STRUCTURE AND PROPERTIES OF NON-AUTOCLAVED AERATED CONCRETE

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ANNOTATION

Unlike standard concrete, aerated concrete is notably more uniform because it lacks coarse aggregates. However, despite this internal consistency, it displays a wide spectrum of performance levels. The specific characteristics of aerated concrete are dictated by its microscopic structure and chemical makeup, which are shaped by the choice of binding agents, the technique used to create air pockets, and the curing process. While it was originally valued primarily for its thermal insulation, there is a growing focus on its structural potential. This shift is driven by its low density, the reduction in raw material consumption, and its capacity to incorporate industrial byproducts, such as cast iron slag, on a massive scale. This document categorizes research into aerated concrete based on three primary pillars:

1. Introduction

Aerated concrete is a category of lightweight concrete produced by introducing air bubbles into a cement or lime-based mortar using specialized aerating agents. It is generally classified as a type of cellular concrete, a group that also includes materials like microporite. The most significant benefit of aerated concrete is its low mass, which reduces the load on foundations and supporting walls, leading to more economical structural designs. Its porous composition not only results in significant material savings but also provides exceptional thermal insulation. Depending on the manufacturing process, its density can be adjusted between 300 kg/m³ and 1800 kg/m³, allowing for a versatile range of applications - from purely insulating layers to load-bearing structural components. In particular, the Decree of the President of the Republic of Uzbekistan No. PF-158 dated September 11, 2023 "On the Strategy of Uzbekistan - 2030" sets out specific goals for doubling energy efficiency in economic sectors and transitioning to a "green economy". Also, the priority tasks set out in the Decree No. PF-60 on the Development Strategy of New Uzbekistan for 2022-2026 provide for bringing the production of building materials to a new level.

2. Classification of aerated concrete

2.1. Based on the method of pore-formation

The formation of voids within aerated concrete is primarily achieved through three distinct methodologies: the air-entraining (gas concrete) technique, the foaming (foamed concrete) strategy, and a combined hybrid approach. In the gas-forming method, chemical additives are integrated into the lime or cement mortar while it remains in a liquid or plastic state, causing a volumetric expansion that leaves behind a porous framework once the gases escape. Common agents for this include hydrogen peroxide or calcium carbide, though aluminium powder remains the most prevalent choice due to its liberation of hydrogen; its performance is specifically governed by the powder's fineness, purity, and the alkalinity of the cement, sometimes requiring the addition of sodium hydroxide or lime to ensure a proper reaction.

Conversely, the foaming method is frequently cited as the most budget-friendly and easily regulated process because it avoids complex chemical reactions, instead relying on mechanical agitation. This is executed either by pre-forming a foam from water and an agent before mixing or by foaming the mortar directly, utilizing various surfactants such as detergents, resin soaps, saponins, or hydrolyzed proteins like keratin. Finally, a combined pore-forming strategy merges these two concepts, simultaneously employing both air-entraining agents like aluminium powder and mechanical foaming stabilizers such as glue resins to manufacture cellular concrete with a highly specialized internal architecture.

2.2. Based on the method of curing

The classification of aerated concrete is primarily determined by the curing process employed, resulting in either non-autoclaved aerated concrete or autoclaved aerated concrete. The specific curing technique and its total duration exert a direct influence on critical material properties, such as compressive strength, moisture absorption, and drying shrinkage. When utilizing moist-curing methods, the development of structural strength tends to be a relatively gradual process. In contrast, the autoclaving process triggers a vital hydrothermal reaction between lime and components containing silica or alumina. While the exact parameters vary among researchers, typical autoclaving cycles involve pressures ranging from 4 to 16 MPa over a period of 8 to 16 hours. Beyond pressure and time, other influential factors include the maturity and state of the mixture at the onset of the cycle, as well as the specific rates at which temperature and pressure are adjusted. A major advantage of autoclaving is its ability to drastically minimize drying shrinkage compared to non-autoclaved alternatives. Consequently, this high-pressure steam treatment is considered indispensable for producing aerated concrete that meets rigorous industry standards for both structural integrity and dimensional stability.

3. Physical properties

3.1. Microstructure

The internal architecture of aerated concrete is defined by a complex dual-pore system consisting of a solid microporous matrix interspersed with larger macropores. These macropores, typically defined as having diameters exceeding 60 µm, emerge from the volumetric expansion during the aeration phase, while the micropores develop within the thin walls separating these larger voids. This porous network significantly alters the orientation and development of cement hydration products. Research further categorizes this system into three distinct functional groups: artificial air pores, inter-cluster pores, and inter-particle pores, all of which dictate the material's ultimate performance. Another widely recognized classification identifies air pores with radii between 50 and 500 µm (notably larger than the 5 µm "large pores" found in standard mortar), microcapillaries measuring 50 nm or less, and a limited number of macrocapillaries ranging from 50 nm to 50 µm. While the general air-void configuration remains similar across different types, the microscopic structure of Autoclaved Aerated Concrete differs significantly from Non-Autoclaved Aerated Concrete due to their unique hydration products. During the autoclaving process, fine siliceous materials react chemically with lime to create a microcrystalline structure with a reduced specific surface area. In contrast, NAAC tends to possess a higher volume of fine pores because of the presence of surplus pore water. Interestingly, studies indicate that the specific size distribution of the macropores does not exert a substantial influence on the material's overall compressive strength.

The relationship between a concrete's structural integrity and its internal void network is fundamental, as attributes like strength, permeability, diffusivity, shrinkage, and creep are all deeply tethered to porosity and pore size distribution.

In the context of aerated concrete, where the total volume of voids can reach as high as 80%, characterizing this architecture becomes even more vital. Both the material's chemical composition and the selected curing protocol play significant roles in shaping these characteristics. Research indicates that the elevated porosity found in aerated concrete is primarily a result of an expanded macropore volume. This expansion naturally leads to thinner internal walls, which consequently reduces the relative share of the micropore volume. Furthermore, the methodology used to measure these traits must be carefully considered; for example, oven-drying samples to calculate porosity can inadvertently cause the internal cell structure to collapse, potentially skewing the data. Interestingly, while the total porosity may differ significantly between foamed and gas-formed autoclaved aerated concrete, their permeability remains remarkably similar. This suggests that the artificial air pores created during the manufacturing process exert very little influence on the material's overall permeability.

3.2 Density

The density of aerated concrete is fundamentally tied to the ratio of water to cementitious materials, as this balance dictates the success of the aeration process. When sand proportions are increased, the water-cement ratio must typically rise to maintain a consistent density. However, for Autoclaved Aerated Concrete incorporating pozzolans, the water-to-solids ratio emerges as the more critical metric, regardless of whether gas-forming or foaming techniques are utilized.

In the specific case of gas concrete, maintaining a precise liquid balance is vital: a ratio that is too low prevents the mix from expanding sufficiently, while an excessively high ratio causes the internal air bubbles to burst and collapse. In both scenarios, the final product becomes denser than intended. Consequently, the water demand should be determined by the actual consistency of the fresh mixture during production rather than strictly following a rigid, pre-set ratio. Because the majority of physical characteristics in aerated concrete are density-dependent—with values typically ranging from 300 to 1800 kg/m³—it is mandatory to correlate all property data with the specific density of the sample. Furthermore, density specifications must clearly state the moisture status of the material, such as whether it is oven-dry or in an atmospheric equilibrium state. It is worth noting that material fresh from an autoclave can be 15% to 25% heavier than its oven-dry counterpart, a figure that can climb to 45% for ultra-lightweight grades. Over time, environmental factors like shifting relative humidity and temperature can trigger carbonation, leading to a measurable increase in density that is directly proportional to the material's initial dry weight.

Manufacturing aerated concrete for specific roles—whether for insulation or structural support—requires adjusting the chemical composition to manipulate the resulting pore size and distribution. Achieving a stable, ideally spherical cell structure is essential for maximizing both functional and structural performance. Uniformity is also key; the air pockets must be evenly dispersed throughout the mass to ensure a consistent density across the entire unit. While the development of larger macropores can significantly lower the overall density, in traditional technical terms, the density of this material remains a direct reflection of its internal porosity and overall compacity.

4. Chemical characteristics

In the preparation of the aerated concrete mixture, the compositions are first placed into a container, and 70% of the water with a temperature of 60°C is added. The mixture is then stirred in a mixer for 2–3 minutes. During this process, aluminum powder is added to the mixture, followed by the addition of lime, and mixing is continued for another 2 minutes. After that, the binders are introduced and the remaining portion of water is added. The mixture is further stirred for 1–2 minutes, after which the prepared slurry is poured into molds. After the mixture expands, the excess part protruding from the mold is cut off, and the specimens are transferred to curing under moist conditions. Subsequently, they were stored for 28 days at a relative humidity of 90–98%. After 28 days, laboratory research and testing were carried out.

Binding construction materials are powdered substances which, when mixed with water, form a plastic-like mass that subsequently hardens into a stone-like solid body. As a binder material, M400 grade Portland cement produced by “EVRO STROY-777” JV LLC was tested in accordance with GOST 10178-85 “Portland Cement and Slag Portland Cement. Technical Specifications.”

The mineralogical composition of the cement clinker was as follows: C_3S – 60%, C_2S – 14%, C_3A – 6.9%, and C_4AF – 11.9%.

The technological preparation stages play a decisive role in the formation of the porous structure of aerated concrete. The physical-mechanical properties and compressive strength of concrete directly depend on the size of the pores within the material, their distribution pattern, and geometry. Under non-autoclave conditions, the expansion level of the aerated concrete mixture and the morphology of its pores are based on the reactivity of lime. During the chemical process, lime reacts with aluminum powder, resulting in the release of hydrogen gas within the system. These gas bubbles cause the expansion of the mixture volume and the formation of a stable porous framework. The general form of this chemical process is based on the following reaction:

$$3Ca(OH)_2 + 2Al + 6H_2O \rightarrow 3H_2\uparrow + 3CaO \cdot Al_2O_3 \cdot 6H_2O + Q$$

The gas formation process in aerated concrete mixtures using caustic soda occurs as a result of the following chemical reaction:

$$2Al + 6NaOH + 6H_2O \rightarrow 3H_2\uparrow + 3Na_2O \cdot Al_2O_3 \cdot 6H_2O + Q$$

This research involved a two-stage experimental program designed to develop and analyze modified aerated concrete samples. The primary objective was to evaluate the feasibility of substituting traditional raw materials with industrial by-products to enhance both the thermal efficiency and structural integrity of the final product.

4.1. Raw Materials and Preparation

The experimental mixtures incorporated construction waste sand as the primary siliceous component and cast iron smelting slag to enhance the reactivity of the binder. The chemical composition of the slag-specifically the presence of calcium and iron oxides (CaO and FeO) plays a critical role in forming a stable crystalline structure of calcium hydrosilicates during hydrothermal treatment. Prior to mixing, the waste sand was processed to achieve a specific surface area comparable to traditional quartz sand, ensuring optimal homogeneity within the matrix. The quantities of components we need to prepare 3 1 dm cubic gas block samples in the experiment. Table 1.

№	Name of components	Unit of measurement	Amount for $3dm^3$
1	Cement	g	828
2	Fine aggregate	g	1242
3	Lime	g	34.5
4	Aluminum powder	g	2.5

5	Water	l	911
6	Caustic soda	g	10

The 56-60°C water used in the preparation of the mixture creates the necessary conditions for the formation of the internal macrostructure of the material during the molding process. The finished samples are gradually stored in a special environment with a humidity of 95% in the laboratory. This approach relieves internal stresses that may arise during the solidification stage of the samples, as a result of which the likelihood of microcracks on the surface of the block is significantly reduced.

Since the size of the iron smelting slag fractions is 10-20 mm, a ball mill "ShLM-100" was used for grinding. Then, it was passed through a sieve No. 008 and added to the cement mixture.

5. Mechanical properties

In this case, D600 aerated concrete blocks were prepared in laboratory conditions using cast iron melting slag, and their strength was determined using a "CD-2000" hydraulic press in accordance with the GOST 10180-2012 standard, and their calculated thermal conductivity was determined in accordance with the requirements of KMK 2.01.04-18 "Construction Thermal Engineering". The physical and mechanical properties of aerated concrete compositions using cast iron melting slag are presented in Table 2.

Cast iron slag, (%)	**Thermal conductivity, W/(m·°C)**	**ρ,kg/m3**	**P_{com}, MPa**
10,2	0.132	610	1.820
10,1	0.134	615	1.825
10,3	0.135	612	1.822
12,9	0.136	620	1.910
13,7	0.138	625	1.915
13,8	0.139	622	1.918
16,2	0.137	628	2.050
16,4	0.140	630	2.065
21	0.142	635	2.120

Table 2. Composition and physical and mechanical properties of aerated concrete using cast iron slag.

Based on the experiments, the influence of cast iron smelting slag content on the physical, mechanical, and thermophysical properties of aerated concrete was investigated. The data presented in the table indicates that increasing the slag content from 10.1% to 21.0% exerts varying effects on the material's density, strength, and thermal conductivity coefficient.

Positive Impacts: Strength Enhancement (P_{com}): It was observed that when the slag content reached 21.0%, the compressive strength limit rose to 2.12 MPa. This is attributed to the high hydraulic activity of the cast iron slag and its reaction with cement to form a denser crystalline lattice.

Density and Insulation: Due to the relatively lightweight nature of the cast iron slag, the density of the blocks remained within the range of 610–635 kg/m³, fully complying with the standard requirements for D600 grade aerated concrete. The low thermal conductivity coefficient (0.132–0.142 W/(m·°C)) serves to enhance the energy efficiency of buildings and improve the thermal protection characteristics of wall structures.

Analysis of the indicators for aerated concrete based on cast iron smelting slag shows that as the slag content increases from 10.1% to 21.0%, it influences material properties differently. According to the research results, the most optimal balance between strength and thermal efficiency is observed when the slag content is in the range of 13.7–13.8%. At this point, the strength increases to 1.91 MPa, while the thermal conductivity coefficient remains low at 0.138–0.139 W/(m·°C). Although maximum strength is achieved at 21.0% content, it was found that the thermal conductivity coefficient also reaches its peak (0.142) at this level.

During the research process, the composition of the aerated concrete mixture based on construction waste sand was developed using mathematical methods of experimental design. Under laboratory conditions, D600 grade specimens with dimensions of 100x100x100 mm were prepared according to the proportions specified in Table 3. To ensure the necessary degree of dispersion, the waste sand was passed through a No. 0.315 sieve before being utilized as a filler. In accordance with standard curing requirements, the prepared samples were placed in a controlled environment with an air temperature of 20°C and a relative humidity of 95%. Throughout the experiment, the physical and mechanical properties of the specimens were comprehensively investigated under normal curing conditions at intervals of 7 and 28 days.

Experiments investigated the physical properties of the mixture based on the following fixed proportions: aluminum powder – 0.47, water – 264, Cement – 220, lime – 10, sodium sulfate – 4.6, and soda – 3, with the filler (sand) set at 312, while specifically varying the mass of the construction waste sand.

Construction waste sand, (%) based on sand mass	**Thermal conductivity, W/(m·°C)**	**ρ, kg/m³**	**P_{com}, MPa**
10,2	0,145	665	1,48
10,1	0,148	680	1,51
10,3	0,149	672	1,49

15,6	0,152	678	1,55
15,8	0,154	670	1,56
15,9	0,156	677	1,56
19,7	0,155	673	1,58
19,8	0,158	671	1,59
19,7	0,16	674	1,59

The laboratory investigation focused on the influence of sand derived from the recycling of construction waste-specifically from the demolition of multi-story residential buildings-on the properties of aerated concrete. During the experiments, varying the waste sand content from 10.1% to 19.8% exerted a direct impact on the density, strength, and thermal conductivity of the aerated blocks. The results indicate that samples maintain stable physical and mechanical parameters when the waste sand content is within the 15.6–15.9% range. At this optimal point, the compressive strength reached 1.56 MPa, with a density ranging between 670 and 677 kg/m³.

The most effective technical solution involves passing the waste sand through a No. 0.315 sieve and maintaining its concentration at approximately 15.6%. This dosage ensures a stable expansion height during the aeration process and provides the necessary thermophysical properties required for D600 grade blocks. While maximum strength (1.59 MPa) was achieved at a content of 19.8%, the thermal conductivity coefficient rose to 0.160 W/(m·°C) in this state, slightly diminishing the material's insulation performance.

Research further demonstrated that in high-concentration compositions where the additive exceeds 20%, density continues to increase by 7–11% and strength by 11–13%. However, this process negatively affects the thermophysical efficiency of the material, leading to a 1.5–2.5% increase (deterioration) in the calculated thermal conductivity coefficient. The analysis of the numerical data confirms that utilizing recycled quartz at a rate of 10–15% of the total sand mass is the most techno-economically efficient solution for achieving an optimal balance between mechanical strength and heat retention.

From a technological standpoint, the highly porous structure of old cement paste residues and brick dust within the waste sand rapidly absorbs a portion of the mixing water. This increases the viscosity of the slurry, creating resistance against the rising hydrogen gas released by the aluminum powder. Consequently, the expansion of the mass may cease before the gas emission process is complete, or an uneven distribution of pores may occur within the block. Furthermore, various chemical and organic impurities in the waste sand—such as lime, gypsum, paint, and dust particles—adversely affect the cement hydration process and the reactions with gas-forming components. Specifically, ultra-fine dust particles weaken the bond between the cement paste and the filler, reducing the mechanical strength of the aerated concrete framework. This often leads to structural settlement after the formation stage and the appearance of large cavities or technological cracks in the finished product.

5. Mechanical properties

The compressive strength of aerated concrete is a multifaceted property influenced by various factors, including the dimensions and geometry of the test specimen, the technique used to create pores, the orientation of loading, and the specific properties of the raw materials. Additionally, the age of the material and its moisture levels at the time of testing play significant roles in performance outcomes. Research indicates that the micro-mechanical state of the pore shells and the overall architecture of the air-void system are fundamental drivers of structural integrity. Specifically, when density is lowered through the creation of oversized macropores, there is a marked decline in load-bearing capacity; generally, however, the relationship between compressive strength and density remains linear.

Curing methods are particularly transformative regarding strength development. The autoclaving process significantly bolsters compressive strength by facilitating the formation of a stable crystalline structure known as tobermorite under high-pressure and high-temperature conditions. In this scenario, the ultimate strength is dictated by the specific duration and pressure of the hydrothermal treatment. For Non-Autoclaved Aerated Concrete, strength gain occurs more gradually, typically increasing by 30% to 80% between the 28-day mark and six months of age, with only slight improvements thereafter. A significant portion of this late-stage strengthening in NAAC is often linked to the natural carbonation process. The compressive strength of aerated concrete exhibits an inverse relationship with its moisture levels. As the material reaches a state of equilibrium with the ambient atmosphere through drying, its strength notably improves, with the most significant gains observed when the concrete is entirely devoid of moisture. Due to this sensitivity, it is standard practice to conduct performance testing only after the specimens have stabilized to the humidity of their environment. To account for these fluctuations in a professional context, researchers have developed specific correction factors that allow for the accurate estimation of strength increases when transitioning from a saturated to a fully dry state.

Conclusion:

The provided laboratory investigation focused on the influence of cast iron slag derived from the recycling of construction waste on the properties of D600 grade aerated concrete. During the experiments, varying the waste sand content from 10.1% to 19.8% exerted a direct impact on the density, strength, and thermal conductivity of the blocks, with the most stable physical and mechanical indicators observed at a range of 15.6–15.9%, yielding a compressive strength of 1.56 MPa and a density of 670–677 kg/m³. It was determined that passing the waste sand through a No. 0.315 sieve while maintaining a concentration of approximately 15.6% is the most effective technical solution for ensuring a stable expansion height and achieving the necessary thermophysical properties, whereas higher concentrations—specifically reaching 19.8%—led to a strength peak of 1.59 MPa but simultaneously increased the thermal conductivity to 0.160 W/(m·°C), thereby diminishing insulation performance. Further research demonstrated that while concentrations above 20% continued to increase density by 7–11% and strength by 11–13%, this trend negatively affected efficiency by causing a 1.5–2.5% deterioration in the thermal conductivity coefficient. These findings confirm that utilizing recycled quartz at a rate of 10–15% of the total sand mass is the most techno-economically efficient approach for balancing mechanical integrity and heat retention. Furthermore, the highly porous structure of old cement residues and brick dust within the waste sand can rapidly absorb mixing water, increasing viscosity and resisting the rise of hydrogen gas, which may cause uneven pore distribution or structural settlement. Additionally, various chemical and organic impurities, such as lime, gypsum, and dust particles, adversely affect cement hydration and weaken the bond between the cement paste and filler, potentially leading to large cavities or technological cracks in the finished product.

Also after experiments with waste sand from the perspective of the material's long-term operational characteristics, it has been determined that the frost resistance indicators of aerated concrete based on construction waste sand are lower compared to those utilizing natural quartz sand. The open micropores within the waste sand facilitate deeper water penetration into the material, which, upon freezing and expanding at low temperatures, leads to internal deterioration of the material framework and premature embrittlement. To mitigate these negative factors, it becomes necessary to stabilize the material structure using polypropylene fibers and chemical modifiers.

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