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Homogeneous pore distribution in foam concrete by two-stage foaming

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Abstract. The article addresses the issues of investigating the homogeneity of foam concrete produced by three methods: the classical method (CM), dry foam mineralization (DM), as well as the proposed method of two-stage foaming (TSF). The study is necessary due to the impact of the manufacturing process on the homogeneity degree of foam concrete. Therefore, the TSF method is aimed at improving the homogeneity of the material structure by evenly distributing the pores through the sequential foam introduction. The homogeneity of the materials produced by the three methods was evaluated by comparing the results of discrete (point and localized) strength testing over the entire volume of the foam concrete blocks, as well as the results of thermal conductivity measurements. The test results obtained gave an understanding of the degree of materials homogeneity, and confirmed the impact of the foam concrete manufacturing process on its quality. Thus, the most homogeneous material structure throughout the entire volume is observed in TSF specimens, as evidenced by the minimum deviations of particular values of strength and thermal conductivity, ranging from 4.19 % (in the analysis of thermal conductivity) to 6.71 % (in the analysis of strength), while the same indicators for CM specimens are 22.4 % and 48.35 %, and for DM specimens are 11.05 % and 19.21 %, respectively.

1. Introduction

The proposed method of production of non-autoclave foam concrete suggests two-stage foaming (hereinafter – TSF): the primary addition of a low-concentration mixture of foam is carried out at the stage of preparation of sand-cement mortar, which is followed by the addition of a high-concentration mixture of foam at the stage of production of a cellular concrete structure. TSF allows obtaining a product with a greater degree of homogeneity, and the reduction of the water-cement ratio reduces setting time. This provides an improvement in strength characteristics and is an additional factor for obtaining a homogeneous structure of the material.

The appearance of great interest in cellular concrete is due to its ability to combine relatively high strength with such physical-mechanical properties as thermal conductivity and frost resistance [1–6]. Important, in this context, can be technological ergonomics in the construction of building structures made of foam concrete (for example, in comparison with brick), as well as low density of the material [7–9]. Thus, a lot of compositions and technologies of cellular concrete production have appeared in the market, but the methods of foam concrete production using energy-saving non-autoclave technologies are of special interest [10–13].

Classically, aerated concrete is divided into aerated concrete and foam concrete [14, 15]. The main distinctive feature of these materials is their pore structure. Aerated concrete is produced by the introduction of gas-forming components that in the process of chemical reaction with a cement binder forms a gas emission, which enables the formation of interacting pores [16]. Foam concrete is produced by adding ready-made foam in the cement-sand mixture, which allows obtaining a closed pore system [17]. One of the most common issues of foam concrete manufacturers is the instability of the structure of the foam

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concrete mortar, shrinkage, uneven density of the material, and, as a consequence, unstable strength and thermal conductivity of the product. The reason for this shortcoming can be many factors, the main of which is a high water-cement ratio, which ultimately leads to heterogeneity of the material at its setting [1, 18].

To solve this problem, plasticizing additives are used. However, because plasticizing additives are surface-active substances (SAS), after decreasing the water-cement ratio, manufacturers of foam concrete faced another problem – shrinkage of the material due to the increasing time of setting under the influence of additives. This also leads to an uneven distribution of the pore structure of the material in the volume. To solve the problem of the quality of foam concrete material, many attempts have been made by using additives of curing accelerators in combination with plasticizers [19, 20]. But no significant result ensuring quality foam concrete has been achieved [21, 22].

A breakthrough solution in eliminating the problem of heterogeneity of foam concrete was the modernization of the technological process of its production. Instead of the classical method (hereinafter – CM) of foam concrete production [7, 23–27], which represents the cement-sand mixture with water and foam concentrate, the technology of foam concrete production by dry mineralization (hereinafter – DM) of foam was proposed [28]. The method of DM is the preparation of foam concrete by mechanical mixing of the dry cement-sand mixture with the foam. As a result of the application of the given technology several questions, concerning the quality of pore structure and density, have been solved. However, the problem of shrinkage of a material in the course of the setting remained unsolved. Despite this, the classical production method is still actively used in combination with various additives [28].

The analysis of CM and DM revealed the advantages and disadvantages of the methods. The disadvantage of CM is a high water-cement ratio, which leads to shrinkage of the material before setting. Besides, foam concrete obtained by CM has low strength and uneven density in the volume of the product. The decrease in strength is due to micro and macropores in the cement dough, which creates a weak skeleton. The disadvantages of the DM method include shrinkage of the material in the process of setting (as a result of partial destruction of the foam structure when combining the foam with dry components of the material), which leads to changes in the final geometric dimensions of the product. Partial destruction of the foam structure is accompanied by its stratification, which leads to the formation of a heterogeneous structure of the material [9, 18, 21, 22, 29].

The unsolved question of obtaining quality foam concrete has defined the goal of this study. Thus, it consists of developing an available technology of foam concrete production by the method of two-stage foaming. Achieving the goal should provide an improved pore structure of the material making the pore distribution more uniform, as well as improved physical-mechanical properties of the material due to the uniform distribution of the load-bearing skeleton structure.

The proposed method of TSF ensures maximum distribution of the foam concentrate over the entire specimen volume: the initial addition of a low-concentration foam mixture takes place at the sand-cement mortar preparation stage, thus improving its wettability and subsequent reduction of the water-cement ratio (reducing the quenching of the foam with water). Afterward, with the secondary addition of a highly concentrated mixture of foam at the stage of making the structure of cellular concrete, a decrease in the water-cement ratio allows to save the primary ratio of foam concentrate, facilitates the formation of a uniform structure of porous material.

The following tasks were set to achieve the goal:

- Testing the strength of foam concrete specimens obtained by CM, DM, and TSF in the laboratory according to [30].
- Measuring the thermal conductivity of foam concrete specimens obtained by CM, DM, and TSF in the laboratory according to [31].
- Comparative analysis of the results of laboratory tests and measurements.

The article presents the results of comparative analysis of methods of foam concrete production, namely the impact of the technological process of preparing the material on its quality, without assessing the possible impact of ingredients (additives to improve the physical-mechanical properties of materials).

For comparison with the proposed TSF method, considered two main methods of foam concrete production are widely used in practice such as CM and DM.

2. Methods

The research methodology includes the following stages:

- Preparation of foam concrete by comparable CM and DM methods;
- Preparation of foam concrete by the proposed method of TSF;

- Laboratory testing of foam concrete specimens;
- Analysis of results.

Preparation of foam concrete by comparable methods was carried out in laboratory conditions following the standard methods, specifications, and the requirements of the normative and technical documentation [14, 32, 33]. An important condition was to maintain the same composition of components and ingredients (additives) of prototypes for each method, as well as their dimensionality. The foam concrete compositions and the ratio of foam concentrate to aggregate are designed from the condition of obtaining the material density of D600 (600 kg/m^3) (Table 1). For each of the 3 methods (including the proposed one), 5 blocks were prepared.

Table 1. Composition of foam concrete of comparable methods.

Method	Cement, kg	Sand, kg	Water, l	Foam concentrate, l
TSF	310	270	124	1.2
CM	310	270	186	1.1
DM	310	270	155	1.2

The technological process of specimen preparation by TSF is shown in Fig. 1.

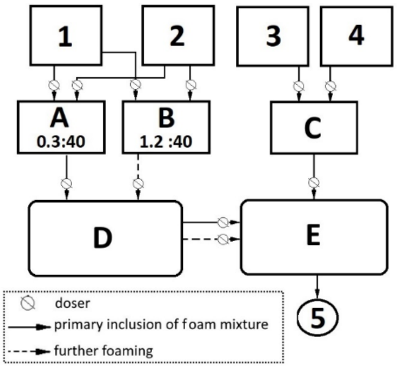

Figure 1. The technology of foam concrete preparation by the method of TSF: 1 – water; 2 – foam concentrate; 3 – cement; 4 – sand; 5 – finished product; A – the container for the low-concentrated mixture of the plasticizing additive of a foam concentrate in water 0.3:40 l, B – the container for a mixture of the modified foam concentrate in water 1.2:40 l, In – the cement-sand mixer, D – the foam generator, E – the mortar mixer.

The technological process consists of three stages. During production, a strict sequence of components must be followed (Fig. 1):

Stage 1: in a container (A) the foam concentrate (1) is thoroughly mixed with water (2), in ratio to water – 0.3:40 l; in parallel (independently) in a container (B) the foam concentrate (1) is thoroughly mixed with water (2), in water ratio – 1.2:40 l; in parallel in a container (C) the cement (3) is mixed with sand (4), in the ratio of cement to sand (1:3);

Stage 2: obtained in a container (A) mortar through the foam generator (C) is converted to foam and combined with cement and sand mixture from the container (D), in a mortar mixer (E);

Stage 3: The mortar obtained in a container (B) is converted to foam through the foam generator (C) and introduced into the mortar mixer (E).

After careful mixing in a mortar mixer, the resulting mortar (5) is poured into forms.

The main evaluation criterion of the quality of the material prepared by different methods is the degree of its homogeneity, or in other words, the even pore distribution in the structure of foam concrete over the entire volume. This indicator is directly related to the technology of foam concrete production. The resulting factors of material homogeneity can be attributed to the homogeneity of physical-mechanical properties of the material over the entire volume.

Evaluation of material homogeneity, through the evaluation of physical-mechanical properties, is reduced to the discrete measurement of physical-mechanical properties over the entire volume (mainly height) of the material of standard size (factory block): 20 cm height, 30 cm width, and 60 cm length. Cylindrical specimens with a height of 20 cm and a diameter of 6.4 mm, segmented by 2 cm in height, were used to assess the strength of the material (Fig. 2a). Also, for point assessment of the strength of factory sized specimen, conducted the tests of small-sized cubic specimens with the dimensions of 2×2×2 cm extracted continuously by height and selectively by the length and width of the factory specimen (Fig. 2b).

To assess the thermal conductivity of the material used the specimens in the form of a rectangular parallelepiped of standard size, selected in steps of 4 cm by the height of the specimen of factory size (Fig. 2c).

a - cylindrical foam concrete specimens

b - small cube specimens

c - standard specimens

Figure 2. Specimens for determining the physical-mechanical properties of foam concrete.

The difference between testing the cylindrical and small specimens is that segments of a cylindrical specimen are tested simultaneously while small specimens are tested separately. In other words, testing cylindrical specimens is necessary to identify the weakest segments of the specimen by height, while testing small specimens will evaluate the distribution of strength characteristics over the entire volume of the material. In both cases, the analyses of the results reveal weaker locations, areas with maximum density, and generally assess the homogeneity of the material.

Assessment of the uniformity of foam concrete in height is due to the influence of gravitational forces on the heavy ingredients of the composition during the setting process (including excess water during foam delamination), leading to an uneven density of the material by volume.

Core cutting was carried out through a cylindrical crown with an electric drive, with an inner diameter of 6.5 mm. To reduce the impact of mechanical action on the skeleton structure, core extraction was carried out with maximum rotation and minimum movement of the crown. In total, 6 specimens were taken from each comparable foam block. The cylindrical and standard specimens were cut by string cutting at maximum rotational speeds to reduce the risk of disturbance of the material structure. Before testing, each element of the specimen was labeled.

The laboratory testing and measurement of foam concrete specimens included the following:

- Determining the strength of segmented cylindrical specimens using the Unconfined compression test (Fig. 3a);
- Determination of the strength of small cube-shaped specimens of material by Dynamic Mechanical Analysis (Fig. 3b);
- Determination of the thermal conductivity of standard specimens of material using the ITP MG-4 instrument (Fig. 3c).

a - determination of the strength of segmented cylindrical specimens

b - determination of the strength of small cube specimens

c - determination of the thermal conductivity of reference specimens

Figure 3. Laboratory testing of foam concrete specimens.

Compressive strength tests on segmented cylindrical specimens were carried out on the “Press Automatic Pilot” equipment with a total compressive load of 500 kN, designed to determine the compressive strength of lightweight concrete and primer-cement specimens.

To evaluate the less robust part of the specimen within the height, segments of one specimen were tested simultaneously. Since the specimens have been mechanically subjected to cutting, the specimen surface has a roughness that can lead to a point transfer of normal stress at the contact edge of the segments. Therefore, for better distribution of normal stress, flexible gaskets [30] of nonwoven geotextile were used. The use of gaskets also simulates the tangential stresses at the contact edge of the segments, which are inherent to a solid, monolithic specimen, when compressed.

Testing was performed before the specimen failed, and strength measurements were made using two control measurements:

A – registration of the load value, at the destruction of at least one segment, to identify the weakest section by the height of the specimen;

B – recording the peak value of the load, to measure the maximum strength of the specimen as a product.

The tests of small specimens of cubic shape for assessing the distribution of strength properties of the material on the volume of specimens of comparable methods were conducted on specialized equipment called “Dynamic Mechanical Analysis”. The device is designed to study the properties of materials under the influence of periodic and constant loads of compression, bending, shearing, stretching of small specimens (height up to 3 cm). In total, 2250 specimens were tested.

To estimate the thermal conductivity and thermal resistance of the materials of the compared methods, specimens of standard sizes in the form of a rectangular prism were used. Measurements were carried out on the device ITP MG-4 on the principle of generation of a stationary heat flow passing through a flat specimen and directed perpendicular to the face edges of the specimen [31]. The heat flow is monitored automatically by the device. In total, 5 specimens of each method were tested, selected at the same distance within the block height (20 mm per step). The error of geometric dimensions of the specimens did not exceed ±0.1 mm. Before the test, to determine the density of the dry specimen, the prototypes were dried to a constant mass, so that the mass change did not exceed 0.1 % during 30 minutes of observation.

The calculation of thermal conductivity λ (effective thermal conductivity) was performed according to Eq. (1), and thermal resistance R_H (in the stationary thermal mode) according to Eq. (2):

$$\lambda = \frac{H \cdot q}{T_h \cdot T_c}, \tag{1}$$

$$R_H = \frac{T_h - T_c}{q} - 2R_k, \tag{2}$$

where, λ is effective heat transfer, W/m °C;

R_H is the thermal resistance of the test specimen, m²·°C/W;

R_k is the thermal resistance between the face of the specimen and the work surface of the instrument panel, m²·°C/W;

H is the measured specimen thickness, mm;

q is the density of a stationary heat flux passing through a measured specimen, W/m²;

T_h is the temperature of the hot edge of the measured specimen, °C;

T_c is the temperature of the cold edge of the measured specimen, °C.

3. Results and Discussion

3.1. Strength results of segmented cylindrical specimens by Unconfined compression test

Comparisons of the values of measurement A (identification of the weakest area within the height of the specimen) expressed by the relation of particular values of strength of TSF specimens with CM and DM are presented in Fig. 4. The presented linear functions have a close relation to the variables as the correlation coefficient in both cases is higher than 0.7. Proportionality coefficients show that the greatest convergence of strength values with TSF is observed in DM specimens (0.82 is closer to 1.0 than 0.66). According to the test results, the partial values of strength of the weakest segments of CM specimens vary from 0.61 to 0.93 MPa, which corresponds to the upper limit of foam concrete mark of D300. This means that all five CM specimens have weaker segments within the height, the density of which does not exceed 300 kg/m³. Particular values of strength of the weakest segments of DM specimens vary from 1.52 to 1.73 MPa, which correspond to the average value of the strength of foam concrete mark of D400. The strength of TSF segments varies from 1.84 to 2.05 MPa, which corresponds to the upper limit of the strength of foam concrete mark of D400 and the average value of foam concrete mark of D500. The results of the study [34, 35], which aimed to assess the degree of homogeneity of foam concrete by measuring its density, showed that the density of the material depends on the setting time and methods of foam concrete preparation and varies on average from 10 to 25 %. In general, the particular values of density [34, 35] lie in a proportional range of obtained particular values of segmented specimens.

Comparing the standard deviations of the obtained results on the strength of three methods that are 0.129 for CM, 0.093 for DM, and 0.087 for TSF, it can be concluded that the greatest variation of the particular values of strength within the height is revealed for the DM specimens. The smallest standard deviation is observed in the TSF specimens, which indicates the maximum concentration of particular values of strength at the height around the arithmetic mean of the particular values.

In general, the results of the assessment showed that CM and DM specimens have a greater variation in height than TSF specimens. The weakest sections of the CM specimen turned mainly the two upper segments 9 and 10 (Fig. 5a), at an average load of 2 kN, which corresponds to a strength of 0.72 MPa. In the DM specimens the weakest sections are located in the upper part of the specimen, mainly the three upper segments 8, 9, and 10 (Fig. 5b), at an average load value of 4.5 kN, which corresponds to a strength of 1.62 MPa. No clear pattern of segment failure was found in the TSF specimens. Where the weakest was the lowest segment 4 (Fig. 5c), at an average load of 5.3 kN, which corresponds to a strength of 1.91 MPa.

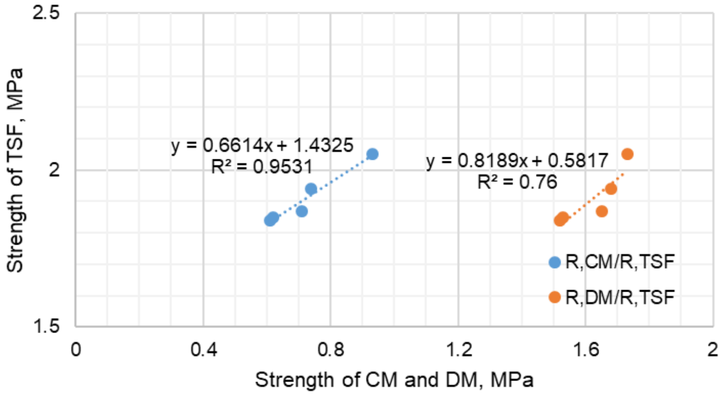

Figure 4. Temperature mode of concrete curing.

Figure 5. Weakest segments of specimens.

At the measurement B (maximum strength measurement) on the CM and partially DM specimens, the tests were continued after the upper segments were removed, otherwise, the peak load value would be limited by the failure of weak specimens due to their low strength value relative to other segments. In general, the maximum strength values of the three methods are close to each other. The average value of maximum strength of CM specimens was 3.2 MPa, which corresponds to the upper limit of the strength of foam concrete mark of D500 or the lower limit of the mark of D600. The DM and TSF specimens showed the strength of 2.5 MPa and 2.7 MPa respectively, which correspond to the average strength of the mark of D500. The obtained results of the maximum strength of CM specimens are due to the removal of weak segments, as well as changes in the ratio of the width of the specimen to its height, which led to data distortion.

Although the selection of foam concrete composition and the ratio of foam concentrate to aggregate is calculated from the condition of obtaining the material density of D600 (600 kg/m^3), the obtained specimens of comparable methods showed different results from the given values [36]. The resulting factor of distortion of the results is a non-standard dimensionality of specimens (due to the height of the standard block and the diameter of the core extractor) in comparison with the required test specimens regulated by the standards. Correction factors for the geometry of the specimens were also not taken into account, as the task of projecting the results of the specimen to the final construction product was not set in the analysis. The fact that the tested segmented cylindrical specimen does not have an integral structure also played a partial role, and since all specimens were tested under equal conditions, the results may vary from those of real values quantitatively, but not qualitatively. And since the task was to compare the results relative to each other, the quantitative factor has no principal importance, since the results are not expressed by particular values but by their ratio.

The results obtained from the tests of segmented cylindrical specimens gave an indirect idea of the degree of homogeneity of materials of the three compared production methods.

3.2. Dynamic Mechanical Analysis results for strength determination of small cube material specimens

The spread of the strength values by the height of the specimen of each compared method, aliquot to the height of an individual cube (2 cm), is shown in Table 2 below.

Table 2. Spreading of particular strength values by height.

Specimen No. (full height)	Particular values of strength, kgf/cm^2					
	CM		DM		TSF	
	Minimum	Maximum	Minimum	Maximum	Minimum	Maximum
10 (20 cm)	10.235	15.984	38.075	42.432	26.870	34.935
9 (18 cm)	13.885	24.253	38.342	44.583	28.944	37.384
8 (16 cm)	24.120	42.439	40.456	46.780	29.118	42.293
7 (14 cm)	31.786	44.328	42.359	48.467	37.881	44.277
6 (12 cm)	35.382	45.827	42.243	49.334	38.420	46.226
5 (10 cm)	38.340	48.105	42.589	49.015	38.318	47.986
4 (8 cm)	39.921	50.368	43.011	49.312	39.020	48.355
3 (6 cm)	42.334	54.492	43.516	50.016	40.267	50.417
2 (4 cm)	54.012	70.439	44.770	52.145	43.455	57.936
1 (2 cm)	77.228	91.870	46.342	54.211	48.171	61.939

According to the test results, particular values of strength of CM specimens vary from 10.235 kgf/cm^2 (≈0.98 MPa) to 91.87 kgf/cm^2 (≈9.60 MPa), DM specimens vary from 38.075 kgf/cm^2 (≈3.72 MPa) to 54.211 kgf/cm^2 (≈5.29 MPa), and TSF specimens vary from 26.87 kgf/cm^2 (≈2.65 MPa) to 61.939 kgf/cm^2 (≈6.10 MPa). According to the study of [37], the strength characteristics of foam concrete specimens of similar composition, on average, amounted to 50 kgf/cm^2, which does not contradict the results obtained and correspond to the average value of the range of CM, the upper value of the strength range of DM and TSF.

For visual comparison, the point strength results are presented in the form of color distribution [38] over 6 significant sections (from two opposite edges and the middle of the block in the transverse and longitudinal direction). Fig. 6 shows the comparison of strength in the planes C1 (in axes 1 – A÷O, Fig. 2b) and L1 (in axes A – 1÷30, Fig. 2b). Fig. 7 shows the comparison of strength in the planes C2 (16 – A÷O, Fig. 2b) and L2 (H – 1÷30, Fig. 2b). Fig. 8 shows the comparison of strength in the planes C3 (30 – A÷O, Fig. 2b) and L3 (1÷30, Fig. 2b). For the best comparative evaluation of each fragment (separate plane), a single-color scale of strength characteristics inherent in the most heterogeneous specimen (method) is given. Thus, the contrast of the scale and the planes under consideration will contribute to a better visual perception of the heterogeneity of the plane under consideration relative to the most heterogeneous specimen (method).

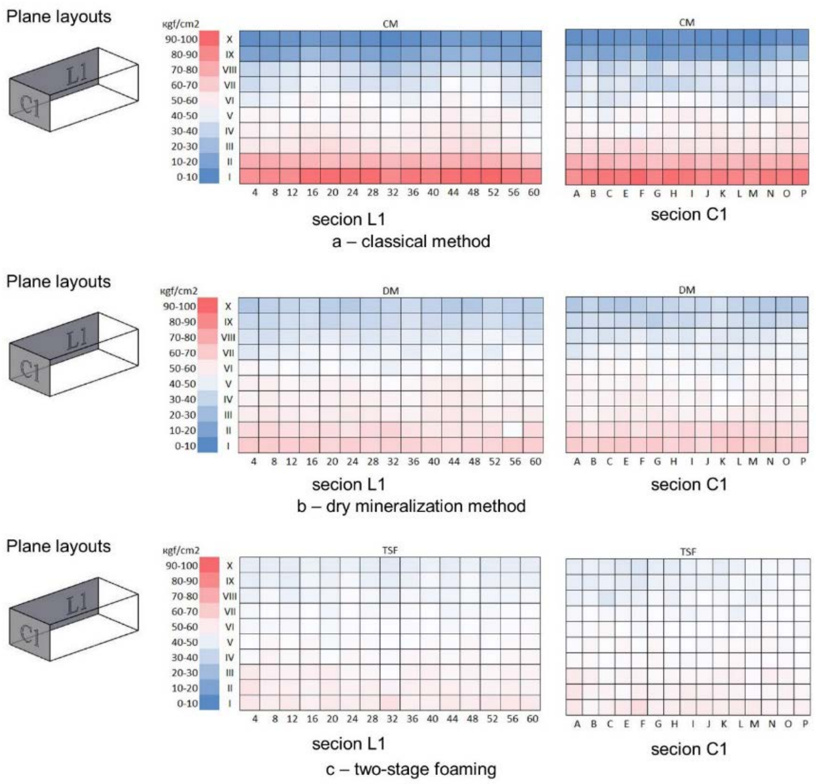

Figure 6. Color diagram of strength distribution in the cross-sections of C1 and L1 unit.

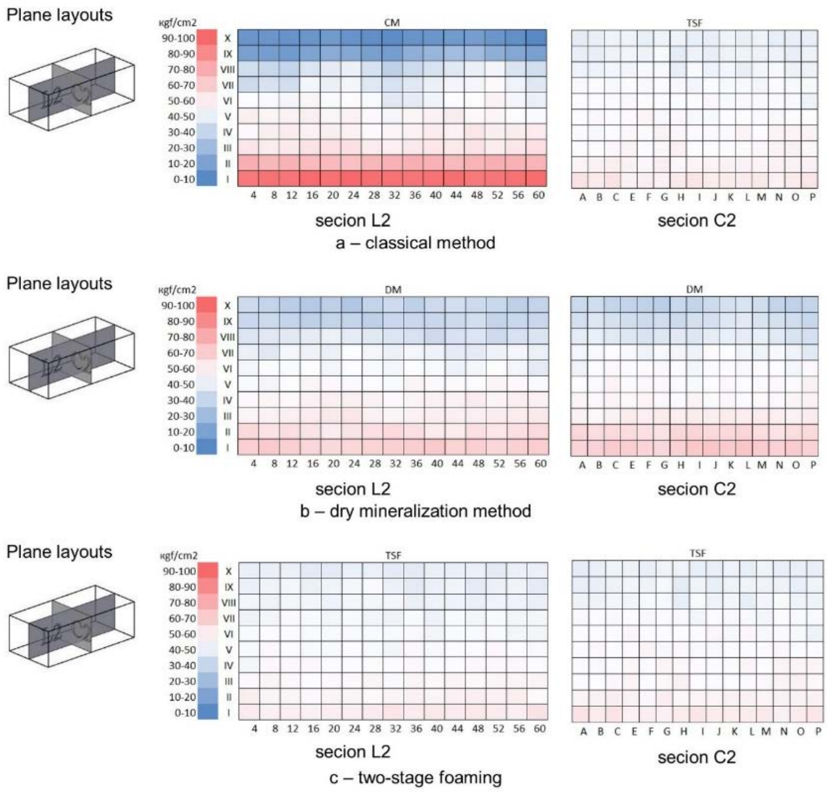

Figure 7. Color diagram of strength distribution in the cross-sections of C2 and L2 unit.

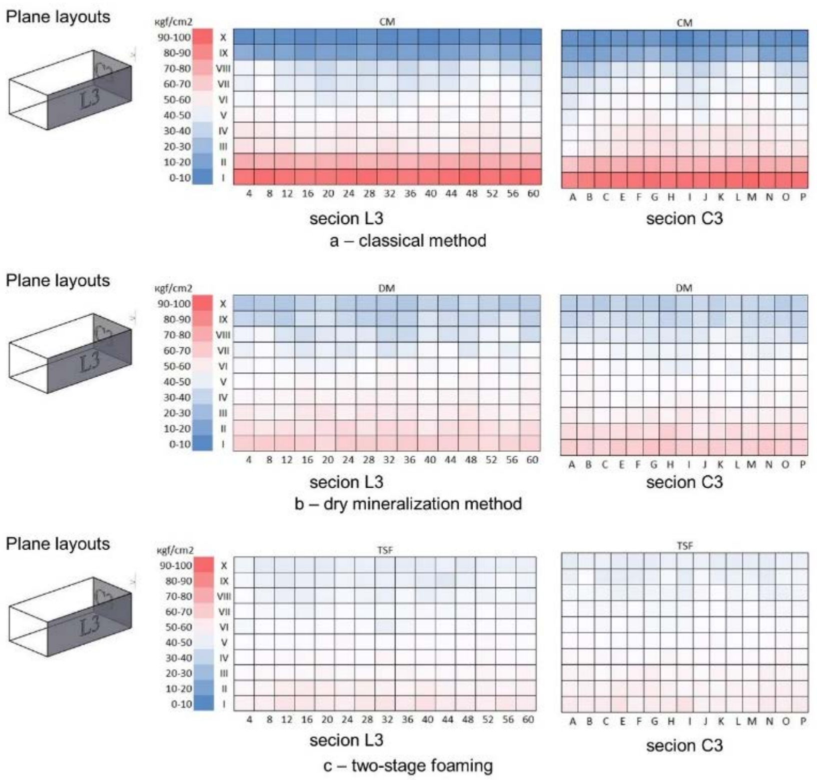

Figure 8. Color diagram of strength distribution in the cross-sections of C3 and L3 unit.

The difference of contrasts of color diagrams of strength distribution along transverse and longitudinal sections clearly shows the difference in the homogeneity of distribution of particular values of strength characteristics of compared methods of foam concrete production. The greatest contrast is observed at CM blocks (in all cross-sections), which testifies to the big dispersion of particular values of strength, therefore, the lowest homogeneity of the material. The greatest homogeneity is observed at blocks of TSF, which testifies to the smallest color contrast within the height of the section. The average degree of homogeneity is observed at DM blocks.

The average value of the minimum strength of CM specimens (all top specimens) is 13.25 kgf/cm^2 (1.30 MPa), and the average value of the maximum strength (all bottom specimens) is 87.9 kgf/cm^2 (8.62 MPa). The squared deviation of particular values of the upper specimens is 0.25, and of the lower specimens is 2.09. The variation coefficient or the deviations of particular values do not exceed 1.86 % of the average value for the upper specimens (an upper plane of the block) and 2.34 % – for the lower (lower plane of the block), which indicates a close relationship of particular values of the strength of all specimens within the plane of the considered height (horizontal plane). The statistical analysis of particular values of strength and standard deviations of DM specimens also showed close relation of particular values of strength within the limits of considered planes within the height. For the lower plane the deviation (variation coefficient) limit is 1.45 %, and for the upper plane is 1.68 %. In the case of the TSF method, the deviation limit for the lower plane is 0.59 %, and for the upper plane is 2.05 %.

This analysis allowed estimating the spread of these strength characteristics within two critical planes of the specimen (upper and lower planes of the foam concrete block) with minimum and maximum particular values of strength. The analysis showed a close relationship of the particular values within the plane of their location, excluding the assumption of random errors (since the number of particular values within one plane is 225 units), thus confirms the assumption of heterogeneity of the material in the transverse plane (in its height) and relatively good homogeneity in the horizontal plane.

A quantitative assessment of the material heterogeneity in height can be made by statistical processing of particular strength values in transverse planes perpendicular to the horizontal plane.

The average value of the transverse plane strength of CM specimens is 43.67 kgf/cm^2 (4.28 MPa), and the average value of squared deviations (within height) is 21.11. Hence, the deviations (variation coefficient) of particular values of strength from the arithmetic mean reach 48.35 %, which indicates a weak bond of particular values of strength within the transverse planes (values on the height of the specimen), as well as the heterogeneity of the material within height. The statistical analysis of particular values of strength and standard deviations of DM specimens showed closer relation of particular values of strength in transverse planes in comparison with CM. At the average value of strength equal to 44.54 kgf/cm^2 (4.37 MPa), the standard deviation was 8.56, and the deviation (variation coefficient) of particular values of strength within 19.21 %. The closest correlation of particular values of strength was found in TSF specimens, where the average value of strength was 43.42 kgf/cm^2 (4.25 MPa). With a standard deviation of 2.91, the deviations of the particular values of strength were within 6.71 %. Statistical analysis of the particular values of strength in transverse planes confirms the obvious heterogeneity of CM specimens concerning DM and TSF.

The results of the tests (point strength distribution of the material) generally correspond to the results of the strength testing of cylindrical specimens, confirming the general trend of strength distribution over the height at each of the 3 methods. Moreover, in contrast, they provide more accurate numerical values of strength over the entire volume of the specimen.

3.3. Results of the determination of the thermal conductivity of standard specimens

The results of measurements are presented in Fig. 9, and comparisons of particular values of measurements of TSF with CM and DM specimens are presented in Fig. 10.

Thermal resistance (R_H), m$^2\cdot$°C/Wt

R_H	CM	DM	TSF
0.14	0.140	0.139	0.158
0.16	0.143	0.159	0.163
0.19	0.165	0.164	0.163
0.21	0.165	0.171	0.158
0.23	0.234	0.164	0.174

Efficient thermal conductivity (λ), Wt/m$\cdot$°C

CM	DM	TSF	λ
0.103	0.110	0.137	0.10
0.132	0.137	0.139	0.12
0.142	0.140	0.137	0.15
0.145	0.144	0.141	0.17
0.190	0.148	0.143	0.19

Figure 9. Particular values of thermal conductivity and thermal resistance.

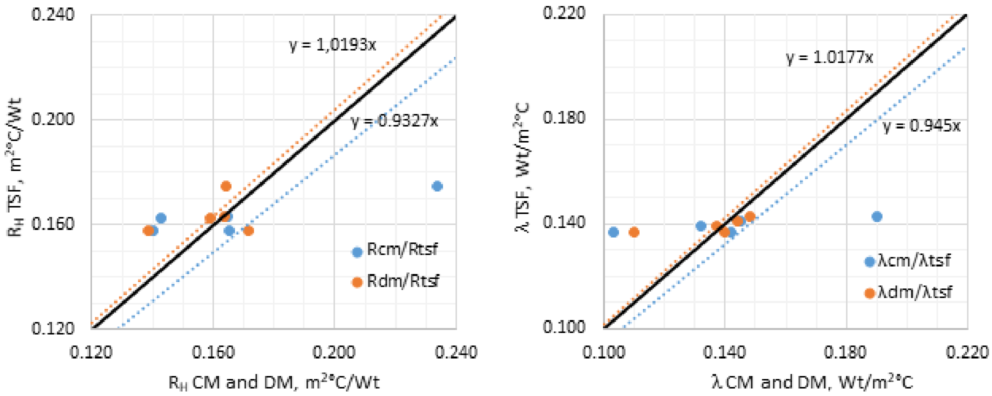

Figure 10. Comparisons of particular values of measurements.

Studies of [39] on the assessment of the thermal conductivity of foam concrete showed values comparable to those indicated in the article according to the density of specimens. The obtained results of thermal conductivity of specimens of three methods do not contradict these results. Thus, the thermal resistance values of CM specimens vary from 0.140 to 0.234 $m^2 \cdot °C/W$, of DM specimens from 0.139 to 0.171 $m^2 \cdot °C/W$, of TSF from 0.158 to 0.174 $m^2 \cdot °C/W$. Values of thermal conductivity of CM specimens vary from 0.103 to 0.190 $m^2 \cdot °C/W$, DM specimens from 0.110 to 0.148 $m^2 \cdot °C/W$, TSF – from 0.137 to 0.143 $m^2 \cdot °C/W$.

Statistical analysis of the data showed that the maximum deviation (variation coefficient) of particular values of thermal resistance (thermal conductivity) from the average for CM specimens is 22.4 % (22.0 %), and the lowest deviation for TSF specimens is 4.19 % (1.87 %). For DM specimens the deviation of thermal resistance is 7.8 %, and of thermal conductivity is 11.05 %.

Comparisons expressed by a linear function (Fig. 10) also indirectly indicate the degree of homogeneity in the structure of the specimens of compared methods. The most uniform distribution of the structure of foam concrete is observed in the specimens of TSF, and the smallest in the specimens of CM. The results of the assessment confirmed a greater dispersion of data within the height of CM and DM specimens, as compared with the specimens of TSF. The binding of the obtained thermal conductivity data to the mark of foam concrete showed the following: CM specimens are referred to the mark from the upper limit of D300 or the lower limit of D400 (upper specimens) to the average limit of D800 (lower specimens); DM specimens – from the average limit of D400 (upper specimens) to the average limit D600 (lower specimens); TSF specimens – from the upper limit of D500 (upper specimens) to the lower limit of D600 (lower specimens).

In general, the test results confirm the impact of the technological process on the homogeneity of the material, and as a consequence, the uneven distribution of its physical-mechanical properties over its volume. The results obtained have a similar trend (in terms of the distribution of physical-mechanical properties in the production of foam concrete) with the works of [34, 35, 37, 39, 40]. Nevertheless, the results obtained have creditable quantitative indicators and are more focused on a comparative evaluation of the TSF method.

4. Conclusion

1. A method for the production of foam concrete is proposed, which implies two stages of foaming: primary inclusion of a low-concentration foam mixture at the stage of preparation and secondary inclusion of a high-concentration foam mixture at the stage of producing a cellular concrete structure. Two-stage foaming provides a maximum distribution of the foam concentrate over the entire volume, as evidenced by the comparison of the results of laboratory measurements.

2. Although the selection of foam concrete composition and the ratio of foam concentrate to aggregate is designed from the condition of obtaining the material density of D600 (600 kg/m^3), the obtained specimens of comparable methods showed the results different from the given values: the density of CM by the height of specimens varies on average from 365.5 kgf/cm^3 to 840.1 kgf/cm^3, DM specimens from 528.3 kgf/cm^3 to 714.2 kgf/cm^3, and TSF specimens from 608.3 kgf/cm^3 to 669.5 kgf/cm^3.

3. Strength tests on small specimens showed that the greatest variety of particular strength values is observed in the transverse plane along with the height of the specimen. The total spread of particular strength values over the entire volume of the CM block amounted from 10 to 92 kgf/cm^2, DM block – from 38 to 54 kgf/cm^2, TSF block – from 27 to 62 kgf/cm^2. The strength values converted into a color chart (Fig. 6-8), clearly shows the different degree of homogeneity of the three methods.

4. Thermal conductivity tests on standard specimens confirmed a greater variation in the height of CM and DM specimens compared to TSF specimens, which is also an indirect assessment of material homogeneity.

5. Furthermore, the study results confirmed the impact of the technological process of foam concrete production on its quality. The proposed TSF production technology enables sufficiently even distribution of physical-mechanical properties of the material (strength and thermal conductivity) over its volume, which can be used as an indirect confirmation of the uniform distribution of the pore structure of the skeleton, and, consequently, improves the quality of the material as a construction product.

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