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Article

Study of the pore structure of foam concrete using a two-stage foaming method

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Abstract. This study presents an in-depth analysis of the pore structure in foam concrete, manufactured using a novel two-stage foam introduction method, with a comparative assessment against traditional foam concrete. Pore structure evaluation was conducted through visual-instrumental inspection and measurements of pore areas in segmented samples, including upper, middle, and lower segments. The results indicate that the proposed foam introduction method Type 1 results in a more stable pore structure distribution compared to classical foam concrete Type 2. In the upper segment, Type 1 samples exhibit an average pore content of 28.977%, while Type 2 samples show 36.112%. Similarly, in the middle segment, Type 1 samples display 27.147%, and Type 2 samples demonstrate 28.410%. The lower segment of Type 1 samples displays 24.054%, with Type 2 samples showing 22.136%. The differences in pore volumes between the lower and upper segments are 12% for Type 1 and 27.11% for Type 2, demonstrating a significant variation in the quality of the pore structure. This research sheds light on the advantages of the proposed two-stage foam introduction method in enhancing the stability and quality of foam concrete's pore structure, with potential implications for its use in various construction applications.
Keywords: foam, foam concrete, two-stage foaming, pore structure, injection.

1. Introduction

One of the primary driving forces behind the development of construction is the invention and implementation of new materials and production technologies, including innovations in concrete technology [1-3]. This article examines the modernization of the technological process for producing foam concrete, a type of lightweight concrete. Currently, a significant portion of lightweight concrete used in construction is composed of aerated concrete (or aerated concrete blocks), primarily due to the relative simplicity of its production compared to foam concrete.

When comparing foam concrete with aerated concrete, as offered in the market, the proposed foam concrete presents several logical advantages:

- It allows for the production of monolithic structures on the construction site, unlike aerated concrete. This is because aerated concrete expands during the hardening process, making it challenging to maintain precise geometric dimensions for construction elements, which are crucial for quality and reliability [4].

- Horizontal structures made of monolithic foam concrete can be easily produced, while doing so with aerated concrete is labor-intensive and not cost-effective. This is because aerated concrete blocks are assembly elements without reinforcement, and they are not designed to withstand significant lateral stresses [5].

- When comparing foam concrete and aerated concrete with equal strength, a structure, such as a wall, made of monolithic foam concrete was exhibit higher compressive and tensile strength than a structure made of assembled aerated blocks. In the case of compression, the distribution of stress and deformation in monolithic foam concrete is more uniform, unlike aerated blocks, and in the case of tension, the strength of aerated blocks is limited by the adhesive bond.

- The monolithic nature of foam concrete provides the construction with greater stability compared to assembled aerated blocks. It improves the resistance of the structure to bending in both the plane and out of the plane [6].

- The ability to perform spatial reinforcement of load-bearing foam concrete structures expands the range of applications for the material compared to assembled aerated blocks [7].

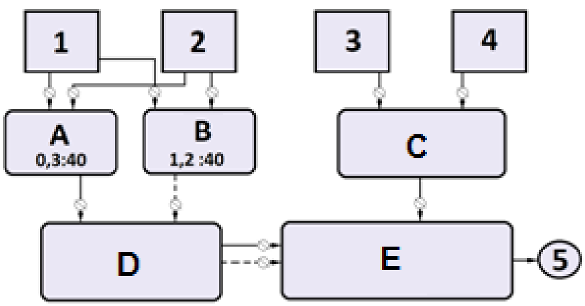
One drawback of foam concrete is the relatively complex assembly of structures, which requires additional formwork. However, with established serial production, this drawback is offset by the complexity of masonry work with aerated blocks and the need for longitudinal reinforcement of the assembly, which is not provided in the aerated block structure (i.e., manual groove cutting is required in aerated blocks) [8].

Undoubtedly, foam concrete has certain advantages over aerated concrete, such as a closed pore structure, which makes it stronger due to a more robust skeleton structure. It also offers relative durability, given the presence of cementitious binding components, as opposed to aerated concrete that includes lime-gypsum binding, which is less resistant to mechanical stress, especially exposure to water. However, these advantages remain theoretical since, under otherwise identical conditions (material reliability and durability), the simplification of the production process becomes the prevailing advantage.

This article was present research on the durability of the proposed foam concrete production method compared to the classical method [9].

2. Methods

The proposed method for producing foam concrete, as opposed to the classical method, involves a two-stage introduction of foam. The initial introduction of a low-concentration foam solution takes place during the preparation of the sand-cement mixture, thereby improving its workability and reducing the water-cement ratio (thus minimizing foam quenching by water) [10]. Subsequently, during the secondary introduction of a high-concentration foam solution in the foam concrete structure manufacturing stage, the reduction in the water-cement ratio allows for maximum preservation of the initial foam concentrate multiplicity and contributes to the formation of a uniform porous material structure. Figure 1 presents a schematic representation of the foam concrete production process using the proposed method.



A - container for low-concentrated solution of plasticising foam concentrate additive in water 0,23:85 l; B - container for solution of modified foam concentrate in water 1,2:40 l; C - cement-sand mixer; D - foam generator; E - mortar mixer; ⦸ - dosing unit; ⟶ - primary foam injection; - - → - secondary foam injection.

Figure 1 – Foam concrete production scheme

To assess the pore structure of foam concrete, research involving direct and indirect tests was conducted. Direct evaluation of the pore structure included a visual examination of pores on the sample surface (Figure 2), both before and after strength testing. Inspection of samples before failure was carried out by tapping opposite faces of cubic-shaped samples, and after failure, by examining the internal fracture surfaces [11]. The comparative criterion used was an indicator characterizing the ratio of the pore area to the area of the inspected section (hereafter referred to as the porosity coefficient). Indirect methods for assessing pore distribution included tests of strength and density [12]. The difference in sample densities provided a quantitative assessment of the material's pore structure. Since the composition of the samples was identical for both methods, lower density would indicate a greater number of pores in the sample. The difference in strengths, in turn, indirectly characterized the quality of the pore structure of the samples, where the result could be influenced not only by the size of the pores but also by their uniform distribution and the presence of micropores in the skeleton walls [13].

To determine the porosity coefficient, the following operations were performed:

- photographs of sections of foam concrete samples were taken, using pre-marked areas.

- the photographs were converted into a graphic editor for digital counting of the total pore area within the marked sections.

Immediately before inspecting the samples (blocks), the areas to be examined were marked (9 sections) in terms of both height and width of the sample (3 sections of 5x5 cm at each height). The height gradation was associated with an assessment of potential non-uniform pore distribution along the sample's height due to more substantial foam quenching at the lower part. AutoCAD was used as the graphic editor. To calculate the pore area, the inspected area was first scaled to match real dimensions. Then, all pore contours on the section were traced using isolines, followed by automated area calculations.

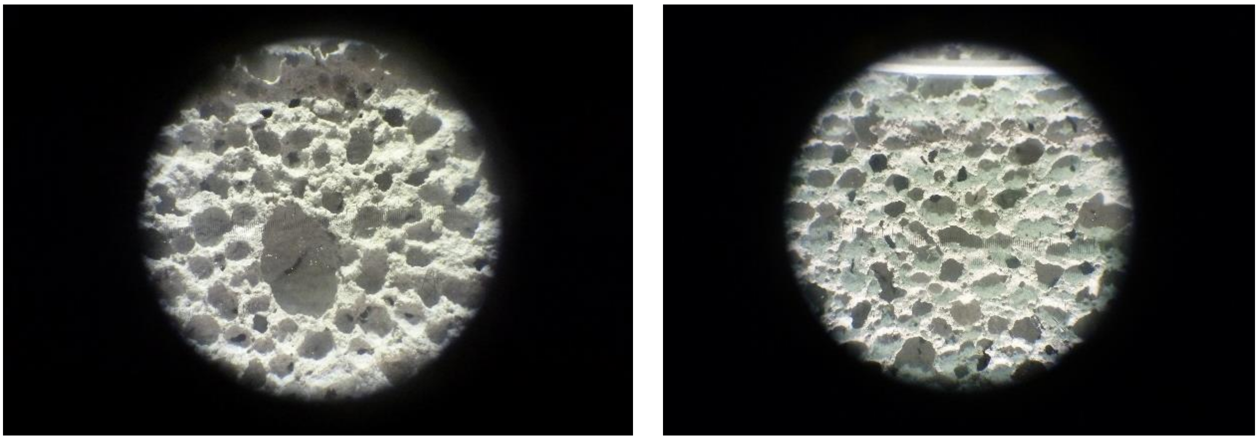


Figure 2 – Pore structure of foam concrete samples

To determine the density and strength of foam concrete blocks, they were segmented into lower, middle, and upper parts by height (Figure 2). From each segment, square-shaped samples (10x10 cm) were selected. The reason for segmenting the samples vertically was also related to the potential non-uniform distribution of pores along the height.

The technological composition of the compared types of foam concrete samples is presented in Table 1.

Table 1 – Technological composition of compared sample types

Type	Cement M400, kg	Fine sand, kg	Ratio of blowing agent to water at primary injection, g:l	Ratio of blowing agent to water at secondary injection, g:l	Water, l	Foam concentrate, g
Type 1	350	250	0.23:85	1.27:40	-	-
Type 2	350	250	-	-	175	1.5

3. Results and Discussion

Figures 3-5 present the results of the quantitative assessment of the pore structure through visual-instrumental inspection of the samples. Figure 3 shows the results of inspections for the upper segments of foam concrete blocks, Figure 4 presents the same inspections for the middle segments, and Figure 5 displays the results for the lower segments. The specific values (data points) of the percentage of pore area to the inspection area were sorted in ascending order for a better understanding of patterns (to visually highlight the differences between the compared types of foam concrete). In other words, the depicted curves do not represent any particular pattern but only indicate differences in pore dimensions.

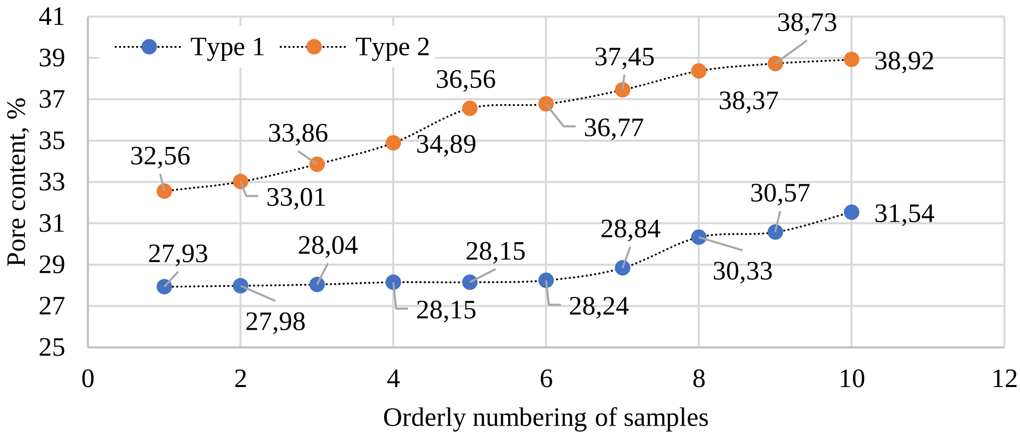


Figure 3 – Evaluation of the upper segments of the samples

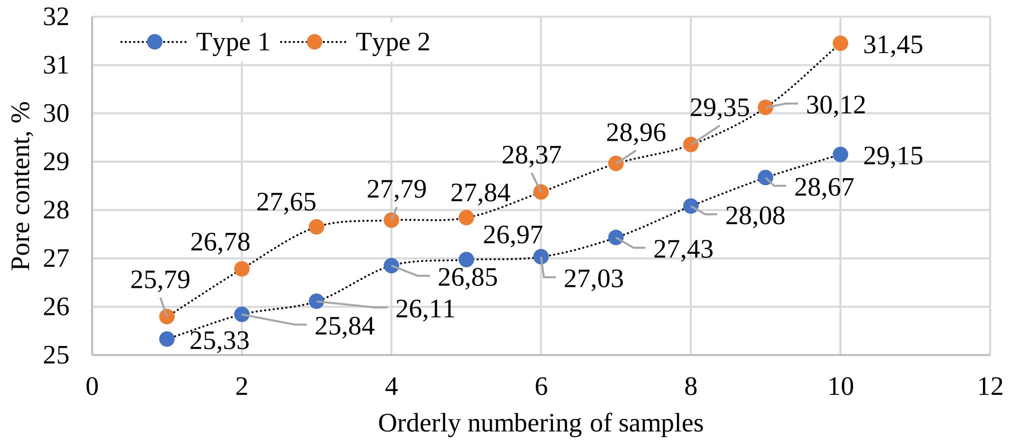


Figure 4 – Estimation of average sample segments

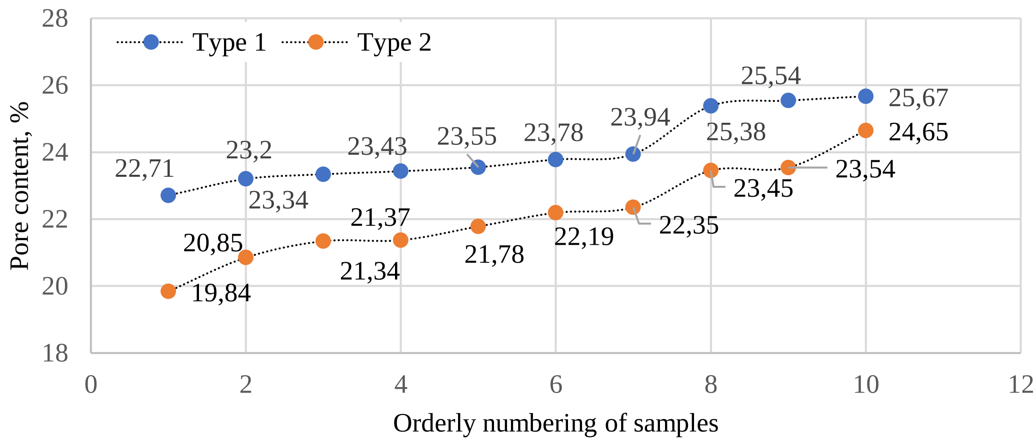


Figure 5 – Assessment of lower segments of samples

According to the results, the percentage distribution of pore content in the upper segments of type 1 samples falls within the range of 27.93% to 31.54%, which is relatively lower than the distribution of type 2 samples, ranging from 32.56% to 38.92%. In the middle segments, a similar pattern is observed in terms of percentage pore content, but the results are quantitatively very close: for type 1 samples, the range is within 25.33% to 29.15%, and for type 2 samples, it is 25.79% to 31.45%. Opposite results are observed in the lower segments. For type 1 samples, the percentage distribution of pore content exceeds that of type 2 samples: for type 1, the range is 22.71% to 25.67%, while for type 2, it is 19.84% to 24.65%.

Figure 6 illustrates the difference in pore distributions across the sample segments (upper, middle, and lower). According to the diagrams, the difference in pore sizes between type 1 and type 2 in the upper segments ranges from 10% to 39%, in the middle segments from 1% to 16%, and in the lower segments from -1% to -17%. Negative values indicate that the density of the lower segments is significantly lower than that of the upper segments, considering the overall trend in density distribution vertically in the foam concrete samples. All obtained data points have a relatively strong correlation and can be considered reliable. Statistical data are presented in Table 2.

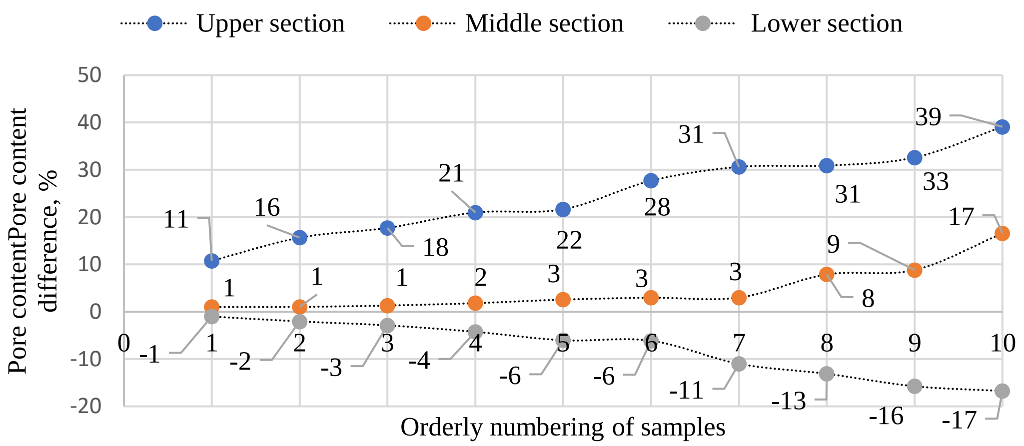


Figure 6 - Percentage difference of pore distribution

Table 2 – Statistical data points

Indicator	Upper section		Middle section		Lower section	
	Type 1	Type 2	Type 1	Type 2	Type 1	Type 2
Mean value, %	28.977	36.112	27.146	28.410	24.054	22.136
Quadratic deviation	1.326	2.382	1.225	1.638	1.073	1.427
Coefficient of variation	4.578	6.596	4.512	5.767	4.459	6.449

The average pore content for all type 1 samples in the upper segment is 28.977%, while for type 2 samples, it is 36.112%. The average pore content in the middle segment of type 1 samples is 27.147%, and for type 2 samples, it is 28.410%. In the lower segment of type 1 samples, the average pore content is 24.054%, and for type 2 samples, it is 22.136%. It should be noted that all data points within the segments (upper, middle, and lower) do not exhibit significant deviations from the mean, with coefficients of variation in all cases not exceeding 7%. However, it is important to note that for type 2 samples, the coefficients of variation on all segments exceed those of type 1 by 27-44%. This suggests that the pore structure of type 2 samples is less stable than that of type 1, as the data points for type 1 samples deviate more from each other, indicating a lower confidence level. According to the obtained data, a general pattern of pore distribution along the sample height is observed, as evidenced by the diagram in Figure 7, which displays the average pore distribution values along the vertical axis. The segments are conditionally labeled on the y-axis (ordinate axis): 1 – lower segment, 2 – middle segment, 3 – upper segment.

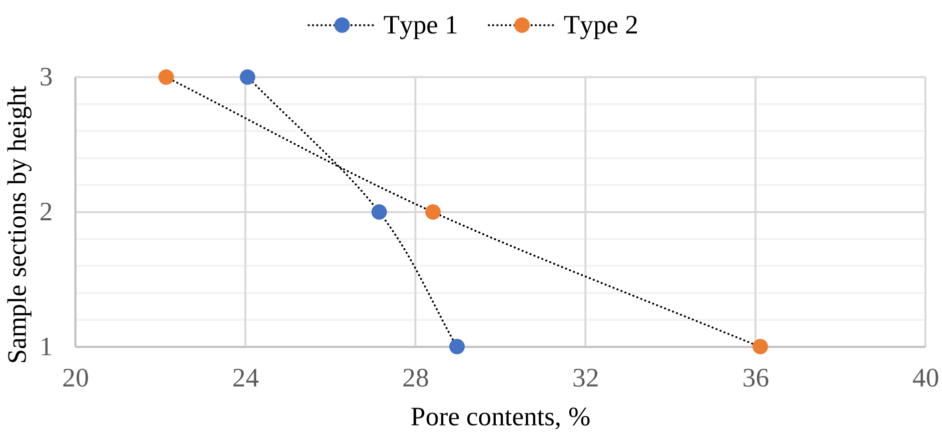


Figure 7 – Pore structure distribution by height

According to the provided diagram, non-uniformity in the distribution of the pore structure along the vertical axis is observed. Comparing the average values for the segments, for type 2 samples, the percentage pore content is (from bottom to top): 24.05%, 27.15%, 28.98%. The difference between the lower and upper segments in type 1 samples is 12%, and between the middle and upper segments is 6%. The same parameters for type 2 samples are (from bottom to top): 22.14%, 28.41%, 36.11%. However, the difference between the segments significantly exceeds (compared to type 1), amounting to 27.11% and 28.34%, respectively. This indicates the quality of the pore structure in the samples: type 2 samples show a substantial increase in pore volume along the sample height, whereas in type 1 samples, the increase in pore content along the height is significantly lower. This pattern is also evident in the slope of the curves, with a steeper slope indicating greater deviations from the mean value. Numerically, the maximum deviations for type 1 samples are 8.4% and 11.11% (for the upper and lower segments), while for type 2 samples, the same figures are 25.02% and 30.49%, respectively.

4. Conclusions

1. A comprehensive study of cellular concrete samples (foam concrete produced by the proposed two-stage method, classical foam concrete, and autoclaved aerated concrete) was conducted to assess their pore structure. The evaluation of pore distribution was carried out through visual-instrumental inspection and measurements of pore areas in segmented samples (divided into three vertical segments: upper, middle, and lower). The assessment was performed in comparison with classical foam concrete.

2. According to the results, the pore structure distribution is more stable in samples manufactured by the proposed method (Type 1) compared to samples of classical foam concrete (Type 2). This is evidenced by the obtained data points of percentage pore content: the average pore content for all Type 1 samples in the upper segment is 28.977%, while for Type 2 samples, it is 36.112%; in the middle segment of Type 1 samples, it is 27.147%, and for Type 2 samples, it is 28.410%; in the lower segment of Type 1 samples, it is 24.054%, and for Type 2 samples, it is 22.136%.

3. The difference in pore volumes in Type 1 samples between the lower and upper segments is 12%, and between the middle and upper segments, it is 6%. The same parameters for Type 2 samples are (from bottom to top): 22.14%, 28.41%, 36.11%. However, the difference between the

segments significantly exceeds that of Type 1, amounting to 27.11% and 28.34%, respectively. This indicates the quality of the pore structure in the samples: Type 2 samples exhibit a substantial increase in pore volumes along the sample height, while in Type 1 samples, the increase in pore content along the height is significantly lower.

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Anatolij Smoljaninov – interpretation, editing.

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