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GRID SQUARE DIAGRAM ANALYSIS OF THE PHYSICAL PARAMETERS OF AUTOCLAVED POROUS AGGREGATE

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Abstract. This paper presents a comparative analysis of the physical parameters of autoclaved porous aggregate using a grid square diagram. The study showed that the granulometric composition significantly influences the bulk density, fill volume (height), and water absorption of the material. An increase in the proportion of fine fractions (2.5–5 mm) results in higher bulk density and lower fill volume (height) due to denser packing of the grains. As the content of fine particles increases, water absorption also rises because of the larger specific surface area and porosity. Coarse fractions (20–40 mm) contribute to reduced bulk density and water absorption but increase the fill volume (height) at a fixed mass. During the research, clear dependencies were established between the fractional composition of porous aggregate and its main physical and technical characteristics. The results make it possible to optimize the composition of porous aggregate to improve the technical characteristics of lightweight concrete.
Keywords: aerated concrete crumb, aggregate, autoclave, bulk density, fill volume (height), water absorption

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1. Introduction. Lightweight concrete with porous aggregates is a special type of concrete in which lightweight materials with a porous structure are used instead of heavy aggregates. As a result, the density of such concrete is lower than that of conventional concrete. Materials such as expanded clay, agloporite, expanded vermiculite, perlite, slag pumice, and foam glass are used as aggregates. These materials have different physical and mechanical properties compared to heavy aggregates. The amount and type of aggregate influence important concrete properties, such as density, strength, thermal conductivity, workability, water absorption, and shrinkage. To obtain concrete with high strength and a dense structure while reducing cement consumption, a mixture of aggregates of different grain sizes is used, which promotes denser particle packing and reduces porosity. Multifractional aggregates are often used to ensure better contact between particles. Important characteristics of aggregates include their bulk density and water absorption capacity—these parameters determine the physical properties of the aggregates [1–5].

In recent years, considerable attention has been given in Uzbekistan to the production of autoclaved cellular concrete. Autoclaved aerated concrete is characterized by a uniformly distributed porous structure throughout the entire volume of the material. During the production process, defective products are generated; these are either stored in open areas or crushed using a crusher. The resulting crushed aerated-concrete granulate is used in construction as a loose thermal insulation material [6–9].

Aerated-concrete granulate is considered a promising alternative to traditional porous aggregates such as expanded clay. The scientific and technical literature presents various approaches to using aerated-concrete granulate in the production of building materials [10–14].

When designing mixes for lightweight concrete, two, three, or sometimes more fractions of coarse and fine aggregates are typically used. The ratio between these fractions affects grain packing density, intergranular void content, bulk density, water absorption, and other properties of the porous aggregate. Optimizing these parameters has a significant impact on the technological characteristics of concrete mixes, as well as on the structural and thermal-insulation properties of the finished concrete products.

The grid square diagram is a graphical method of data representation in which information is visualized as a grid of squares, each reflecting a specific parameter or characteristic [15–18]. In construction materials science, such a diagram can be useful for comparing the properties of various building materials (for example, strength, thermal conductivity, water absorption, cost, etc.). The color or intensity of each square (a heat map) represents the level of the corresponding parameter [19–22].

Comparative analysis of the influence of fractional composition on certain characteristics of building materials using a grid square diagram is of interest, as the granulometric composition affects packing density, water permeability, bulk density, and other properties.

2. Purpose and objectives of the study. The aim of the present work is to develop and apply a grid square diagram for studying certain physical characteristics of autoclaved porous aggregate.

3. Raw materials and research methods. The selected fractions were 2.5–5 mm, 5–10 mm, 10–20 mm, and 20–40 mm. In the mixtures, the content of the fractions varied from 0 to 50% by mass. Additionally, all fractions were examined individually at a content of 100%. Autoclaved aerated-concrete granulate from the *“Arton” (SP LLS “EAST MINING INVEST”)* plant was used to determine the characteristics. The granulate was first separated into fractions using a sieve and then dried to constant mass in a laboratory drying oven at a temperature of 100 ± 5 °C. Figure 1 shows photographs of the fractions under study.

Fig. 1. Fractions of autoclaved porous aggregate

Bulk density, fill height (or volume), and water absorption were selected as the parameters to be determined. The average grain diameters of the mixtures were also calculated. In this case, the varying parameter was the fractional composition of the aggregate.

The bulk density in an uncompacted state and the water absorption were determined using standard methods. To determine the fill height (volume), a 1000-ml graduated glass vessel with 20-ml divisions was used.

The formula for calculating the average diameter is as follows:

$$d_{avg} = \frac{\sum(d_i \cdot \Delta P_i)}{100}$$

where: d_i — the average diameter of the particles retained on the i-th sieve (in mm);
ΔP_i — the percentage of the aggregate mass retained on the i-th sieve (in %).

Typically, d_i is taken as the arithmetic mean of the sizes of two neighboring sieves.
In our case, this is expressed as follows:

$$d_{avg} = \frac{d_1 \cdot m_1 + d_2 \cdot m_2 + d_3 \cdot m_3 + d_4 \cdot m_4}{m_1 + m_2 + m_3 + m_4}$$

4. Research results and discussion. The obtained results allow us to draw important conclusions. The table presents the results for individual fractions at 100% mass content.

Table 1. Physical characteristics of autoclaved porous aggregate

№	Fraction content (mm), %				Average grain diameter (d_{avg}), mm	Bulk density, g/cm³	Fill height (volume), ml (for 150 g)	Water absorption, % (24 hours)
	2,5-5	**5-10**	**10-20**	**20-40**				
1	100	0	0	0	3,75	0,3625	463,33	138,80
2	0	100	0	0	7,50	0,3213	500,00	114,77
3	0	0	100	0	15,0	0,3104	523,33	99,21
4	0	0	0	100	30,0	0,2775	573,33	86,93

An inverse relationship is observed between the average grain diameter and the bulk density of the material: as the grain size increases, the bulk density decreases from 0.3625 to 0.2775 g/cm³. This is due to the increase in intergranular space as particle size grows, which leads to a reduction in the density of the bulk layer.

At a constant aggregate mass, the fill height (volume) increases with increasing average grain size, which is associated with the decrease in bulk density. This effect reflects the increase in porosity and the volumetric space between larger grains.

Water absorption also shows a decreasing trend with increasing fraction size: from 138.80% for the 2.5–5 mm fraction to 86.93% for the 20–40 mm fraction. This is due to the reduction in the specific surface area of the grains and the decrease in the volume of capillary pores capable of retaining moisture. Fine-grained fractions have a larger specific surface area and, consequently, higher water absorption capacity.

Figure 2 shows photographs illustrating the packing density of different fractions of autoclaved porous aggregate. It can be seen that as the grain size decreases, a denser packing of the material is achieved, with smaller intergranular voids.

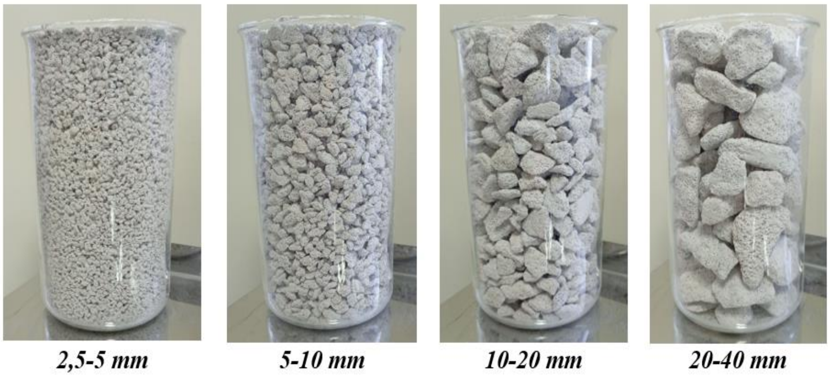

Fig. 2. Packing density of different fractions of autoclaved porous aggregate

Analysis of mixtures with different fraction ratios. Analysis of mixtures with different fraction ratios showed that at low fine-particle content, there is a shortage of grains needed to fill the intergranular voids created by coarse fractions. This leads to increased porosity and reduced packing density of the mixture.

In the case of high fine-fraction content, a visual *"floating"* effect of the coarse particles in the material mass is observed. Despite minimal intergranular voids, an excess of fine grains disrupts the stability of the framework formed by the coarse fractions, reducing their mutual cohesion and the ability to form a stable structure.

Further analysis focused on studying these characteristics in mixtures with different fraction proportions. At a constant content of coarse fractions, increasing the share of the finest fraction (2.5–5 mm) leads to an increase in bulk density. This is explained by the improved filling of intergranular space with fine particles, which reduces the overall porosity of the mixture.

Increasing the content of the 5–10 mm and 10–20 mm fractions also contribute to higher bulk density, though to a lesser extent. These fractions help form a more compact structure due to the optimal size ratio and efficient filling of voids between coarse grains (*Fig. 3*).

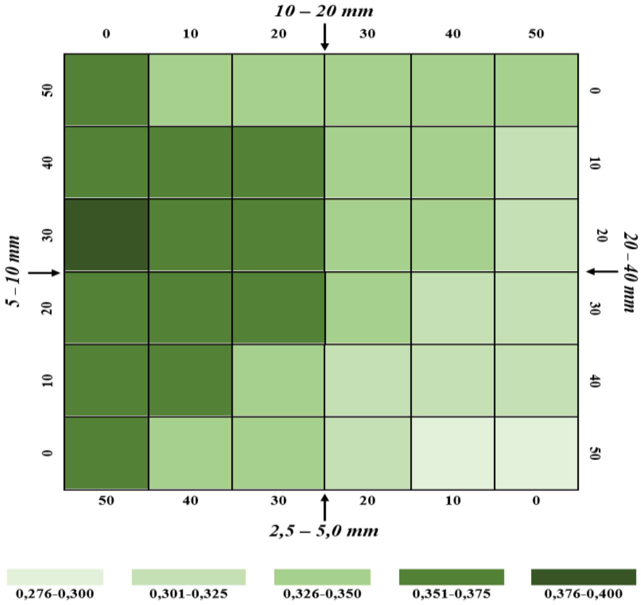

Fig. 3. Grid square diagram of bulk density of porous aggregate mixtures (g/cm³)

Effect of fractional composition on density and fill volume. Reducing the proportion of coarse fractions leads to an increase in packing density. Large grains form a looser structure with larger pores, so mixtures with a higher content of coarse fractions have lower bulk density. High bulk density is achieved with an increased proportion of fine and medium grains, which promotes denser particle packing and reduces the total void volume.

As the fine-fraction content increases, the fill height decreases. This is explained by the denser packing of fine grains, which reduces the fill volume at a constant mass. Increasing the proportion of coarse-grained fractions (10–20 mm and 20–40 mm) results in a higher fill height, which is associated with an increase in volume and porosity of the packing. At a constant mixture mass, larger grains form a more voluminous but less dense layer. Thus, the fill height is inversely proportional to bulk density: as the mixture density increases, the volume, and hence the fill height, decreases (*Fig. 4*).

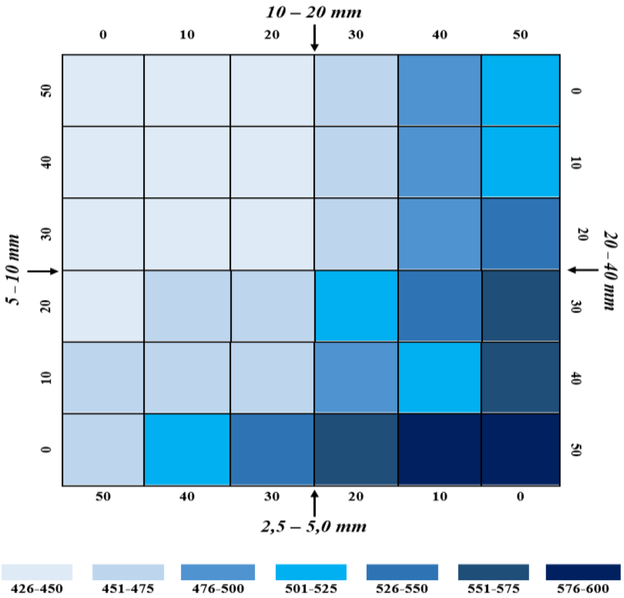

Fig. 4. Grid square diagram of fill volume (height) of porous aggregate mixtures (ml)

Structural features of the aggregate and its behavior during water saturation. It should be noted that the grains of the porous aggregate differed in terms of their internal structure. The mixture contained both coarse-porous and fine-porous grains. However, the majority of the particles had a medium-porous macrostructure, evenly distributed throughout the grain volume. These structural features were clearly visible both in the dry state and after water absorption, indicating the stability and reproducibility of the material's porous structure.

During the immersion of the aggregate in water, dust particles located on the grain surfaces and within the pores of their surface layer are washed out. This causes the water to become cloudy, visually appearing as a beige tint in the water. As these particles settle to the bottom of the vessel, the water gradually becomes clearer and more transparent, confirming the mechanical nature of the contamination and the limited volume of easily removable particles.

After testing, the water-saturated grains retained their shape and porous structure, indicating sufficient strength and resistance of the material to water saturation. Upon careful visual inspection, it was found that the grains differed in color: the sample contained dark and light gray, dark and light beige, as well as mustard-colored grains (*Fig. 5*).

The variety of color shades and pore sizes in the grains of the porous aggregate may indicate that the material is a crushed product of industrial origin. Most likely, the aggregates were obtained by crushing rejected autoclaved aerated concrete blocks, which differed in composition and average density. This explains both the heterogeneity of the macrostructure and the color variability of the grains.

When the aggregate mixtures were immersed in water, it was observed that the fine fractions (2.5–5.0 mm and 5.0–10.0 mm) quickly settled to the bottom of the vessel, while the coarse fractions exhibited positive buoyancy—some rose upward, and individual grains even floated to the water surface. This behavior indicates a lower average density of the coarse fractions, likely due to their more developed porous structure and, consequently, lower bulk density compared to the fine grains.

Fig. 5. Photographs taken during the study of water absorption characteristics of autoclaved porous aggregate

In mixtures with an increased content of fine fractions (2.5–5.0 mm and 5.0–10.0 mm), it was noted that individual coarse grains became mechanically trapped between fine particles. As a result, they remained at the bottom and could not move upward or float to the surface, despite their potential positive buoyancy. This demonstrates the significant influence of dense packing of fine grains on the mobility and redistribution of coarse particles in the aqueous medium.

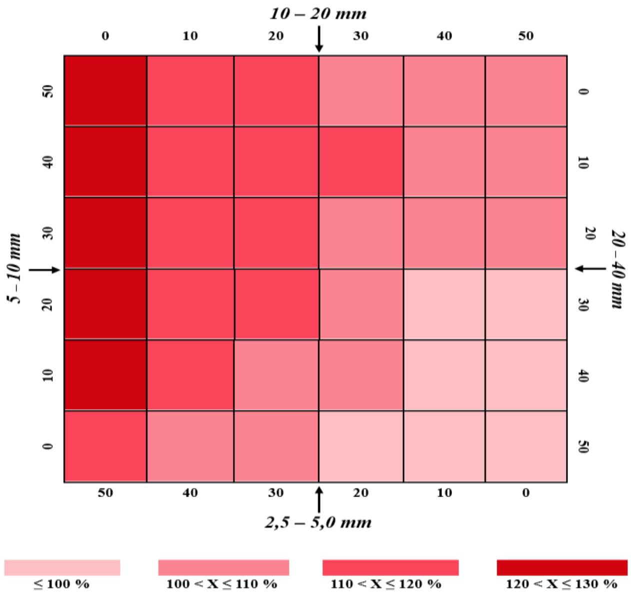

Fig. 6. Grid square diagram of water absorption of porous aggregate mixtures (%)

As the content of the finest fraction (2.5–5.0 mm) increases, a significant rise in water absorption is observed (*Fig. 6*). This is explained by the increased specific surface area of the fine particles, as well as the higher porosity and capillarity of the fine-grained components. An increase in the proportion of medium-sized grains is accompanied by a moderate increase in water absorption.

A decrease in the content of coarse fractions leads to higher water absorption, since coarse grains have a smaller specific surface area and form a less dense packing. Fine grains, having a larger specific surface area, contribute to the adsorption of a greater amount of water. The denser packing of the mixture with a higher content of fine grains enhances capillary effects, further increasing the water absorption of the material.

Relationship between average grain diameter, bulk density, and water absorption. Next, the average grain diameter of the porous aggregate mixtures was calculated. An increase in the content of the 2.5–5.0 mm fraction reduces the average diameter of the mixture, whereas an increase in the 20–40 mm fraction, on the contrary, leads to its growth (*Fig. 7*). Changes in the average diameter occur smoothly, indicating a correct gradation of the composition.

A clear relationship was established between the content of fine and coarse fractions and the average diameter. At the same time, some mixtures, despite differences in fractional composition, exhibited the same average diameter. This indicates that mixtures with different structures can achieve the same average diameter when the mass balance is appropriately adjusted.

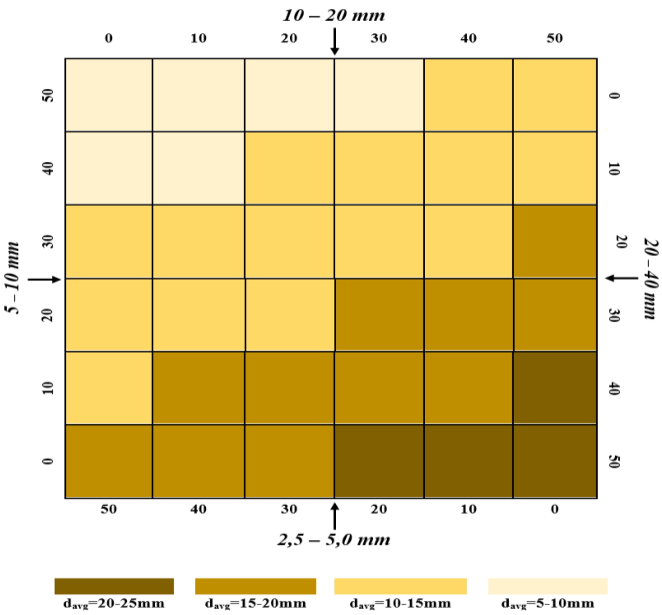

Fig.7. Grid square diagram of the average grain diameter (d_{avg}) of porous aggregate mixtures

The analysis showed that the smaller the average grain diameter, the higher the bulk density. This is because fine particles can pack more efficiently, creating fewer voids, which increases the mass of material per unit volume. Thus, bulk density depends not only on the average diameter but also on the quality gradation of the mixture—that is, on the compatibility of fractions in terms of dense packing. Maximum bulk density is achieved not by using a single fine fraction, but by an optimally selected combination of different fractions. The increase in bulk density is particularly noticeable when the 2.5–5.0 mm fraction is introduced.

Interestingly, different mixtures can exhibit the same bulk density despite differences in average diameter. This confirms that the distribution of fractions is at least as important as the average grain size itself.

An inverse relationship is observed between the average diameter and water absorption: the finer the grain (smaller d_{avg}), the higher the water absorption. This is because fine fractions have a larger specific surface area, well-developed microporosity, and capillary structure, which promote moisture retention. In contrast, coarse fractions have a smaller surface area and form a less dense packing with larger pores, reducing the overall water absorption capacity.

A direct relationship was also established between water absorption and bulk density. Denser packing of grains (higher bulk density) promotes an increase in the number of capillaries that retain moisture. Mixtures containing a higher proportion of fine fractions (especially 2.5–5.0 mm) exhibit the maximum water absorption values. To reduce water absorption, it is recommended to increase the proportion of coarse fractions (20–40 mm) and decrease the content of the finest fraction (2.5–5.0 mm).

Analysis of the results revealed the possibility of developing a model to predict the fill height:

$$h = f\ (\text{fraction composition})\ \text{or}\ h = f(d_{avg})$$

where: h – fill height, d_{avg} – average grain diameter.

The study also established clear relationships between the fractional composition of the porous aggregate and its main physical and technical characteristics. In particular, the following correlations were identified:

- *Fractional composition – bulk density:* an increase in the proportion of fine fractions (2.5–5.0 mm) promotes higher bulk density of the mixture;
- *Fractional composition – fill volume (height):* predominance of coarse fractions (10–20 mm and mainly 20–40 mm) leads to an increase in the mixture volume (height) in a graduated vessel due to less dense packing;
- *Fractional composition – water absorption:* an increase in the content of fine fractions is accompanied by higher water absorption of the mixture due to the larger specific surface area and developed porosity of fine grains;
- *Fractional composition – average grain diameter:* the higher the proportion of coarse fractions, the larger the average grain diameter, and conversely, an increase in the fine fraction (2.5–5.0 mm) reduces d_{avg}.

5. Conclusion. The granulometric composition has a significant impact on the physical properties of granular material. As the average grain diameter increases, bulk density and water absorption decrease, while the fill height at a constant mass increase. The fill height at a constant mass of the granular mixture is an indicator of its packing density and porosity. An increase in the proportion of fine fractions contributes to denser packing, a reduction in fill height, and an increase in bulk density. Conversely, an increase in grain size leads to a decrease in the bulk density and water absorption of the porous aggregate, as well as an increase in the fill height at a fixed mass.

Author Contributions. M.A.M. (Mukhamedbaev Abdugafur Mukhamedbaev) conceived and designed the study, developed the research methodology, performed the experimental investigation and data analysis, interpreted the results, prepared the figures and tables, wrote the original draft of the manuscript, revised the manuscript, and approved the final version for publication.

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Data Availability. The data supporting the findings of this study are available from the corresponding author upon reasonable request.

Declarations

Conflict of Interest. The author declares that there are no competing interests or conflicts of interest related to this work.

Ethical Approval. This article does not involve studies with human participants or animals. Therefore, ethical approval was not required.

Informed Consent. Not applicable.

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