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Influence of the technological foam concrete manufacturing process on its pore structure

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Abstract. A two-stage foaming method of foam concrete production is proposed. The technical result of this method is aimed at improving the pore structure of the material. To assess the impact of the proposed production technology on the quality of the material, the construction properties of materials obtained by the classical method and the method of dry mineralization of foam were compared. The main assessment criterion of the quality of materials is the degree of homogeneity of foam concrete throughout the volume. Assessment of material porosity was carried out by analyzing the structure of dried specimens after soaking in water with and without colorant, as well as by pressing cylindrical specimens, segmented by height, while the assessment of material homogeneity was carried out through the analysis of discrete, particular measurements of the strength properties of the material at its height. The results of the porosity assessment gave a clear regularity of pore structure distribution of the materials of the methods compared. In general, the results of the comparison of water absorption and strength gave us an idea of the impact of technological production on the quality of foam concrete as a building product. The result of the research is the technology of foam concrete production by two-stage injection of foam: it is aimed at improving the pore structure of the material due to the uniform distribution of pores, as well as increasing the strength characteristics of the material by reducing the water-cement ratio and uniformly distributed structure of the supporting skeleton.

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1. Introduction

The relevance of the study is due to the high demand for aerated concrete in the construction market. The reasons for the great interest in the material are the characteristics of aerated concrete, its density, thermal conductivity and features of a cellular structure.

Cellular concrete is divided into aerated concrete and foam concrete [1, 2]. The main distinctive feature of these materials is their porous structure. Aerated concrete is produced by the introduction of gas-forming components, which in the process of chemical reaction with a cement binder forms a gas emission, which facilitates the formation of intercommunicating pores [10]. Foam concrete is produced by the introduction of ready foam in the cement-sand mixture, which allows obtaining a closed pore system [3, 4].

The main competitor in the market of building materials for cellular concrete are lightweight aggregate concretes such as polystyrene concrete, expanded clay aggregate (ECA) concrete, slag-concrete, and others [5–9]. Each of these materials has its advantages and disadvantages. For example, polystyrene concrete is produced using foamed polystyrene as an aggregate presented in the form of balls. The main disadvantage of polystyrene concrete is the low density of aggregates from 6 to 25 kg/m^3. Since polystyrene is much lighter than cement-sand mixture, as a result of its low density, it rushes to the surface of the mortar, resulting in uneven distribution of the aggregate in the structure of the mortar. The striving of polystyrene in the structure of concrete to the surface of the mixture creates the maximum concentration of polystyrene on the surface of the material, which leads to the formation of unstable and weak structure, easily deformed, and locally does not provide sufficient strength of the skeleton of the material as a building product. The latter also has a negative impact in the production of construction and installation works because the adhesion decreases when laying the material [10].

ECA and slag-concrete are alternative materials for cellular concrete, but the main disadvantage of these materials is the restricted density limit. The density limit of ECA concrete is from 800 to 1800 kg/m^3, which limits the use of this material. If it is necessary to reduce the density of the material to less than 800 kg/m^3, for example, to reduce the load on the supporting area of the structure, it is not possible with the ECA concrete. Therefore, the use of cellular concrete as wall structures in the construction of buildings and structures can reduce the structural load. It becomes especially relevant for high-rise construction when there is a need to reduce the load on the bases and foundations. Also, slag and ECA concrete are significantly inferior to cellular concrete in terms of thermal conductivity and soundproofing ability [11–14].

An additional advantage of using foam concrete is its technological ergonomics in the construction of building structures, and the resulting building structures of foam concrete have high thermal properties [15]. Thermophysical properties of cellular concrete open up possibilities of application of these materials in humid continental climatic conditions and in permafrost conditions [16–18]. The porous structure of the material allows to retain heat, and the use of thin-layer adhesive mortars for installation, due to the reduction of thermal bridges, allows reducing heat transfer to a minimum. No minor factor is the durability of cellular concrete in the basis of the composition of which is a cement binder and fine aggregate [19].

Despite the advantages among the analogues, one of the frequently encountered problems of foam concrete manufacturers is the instability of the structure of the foam concrete mortar, shrinkage, uneven density of the material and as a consequence, unstable strength and thermal conductivity of the product [20]. The reason for this shortcoming can be many factors, the main one of which is a high water cement ratio [21]. To solve this problem, plasticizing additives have been used. But since plasticizing additives are surface active substances (SAS), then, having received a decrease in the water-cement ratio of foam concrete manufacturers faced another problem: shrinkage of the material due to an increase in the setting time under the influence of the additive. To solve the problem with the quality of foam concrete material, many attempts were made with the use of additives accelerating curing in combination with a plasticizer. But a significant result ensuring the quality of foam concrete was not achieved [22, 23].

Despite the shortcomings of the practice of using foam concrete showed that this material deservedly takes a worthy place among the popular building materials and despite the existing technological and manufacturing shortcomings continues to develop actively.

The technology of geopolymer foam concrete production attracts a lot of research interest in construction. Its porous structure has such merits as lightweight, acoustic and thermal insulation [24]. Other technologies include fiber and special additives during technological process of foam concrete for increased compression, thermal and sound insulation [25]. But all of these technologies include some additives. the Introduction of foam concrete production technology by dry mineralization with foam was a breakthrough in the technological process of foam concrete production [26]. As a result of this technology, a number of issues concerning the quality of the pore structure and density have been solved, but the problem of shrinkage of the material in the process of setting has not been solved yet.

The unresolved problem of obtaining quality foam concrete has determined the purpose of this research work: to develop an affordable technology for the production of foam concrete, the technical result of which is aimed at improving the pore structure of the material due to the uniform distribution of pores, as well as increasing the strength characteristics of the material by reducing the water-cement ratio and uniformly distributed structure of the supporting skeleton.

The following tasks have been set to achieve this goal:

- study the theoretical features of the application of existing methods of foam concrete production;
- study the features of the formation of the structure of foam concrete in the application of various methods of its production;
- to make a comparative analysis of the methods under study.

The paper presents a comparison of methods of production of cellular concrete [27, 28], in particular, foam concrete, and the peculiarities of the technological process of preparing the material [29–32], without comparing the composition of ingredients (additives) to improve the physical, mechanical and building properties of materials. Proposed method provides better distribution of pores which enhances durability, thermal and sound insulation of products.

For comparison with the proposed method, two main methods of foam concrete production with wide practical application have been adopted:

Method 1: Classical method (CM) [26];

Method 2: Dry mineralization method (DM) [26];

Method 3: The proposed method of two-stage foaming (TSF).

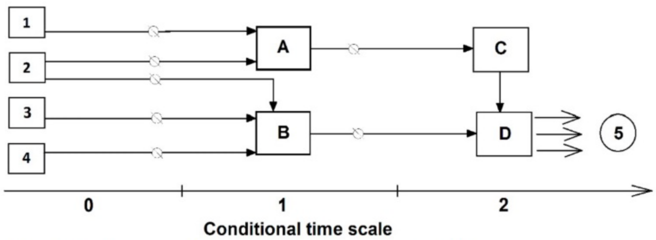
2. Materials and Methods

The research methodology includes the following stages:

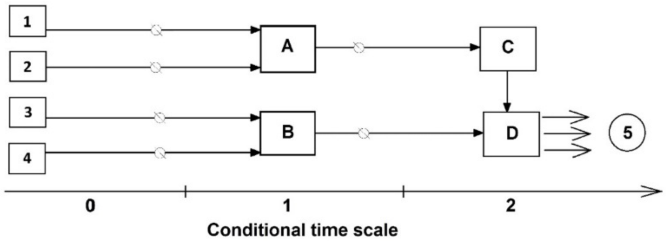
- Preparation of foam concrete using comparable methods;
- Preparation of foam concrete by the proposed method of two-stage foaming;
- Laboratory testing of foam concrete specimens;
- Analysis of results.

Preparation of foam concrete by comparable methods was carried out in laboratory conditions in accordance with standard methods, specifications and the requirements of regulatory and technical documentation [1, 33]. An important condition was to maintain the same composition of components and ingredients (additives) of specimens for each method, as well as their dimensionality. For each of 3 methods (including the proposed one) 5 blocks were prepared.

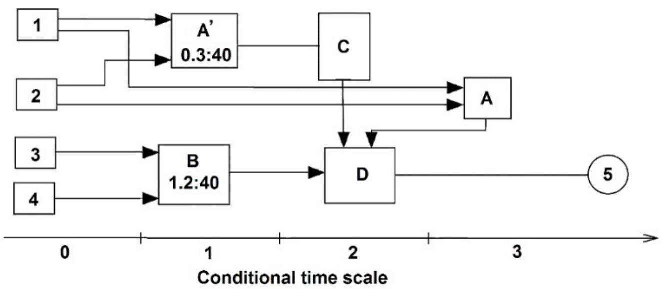
Technological processes of specimens' preparation by CM, DM and TSF are presented in Fig. 1A, 1B, and 1C respectively.



A – technological process of foam concrete preparation by CM



B – technological process of foam concrete preparation by DM



C – technological process of foam concrete preparation by TSF

Notations:

- 1 – water, 2 – foam concentrate, 3 – cement, 4 – sand, 5 – final product;
- A' – tank for low-concentration mortar of plasticizing additive of foam concentrate in water 0,3:40 l,

A – tank for modified foam concentrate mortar in water 1.2:40 l, B – cement and sand mixer, C – foam generator, D – solvent mixer.

Figure 1. Technology of foam concrete preparation by the method of two-stage foaming [33, 34].

The technological process of TSF consists of three stages. In the production process, it is necessary to follow a strict sequence of combination of components.

Stage 1: in a tank (A') foam concentrate (1) is thoroughly mixed with water (2), in a 0.3:40 l ratio to water; in parallel (independently) in a tank (A) foam concentrate (2) is thoroughly mixed with water (1), in a 1.2:40 l ratio; in parallel in a tank (B) cement (3) is mixed with sand (4), in a cement-to-sand ratio 1:3.

Stage 2: The mixture obtained in container (A') by means of foam generator (C) is transformed into foam and combined with a cement-sand mixture from container (D), in a mortar mixer (B).

Stage 3: The mixture obtained in container (A) is converted to foam by means of foam generator (C) and introduced into the solvent mixer (D).

After thorough mixing in a solvent mixer, the obtained mortar (5) is poured in the forms.

The main assessment criterion of the quality of the material prepared by different methods is the degree of its homogeneity, namely, even distribution of pores in the structure of foam concrete throughout the volume. This indicator is directly related to the technology of foam concrete production. The resulting factors of homogeneity of the material can be attributed to the homogeneity of construction properties of the material throughout the volume.

To study the homogeneity of the material, cylindrical specimens were used, which were 20 cm high, 6.4 mm in diameter, segmented by 2 cm in height (Fig. 2). Special attention is given to the height of foam concrete in terms of assessing its homogeneity because gravitational forces influence heavy ingredients (including excess water in the foam stratification) in the composition in the process of setting, which leads to uneven density of the material in volume.

Assessment of material porosity was carried out by analyzing the structure of the dried sample after soaking (up to a constant mass) in water with colorant, as well as pressing cylindrical specimens, segmented by height.

Assessment of material uniformity was carried out through the assessment of discrete, particular measurements of the strength properties of the height of the material of standard (factory) size: height of 20 cm, width of 30 cm, length of 60 cm.

Figure 2. Specimens for determining the construction properties of foam concrete.

Core cutting was carried out by means of a cylindrical crown with an electric drive with an inner diameter of 6.5 mm. To reduce the impact of mechanical action on the structure of the skeleton, the cutting was carried out with maximum rotation and minimum movement of the crown. In total, 6 specimens were taken from each compared foam block. Cutting of cylindrical and standard specimens was carried out by string cutting at maximum rotation, to reduce the risk of structural damage to the material. Prior to testing, each element of the specimen was labeled.

Laboratory testing and study of foam concrete specimens included:

- Determination of material water absorption by soaking samples with and without colorant (Fig. 3A);
- Determination of the porosity of the material by pressing it (Fig. 3B);
- Determination of the strength of solid and segmented cylindrical specimens by unconfined compression test (Fig. 3C).

Figure 3. Laboratory testing of foam concrete specimens.

Segmented cylindrical specimens were soaked to assess their water absorption. The soaking was carried out with holding out until the full absorption of water, to a constant mass (mass change did not exceed 0.1 % during 120 minutes of the observation). Specimens submerged in water at full soaking displace the volume of water commensurate with the volume of inert components, i.e., the skeleton volume of the specimen. At incomplete soaking, but maximum saturation with water, the filtration capacity of the material is revealed, which can be used to indirectly assess the structure and nature of pore distribution. This method of assessing the pore structure of foam concrete is considered acceptable because the material is made on a cement binder, the absorption of water by the material is absent.

Since water absorption implies the ability of the material to absorb (pass) water, its evaluation is reduced to comparing the values of water absorption of the material to its pore structure, expressed by the ratio of moisture at maximum water saturation of the specimen to moisture at full water saturation. Thus, the estimation of water permeability of segmented specimens is described by Eq. (1).

$$W_{\%} = \frac{m_s - m_d}{v_w \cdot \rho_w}, \quad (1)$$

where $W_{\%}$ is water absorption to pore volume ratio, %; m_s is wet specimen mass with total water absorption, g; m_d is dry specimen mass after drying to a constant mass, g; v_w is pore volume, cm^3; ρ_w is water density, g/cm^3.

When assessing the presence of communicating pores, green and red colorants were added to the water for greater contrast. After drying, samples were cut through the middle part to analyze the cross-sectional coloration of the material and to assess the capacity of the foam concrete. To ensure maximum access to the surface area for improved wetting and liquid penetration, the specimens were hanged. After achieving maximum soaking, the specimens were dried to a constant mass (mass change did not exceed 0.1 % during 30 minutes of observation). To assess the effect of the colorant on water penetration (after coloring), the results were corrected with respect to water permeability of specimens when soaked with water without colorant. The difference in masses of wetted specimens with the colorant and without one served as an assessment of the influence of the colorant on the water permeability, and the different nature of their distribution by height testified for the different degree of homogeneity in the pore structure of the specimens of the compared methods.

Determination of water permeability of specimens of three methods is made by calculating the ratio of volumes of displaced water when soaked with colorless water to actual volumes of pores obtained by pressing (average density of specimens).

Material porosity was assessed by pressing the specimens. When pressing foam concrete, the pore structure of the material is destroyed, the inert aggregate of the material is compressed in volume, releasing the pores. The pressing was carried out on the equipment Press Automatic Pilot, with a total compressive load of 500 kN (50 tons). The lower strength limit of D600 foam concrete specimens is 4.2 MPa, and the upper one is 6.4 MPa. Since the specimens are subject to 25 times of maximum compressive strength of the specimen (160 MPa) with triple sequential pressing, the condition of pore release close to the maximum was accepted. Therefore, the difference in specimen volume before and after pressing will be equal to the pore volume.

Both monolithic and segmented specimens were tested. Monolithic specimens were tested using strain gauges to obtain accurate stress distribution results in the specimens compression. The results obtained were used to assess the test results of segmented specimens.

The segmented specimens were used to assess the less robust part of the specimen by height. Segments of one specimen were tested simultaneously. Since the specimens were mechanically subjected to cutting, the specimen surface had 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, supple gaskets made of nonwoven geotextile were used (Interstate standard GOST 8462-85, n.d.). The use of gaskets also simulated the tangential stresses at the contact edge of segments, which are inherent to a solid, monolithic specimen, when it is compressed.

Segmented specimens were tested until the specimens were completely broken, and strength measurements were made using two control readings:

A is registration of the load value, when breaking at least one segment, in order to identify the weakest area by the height of the specimen;

C is registration of the peak value of load to measure the maximum strength of the specimen as a product.

3. Results and Discussion

3.1. Results and discussion of determining water absorption

The homogeneity analysis of the specimen structure according to three methods was performed by estimating the ratios of particular values of water absorption of segmented specimens by its height (Fig. 4). The greater is the difference of particular values of water absorption of segments, the greater is the heterogeneity of the material by specimen height [35].

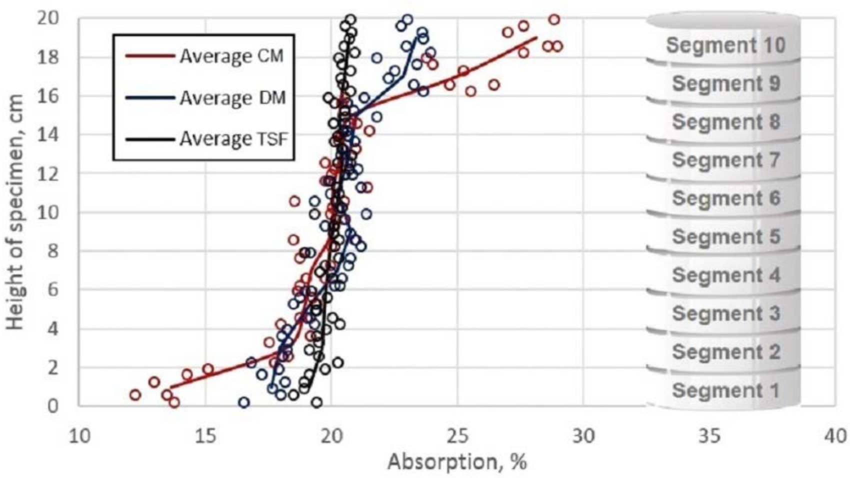


Figure 4. Change in water absorption across sample heights.

The largest difference was observed in CM specimens, the maximum values of water absorption were found in the upper segments, ranging from 56 to 69 %. Minimal water absorption was found in the lower segments, ranging from 7.3 to 9.7 %. The average particular values of water absorption were 63.5 % in the upper segments and 8.68 % in the lower segments. The squared deviation of particular values was 4.89 for the upper specimens and 0.86 for the lower ones, and the average value of the squared deviation in height of the specimens was 15.31. The deviations of particular values did not exceed 7.7 % for the upper segments (in the upper horizontal plane of the block) and 9.9 % for the lower segments (in the lower horizontal plane of the block); the deviations of particular values by height (in the vertical plane of the block) was 62.1 %. Consequently, the homogeneity of CM specimens, which was assessed by the ability of the material to absorb water, has a better distribution in the horizontal direction than in the vertical one. Maximum values of water absorption for DM specimens ranged from 28 to 33 % in the upper segments, the minimum values ranged from 13 to 16 % in the lower segments. Deviations of particular values did not exceed 5.82 % for the upper segments and 6.61 % for the lower segments; deviations of particular values by height (in the vertical plane of the block) were 23.9 %. DM specimens had a better distribution in the horizontal direction than in the vertical one; however, in comparison with CM, they had a smaller spread in both directions. Water absorption of TSF specimens was ranging from 21 to 23 % for the upper segments and from 17 to 19 % for the lower segments. Deviations of the upper specimens did not exceed 2.23 %, the lower ones did not exceed 3.96 %, and deviations of particular values by height (in the vertical plane of the block) were 7.57 %. TSF specimens have lower dispersion of water absorption values in both directions in comparison with CM and DM specimens, therefore, better homogeneity in both horizontal and vertical planes.

The analysis of structure homogeneity was also performed by the ratio of specimen moisture at maximum water absorption to specimen moisture at full water absorption (100 % saturation of the pore structure with water), Fig. 5. The percentage ratio of the volume of water-filled pores to the volume of pores indirectly testified for the quality indicators of the pore structure of the material (different pore size, presence of communicating pores, etc.).

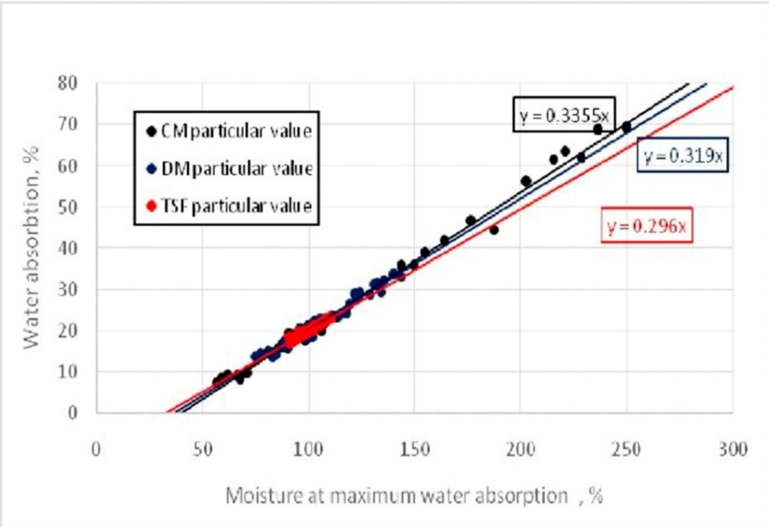


Figure 5. Assessment of absorption capacity.

According to the diagram, the maximum average absorption capacity was found in CM specimens (33.5 %), the lowest in TSF specimens (29.6 %). Comparing particular values, we obtained that CM specimens have a range of values from 12.24 % (lower segments) to 28.98 % (upper segments), which indicates a large difference in pore structure between the upper and lower segments. The range of values of DM specimens is in the range from 16.54 % to 23.97 %. The most homogeneous pore structure is in the TSF specimens, which values are in the range from 18.16 % to 20.94 %. It is possible to estimate the local heterogeneity of the pore structure within the segments of the same density located on one horizontal plane by comparing particular values of water absorbing capacity by material density. Thus, specimens of CM showed heterogeneity within 10 %, specimens of DM within 18 %, and specimens of TSF – 16 %. The CM specimens showed more stable results, however, more data are required for a complete statistical analysis of the local heterogeneity.

Fig. 6 shows the comparison of water absorption of the three methods, expressed by the ratio of particular values of TSF to CM and DM $\left(W_{TSE}/W_{CM},\ W_{TSFF}/W_{DM}\right)$.

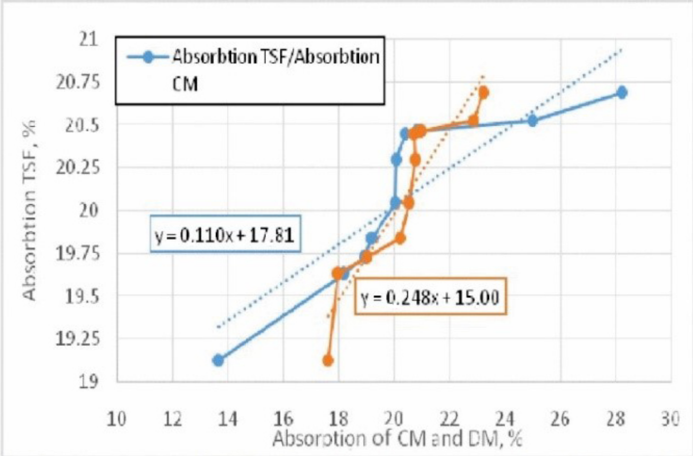


Figure 6. Comparison of particular values of water absorption of three methods.

According to the diagram, the difference in particular values of water absorption of TSF and CM specimens is from 0.73 (for the upper segments the difference in particular values is 73 %) to 1.40 (for the lower segments, the difference is 140 %). The difference between the values of TSF and DM specimens is from 0.89 (89 % for the upper segments) to 1.09 (109 % mainly for the lower segments). The results of comparisons showed that the greatest convergence of particular values of water absorption was for the TSF to DM ratio, in contrast to the comparison with CM, which confirmed the lowest homogeneity of CM specimens.

Fig. 7 shows the results of quality assessment of the pore structure of specimens made soaking them in water with colorant. Fig. 7a shows the sections of the most saturated specimens of the three methods after their drying to achieve maximum saturation. Fig. 7b shows the correction factors for the influence of the colorant on the absorbing capacity of specimens.

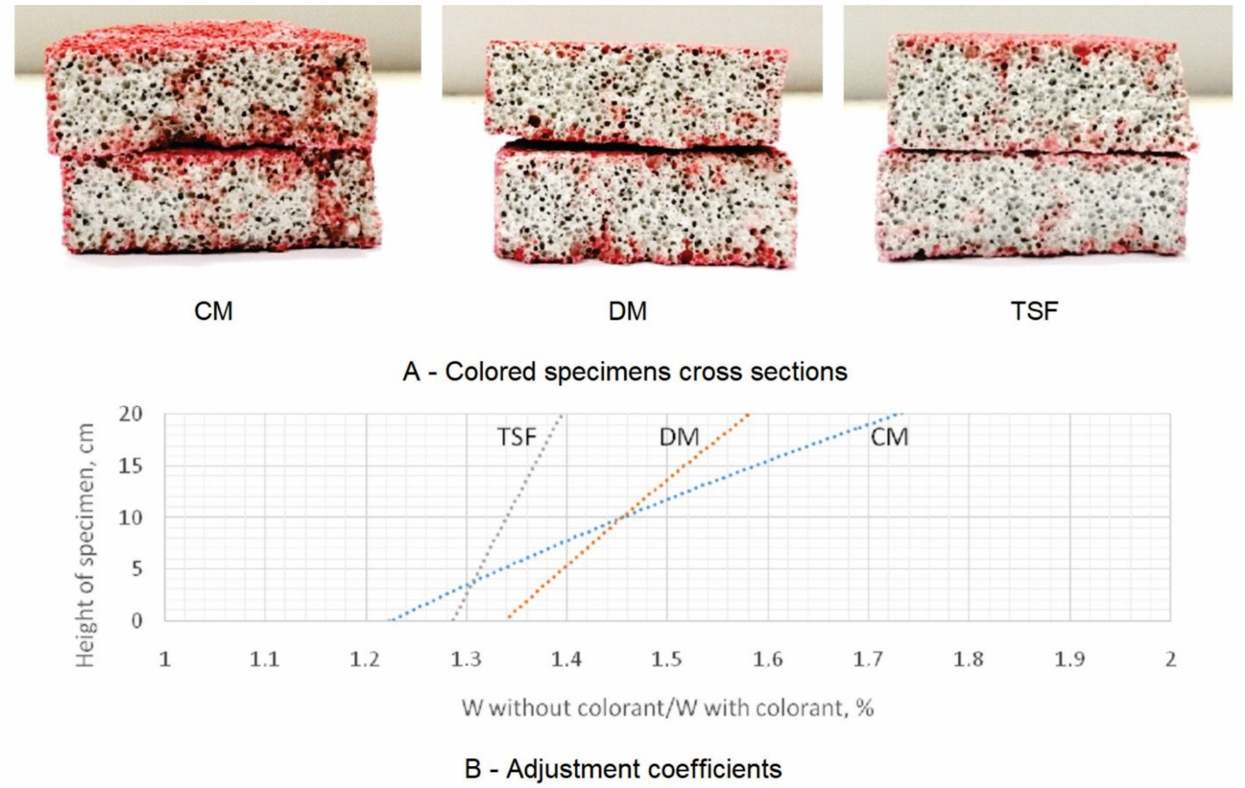


Figure 7. Comparison of specimens soaked in the colorant.

Visually, the greatest absorption is observed in CM samples, in the TSF and DM specimens, the absorption is within comparable ranges. After drying, all specimens have 100 % color of the contact zone (surface), which indicates a sufficiently reliable coloration of the material to assess the internal structure of the specimen. The internal structure of CM specimens had large local coloration areas in the cross-section (as compared to TSF and DM), which indirectly may indicate a greater number of communicating pores in CM specimens. In contrast, TSF and DM specimens demonstrated point-like coloration of the internal structure, which indicates a lower degree of the presence of communicating pores. Comparing the dynamics of changes in height adjustment coefficients of the specimens, heterogeneity of the material can be deduced, because infiltration (except for the factor of communicating pores) is proportional to the pore size. In other words, if conditionally the quality of the communicating pores is identical, water absorption will be limited by the total volume of open surface pores.

3.2. Results of determining water absorption

Fig. 8 shows the results of density estimation of materials of three methods by height of specimens. The maximum density was observed in the lower segments of CM specimens, with an average density of 840 kg/m^3. The minimum density value was on average 365 kg/m^3, also observed in the specimens of CM, mainly in the upper segments. The density of DM specimens by height varied from 528 kg/m^3 (lower segments) to 630 kg/m^3 (upper segments), and in TSF specimens, from 608 kg/m^3 (lower segments) to 635 kg/m^3 (upper segments). As for the height, CM specimens were represented by grades of foam concrete from D350 to D800, DM specimens – from D500 to D600, and TSF specimens – D600.

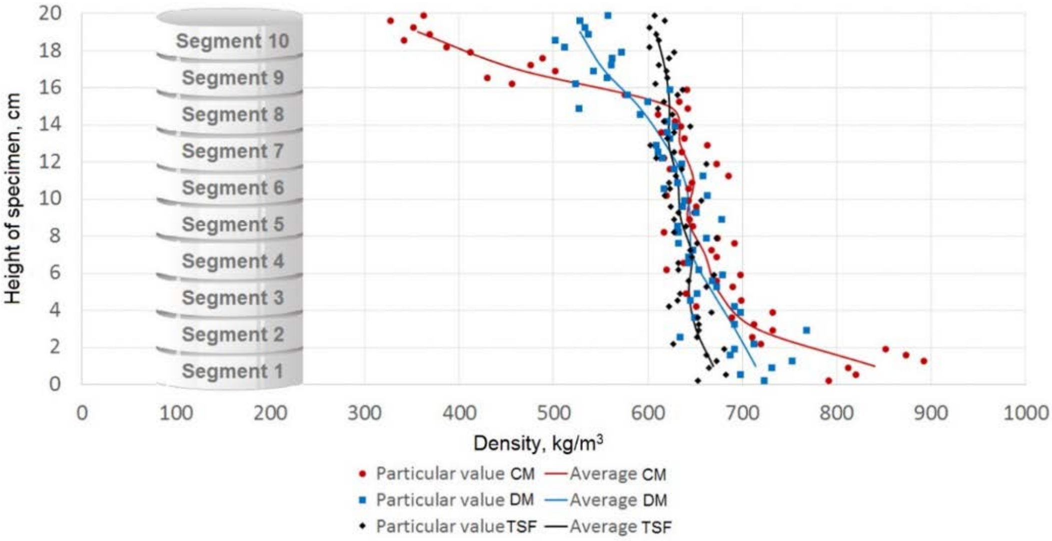


Figure 8. Comparison of specimen densities.

The degree of homogeneity in terms of material density by height of CM specimens was from 56.9 to 65.7 %, with a standard deviation of 125.8. For DM specimens the degree of homogeneity in height made up from 83.9 to 86.6 %, at a standard deviation of 55.6. The degree of homogeneity of TSF specimens was from 94.5 to 95.8 %, at the standard deviation of 17.2. Comparing particular values of density in the horizontal plane, we obtained: the degree of homogeneity of CM specimens was from 89.4 to 97.3 %, with the heterogeneity observed from a height of 16 mm, DM specimens from 89.2 to 97.8 %, with the maximum heterogeneity observed at a height of 14–16 mm, the degree of homogeneity of TSF was not less than 96.2 %. Thus, the compared methods had equally acceptable homogeneity in the horizontal direction in comparison with their homogeneity in height, where the worst is the specimen of CM [4].

3.3. Results and discussions of strength determination of segmented cylindrical specimens by unconfined compression test

The results of strength tests of monolithic and segmented specimens are shown in Fig. 9. Maximum values of monolithic strength were shown by TSF and DM specimens, on average: strength of TSF exceeded strength of CM by 6.7 %, and strength of DM by 6.1 %. In general, individual values of monolithic strength of the three methods were closely related and lay within the following ranges: from 4.25 to 5.87 MPa for CM, from 4.56 to 5.76 MPa for DM, and from 4.65 to 5.72 MPa for TSF. Average values of monolithic strength were: 4.89 MPa for CM, 5.21 MPa for DM, and 5.25 MPa for TSF.

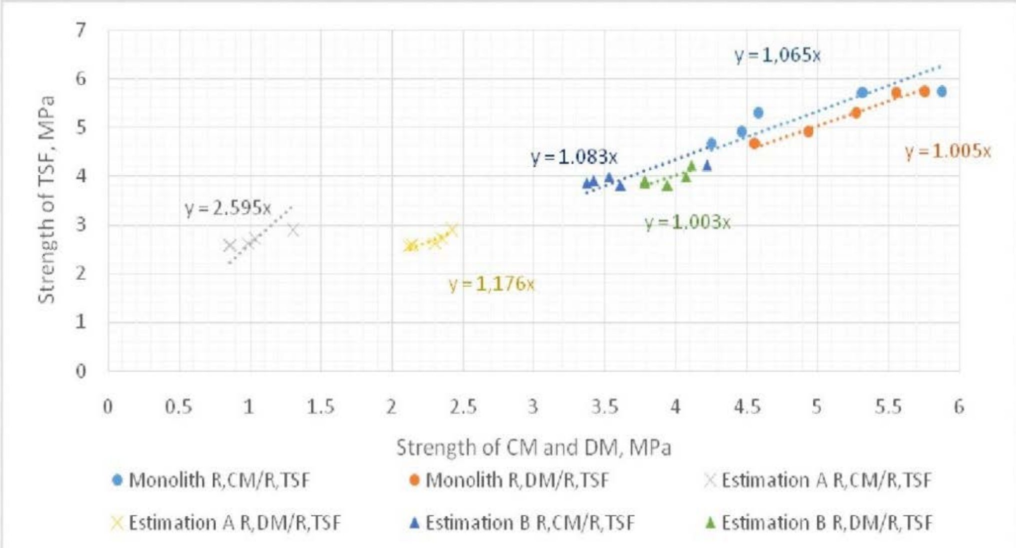


Figure 9. Strength test results.

In comparison of A, assessment values (identification of the weakest area by specimen height) also were expressed by the ratio of particular strength values of TSF specimens to CM and DM. According to the test results, the particular values of strength of the weakest segments of CM specimens varied from 0.85 to 1.31 MPa, which corresponds to the average value of foam concrete strength grade of D350. This means that all five CM specimens had weaker segments in height, the density of which did not exceed 350 kg/m^3. Particular values of strength of the weakest segments of DM specimens varied from 2.12 to 2.44 MPa, which corresponds to the average value of strength of foam concrete grade of D400. Strength of TSF segments varied from 2.57 to 2.87 MPa, which corresponds to the upper limit of strength of D400 grade foam concrete. Comparing the standard deviations of the obtained results on the strength of three methods (equal for CM specimens – 0.181, DM – 0.131, TSF – 0.122), it can be deduced that the greatest variation of the particular strength values was found in CM specimens. The smallest standard deviation was observed in the specimens of TSF, which indicates the maximum concentration of particular values of strength around the arithmetic mean of particular values. The ultimate deviations of particular values of were 17.8 % for CM specimens, 5.74 % for DM specimens and 4.57 % for TSF specimens, which indicates the heterogeneity of CM material in terms of strength in the horizontal plane (not only in the vertical plane).

In general, the assessment results showed that CM and DM specimens had a greater variation in height than TSF specimens. The weakest parts of the CM specimen were mainly the two upper segments 9 and 10 (Fig. 10A), with an average load of 2.8 kN, which corresponds to a strength of 1.01 MPa. The weakest parts of DM specimens were located in the upper part of the specimen, mainly in the three upper segments 8, 9 and 10 (Fig. 10B), with an average load value of 6.4 kN, which corresponds to a strength of 2.27 MPa. The lowest segment 4 (Fig. 10C) was not found in TSF specimens with an average load of 7.6 kN, which corresponds to a strength of 2.67 MPa.

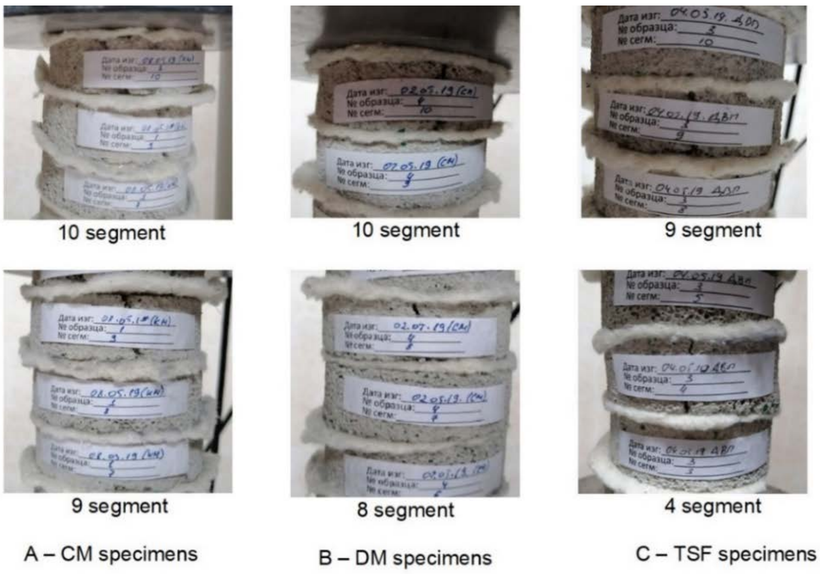


Figure 10. Weakest specimen segments.

In assessment B (maximum strength measurement) of CM and partially DM specimens, the tests were continued after removal of broken upper segments, otherwise, the peak load value would have been limited by the breakage of weak specimens due to the low value of their strength relative to other segments. In general, the values of maximum strength of the three methods are close to each other. The average value of maximum strength of CM specimens was 3.63 MPa, which corresponds to the average value of D500 grade foam concrete. DM and TSF specimens showed the strength of 3.93 and 3.95 MPa respectively, which corresponds to the upper limit of D500 grade.

Despite the fact that 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 segmented specimens of the compared methods showed different results from the given values. The resultant factor of distortion of the results is the non-standard dimensionality of specimens and the fact that the specimens had no integral structure. But since all specimens were tested under the same conditions, the results may differ slightly from the actual 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 expressed not by particular values, but by their ratio. Moreover, the obtained regularity of the ratio of strength parameters of the compared methods corresponds to the results of tests of monolithic specimens, therefore, tests of segmented specimens are suitable for qualitative evaluation of the strength distribution of the compared methods [20]. The results of strength showed high values compared with other technologies with and without additives, where the results were within 0.96–1.44 MPa [36, 37].

4. Conclusions

1. The resulting factor in the quality of foam concrete, with the same quality of components and ingredients, is the technological process of its production, as evidenced by the results of comparison of three methods of production: the classical method, the method of dry mineralization and the proposed method of two-stage foaming.

2. Evaluation of the homogeneity of the material was reduced to an analysis of its pore structure in volume, so the basis was taken as a discrete study of its local areas. Thus, the results of ratios of particular values of water absorption of segmented specimens by their height showed the degree of homogeneity of the compared methods: the maximum values of water absorption were found in CM samples (variation was from 7.3 to 69 %), the average values were in DM specimens (from 13 to 33 %), and the minimum values were in TSF (from 17 to 23 %). Consequently, TSF specimens have the maximum degree of homogeneity in height, because the greater the difference in particular values of water absorption of segments in height, the greater the difference in pore structure of individual segments.

3. Visual assessment of coloration of the internal structure of the specimens during soaking showed that the internal structure of CM specimens had large local areas of coloration in the cross-section (compared with TSF and DM), which may indirectly indicate a greater number of communicating pores in CM specimens. In contrast, TSF and DM specimens demonstrated point-like coloration of the internal structure, which indicates a smaller number of communicating pores.

4. The direct method of homogeneity was estimated by comparison of the obtained density values. In general, the density analysis showed that all the specimens of compared methods have the same acceptable homogeneity in the horizontal direction in comparison with their homogeneity in height, where the CM specimen performed the worst: with respect to height, CM specimens were represented by D350 to D800 grades of foam concrete (density from 350 to 800 kg/m^3), DM specimens – from D500 to D600 (from 500 to 600 kg/m^3), TSF specimens – from D600 to D600 (from 500 to 600 kg/m^3).

5. Comparisons of strength of monolithic specimens showed close results: 4.89 MPa, 5.21 MPa and 5.25 MPa for CM, DM and TSF specimens, respectively. The reason, albeit minor, for the difference is the dispersion of strength parameters by height and, as a consequence, the presence of weaker segments. The strength of the weakest segments: 0.85MPa for CM, 2.27 MPa for DM, and 2.67 MPa for TSF.

6. In general, the findings of the study confirmed the impact of the technological process of foam concrete production on its quality. The proposed production technology allows improving the pore structure of the skeleton due to the uniform distribution of pores, and as a consequence, increase the strength, physical and mechanical characteristics of the material as a product.

References

1. Kurweti, A., Chandrakar, R. Specification and Quality Control of Light Weight Foam Concrete. 2017. 5. 7.
2. Russian State Standard Gost|Official Regulatory Library – GOST 25485-2019 Available online: https://www.russiangost.com/p-375403-gost-25485-2019.aspx
3. Mohammed, J.H.; Hamad, A.J. Materials, Properties and Application Review of Lightweight Concrete. 2014, 37, 6.

4. Nguyen, T.T., Bui, H.H., Ngo, T.D., Nguyen, G.D., Kreher, M.U., Darve, F. A Micromechanical Investigation for the Effects of Pore Size and Its Distribution on Geopolymer Foam Concrete under Uniaxial Compression. Engineering Fracture Mechanics. 2019. 209. Pp. 228–244. DOI: 10.1016/j.engfracmech.2019.01.033
5. Babu, D.S., Ganesh Babu, K., Tiong-Huan, W. Effect of Polystyrene Aggregate Size on Strength and Moisture Migration Characteristics of Lightweight Concrete. Cement and Concrete Composites. 2006. 28. Pp. 520–527. DOI: 10.1016/j.cemconcomp.2006.02.018
6. Berndt, M.L. Properties of Sustainable Concrete Containing Fly Ash, Slag and Recycled Concrete Aggregate. Construction and Building Materials. 2009. 23. Pp. 2606–2613. DOI: 10.1016/j.conbuildmat.2009.02.011
7. Pioro, L.S., Pioro, I.L. Production of Expanded-Clay Aggregate for Lightweight Concrete from Non-Selfbloating Clays. Cement and Concrete Composites. 2004. 26. Pp. 639–643. DOI: 10.1016/S0958-9465(03)00103-3
8. Yang, K.-H., Song, J.-K., Lee, J.-S. Properties of Alkali-Activated Mortar and Concrete Using Lightweight Aggregates. Materials and Structures. 2010. 43. Pp. 403–416. DOI: 10.1617/s11527-009-9499-6
9. Arellano Aguilar, R., Burciaga Díaz, O., Escalante García, J.I. Lightweight Concretes of Activated Metakaolin-Fly Ash Binders, with Blast Furnace Slag Aggregates. Construction and Building Materials. 2010. 24. Pp. 1166–1175. DOI: 10.1016/j.conbuildmat.2009.12.024
10. Cadere, C.A.; Barbuta, M.; Rosca, B.; Serbanoiu, A.A.; Burlacu, A.; Oancea, I. Engineering Properties of Concrete with Polystyrene Granules. Procedia Manufacturing. 2018. 22. Pp. 288–293. DOI: 10.1016/j.promfg.2018.03.044
11. Bogas, J.A., de Brito, J., Figueiredo, J.M. Mechanical Characterization of Concrete Produced with Recycled Lightweight Expanded Clay Aggregate Concrete. Journal of Cleaner Production. 2015. 89. Pp. 187–195. DOI: 10.1016/j.jclepro.2014.11.015
12. Shafigh, P., Ghafari, H., Mahmud, H. Bin, Jumaat, M.Z. A Comparison Study of the Mechanical Properties and Drying Shrinkage of Oil Palm Shell and Expanded Clay Lightweight Aggregate Concretes. Materials & Designю 2014. 60. Pp. 320–327. DOI: 10.1016/j.matdes.2014.04.001
13. Committee, C. Specification for Slag Cement for Use in Concrete and Mortars; ASTM International;
14. Jiang, Y., Ling, T.-C., Shi, C., Pan, S.-Y. Characteristics of Steel Slags and Their Use in Cement and Concrete – A Review. Resources, Conservation and Recycling. 2018. 136. Pp. 187–197. DOI: 10.1016/j.resconrec.2018.04.023
15. Mikulica, K., Hájková, I. Testing of Technological Properties of Foam Concrete. Materials Science Forum. 2016. 865. Pp. 229–233. DOI: 10.4028/www.scientific.net/MSF.865.229
16. Stolz, J., Boluk, Y., Bindiganavile, V. Mechanical, Thermal and Acoustic Properties of Cellular Alkali Activated Fly Ash Concrete. Cement and Concrete Composites. 2018. 94. Pp. 24–32. DOI: 10.1016/j.cemconcomp.2018.08.004
17. Awwad, T., Shakhmov, Zh.A., Lukpanov, R.E., Yenkebayev, S.B. Experimental Study on the Behavior of Pile and Soil at the Frost Condition. Sustainability Issues for the Deep Foundations. GeoMEast 2018. Sustainable Civil Infrastructures. Springer, Cham. DOI: 10.1007/978-3-030-01902-0_7
18. Wu, H.; Liu, J.; Zhang, X. Feasibility Study on Use of Cellular Concrete for Air Convection Embankment on Permafrost Foundations in Fairbanks, Alaska. Transportation Geotechnics. 2020. 22. 100317. DOI: 10.1016/j.trgeo.2020.100317
19. Shakhmov, Z.A., Zhussupbekov, A.Z. Frost Susceptibility of Soil and In-Situ Monitoring of Frost Depth in Construction. Proceedings of the 15th Asian Regional Conference on Soil Mechanics and Geotechnical Engineering, ARC 2015: New Innovations and Sustainability; 2015.
20. Grinfeld, G.I., Gorshkov, A.S., Vatin, N.I. Tests Results Strength and Thermophysical Properties of Aerated Concrete Block Wall Samples with the Use of Polyurethane Adhesive. Advanced Materials Research. 2014. 941–944. Pp. 786–799. DOI: 10.4028/www.scientific.net/AMR.941-944.786
21. Hilal, A.A., Thom, N.H., Dawson, A.R. Failure Mechanism of Foamed Concrete Made with/without Additives and Lightweight Aggregate. Journal of Advanced Concrete Technology. 2016. 14. Pp. 511–520. DOI: 10.3151/jact.14.511
22. Nambiar, E.K.K., Ramamurthy, K. Shrinkage Behavior of Foam Concrete. Journal of Materials in Civil Engineering. 2009. 21. Pp. 631–636. DOI: 10.1061/(ASCE)0899-1561(2009)21:11(631)
23. Sun, C., Zhu, Y., Guo, J., Zhang, Y., Sun, G. Effects of Foaming Agent Type on the Workability, Drying Shrinkage, Frost Resistance and Pore Distribution of Foamed Concrete. Construction and Building Materials. 2018. 186. Pp. 833–839. DOI: 10.1016/j.conbuildmat.2018.08.019
24. Dhasindrakrishna, K., Pasupathy, K., Ramakrishnan, S., Sanjayan, J. Progress, Current Thinking and Challenges in Geopolymer Foam Concrete Technology. Cement and Concrete Composites. 2021. 116. 103886. DOI: 10.1016/j.cem-concomp.2020.103886
25. Liew, A.C.M. New Innovative Lightweight Foam Concrete Technology. In Use of Foamed Concrete in Construction. Conference Proceedings; Thomas Telford Publishing, 2005. Pp. 45–50. ISBN: 978-0-7277-4031-1.
26. Technological Parameters Influence on the Non-Autoclaved Foam Concrete Characteristics: AIP Conference Proceedings: Vol. 1800. No. 1 Available online: https://aip.scitation.org/doi/abs/10.1063/1.4973028
27. Chica, L., Alzate, A. Cellular Concrete Review: New Trends for Application in Construction. Construction and Building Materials. 2019. 200. Pp. 637–647.
28. Vardhan, R., Chandel, S., Sakale, R. Study of Cellular Light Weight Concrete. International Journal for Scientific Research and Development. 2016. Vol. 4. No. 07.
29. Amran, Y.H.M., Farzadnia, N., Abang Ali, A.A. Properties and Applications of Foamed Concrete; a Review. Construction and Building Materials. 2015. 101. Pp. 990–1005. DOI: 10.1016/j.conbuildmat.2015.10.112
30. Vine-Lott, K. Apparatus and Method for Producing Foamed Materials 1992.
31. Dunton, H.R., Rez, D.H. Apparatus and Method to Produce Foam, and Foamed Concrete 1988.
32. Ramamurthy, K., Kunhanandan Nambiar, E.K., Indu Siva Ranjani, G. A Classification of Studies on Properties of Foam Concrete. Cement and Concrete Composites. 2009. 31. Pp. 388–396. DOI: 10.1016/j.cemconcomp.2009.04.006
33. Interstate Standard, G. 21520-89. Small-Sized Wall Blocks of Cellular Concrete.
34. Lukpanov, R.E., Dyussembinov, D.S., Utepov, Ye.B., Bazarbayev, D.O., Tsygulyov, D.V., Yenkebayev, S.B., Shakhmov, Zh.A. Homogeneous pore distribution in foam concrete by two-stage foaming. Magazine of Civil Engineering. 2021. 103(3). Article No. 10313. DOI: 10.34910/MCE.103.13
35. Raj, A., Sathyan, D., Mini, K.M. Physical and Functional Characteristics of Foam Concrete: A Review. Construction and Building Materials. 2019. 221. Pp. 787–799. DOI: 10.1016/J.CONBUILDMAT.2019.06.052

36. Hilal, A.A., Thom, N.H., Dawson, A.R. On Entrained Pore Size Distribution of Foamed Concrete. Construction and Building Materials. 2015. 75. Pp. 227–233. DOI: 10.1016/j.conbuildmat.2014.09.117

37. Steshenko, A.B., Kudyakov, A.I., Ryabtseva, N.E. Cement Based Foam Concrete with Hardening Accelerators. IOP Conf. Ser.: Mater. Sci. Eng. 2020. 911. 012003. DOI: 10.1088/1757-899X/911/1/012003

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