the higher-density layer, respectively 2.24 %. Therefore, the greater content of the binder in the lower-density layer affected the higher σ_{10} value, which was approaching the σ_{10} value of the higher-density layer (but with lower content of the binder).

It is known that, when compressing the mixed or layered structure materials, the lower-density (or lower-strength) layer deforms first; therefore, the mechanical and deformation properties of the whole product also depend on its properties. During the tests on the compressive stress for the dual-density slabs (for the whole product), the uneven deformation of both layers can be clearly seen. From Figure 3, we can see that the layers of the different density deform differently in the product structure. The stress-strain curves for the whole product (Fig. 3, curve 1) and lower-density layer (Fig. 3, curve 2) is of the similar shape. These both curves were more right-angled (the stress increases in the beginning of compression) at the initial stage of compression, and after the specimens reached about 4 % – 6 % deformation, the more significant inclination of the curves was recorded and the lower increase of the compressive stress, in comparison with the deformation, continued. Whereas, the deformation of the higher-density layer (Fig. 3, curve 3) shows that the compressive stress of the specimen in the beginning of compression was increasing more slowly at the sufficiently even deformation through the compression time (the almost straight linear curve), and only after reaching the deformation of about 10 %, it slightly inclines.

Table 1. Average values and deviations of the density and compressive stress of the dual-density stone wool slabs

Type of test specimen	Density (ρ), kg/m^3			Compressive stress at 10 % deformation (σ_{10}), kPa		
	Whole product	Layers of product		Whole product	Layers of product	
		higher-density	lower-density		higher-density	lower-density
MW-DM	145 / ± 3.1	200 / ± 3.3	132 / ± 5.5	55 / ± 2.1	78 / ± 9.8	53 / ± 2.0
MW-MM	131 / ± 7.1	168 / ± 7.7	103 / ± 3.8	48 / ± 5.8	76 / ± 3.3	41 / ± 4.7
MW-HR	122 / ± 5.5	181 / ± 5.2	97 / ± 7.5	32 / ±1.7	64 / ± 2.4	31 / ± 2.3
MW-HF	103 / ± 2.9	142 / ± 5.3	87 / ± 3.7	30 / ±1.5	31 / ± 2.0	28 / ±1.6

Note: The numerator indicates the value of the density and/or compressive stress, and the experimental standard deviation is given in the denominator.

From the curves shown in Figure 3, it can be seen that, when the layered-structure dual-density specimen is affected by the compressive load, the part (layer) of the lower-density slab deforms first, and when it reaches a certain limit of consistence, the higher-density layer slightly deforms, as well. The higher-density layer in the product gradually transfers and distributes the compressive load acting on the surface – for the lower-density layer in the much bigger area (through the thickness of the product).

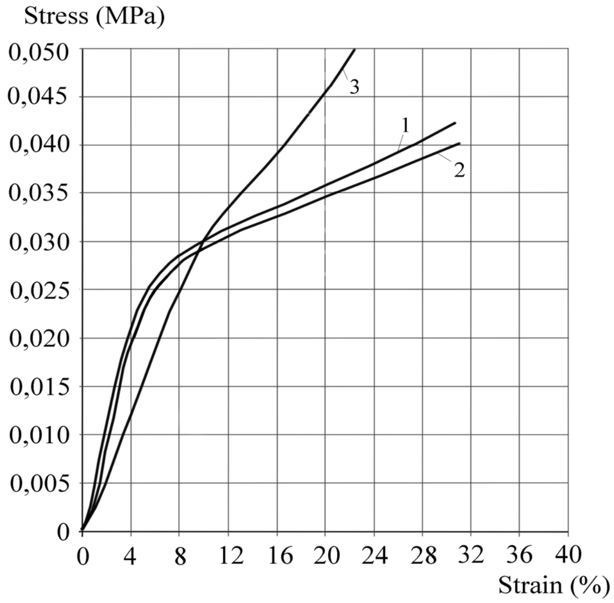

Fig. 3. Stress-strain diagram of the layered-structure dual-density slab. 1 – to the whole product, 2 – to the lower-density layer, 3 – to the higher-density layer

When visually examine the structure of the dual-density slab (in the section through the product thickness), we will be able to easily notice the layers of the different thickness and density. In order to evaluate the effect of the separate layers on the compressive stress of the whole layered-structure slabs, it is, first of all, necessary to determinate the dependence the σ_{10} values of each separate layer on its density. Therefore, the results of the tests (for the each layer) are showed in diagram form and presented in Figures 4 – 6.

From Figures 4 – 6, we can see that the regressive lines are ascending (i. e. with the increase in the density of the specimens, their values of the compressive stress increase, as well). Thus, these relationships may be expressed by the regressive equations with the correlation coefficients (*R*) [21]:

– for the whole product:

$$\sigma_{10.wp} = 0.5538 \cdot \rho_{wp} - 28.271 \quad (1)$$

with the correlation coefficient $R_{\sigma \cdot \rho_{wp}} = 0.8200$;

– for the higher-density layer:

$$\sigma_{10.hdl} = 0.7242 \cdot \rho_{hdl} - 63.341 \quad (2)$$

with the correlation coefficient $R_{\sigma \cdot \rho_{hdl}} = 0.8129$;

– for the lower-density layer:

$$\sigma_{10.ldl} = 0.5286 \cdot \rho_{ldl} - 16.674 \quad (3)$$

with the correlation coefficient $R_{\sigma \cdot \rho_{ldl}} = 0.9178$;

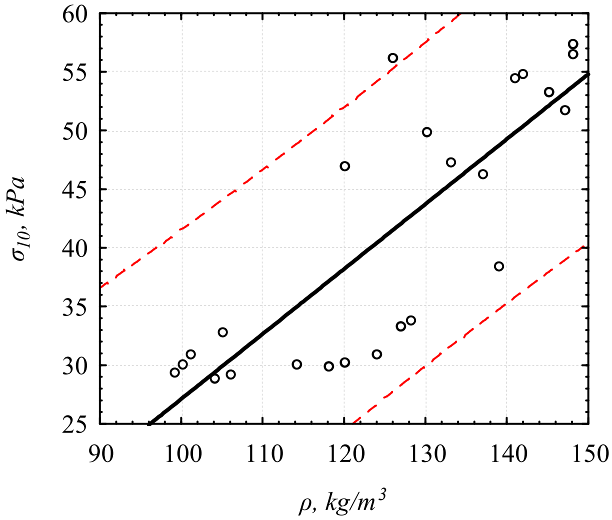

Fig. 4. The dependence of the compressive stress of the whole product ($\sigma_{10.wp}$) on density (ρ_{wp})

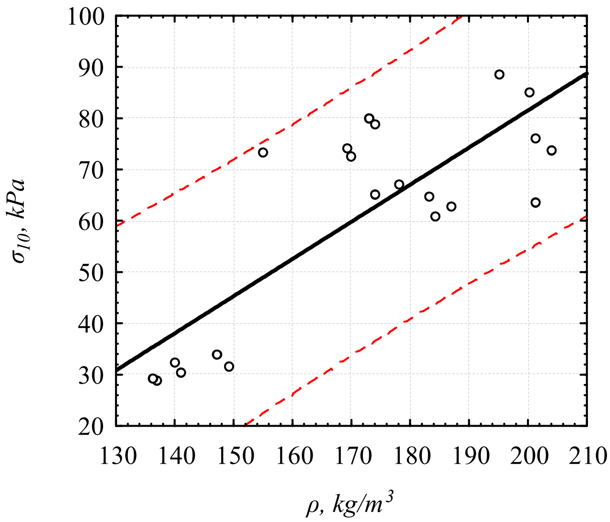

Fig. 5. The dependence of the compressive stress of the higher-density layer ($\sigma_{10.hdl}$) on density (ρ_{hdl})

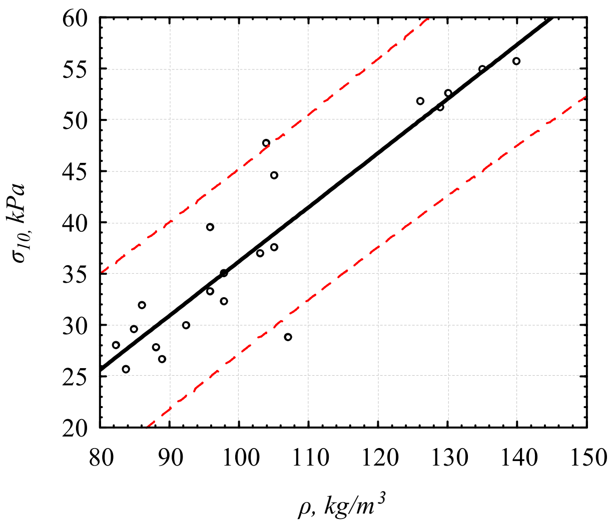

Fig. 6. The dependence of the compressive stress of the lower-density layer ($\sigma_{10.ldl}$) on density (ρ_{ldl})

By using the regressive equations (1) – (3) and knowing the density of the whole product and/or its separate layers, it is possible to assess their empirical compressive stress at the 10 % relative deformation.

In our case, by comparing the relationship of the values of the compressive stress for the whole product with the lower-density layers obtained during the tests (the assessed regressive relationship) [21], we concluded that the value of the compressive stress of the whole product depends in 78 % on the measured value of compressive stress of the lower-density layer (part). Furthermore, also other factors, such as the diameter of the mineral wool fibres, number of fibre crossing points, unevenness and defects of the fibre structure (areas with the reduced or increased content of binder, content of non-fibrous inserts, etc.), amount of the organic content and the evenness of its distribution affect the strength and deformation properties of the mineral wool products.

CONCLUSIONS

The values of the compressive stress (σ_{10}) of the separate layers of the dual-density stone wool slabs are determined by their density, and the σ_{10} of the whole product greatly depends on the ρ value of the lower-density layer.

While applying to the layered-structure dual-density slabs by the compressive load, the layers of the different density in the product structure deformation gradually: first of all, the lower-density slab part (layer) deforms, and, after it reaches a certain limit of consistence, the higher-density layer deforms slightly, as well.

The purpose of the higher-density layer in the product structure is to transfer and distribute the compressive load acting on the surface – for the lower-density layer in the much bigger area (through the thickness of the product).

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