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Approximative approach to optimize concrete foaming concentration in two stage foaming

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Abstract. The article presents the results of a study on foam concentration for the production of foam concrete using a two-stage foam introduction method. The research was conducted by evaluating the strength and density of foam concrete samples manufactured using both the proposed and conventional methods. The optimal composition was determined through several iterations, considering adjustments to the overall quantity of foaming agent and the water-cement ratio. The study revealed that the two-stage foam introduction method enhances the strength properties of foam concrete by promoting the formation of a more uniform porous structure within the material. The initial introduction of a low-concentration foam solution in water creates favorable conditions for the subsequent introduction of a high-concentration foam solution, serving as a structural-forming component. The optimal approach for achieving a stable porous structure involves an initial foam introduction of 15% and a subsequent introduction of 85%. Furthermore, the research highlights the nuances of the relationship between foam concentration, strength, and density of foam concrete, offering deeper insights into the structural properties of the material. The effectiveness of the proposed methodology is substantiated by the achieved technological solution, which provides a pragmatic approach to enhancing the efficiency of foam concrete production through precise foam concentration at both the initial and subsequent stages of the manufacturing process.
Keywords: foam, microsilica, optimal foam, foam concrete, two-stage foaming.

1. Introduction

Lightweight concrete is increasingly finding applications in modern construction. Among the various lightweight concrete options, aerated concrete is predominantly favored by construction organizations. However, foam concrete has gained considerable traction recently due to its diverse range of applications. Unlike aerated concrete, foam concrete structures can be constructed monolithically, making it a more versatile material [1].

Certain distinct advantages of foam concrete over aerated concrete may include the closed pore structure of foam concrete compared to aerated concrete, rendering it stronger due to a more robust skeletal structure. Additionally, the relative durability of foam concrete can be attributed to the inclusion of cementitious binders in its composition, unlike aerated blocks which contain lime-gypsum binders, exhibiting lower resistance to mechanical forces, especially water-induced impacts. Nevertheless, these advantages often remain theoretical, as under equivalent reliability and durability conditions, the simplification of the production process takes precedence [2].

In the construction market today, three primary methods for foam concrete production exist: the classic method, the air entrainment method, and the dry foam mineralization method. The classic method involves blending cement slurry with water and foam, while the air entrainment method entails high-speed mixing of cement slurry with a foam concentrate [3]. The dry foam mineralization method involves mechanical blending of dry cement mix with foam. Each method possesses distinctive technological characteristics, advantages, and drawbacks. However, a common challenge faced by foam concrete producers is the instability of the foam concrete mixture's structure, shrinkage, uneven material density, consequently resulting in unstable strength and thermal conductivity of the product [4]. The unresolved matter of obtaining high-quality foam concrete has driven one of the objectives of this research – the development of an accessible foam concrete production technology. The technical outcome of this research aims to improve the material's pore structure by ensuring uniform pore distribution, thereby enhancing material strength by reducing the water-cement ratio and achieving an evenly distributed skeletal structure and to develop a technological solution for the optimal composition of primary and subsequent foam introductions for foam concrete production using the proposed method [5].

2. Methods

From a technological perspective, the proposed production method significantly deviates from preceding technologies, incorporating a novel two-stage foam introduction technique (Figure 1). This method ensures the maximal distribution of the foam concentrate throughout the sample volume [6]. The initial introduction of a low-concentration foam solution occurs during the preparation stage of the sand-cement mixture, enhancing its wetting capability and subsequently reducing the water-cement ratio (by mitigating foam quenching with water). Subsequently, during the secondary introduction of a high-concentration foam solution in the structural formation stage of cellular concrete, the reduction in water-cement ratio allows for the optimal preservation of the initial foam concentrate multiplicity. This aids in the formation of a uniform porous material structure [7].

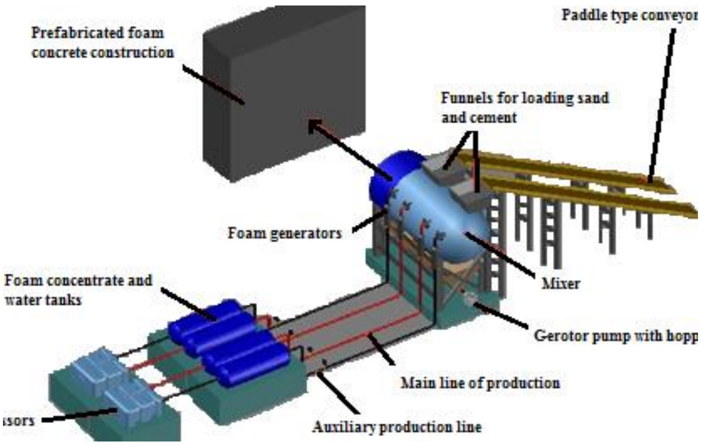


Figure 1 – Foam concrete production scheme using two-stage foam introduction

The variability in foam concentrations for which studies were conducted is outlined in Table 1. The diverse percentage ratio of foam concentrate in foam concrete composition is calculated based on the requirement of achieving D600 grade foam concrete. The mass fraction of the total foam concentrate is chosen considering its standard proportion in the composition of conventional D600 grade foam concrete [8]. Evaluating the varied compositions of primary and secondary foam introduction allows determining the best or optimal technological solution corresponding to: Best – highest material strength under the conditions of obtaining D600 grade foam concrete; Optimal – minimum foam concentrate consumption for standard strength D600 grade foam concrete.

In the context of the first point, the objective is to achieve the highest foam concrete strength through the uniform distribution of pores within the structure, rather than through foam quenching and obtaining a denser material. The latter can occur due to improperly observed foam concentrate proportions [9].

Regarding the second point, the aim is to reduce foam concentrate consumption, not driven by cost savings but resulting from an excess of foam concentrate due to an even distribution of the pore structure. This can lead to less foam quenching, hence a greater fractional participation of foam in the material's volume [10]. The outcome is a product with a higher degree of pore uniformity but lower density. Therefore, alignment with the foam concrete grade is necessary, with strength parameters being the evaluative criterion corresponding to the specific grade of conventional foam concrete [11].

If the research follows the second point, it will be necessary to adjust the overall quantity of foam concentrate, but in those percentage ratios corresponding to the best technological solution of the first approximation's variability (Table 1). The variability of the overall foam concentrate quantity will involve a multiple reduction in its composition within foam concrete by mass [12].

The conventional composition for foam concrete is adopted as follows: Portland cement of grade 400 – 350; fine sand – 250 kg, water-cement ratio 0.5. With such a water-cement ratio, the mass fraction of initial water addition will be 135 g, and secondary addition will be 40 g.

Table 1 – Compared foam concentration compositions

Type	Initial foam injection		Secondary foam injection	
	%	g	%	g
Type 1 – Reference type	0%	0	100%	1,5
Type 2	5%	0.075	95%	1.425
Type 3	10%	0.015	90%	1.350
Type 4	15%	0.225	85%	1.275
Type 5	20%	0.300	80%	1.200
Type 6	25%	0.375	75%	1.125

The main research methods included: Density assessment according to [13] and Strength determination according to [14] (Figure 2).

The tests were conducted on cubic specimens with dimensions of 10×10×10 cm. In order to obtain reliable results, six specimens of each type were tested, and the data were subjected to statistical analysis for accuracy [15].

Figure 2 – Laboratory testing of foam concrete samples

3. Results and Discussion

Figure 3 shows the results of the cubic samples strength measurement by hydraulic press.

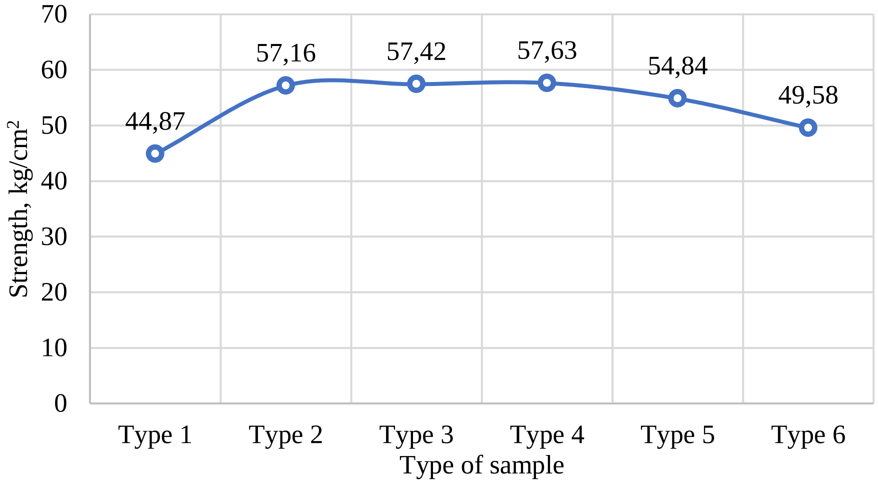


Figure 3 – Strength measurement results

According to the strength assessment results, the highest values, relative to the reference type, were exhibited by Type 3 specimens with a 15% foam concentrate introduction, while the lowest were observed in Type 6 specimens with a 25% introduction. In relative terms, Type 1 specimens showed a strength increase of 12.7%, Type 2 specimens showed an increase of 12.8%, Type 3 specimens showed an increase of 12.8%, Type 4 specimens showed an increase of 12.2%, and Type 5 specimens showed an increase of 11.1%. Thus, a peak dependence of strength on the amount of foam concentrate in its initial introduction is observed. The increase in strength is observed up to an initial foam concentrate increase of 15%. Beyond this concentration, a reduction in material strength characteristics occurs due to the subsequent increase in foam concentrate. Consequently, at excessively high foam concentrate concentrations exceeding 15%, the effectiveness of the two-stage foam introduction is diminished. This is because during the secondary foam introduction, the foam's multiplicity (density) increases due to its low concentration, rendering it less stable upon contact with the mixture from the primary foam introduction. On the other hand, excessively low concentrations below 15% do not achieve the maximum effect in improving strength characteristics. All obtained results exhibit a high degree of reliability, as the coefficients of variation range within 8-12%.

Figure 4 depicts the density measurement results of the compared foam concrete types.

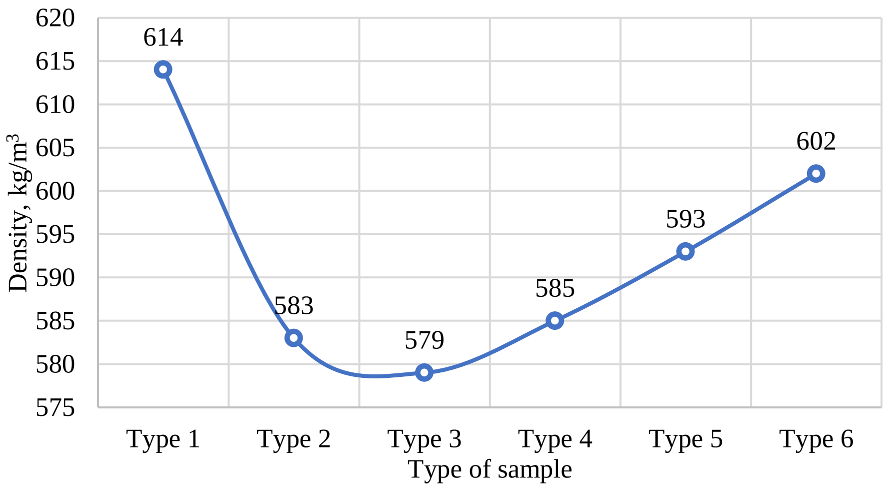


Figure 4 – Density measurement results

According to the obtained results, the maximum density values were observed in Type 1 specimens - the reference type, averaging at 614 kg/m³. The minimum density corresponds to Type 3 specimens, averaging at 579 kg/m³. Although Type 2 and Type 3 specimens showed similar density values in comparison to each other, they differed from the reference type, measuring 583 kg/m³ and 585 kg/m³ respectively. Type 5 specimens exhibited a density that closely matched the declared D600 foam concrete grade, with a minimal deviation from the reference type. The obtained results also demonstrate a high convergence of individual values, confirming the experiment's precision. The coefficients of variation do not exceed 10%.

From the above, it can be concluded that the two-stage foam introduction technology influences the material's pore structure. The shrinkage of Type 1 and Type 5 specimens is significantly greater than that of Type 3 specimens. The shrinkage of Type 2 and Type 4 specimens is relatively comparable to Type 3 specimens but still exceeds it. The relatively low density of Type 3 specimens indicates that foam quenching during the setting period was lower, resulting in fewer pore releases due to quenching. This indirectly suggests a more stable distribution of the pore structure within the material.

Despite the lower density compared to the other types, Type 3 specimens showed the highest strength values. The trend is very close to that of Type 2 and Type 4 specimens, with a slight difference in density values (not exceeding 2%) and strength values (within 5%) compared to Type 3. However, the best strength improvement with a reduction in density was observed in Type 3 specimens.

Despite the positive results, the obtained composition does not meet the requirements of the D600 foam concrete grade. Therefore, adjustments were made to the total foam concentrate amount concerning the initial foam introduction ratio, with a fixed ratio of primary and secondary foam introduction (15% and 75%).

Figure 5 shows the results of the corrective composition actions.

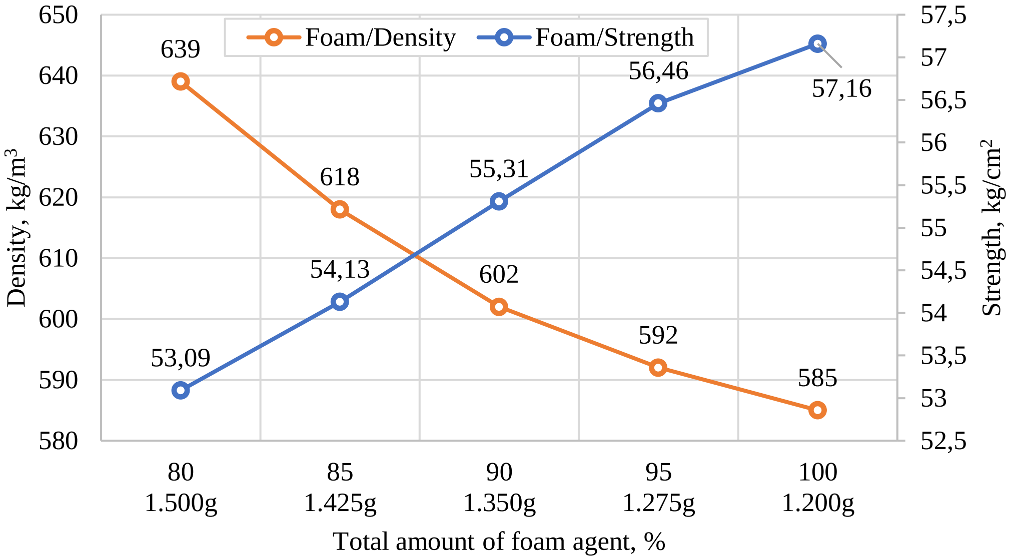


Figure 5 – Composition adjustment results

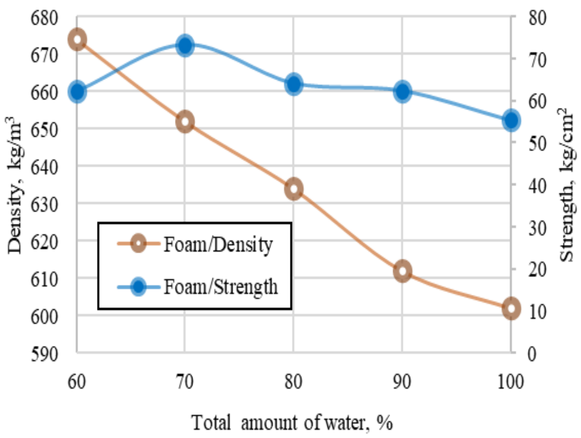
According to the obtained results, a reduction in the total foam concentrate amount leads to an increase in density due to increased shrinkage. This is a result of increased foam multiplicity, leading to more significant foam quenching before the setting period completes. The best indicator for the total foam concentrate content is 1.35 g of foam concentrate and 175 g of water, representing a 10 % reduction from the initial amount in the composition. With this foam concentrate ratio, the density corresponds to the D600 foam concrete grade, measuring 602 kg/m³.

From the generated diagrams, we can observe the inverse trend of decreasing strength parameters of foam concrete. This could be attributed to the constant water-cement ratio. Therefore, subsequent modifications to the composition were made by altering the water-cement ratio and adjusting the total foam concentrate amount.

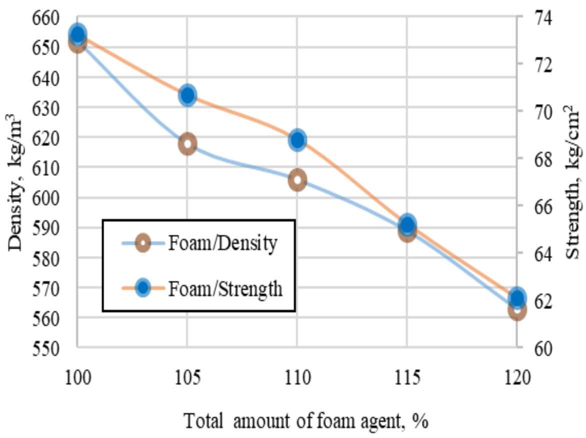
In Figure 6a, the diagrams illustrating the dependence of strength and density on changes in the water-cement ratio are presented, while Figure 6b shows the same dependence on changes in the total foam concentrate amount.

According to the results from the diagrams in Figure 6a, we observe a tendency of increased strength with a decrease in the water-cement ratio. However, the obtained dependency reaches a peak value, meaning the trend is disrupted when reducing the water content by 60% (a reduction of 70 g from the initial 175 g). Lowering the water-cement ratio leads to an insufficient amount of water required for the complete hydration process, resulting in reduced strength gain of the foam concrete. Consequently, the optimal value of the water-cement ratio was chosen where the peak strength is observed.

However, decreasing the water-cement ratio collectively leads to increased density due to reduced foam multiplicity (and consequently reduced foam quenching). Based on the previously derived patterns, additional adjustments were made to reduce density by decreasing foam multiplicity, i.e., increasing the total foam concentrate amount.



a)



b)

Figure 6 – Composition adjustment results

At first glance, the carried out manipulations might appear to have a cyclic nature, but this is not the case. The influence of the water-cement ratio on strength and density and the influence of the total foam concentrate amount on strength and density have distinct mechanics. Through numerous iterations, it is possible to arrive at an optimal solution. Figure 5b demonstrates the relationship of key transformational processes, according to which the final proportions of the water-cement ratio and foam concentrate were determined. Based on the research, the optimal composition for foam concrete production using the two-stage foam introduction method was obtained, as presented in Table 2.

Table 2 – Optimal Composition of the Proposed Production Method

Indicator	Unit	Quantity
M400 grade cement	kg	350
Fine sand	kg	250
Foaming agent to water ratio at primary injection	g : l	0.23 : 85
Foaming agent to water ratio at secondary injection	g : l	1.27 : 40

4. Conclusions

1. A comprehensive set of laboratory experiments was conducted to determine the optimal composition of foam concrete produced using the proposed technology, employing the two-stage foam introduction method. Strength and material density were the evaluative criteria for the composition selection. The optimal composition was determined through several approximations.

2. According to the obtained results, it was determined that the two-stage foam introduction contributes to the improvement of strength characteristics of foam concrete by forming a more uniform pore structure in the material. During the primary foam introduction with a low-concentration foam-forming agent solution in water, the initial transformation of the pore structure occurs. Although a high foam concentration of the low-concentration solution leads to faster foam extinguishing upon contact with the mixture, it still contributes favorably to the primary transformation of the pore structure. In other words, during the primary foam introduction, the cement-sand mixture becomes less dense, more mobile, and, most importantly, hydrated. Thus, favorable conditions are created for the secondary introduction of the high-concentration foam-forming agent solution, which is essentially a structure-forming component. The foam extinguishing process during the secondary introduction proceeds more slowly, as the already moistened mixture has a more loose structure. Earlier setting of the mixture (during the primary introduction) reduces the setting time of foam concrete compared to the secondary introduction of the structure-forming foam concentrate.

3. According to the initial approximations, the optimal option for obtaining foam concrete with a more stable pore structure is Option 3: 15% introduction of the primary foam concentrate in water, followed by the secondary introduction of an 85% foam concentrate. However, at this concentration of the foam-forming agent for both primary and secondary introductions, the total foam concentrate adopted in the first approximation is not rational, as a decrease in specimen shrinkage led to a reduction in material density. The subsequent approximation was made considering corrections to the water-cement ratio, as a negative trend in material strength indicators was observed. The resulting factor for corrective actions was a subsequent adjustment of the total foam-forming agent amount at a specific peak (optimal) water-cement ratio. The final composition of the method's components is presented in Table 2.

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Anatolij Smoljaninov – interpretation, editing.

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