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New Method for Determination of Mineral Wool Products Macrostructure

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This paper presents the research on the estimation of mineral wool macrostructure parameters. The orientation of fibres in the mineral wool structure can be described by the macrostructure parameter $S_{L\text{-}C}$. It was determined that product with a homogeneous structure may be classified based on the numerical values of macrostructure parameters: the product with a quasi-horizontal orientation the value $S_{L\text{-}C}$ is ≤ 0.75 and if the value $S_{L\text{-}C}$ is ≥ 1.10 products are quasi-vertical orientation. Products with intermediate $S_{L\text{-}C}$ value (0.76 – 1.09) have a quasi-chaotic orientation. The developed method may be used to optimize production processes and/or improve the physical-mechanical properties of the mineral wool products.
Keywords: mineral wool, fibres, structure, macrostructure parameter, orientation.

1. INTRODUCTION

One of the most effective thermal insulation materials is mineral wool. Mineral wool products are widely used in building structures due to their low thermal conductivity, durability, non-combustibility and acoustic properties.

When producing mineral wool according to traditional technology, most fibres located horizontally on the conveyor belt. However, due to peculiarities of the production process a certain amount of the fibres is always oriented randomly. In terms of structure, mineral wool can be described as a spatial system comprising many intertwining fibres arranged in a certain manner in relation to each other. Such composite materials have an original structure, and their properties differ depending on the direction of fibres [1, 2].

Visual evaluation allows to recognize different mineral wool products with fibre orientation in the structure. When mineral wool is studied on a microscopic level, it is clearly seen the fibres, yet, as indicated by the author [3], analysis by means of a microscope also allows us to see the shape and diameter of non-fibrous melt inserts, contacts between fibres and highly dense areas in the products. As stated in [4] the quality of ready-made products depends on the fibre structure and on the amount of non-fibrous melt inserts in the wool. Fibres themselves are assessed considering their thickness (diameter) and length and the fluctuations in the ratio of thickness and length.

However, when carrying out studies with various microscope-type devices, the problem of the limited area being studied is often encountered. For this reason, it is impossible to observe the arrangement of fibres or fibre orientation dominating in the mineral wool structure. In order to analyse the microstructures of fibrous materials, other methods and study devices must be used. The identification of the macrostructure and the test results of the establishment of fibre orientation by describing the impact of changing the direction of fibre orientation on the properties of the materials are presented in the publications [5, 6]. Instrumental studies of the parameters and analysis of the structure are described in papers [7, 8], which show that the structure image methods can help to optimize production processes and improve the quality parameters of materials produced.

According to [9], the fibrous structure can be represented as a complex relational system comprising numerous elementary systems one on top of the other (it can be showed graphically as a triangle on a two-coordinate axis, and angles α and β of the triangle vary from 0º to 180º). Each of these systems comprises the following structural elements: fibre, small organic material particles, and non-fibrous melt inserts.

The work [10] specifies that fibre orientation in non-woven materials may be characterised by the orientation distribution function ψ; therefore, ψ is also a function of angle α. The ψ integral of this function between angles α_1 and α_2 equals the probability that the fibre is located between angles α_1 and α_2. A function of the orientation of fibres because their direction determines the values of the physical and mechanical properties of the products.

However, with the development of technology, digital and computer tools are becoming popular for recording and analysing the macrostructure of fibrous materials [11]. Analysis of the macrostructure (larger areas) can be carried out by using the surface scanning and image analysis technique [12]. Surface scanners are used for scanning and analysis of the images is conducted by using available computer software.

The management of the fibrous structure by regulating the direction of fibres during the technological process stage enables the production of mineral wool products with the desired thermal, strength, and deformational properties [13 – 15]. Individual elementary fibres, the nature of their spatial orientation and the presence of binding agents determine the structure of thermal insulation materials and the main properties of the products: density, strength, and thermal conductivity [16, 17]. Therefore, the fibres

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orientation in the structure influences on the effectiveness and determines durability of thermal insulation.

Aim of the research – developing a methodology allowing estimation of the directionality of fibres in the mineral wool product structure and qualitative identification it by using the macrostructure parameters. The determination of dominating fibres in the product structure based on macrostructure parameters enables a quality assessment of mineral wool products with respect to their fibre orientation.

2. TEST SPECIMENS AND METHODS

2.1. Description of test specimens

Mineral wool slabs with a homogeneous structure with directional and chaotic fibre orientation and a density within the range of (33 – 200) kg/m^3 were analysed. The slabs were produced and marked in accordance with requirements of the harmonised standard EN 13162 [18].

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

Table 1. Mineral wool slabs used in tests to determine dominant orientation of fibres

Test specimen	n, pcs	d, mm	ρ, kg/m^3	σ_{10}, kPa
MW-1.1	9	30–50	45	–
MW-1.2	11	50–200	100	≥10
MW-1.3	9	200	100	≥10
MW-1.4	9			
MW-1.5	9	100	110	≥50
MW-1.6	9	40–50	150	≥20
MW-1.7	9	40–50	170	≥60

n – number of test results; d – thickness; ρ – density; σ_{10} – nominal compressive stress at 10 % deformation.

2.2. Methodology

2.2.1 Surface scanning and image analysis

The dominating orientation of fibres and fibre groups in the structure was determined using the method of digital scanning and analysis of the macrostructure. Surface of 200 mm × 200 mm size test specimens cut from slabs were scanned throughout their thickness by a flat scanner (Hewlett Packard ScanJet 7400C was used).

Test specimens were placed on the scanner in such a manner as to ensure that the side of the test specimen being studied coincided on axis x with the direction of scanning and the side of the test specimen on axis y was perpendicular to the direction of the light emitted by the scanner (Fig. 1).

The surfaces analysed were scanned in the (120 – 400) dpi resolution in the black-and-white mode and the images were saved as (1000 × 500) pixel or different size BMP, TIF, GIF or JPEG format images.

Afterwards, the computerised digital image analysis method was used to determine the direction of fibres. Software UTHSCSA Image Tool 3.0 for Windows, which is intended for the analysis of images. Prior to starting work, the proper settings must be selected in the software "Image Tool" and the images were processed according to the certain procedure [19].

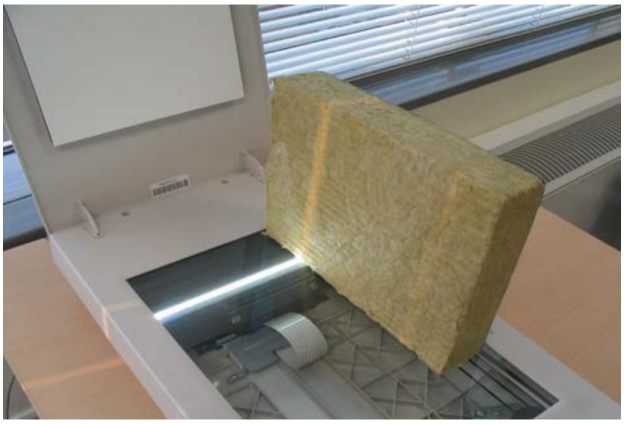


Fig. 1. Scanning of surface of test specimen by scanner

2.2.2. Determination of macrostructure parameters

Since it is nearly impossible to measure the orientation of all the individual fibres in the structure where the area is relatively large, the common method is to measure the average inclination angle of the fibre groups dominating in the macrostructure with respect to the axis being analysed. The macrostructure parameter (S) is used to express the dominating fibre orientation and direction, which is calculated according to the following formula (1):

$$S = \frac{\alpha_x}{\alpha_{x'}}, \quad (1)$$

where: α_x is value of the average angle of orientation of fibres dominating in the given cross section with regard to axis x; $\alpha_{x'}$ is value of the average angle of fibres dominating in the given cross section, which are perpendicular to axis x.

This parameter (S) describes 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 with respect to the principle axis x and axis x' which is perpendicular to it. In this case, axis x' is obtained by turning the surface of the same test specimen at an angle of 90º. Axis x is considered the principle axis because it coincides with the direction of movement of the fibre web on the conveyor (Fig. 2, a); this is why fibre orientation in the final product is characterised by taking this into consideration.

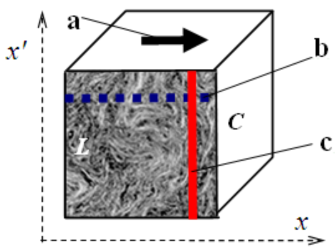


Fig. 2. The surface of the test specimen in L section with a chaotic structure: a – direction of fibre web movement; b – orientation of fibres in parallel to axis x; c – orientation of fibres perpendicularly to axis x

The expression of the macrostructure parameter by the ratio of angles increases measurement precision (in

Table 2. Measured average values of fibres tilt angles and macrostructure parameters for all types of test specimens

Test specimen	Section L		Section C		S_L	S_C	$S_{L\text{-}C}$
	α_x°	$\alpha_{x'}$°	α_x°	$\alpha_{x'}$°			
MW-1	32.12	52.20	31.96	51.96	0.62	0.62	0.62
MW-2	41.02	45.38	37.68	49.05	0.90	0.77	0.84
MW-3	46.16	39.48	48.12	37.53	1.17	1.28	1.23
MW-4	45.78	40.77	40.44	45.73	1.12	0.88	1.00
MW-5	42.35	43.68	49.16	35.94	0.97	1.37	1.17
MW-6	37.07	46.51	35.23	48.62	0.80	0.73	0.76
MW-7	39.48	44.82	36.84	48.13	0.89	0.77	0.83

particular in products with a chaotic fibre orientation because when fibre orientation is directional, its layout is clearer) since the angles of fibres dominating in the structure are measured in two directions: longitudinally (Fig. 2, b) and perpendicularly (Fig. 2, c) to axis x.

A different orientation of fibres in both sections was observed in some test specimens. Therefore the direction of movement of the fibre web on the conveyor has to be established and the following has to be marked accordingly: section L – in parallel to the direction of movement (lengthwise), section C – perpendicularly to the direction of movement (crosswise) (Fig. 2), it means the values of macrostructure parameters were calculated separately and marked with the first letters of the relevant section (L or C).

3. RESULTS AND DISCUSSION

The average values of the dominating fibre tilt angles and macrostructure parameters measured and calculated during the experimental testing are provided in Table 2.

The results presented in Table 2 show that the calculated average values of angles in relation to axes x and x' for test specimens of different types are different. The greatest differences in the angles were measured for the test specimens whose fibre orientation is also clearly visible. For MW-1 test specimens, the difference between average angles α_x and $\alpha_{x'}$ was 20.08°. For MW-5 test specimens, the average angle difference between α_x and $\alpha_{x'}$ was 13.22°. Of all test specimens, the greatest angle difference was established for the MW-1 (in section C) test specimens, which was 29.19°.

Below visual illustrations of one test specimen (those calculated angles and macrostructure parameters are close to the average value for the relevant type) are presented. The surface structure fragments presented for both sections (L and C) of each MW-1–MW-7 test specimen type.

It was established after visual inspection of the MW-1 type test specimen that the structure is dominated by horizontally oriented fibres and that the layout of fibres in both sections (L and C) with regard to axis x is similar.

This is also confirmed by the measured close values of angles α_x (31.2° in section L and 33.48° in section C). Whereas angles $\alpha_{x'}$ are slightly different: an average $\alpha_{x'}$ = 52.54° was measured for section L and 49.89° was measured for section C. After calculation of macrostructure parameters in the relevant sections (Fig. 3, a and b), similar values obtained for both sections (S_L = 0.60 and S_C = 0.67). Only macrostructure parameters, rather than numerical values of angles, are used below to characterise the peculiarities of the fibre orientation in test specimens of different types.

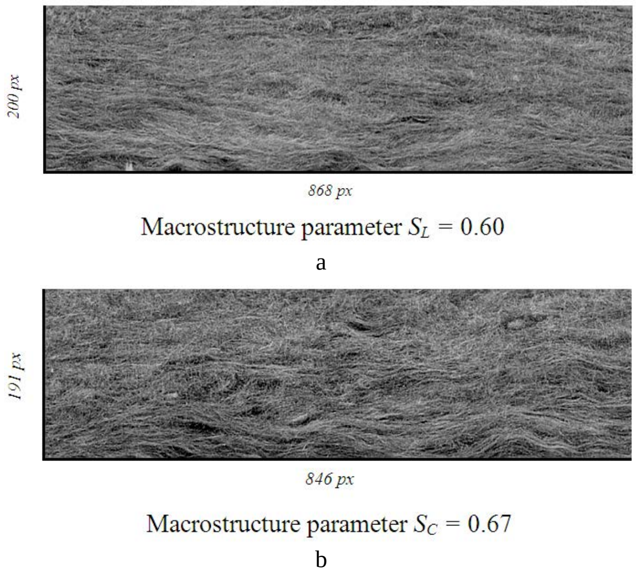


Fig. 3. Fragments of macrostructure and parameters for MW-1 test specimen: a – in section L; b – in section C

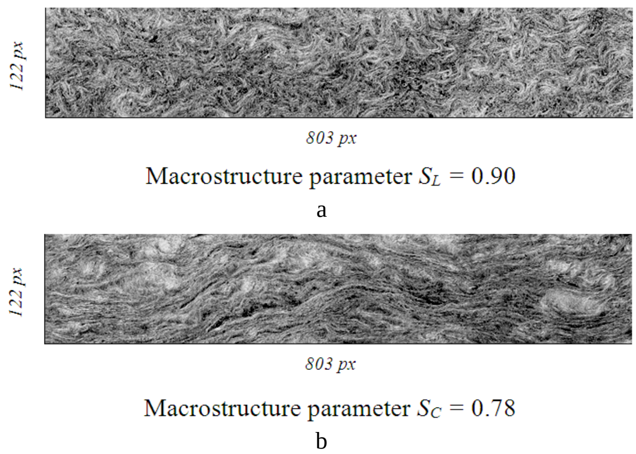
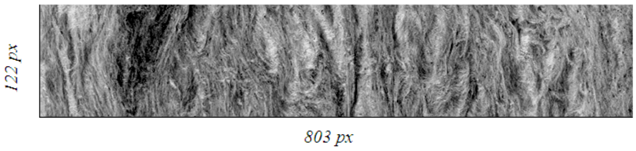


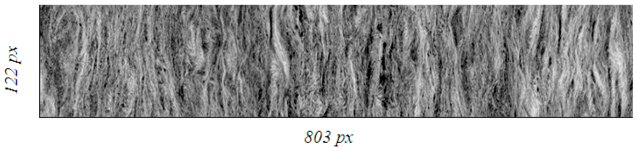
Fig. 4. Fragments of macrostructure and parameters for MW-2 test specimen: a – in section L; b – in section C

A different orientation of fibres (Fig. 4) was determined in cross sections L and C of MW-2 type test specimen: fibres with a fairly chaotic orientation dominate in section L, whereas section C is characterised by a greater number of fibres oriented longitudinally. Therefore, the calculated macrostructure parameters differ accordingly (0.9 for cross section L and 0.78 for cross section C) (Fig. 4, a and b).



Macrostructure parameter S_C = 1.16

a

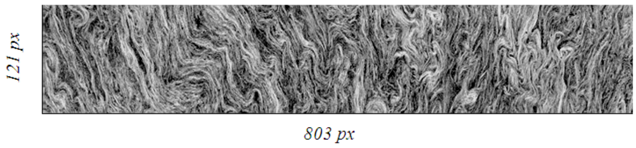


Macrostructure parameter S_C = 1.32

b

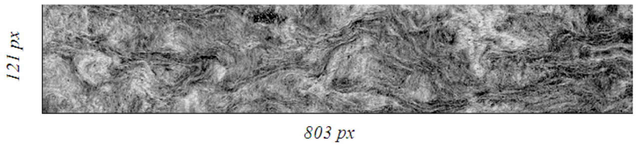
Fig. 5. Fragments of macrostructure and parameters for MW-3 test specimen: a – in section *L*; b – in section *C*

The values of measured angles α_x and calculated parameters S_L and S_C of MW-3 type test specimen (Fig. 5, a and b) were very high (1.16 and 1.32) compared to the calculated macrostructure parameters of the test specimens analysed before (MW-1 and MW-2). In the test specimen, both sections demonstrate a directional domination of vertically oriented fibres in the structure.



Macrostructure parameter S_L = 1.11

a



Macrostructure parameter S_C = 0.89

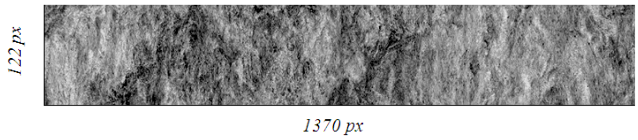
b

Fig. 6. Fragments of macrostructure and parameters for MW-4 test specimen: a – in section *L*; b – in section *C*

Fragments of Fig. 6, a and b, show that the two sections of the test specimen MW-4 are fairly different: vertical fibre orientation is clearly seen in section *L* (because $\alpha_x = 45.41°$ and $\alpha_{x'} = 40.78°$, while $S_L = 1.11$). Section *C* does not demonstrate any clear spread of dominating fibres with regard to either of the axes; therefore, the macrostructure parameter S_C equals 0.89.

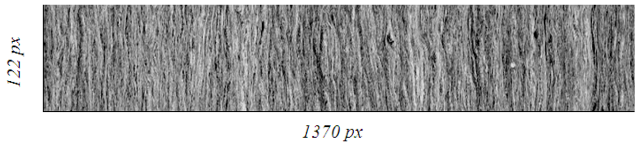
The structure of the test specimen MW-5 is dominated by the fibres which is very similar to that of MW-3 test specimens (Fig. 5).

Fig. 7, a, shows that section *L* of MW-5 test specimen is dominated by a chaotic fibre structure ($S_C = 0.96$), whereas section *C* clearly demonstrates a fairly orderly vertical orientation of fibres (Fig. 7, b). This is also confirmed by the calculated macrostructure parameter ($S_C = 1.40$), which is the highest (for the section in question) of all the test specimens used in this testing.



Macrostructure parameter S_L = 0.96

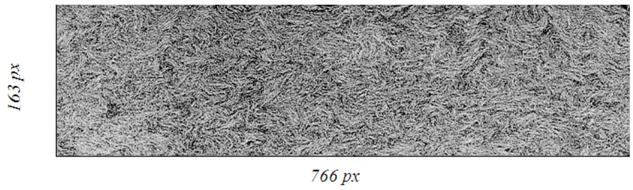
a



Macrostructure parameter S_C = 1.40

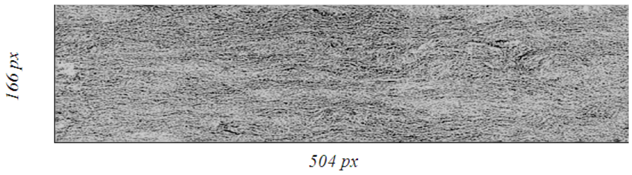
b

Fig. 7. Fragments of macrostructure and parameters for MW-5 test specimen: a – in section *L*; b – in section *C*



Macrostructure parameter S_L = 0.82

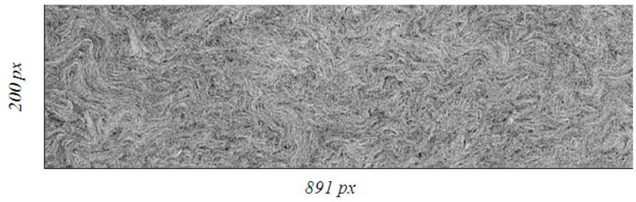
a



Macrostructure parameter S_C = 0.75

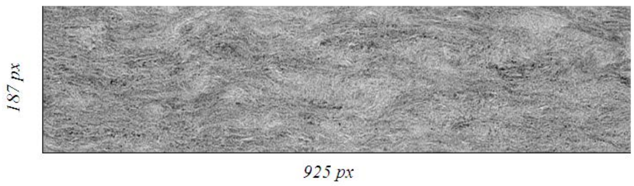
b

Fig. 8. Fragments of macrostructure and parameters for MW-6 test specimen: a – in section *L*; b – in section *C*



Macrostructure parameter S_L = 0.87

a



Macrostructure parameter S_C = 0.77

b

Fig. 9. Fragments of macrostructure and parameters for MW-7 test specimen: a – in section *L*; b – in section *C*

A chaotic fibre orientation was determined for both sections (*L* and *C*) of test specimens MW-6 and MW-7. Although, as it can be seen from fragments b of Fig. 8 and Fig. 9 and from the calculated low (0.75 and 0.77) macrostructure parameters, a trend of the fibre orientation becoming more horizontal with regard to axis x is observed (i. e. some of the fibres in the structure are parallel to the direction of movement of the fibre web).

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.

On relating the spread of the values $S_{L\text{-}C}$ (Fig. 10) with the fragments a and b of Figs. 3–9, it is seen that the direction of dominating fibres in the structure may be characterised by the macrostructure parameter. The value $S_{L\text{-}C}$ of test specimens MW-1, whose structure is dominated by horizontally oriented fibres (Fig. 3), is low (0.5–0.73), and the calculation variation coefficient varies by ±14.8 %.

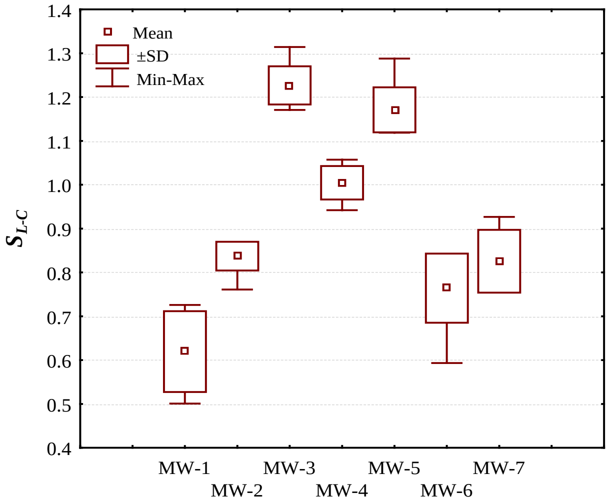


Fig. 10. The spread of the average values of the macrostructure parameter $S_{L\text{-}C}$ for all types of test specimens

The value $S_{L\text{-}C}$ of test specimens MW-3 and MW-5 (Figs. 5 and 7), whose structure is dominated by vertically oriented fibres, is high (1.12–1.31), but the variation coefficient is fairly low ±(3.5–4.4)%. Considering these values of the variation coefficient, is possible to state that the structure of test specimens with a vertical fibre orientation is more homogenous. The parameter $S_{L\text{-}C}$ of the remaining test specimens with a chaotic structure varies and spreads between the minimum and maximum values determined for the directional structure (0.76–1.09) due to the absence of any clear fibre orientation.

The average values of the macrostructure parameters calculated, the standard deviations, and the spread of the lowest and highest values are presented in Fig. 10.

Thus, it could be stated that the macrostructure parameters S_L, S_C, and $S_{L\text{-}C}$ are suitable for quantitative assessment of fibre orientation in the structure of mineral wool. The orientation of the fibres domination can be determined by using the values of the parameters obtained.

The categorisation of products with different structures into groups is based on the structural differences which are determined by fibre orientation. To prove this, were used the numerical values of the macrostructure parameter which are calculated considering the results obtained during experimental testing following testing of products with a homogeneous structure and different orientation.

The characterisation of the layout of fibres in the product structure was chosen taking into account the position of dominating fibres with regard to the direction of working of compression loads and the direction of movement of the fibre web on the conveyor. For instance, fibres with a horizontal directional orientation in the product structure are perpendicular to the direction of working of the load and the direction of dominating fibres coincides with the direction of movement of the fibre web, i. e. with the horizontal direction.

The results show that products with a homogeneous structure in which fibres are mostly orientated in parallel to axis x can be called products with a quasi-horizontal orientation (their value $S_{L\text{-}C}$ is ≤ 0.75). Products in which fibres are predominantly orientated perpendicularly to axis x are called products with a quasi-vertical orientation (value $S_{L\text{-}C}$ is ≥ 1.10). Products with randomly located fibres or fibres orientated in a clearly undefined direction (orientation) are called products with a quasi-chaotic orientation (value $S_{L\text{-}C}$ varies between 0.76–1.09).

The commonly categorisation of the fibre structure into groups is fairly theoretical in nature because the production of perfect products with a strictly specific structure is very unlikely.

The classification allows describing and evaluating the mineral wool products of different structure when solving traditional problems connected with the effectiveness of fibre structure, changing direction of fibre orientation, and use of different densities and/or layers in the production process determine the main strength and deformational properties of mineral wool products.

On conducting an overview of different references and sources dealing with the fibrous structures limited amount of the relevant publications were found. Publication [20] provides the comparable studies. The authors used the parameters *Tau* (T) and *Kappa* (K) to express fibre orientation. The parameters define the directionality of the structure and the degree of distribution of dominating fibres. The parameter T indicates the local organisation of the structure (i. e. the existence of a direction in the structure). The parameter K defines the degree of distribution of different angles in the structure being studied. Pair correlational analysis of the parameters was carried out to establish the interrelation of the parameters in question.

Calculations [19] show that correlational relationships exist between the parameters. Having compared the both parameters define that the value of critical compression stress of the same test specimen can be calculated with 90 % precision using the parameter $S_{L\text{-}C}$ and with 50 % precision using the parameters T and K. Thus, it states that the macrostructure parameter ($S_{L\text{-}C}$) characterises the functional relation between the macrostructure and the physical and mechanical properties more precisely compared to other parameters.

4. CONCLUSIONS

1. The orientation of fibres in the mineral wool structure can be described by the macrostructure parameters S_L, S_C or $S_{L\text{-}C}$. Products with a homogeneous structure may be classified as follows based on the numerical values of macrostructure parameters: products in

which most fibres are arranged in parallel to axis x are called products with a quasi-horizontal orientation, and their value S_{L-C} is ≤ 0.75. Products in which fibres perpendicular to axis x dominate are referred to as having a quasi-vertical orientation, and their value S_{L-C} is ≥ 1.10. Products with randomly arranged fibres or with fibres whose direction (orientation) is undefined are called products with a quasi-chaotic orientation because their value S_{L-C} is $0.76 - 1.09$.

2. The developed and presented new method may be used for the purpose of non-destructive control of the properties of the mineral wool products; allow control of the homogeneity of the fibre web produced on the production line and prompt adjustment of the directionality of fibre arrangement. Further investigation and experiments would arranged for increasing of accuracy, reliability and reproducibility of the results.

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