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RESEARCH ARTICLE

OPTIMIZATION OF EXPANDED CLAY CONCRETE MIXTURE FOR MODULAR STRUCTURES WITH CONSIDERATION OF SUSTAINABILITY

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Abstract. *The purpose of this study is to experimentally substantiate the effect of the concrete mixing methods on the physical and mechanical properties of expanded clay concrete used in modular construction. In the framework of research two technological approaches of mixing are compared: traditional (according to GOST) and alternative method of "suspension concrete". The study was conducted on identical compositions of lightweight concrete with expanded clay aggregates with fractions of 0-10 mm at a constant dosage of cement, sand, water and chemical admixtures. Control samples were produced for each mixing method and compressive strength tests were conducted at the ages of 1, 3, 7 and 28 days to determine the average density of the samples. The results show that changing the order of introducing the components has a significant impact on material structure formation. The use of the suspension mixing method, in which a cement-water suspension is formed before the introduction of aggregates, provides an increase in the strength of expanded clay concrete by up to 19% on day 28 compared to traditional technology. In addition, there was an improvement in the uniformity and surface quality of samples. At the same time, workability and the density of the concrete mixture remained at the same level. Therefore, suspension mixing can be considered an effective way to strengthen the structure of expanded clay without changing its composition, which is particularly important in industrial production of precast products. The obtained data are of practical significance and can be used to improve production technologies for lightweight concrete with enhanced performance properties.*

Keywords: *expanded clay concrete, lightweight concrete, mixing method, suspension concrete, compressive strength, density, modular construction.*

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ТҰРАҚТЫЛЫҚТЫ ЕСКЕРЕ ОТЫРЫП, МОДУЛЬДІК КОНСТРУКЦИЯЛАР ҮШІН КЕҢЕЙТІЛГЕН САЗДЫ БЕТОННЫҢ ҚҰРАМЫН ОҢТАЙЛАНДЫРУ

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Аңдатпа. *Бұл зерттеудің мақсаты модульдік Құрылыста қолданылатын кеңейтілген сазды бетонның физика-механикалық сипаттамаларына бетон қоспасын араластыру әдісінің әсерін эксперименттік негіздеу болып табылады. Зерттеу аясында араластырудың екі технологиялық тәсілін салыстыру жүргізілді: дәстүрлі (ГОСТ бойынша) және балама "суспензиялық бетон"әдісі. Зерттеу цемент, құм, су және химиялық қоспалардың тұрақты дозасында 0-10 мм фракциялық кеңейтілген сазды агрегаты бар жеңіл бетонның бірдей құрамдарында жүргізілді. Араластырудың әр әдісі үшін бақылау үлгілері жасалды және 1, 3, 7 және 28 тәулік жасында қысу беріктігі сыналды, сонымен қатар үлгілердің орташа тығыздығы анықталды. Нәтижелер бетон қоспасының компоненттерін енгізу тәртібінің өзгеруі материалдың құрылымын қалыптастыруға айтарлықтай әсер ететіндігін көрсетті. Суспензияны араластыру әдісін қолдану, онда цемент-су суспензиясы агрегаттар енгізілгенге дейін қалыптасады, дәстүрлі технологиямен салыстырғанда кеңейтілген сазды бетонның беріктігінің 28 тәулікке 19% - ға дейін өсуін қамтамасыз етті. Сонымен қатар, үлгілердің біртектілігі мен бетінің сапасы жақсарды. Бетон қоспасының жұмыс қабілеттілігі мен тығыздығы бірдей деңгейде қалды. Осылайша, суспензияны араластыруды композицияны өзгертпестен кеңейтілген сазды бетон құрылымын күшейтудің тиімді әдісі ретінде қарастыруға болады, бұл әсіресе Құрама бұйымдардың өнеркәсіптік өндірісі жағдайында маңызды. Алынған мәліметтер қолданбалы мәнге ие және өнімділігі жоғары жеңіл бетон жасау технологияларын жетілдіру үшін пайдаланылуы мүмкін.*

Түйін сөздер: *керамзитбетон, жеңіл бетон, араластыру әдісі, суспензиялық бетон, қысуға беріктік, тығыздық, модульдік құрылыс.*

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НАУЧНАЯ СТАТЬЯ

ОПТИМИЗАЦИЯ СОСТАВА КЕРАМЗИТОБЕТОНА ДЛЯ МОДУЛЬНЫХ КОНСТРУКЦИЙ С УЧЕТОМ УСТОЙЧИВОСТИ

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Аннотация. *Целью настоящего исследования является экспериментальное обоснование влияния способа перемешивания бетонной смеси на физико-механические характеристики керамзитобетона, применяемого в модульном строительстве. В рамках исследования выполнено сравнение двух технологических подходов к перемешиванию: традиционного (по ГОСТ) и альтернативного метода «суспензионного бетона». Исследование проводилось на одинаковых составах легкого бетона с керамзитовым заполнителем фракции 0–10 мм при постоянной дозировке цемента, песка, воды и химических добавок. Для каждого способа перемешивания были изготовлены контрольные образцы и проведены испытания прочности на сжатие в возрасте 1, 3, 7 и 28 суток, а также определена средняя плотность образцов. Полученные результаты показали, что изменение порядка введения компонентов бетонной смеси оказывает существенное влияние на формирование структуры материала. Применение метода суспензионного перемешивания, при котором цементно-водная суспензия формируется до ввода заполнителей, обеспечило прирост прочности керамзитобетона до 19% на 28 сутки по сравнению с традиционной технологией. Кроме того, было отмечено улучшение однородности и качества поверхности образцов. Удобоукладываемость и плотность бетонной смеси при этом оставались на одинаковом уровне. Таким образом, суспензионное перемешивание может рассматриваться как эффективный способ интенсификации структуры керамзитобетона без изменения состава, что особенно актуально в условиях промышленного производства сборных изделий. Полученные данные имеют прикладное значение и могут быть использованы для совершенствования технологий изготовления легких бетонов с повышенными эксплуатационными характеристиками.*

Ключевые слова: *керамзитобетон, легкий бетон, способ перемешивания, суспензионный бетон, прочность на сжатие, плотность, модульное строительство.*

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CONFLICT OF INTEREST

The authors state that there is no conflict of interest

АЛҒЫС / ҚАРЖЫЛАНДЫРУ КӨЗІ

Зерттеу жеке қаржыландыру көздерін пайдалана отырып жүргізілді.

МҮДДЕЛЕР ҚАҚТЫҒЫСЫ

Авторлар мүдделер қақтығысы жоқ екенін растайды.

БЛАГОДАРНОСТИ/ИСТОЧНИК ФИНАНСИРОВАНИЯ

Исследование проводилось с использованием частных источников финансирования.

КОНФЛИКТ ИНТЕРЕСОВ

Авторы подтверждают, что конфликта интересов нет.

1 INTRODUCTION

Modern construction is moving towards industrialized and modular production methods, which requires the use of lightweight, durable, and technologically advanced concrete mixtures that ensure structural reliability and sustainability. Expanded clay concrete, a type of lightweight concrete made with porous aggregate, has become increasingly popular due to its low density, satisfactory strength, and enhanced thermal and acoustic insulation properties.

One of the most promising areas for the use of this material is in modular construction. Here, reducing the dead weight of the structures directly affects their transportability, assembly, and load on the foundation.

However, one of the main challenges limiting the widespread adoption of expanded clay concrete is its heterogeneous structure and reduced strength. This is particularly true in the contact zones between the expanded clay grains and the cement matrix. This is because of the high porosity of the clay aggregate and the weak adhesion at the interface.

In the context of implementing the Sustainable Development Goals (SDG 9 - Industrialization, SDG 11 - Sustainable Cities, and SDG 12 - Responsible Consumption and Production), it is an urgent task to optimize not only the composition but also the technical parameters of concrete mixture preparation. One of the most effective ways to conserve resources and enhance performance is to enhance mixing techniques. In this study, the "suspension concrete" method is explored, in which a cement-water paste is formed prior to the addition of aggregates. This approach is believed to contribute to a more homogeneous distribution of the binding agent, reduce delamination, improve uniformity, and increase strength due to enhanced coating of clay granules.

The current study aims to optimize the composition of expanded clay concrete for use in modular structures, considering the requirements for strength, manufacturing processability, and sustainability. Additionally, it aims to assess the impact of suspension mixing techniques on the physical, mechanical, and structural properties of the material.

2 LITERATURE REVIEW

Expanded clay concrete is a lightweight concrete based on a porous aggregate (expanded clay gravel or sand). It is widely used in construction due to its combination of sufficient strength and reduced density. This reduces the mass of structures and improves their thermal protection properties (**Rashad 2018; Zega and Di Maio, 2011**). However, the porosity of the lightweight aggregate and the structural features of expanded clay concrete can lead to the fact that the strength characteristics of such concrete are lower than those of heavy concrete of the same cement concentration (**Litsomboon et al., 2008**). An important task is to increase the strength and uniformity of expanded clay concrete without significantly increasing its density. It is known that technological factors in the preparation of a concrete mixture – in particular, the mode and sequence of mixing of the components – can significantly affect the formation of the structure of cement stone and the contact zone with the aggregate, and therefore the strength and durability of concrete (**Ozolins et al., 2021; Amran et al., 2015**).

Currently, expanded clay concrete is actively used in industrial housing construction, including the production of volumetric modular blocks for residential and commercial buildings. In particular, expanded clay concrete is used at the ModeX Astana enterprise as the main structural material in the manufacture of factory-ready modules (**Teshev et al., 2024**). This approach allows not only to reduce construction time, but also to ensure high energy efficiency and durability with minimal weight of elements.

Numerous studies indicate that the properties of expanded clay concrete depend not only on the composition, but also on the technological parameters of preparation. The standard technology for the preparation of concrete mixtures, regulated by regulatory documents (for example, GOST 27006-2019 and GOST 7473-2010), usually involves the sequential introduction of components: first dry aggregates, then cement, then water with additives, with intermediate mixing. The mixing technology of the components has a significant impact on the properties of expanded clay concrete, especially when using lightweight aggregates such as LECA. The high porosity of expanded clay requires precise selection of the mixing mode and the order of the components to ensure the uniformity of the mixture and the strength of the material. Scientists (**Li et al., 2017**) proposed a method for designing the LWASCC composition that takes into account the thickness of the cement shell around the grains and the packing density. They emphasized that uniform distribution of the solution is possible only with strict control of the water-cement ratio and the mixing stage. Исследователи (**Kaffetzakis & Papanicolaou, 2016**) pointed out the need to pre-create a cement paste before adding aggregates to increase the stability of the composition and prevent delamination. Their colleagues take a similar position (**Vakhshouri & Nejadi, 2016**), focusing on step-by-step and "soft" mixing. Researchers (**Bogas & Gomes, 2013**) associate the nature of the fracture and the strength properties of light concrete with the quality of the contact zone between expanded clay and cement stone, which directly depends on the mixing technology. In their works (**Issa & Al-ASADI, 2022**), they also note that the saturation of the aggregate and the order of component insertion significantly affect the mechanical properties of LECA concrete. Scientists (**Dabbaghi et al.. 2022**) have confirmed that pre-dispersion of cement in water makes it possible to increase the strength, uniformity and fire resistance of concrete. The study (**Uysal et al., 2024**) showed that the effectiveness of using expanded clay directly depends on the mixing sequence and the quality of coating the grains with cement paste..

One of the promising methods is the so-called "suspension concrete", in the preparation of which a cement-water suspension (cement "paste" with chemical admixtures) is first created, and only then aggregates are injected. It is assumed that this mixing method can provide a more uniform coating of expanded clay grains with cement mortar and filling of pores, which should have a beneficial effect on the structure of concrete (**Demissew, 2022; Xu & Garrecht, 2024**). Studies (**Ahmad & Chen, 2019**), as well as (**Ahmad et al., 2019**) show that lightweight concretes based on expanded clay aggregate are characterized by a sensitive contact zone structure, especially with a high water-cement ratio. To increase uniformity and strength, such formulations require optimization of cooking technology. In particular, researchers (**Bogas et al., 2012**) indicated that the preliminary formation of the cement suspension before the injection of aggregates contributes to the uniform distribution of the binder and reduces the effect of water extraction with a porous aggregate. In their work (**Kroviakov et al., 2019**) note that the mixing sequence has a significant impact on the formation of quality criteria for expanded clay concrete, including strength, uniformity and resistance to segregation.

In this article, the effect of two different mixing methods, traditional (according to GOST), is experimentally investigated and suspension – for the strength and density characteristics of expanded clay concrete. The aim of the study is to determine how a change in the sequence of component introduction and mixing mode affects the density of the mixture, workability, strength gain dynamics and the quality of the structure of lightweight concrete on expanded clay aggregate with fraction 0-10 mm.

3 MATERIALS AND METHODS

The tests were carried out on an expanded clay concrete mixture with the same composition prepared in two different ways: according to the traditional method (GOST 27006-2019) and using the "suspended concrete" method. The cement used was Portland cement CEM I - 42.5 H produced by Central Asian Cement JSC (Kazakhstan), conforming with GOST 31108-2020 "Cements. General Technical Conditions". Construction sand used as a fine aggregate, with a grain modulus of M_k=3.2, and bulk density of 1637 kg/m³ (from the village of Kyzyljar, Akmolinsk region). The granulometric composition of the sand confirmed to GOST 8735 - 88 "Sand for Construction Works. Test Methods" as shown in **Table 1**.

Table 1
Granulometric composition of sand (author's materials).

No	The size of the sieve cell, mm	Full residual, %
1	2.5	25.1
2	1.25	43.1
3	0.63	72.9
4	0.315	88.9
5	0.16	98.7
6	<0.16	100

Expanded clay gravel with a particle size of 0-10 mm was used as a lightweight porous aggregate (**Figure 1**), provided by Stroitel LLP in Taldykorgan. The bulk density of the material is 585 kg/m³, which corresponds to GOST 9757-90 and GOST 9786-86 standards.

Figure 1 – Expanded clay fractions of 0-10 mm (author's materials).

The chemical admixture MC PowerFlow 7951H, produced by MC-Bauchemie in Germany, was used to improve the workability and manufacturability of the concrete mixture. This admixture corresponds with the European standard EN 934-2 and the ISO 14001:2016 standard for environmental management systems. The dosage of the admixture was 1% of the weight of cement, which is approximately 4.6 kilograms per cubic meter of concrete.

Drinking water was used to mixing the concrete, and it meets the requirements of the ST RK 1015-2000 standard for "Water. Gravimetric method for determining sulfate content in natural wastewater", as well as the GOST 23732-2011 standard for "Water for concrete and mortar. Technical specifications."

The compositions of the concrete mixtures are presented in **Table 2**. The first mixing, with composition No. 1, was prepared according to the traditional method in accordance with GOST 27006-2019. First, dry aggregates (sand and expanded clay), measured in advance, were loaded into a mixer and mixed for 30 seconds. Then, cement was added, and the dry mixture was mixed again (for 30-60 seconds). After that, a measured amount of water was added, pre-mixed with a liquid admixture. The mixture was stirred until it became smooth (for another 1-2 minutes).

The second mixing, with composition No. 2, was prepared using the "suspended concrete" method. All the calculated water, along with the chemical admixture dissolved in it, was poured into the mixer first. Cement was then added immediately, while stirring, to create a homogeneous cement-water mixture within 1 minute. Sand and expanded clay, pre-weighed, were then added to the cement paste, and the mixture was further mixed for another 1-2 minutes to achieve the desired consistency. In both cases, the total mixing time was three minutes.

Table 2
Compositions of concrete mixtures (author's materials).

No of specimen	Cement, kg	Coarse sand, kg	Expanded clay fractions 0–10mm, kg	PCE, kg	Water, kg
1	0.460	1.030	0.351	0.046	0.220
2	0.460	1.030	0.351	0.046	0.220

The readiness of the concrete mixture was assessed based on its workability and density. We used the slump test method to check the workability of the mixture according to GOST 10181-2014. The density of the freshly mixed concrete was measured by filling a known volume measuring cone and weighing it, also according to GOST. Control samples were taken from each batch of the prepared mixture for strength testing. Metal cube molds with a size of 100×100×100 cm were used, and a total of eight samples were prepared for each composition. Two samples were tested at each age: 1, 3, 7, and 28 days after mixing. After casting, all samples were subjected to the same holding regimen: initially, they were treated with heat and moisture in a chamber according to the plant's technological process.

Compressive strength was determined in accordance with GOST 10180-2012 using a hydraulic press and by breaking cubes with flat faces. The quality and uniformity of the concrete were controlled in accordance with GOST 18105-2018, and the classification of the concrete by density and strength was assessed in accordance with the requirements of GOST 25820-2014 for lightweight concretes.

4 RESULTS AND DISCUSSION

The workability of the concrete mixture for both compositions was between 25 and 27 centimeters, which indicates that the mixtures have equally high workability and are close to self-flowing, confirming the technological compatibility of the method with current production lines.

As shown in **Figure 2**, the density of the concrete mixtures did not differ significantly, with values of 1831 kg/m^3 and 1835 kg/m^3, respectively. Additionally, the density of the concrete has significantly improved with the new mixing method, with the average density of suspended concrete samples being 10 - 30 kg/m^3 higher than that of concrete produced according to GOST standards. For example, after 28 days, the density of specimens from composition No. 2 was 1753 kg/m^3, while that of composition No. 1 was 1723 kg/m^3. An increase in the density indicates a more compact structure and lower overall porosity in the material produced using the suspension mixing technique.

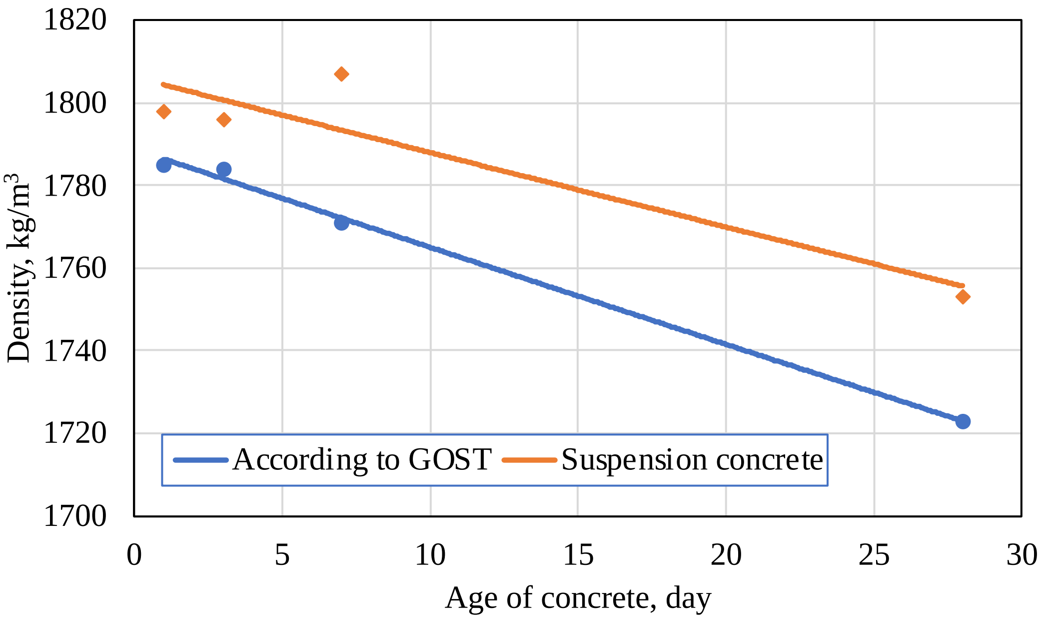

Figure 2 – Dependence of density on age of concrete (author's materials).

The comparative dynamics of strength gain for the two compositions are shown in **Figure 3**. On the first day, the difference between the two was minimal, with the strength of concrete made using the traditional method being 20.1 MPa and that of the suspension-based concrete being 19.45 MPa. However, by the third day, the strength of the suspension concrete began to steadily outpace the traditional concrete, reaching 22.2 MPa by the seventh day. By day 28, this difference had significantly increased, with the suspension concrete showing a strength of 27.8 MPa compared to the 23.3 MPa of the control sample, an increase of almost 19%.

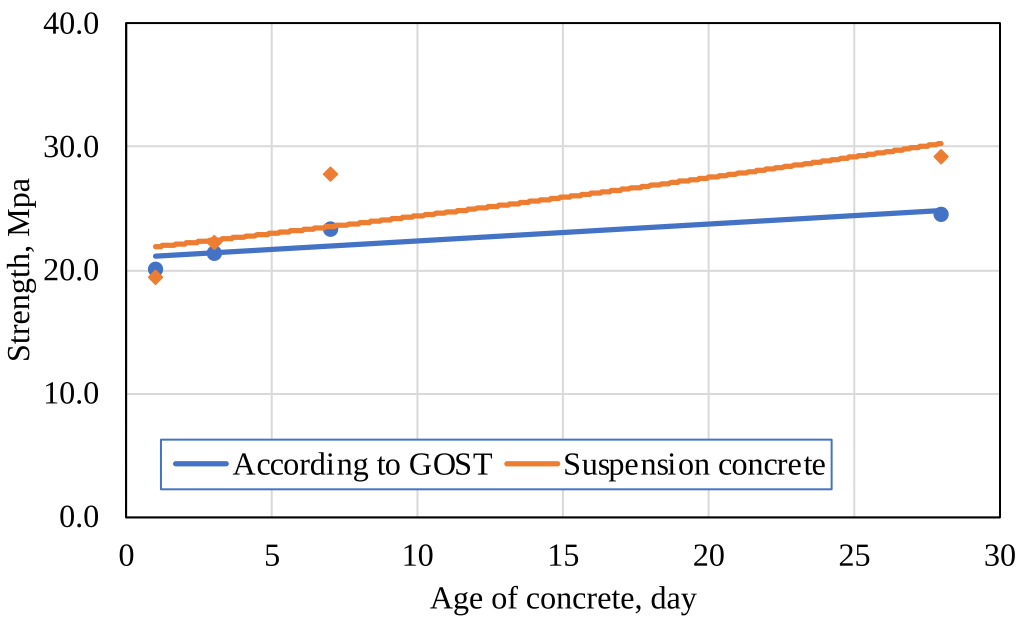

Figure 3 – Dependence of compressive strength on the age of concrete (author's materials).

The maximum effect was seen on day 28, where the strength of suspension concrete reached 29.2 MPa, compared to 24.5 MPa for the control mixture. This represents an increase in strength of 19% compared to the traditional method, indicating an increase in concrete grade and more efficient use of cement in the same composition.

In addition to the quantitative indicators of strength and density, a difference in the quality of the hardened concrete structure was recorded. A visual inspection of the samples revealed that the surface of the expanded clay concrete produced by the suspension method was smoother and more uniform, with fewer shell-like structures and surface pores. Conversely, samples made using the standard technique exhibited larger pores (shell-like features) on the concrete surfaces, likely associated with air pockets around expanded clay particles and a less consistent cement film. **Figure 4** illustrates a comparison between the surfaces of samples produced by the two different methods.

As can be seen in **Figure 4** b, the suspension concrete sample has a denser and smoother surface. The pores on this sample are much smaller and less numerous than on a concrete sample prepared using the traditional method (on the left). This indicates a better filling of the mold and distribution of the mortar in the suspension concrete, which correlates with its increased average density and strength.

a) b)

Figure 4 – Comparison of the surface of expanded clay concrete samples: (a) specimen No. 1, mixing according to GOST; (b) specimen No. 2, suspension mixing (author's materials).

The results suggest that the mixing order of the ingredients has a significant impact on the structure and properties of expanded clay concrete. Using the "suspension concrete" method of mixing ensures more efficient usage of cement and enhanced adhesion of the cement paste to the porous aggregate.

It should be noted that the increased strength is achieved without changing the composition of the concrete mixture, that is, by optimizing the mixing process and not increasing the cement content or adding expensive additives. This difference is most noticeable after a longer period of hardening, ranging from 7 to 28 days, which suggests an improvement in the structure of the cement matrix and the contact area with expanded clay using suspension technology.

The practical conclusion from this study is that, when producing expanded clay concrete or other lightweight concrete, it is important to pay attention not only to selecting the optimal composition but also to improving mixing technology. The suspended mixing method has proven to be an effective way to increase the strength and quality of lightweight concrete without adding additional material costs. This improvement in surface density (fewer voids) is important for manufacturing architectural and decorative elements, such as wall panels, which require high standards of appearance and uniformity.

5 CONCLUSIONS

It has been experimentally proven that changing the order of mixing the components of concrete significantly affects the properties of expanded clay concrete.

1. The suspension mixing method provides higher compressive strength at all stages of hardening compared to the traditional method. On the 28th day, the strength gain was up to 19%.

2. The density of the concrete mixture and finished samples was comparable in both methods, but with the suspension method a more homogeneous structure and stable characteristics were observed.

3. Visual and technological indicators, such as workability and surface quality, demonstrate the advantage of the suspension method.

4. In terms of sustainable development, using the "suspension concrete" method can reduce cement consumption, waste, and increase durability, while also allowing for the use of local raw materials.

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