ISSN 1392–1320 MATERIALS SCIENCE (MEDŽIAGOTYRA). Vol. 22, No. 1. 2016

Mineral Wool Macrostructure Parameter's Relation with the Product's Mechanical Properties

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http://dx.doi.org/10.5755/j01.ms.22.1.9434

Received 15 January 2015; accepted 31 March 2015

The experimental tests established the relations of rigid mineral wool products (with different structure) macrostructure parameters with main their mechanical characteristic – compressibility. The products within the nominal density between 45 and 170 kg/m^3 were analysed. Determined that strong functional relationship exists between the values of critical compressive stress and macrostructure parameters, density and organic content of mineral wool products, because the value of the multiple correlation coefficient equals 0.95. Using the obtained empirical equation is possible predict and calculate the mechanical behiaviour (compression stress) of mineral wool slabs by using macrostructure parameters and other (density, organic content) characteristics.

Keywords: mineral wool, structure, compressive stress, macrostructure parameter, mechanical properties.

1. INTRODUCTION

The energy consumption of the building is one of the most important factors determining not only the architectural solutions or the microclimate of premises, but also the costs of construction and maintenance of the building. The energy performance of building depends on the different characteristics of the building envelope and particularly on the thermal resistance of the insulation material used [1]. When usage of insulation materials, of indisputable importance in terms of energy conservation, is considered the concept of sustainability in environmental features and economic senses is becoming important as well [2]. The traditional performance criteria based on physical properties (density, durability, thermal resistance, sound insulation, resistance to fire and humidity, etc) widely used in the classification of insulation materials [3]. Other properties of insulation products such as strength should not be omitted. Compression behaviour is one of the most important properties of thermal insulating materials and products [4].

Inorganic fibrous materials (such as mineral wool) are expected to play the main role on European market of insulating materials and are widely used in structures and building envelopes due to their low thermal conductivity, non-combustibility and good noise insulation properties, large availability of raw materials needed for their production, wide scope of application of the products, etc [5, 6]. The mechanical characteristics of mineral wool slabs are subjected to structure, density of material, percentage of binder in product, as well as production techniques. The deformability of mineral wool products is determined by mobility of fibrous structure, which is best observed under compression [7].

Due to anisotropic (crimped) structure and some methodological factors of mineral wool products determination of compression strength is considerable with complications [4, 8]. The research [9] showed that mechanical deformation of resilient materials has different influence on its compressive strength. In some works [10, 11] examined the relation between compression strength and function of product's density. However other characteristics as mineral wool structure, convolution degree, the content of polymeric binders of fibres, etc are close related with mechanical properties [11, 12].

The purpose of this study was by experimental research investigate the dependency of compressive strength of mineral wool products on dominating fibres in the product structure based on macrostructure parameters and main physical characteristics (density, organic content).

2. EXPERIMENTAL DETAILS

2.1. Test specimens

Rigid mineral wool slabs produced according to standard EN 13162 [13] with a homogeneous structure with directional and chaotic fibre orientation used.

Table 1. Data of mineral wool slabs used in testing

Test specimen	n, pcs	d, mm	ρ, kg/m^3	σ_{10}, kPa	M, %
MW-1	9	30 – 50	45	–	3.6
MW-2	11	50 – 200	100	≥ 10	3.5
MW-3	9	200	100	≥ 10	3.5
MW-4	9				
MW-5	9	100	110	≥ 50	4.2
MW-6	9	40 – 50	150	≥ 20	4.0
MW-7	9	40 – 50	170	≥ 60	4.8

n – number of test results; d – product thickness; ρ – nominal density; σ_{10} – declared value of compressive stress at 10 % deformation; M – nominal amount of organic content.

Nominal density within the range of 45 – 170 kg/m^3 was tested during experimental research. Initial products

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characteristics of the test specimens used in the experimental testing are presented in Table 1.

2.2. Methodology

2.2.1. Density

Regulatory documents [13] do not set any requirements concerning the density of thermal insulation products. However, the determination of density of products, as an indirect test, is carried out during manufacturers' internal production control, because the results obtained enable other physical and mechanical properties of the products to be identified. Density (ρ) of the test specimens was determined according to the requirements of standard EN 1602 [14].

2.2.2. Determination of compressive stress and/or compressive strength

The compressive stress and/or compressive strength of the test specimens were determined according to the requirements of standard EN 826 [15]. A prepared test specimen was compressed in such a manner as to ensure that its surface subjected to compression is perpendicular to the direction of the working of the load and that compression takes place on the vertical axis.

During the tests, the force and deformation curves were recorded, which show the dependency of deformation on the load. It is stated that if during testing a test specimen reaches a deformation of 10 % or more, the compressive stress (σ_{10}) at 10 % deformation is calculated and presented (Fig. 1 a). If test specimens rupture before reaching 10% deformation, the maximum force is measured and the compressive strength (σ_m) is calculated (Fig. 1 b).

However, to compare the strength properties of mineral wool products with different structures (when compressive stress at 10 % deformation (σ_{10}) was measured for some of the test specimens and compressive strength (σ_m) was determined for other test specimens), the value of critical compressive stress (σ_e) was used. The critical compressive stress is determined in the elastic area, where the force and deformation increase proportionally (relationship is linear). σ_e is measured at the end of the proportionality point and corresponds to ε_e deformation (i.e. a linear dependency of the force-deformation curve) because it describes the limit of elastic deformations [11], which when it is exceeded causes the material to start damaging and irreversible structural changes to take place.

The computerised compression testing machine was used for compression testing (the force meter and reading accuracy is ≤ 1 %, and the precision of deformation shift measurement and reading is ± 0.1 mm).

Critical compressive stress in the end of elasticity point (σ_e) is calculated according to the formula (1):

$$\sigma_e = 10^3 \frac{F_e}{A_0} \text{, kPa} \tag{1}$$

where: F_e is test specimen force at the end of the elasticity area, N; A_0 is initial area of the cross section of the test specimen, mm^2.

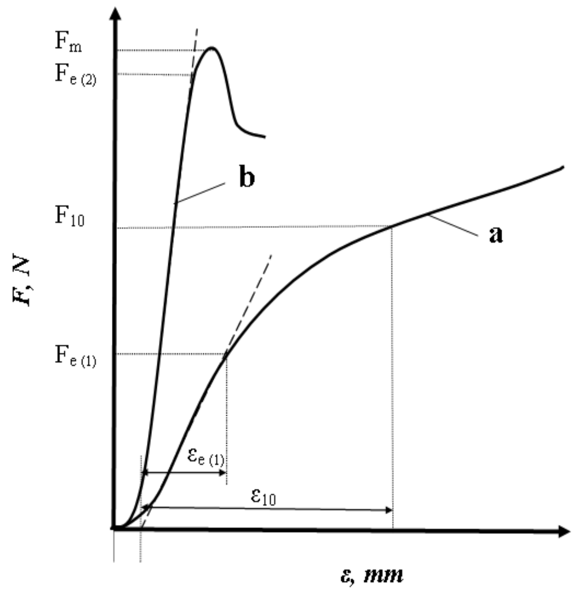

Fig. 1. Force-deformation curves of test specimens: a – compressive stress at 10 % deformation; b – compressive strength

2.2.3. Determination of macrostructure parameters

For expression the dominating fibre orientation and direction in product's structure, the macrostructure parameters were used. The macrostructure parameter (S) describe the ration of the angles of dominating fibres and dominating fibre group orientation of the flat cross section (throughout the thickness) of the test specimen. Due to observed different orientation of fibres in both sections of test specimens, two surface sections were examined and calculated accordingly: section L – in parallel to the direction of movement (lengthwise), section C – perpendicularly to the direction of movement (crosswise), it means the values of macrostructure parameters were calculated separately for the relevant section (S_L or S_C). Since the calculated values of macrostructure parameters S_L and S_C for the same test specimen are different, the average of the parameters was calculated and one value $S_{L\text{-}C}$ was presented instead of the macrostructure parameters for separate cross sections.

Detailed procedure for determination of the macrostructure parameters described in dissertation [12].

2.2.4. Determination of amount of the organic content

The amount of organic binding material (binder resin, oil) present in mineral wool products was determined according to the standard EN 13820 [16]. During the testing, changes in the weight of the test specimens were measured after heating fragments of the test specimens at a temperature of 500 ± 20 °C for at least 120 minutes.

3. RESULTS AND DISCUSSION

On visual inspection of the test specimens, the different structure of the products is clearly distinguished. The macrostructure parameters determined and described in the previous section conforms that. The measured average values of density, critical compressive stress, organic content, and macrostructure parameters are summarised in Table 2.

The determination of the critical compressive stress (σ_e) was chosen because test specimens with different structures undergo deformation differently: for some test specimens, the value σ_{10} is measured, while for others the value σ_m is measured.

The average measured values of density are found in a wide range: the lowest average density was measured for MW-1 test specimens and equals 48.9 kg/m^3, whereas the highest was measured for MW-7 test specimens and equals 178.8 kg/m^3.

Since MW-1 test specimens have low density (33.3 – 67.4 kg/m^3), the values of compressive stress for these test specimens are not declared, and the measured values are very low (1.1 – 3.5 kPa), decided will not consider these test specimens in these calculations. The calculated ρ average values of standard deviation (s) for each type of test specimens are different and vary 5.7 – 11.9 kg/m^3. The average values M are similar 3.63 – 4.26 %, and the calculated $s = 0.05 – 0.88$ %.

Table 2 shows that the values of σ_e mostly depend on density and macrostructure parameters. Since in some test specimens the dominating fibre angles in sections L and C are different, the calculated macrostructure parameters for each section are also different. In order to determine the functional interdependencies of physical and mechanical properties and macrostructure parameters, statistical multiple regression calculations were carried out and the following empirical equation was obtained:

$$\sigma_e = -107.77 + 0.51 \cdot \rho + 5.93 \cdot M + 54.81 \cdot S_C + 7.02 \cdot S_L. \quad (2)$$

The statistical parameters of the empirical equation (2) are: correlation coefficient $R = 0.96$; determination coefficient $R^2 = 0.92$; standard deviation $s_e = 5.83$; Student's criterions: $t_{\rho s} = 13.94$; $t_M = 3.35$; $t_{Sc} = 15.19$; $t_{SL} = 2.27$.

Calculated statistical parameters show that all the parameters being analysed, i.e. density, organic content, and macrostructure parameters of sections L and C are significant, because the values of Student's criterion calculated for all of them (2.27 – 15.19) are higher than its critical table (2.021) value [17].

However, macrostructure parameters have different impacts on the values σ_e: the value of S_C has a greater impact than that of S_L, because the value of Student's criterion for parameter S_C is more than six times greater than of parameter S_L.

This occurred because of fibre distribution during the production process since, as described above, the edges of the test specimens were marked considering the direction of movement of fibre webs on the conveyor: section L – in parallel to the direction of movement, and section C – perpendicularly to the direction of movement. However, in real conditions and/or in the case of availability of just a small fragment of the materials it can be fairly difficult to determine the direction of movement of the conveyor and mark the edges of the sections correctly. And if the sections are marked incorrectly, the results of the calculations will be inaccurate.

Therefore, in order to avoid any imprecision during the measurement, additional statistical calculations were carried out, whereby the impact of the average values of both macrostructure parameters, of density, and of the organic content on critical compressive stress was determined. An adjusted empirical equation (3) obtained to describe the relation:

$$\sigma_e = -140.66 + 0.55 \cdot \rho + 8.06 \cdot M + 82.35 \cdot S_{L-C}. \quad (3)$$

The values of the multiple correlation coefficient R, the determination coefficient R^2, the standard deviation s_e and Student's criterion for empirical equation (3) are presented in Table 3.

Table 3. The functional dependencies and significances of the impact of S_{L-C}, ρ and M on the values σ_e calculated by using the multiple regression method

R^2	s_e	Values of Student's criterion		
		ρ	M	S_{L-C}
0.90	7.2	12.43	3.79	14.03

Having compared the values of the multiple correlation and determination coefficients, and standard deviation for empirical equations (2) and (3), it is seen that the differences are minor. Therefore, even by using the one of the parameters (an average value) instead of macrostructure parameters for individual sections, the accuracy of the results will be satisfactory (the probability of obtaining an inaccurate result is eliminated).

The determination coefficient of the empirical equation obtained (3) is greater than 0.7 (Table 3); therefore, the mathematical linear multiple regression model was chosen correctly and the equation properly describes the experimental data [18].

The calculated functional dependencies presented in Table 3 shows that the values ρ and S_{L-C} influence σ_e the most because the calculated Student's criterion values are high (12.43; 14.03). Thus, the interdependency of the key parameters may be depicted graphically by a surface diagram (Fig. 2). The data presented in Fig. 2, equation (3), and Table 3 show that critical compressive stress is mostly dependent on the macrostructure parameter S_{L-C} (the highest value of Student's criterion: 14.03) because it characterises the directionality of the fibre structure.

Table 2. Measured average values of density, critical compressive stress, organic content, and macrostructure parameters for all types of test specimens

Test specimen Parameter	MW-1	MW-2	MW-3	MW-4	MW-5	MW-6	MW-7
Density ρ, kg/m^3	48.9	95.2	98.8	97.1	108.0	119.7	178.8
Critical compressive stress σ_e, kPa	2.6	11.5	46.8	20.4	52.6	21.1	59.3
Organic content M, %	4.15	3.70	3.66	3.63	4.18	4.26	4.01
Macrostructure parameter of L section (S_L)	0.62	0.90	1.17	1.12	0.97	0.80	0.89
Macrostructure parameter of C section (S_C)	0.62	0.77	1.28	0.88	1.37	0.73	0.77
Macrostructure parameter (S_{L-C})	0.62	0.84	1.23	1.00	1.17	0.77	0.83

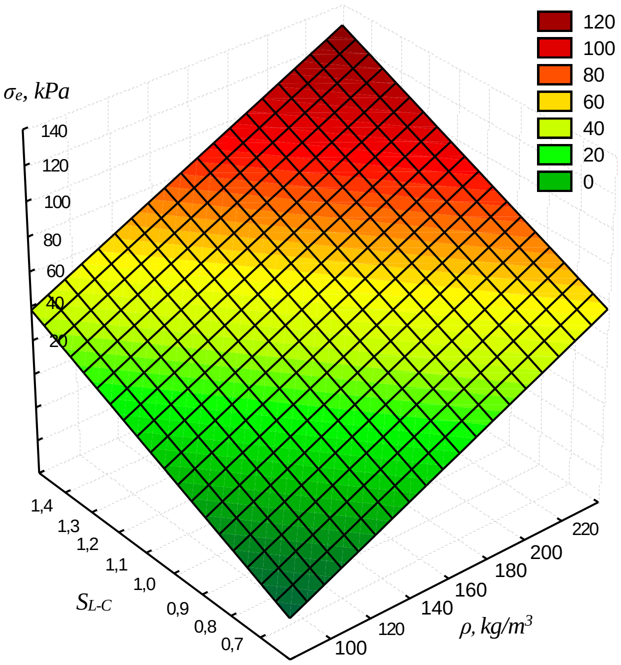

Fig. 2. Diagram of dependency of macrostructure parameter and density on critical compressive stress

The increasing numerical value of this parameter shows an increase in the quantity of vertically oriented fibres (and the direction of the fibres coincides with the direction of working of the external compression load). In this way, the vertically oriented fibres which dominate in the structure are less susceptible to the compression load and undergo less deformation. Then the structure is dominated by horizontally oriented fibres and fibre groups, which are deformed more easily due to the working of the load, because only a small amount of fibres which are oriented vertically or chaotically resist the compression. An important effect of density on compressive stress is also observed (because the value of Student's criterion is 12.43); thus, the strength increases as density increases. In this case, density has a direct relationship with the macrostructure parameter, because it characterises the amount of fibres per unit of volume.

Therefore, as the quantitative number of fibres (i.e. density) and their clear directionality with regard to the load working on them increase, so their mechanical properties increase as well. The significance of the organic content (because the value of Student's criterion is 3.79) shows that the binder and connection between fibres is also important in the fibrous structure. If the amount of binding material is substantial, more glued contacts in the points of contact between fibres; therefore, the working load is distributed in the groups of glued fibres more consistently and works on the entire area.

Having established the dependency of the macrostructure parameters used by different authors [19, 20] in accordance different methods, their relationships with the mechanical properties (i.e. critical compression stress) of the test specimens were analysed statistically. Comparative calculations were carried out to compare the macrostructure parameters (S_C and S_L) with the parameters used by other authors mentioned above. The similar parameters named: *Tau* (*T*) and *Kappa* (*K*) which express fibre orientation and define the directionality of the structure. The parameters *T* and *K* were calculated using the same scanned images of surfaces of MW-2–MW-5 test specimens. Having compared the multiple correlation and determination coefficients, average standard deviations of different macrostructure parameters ($S_{L\text{–}C}$, *T*, *K*), it could be seen that all the macrostructure parameters correlate with the σ_e. As mentioned above the greatest interrelation exists between σ_e and $S_{L\text{–}C}$ (because $R = 0.95$), and the values of critical compression stress can be calculated with a precision of ± 7.2 kPa according to empirical equation (3). The similar parameters *T* and *K* have a smaller correlation with σ_e ($R = 0.71$), and the value of critical compression stress will not exceed ± 14.3 kPa accuracy.

The calculated quantity of standard deviation for equation (3) is high, but it could be explained mainly by uneven distribution of organic binder, the crimping degree of fibres in product structure and partly on fluctuation of apparent density. The publication [4] shows a similar tendency in receiving wide fluctuation of standard deviation results obtained during interlaboratory testing of mineral wool products. The measured values of standard deviation vary between 1.5 – 5.8 kPa, even for preselected and before tests checked apparent density (accuracy was ± 3 kg/m^3) mineral wool test specimens.

The publication [10] indicates the dependency of σ_{10} on density only – the degree model was used and the calculated R^2 is 0.79. On completion of comparative calculations according to the empirical equation presented, very small values of σ_{10} are obtained (for instance, the σ_{10} calculated for a test specimen with a density 100 kg/m^3 is 1.8 kPa). The publication does not provide a detailed description of the test specimens and shows that the measured values of σ_{10} are found in a very wide range, which is explained by the peculiarities of the production process and by the different degree of compression.

Data obtained by experimental research on rigid mineral wool products shows strong relation between the value of critical compressive stress and macrostructure parameters, density and organic content. Thus indirect method allows fairly quickly determining approximate value σ_e (without having common equipment for testing).

4. CONCLUSION

It was determined that a strong functional relationship exists between the values of critical compressive stress and macrostructure parameters, density and organic content of mineral wool products, because the value of the multiple correlation coefficient equals 0.95. By using the proposed empirical equation (3) the value σ_e can be calculated with an accuracy of ± 7.2 kPa, if the average value of macrostructure parameters, and the product density (70 – 200 kg/m^3) and the amount organic binding material are known. This enables predicting of the compressive strength behaviour of mineral wool products using a non-destructive indirect method. The proposed empirical equation is new and definitely has practical interest.

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