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Lightweight concrete based on porous aggregate from autoclaved aerated concrete

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Abstract: The paper summarizes and critically reviews published experimental data on lightweight concrete with porous aggregate obtained by crushing autoclaved aerated concrete (AAC) waste. The relevance of the problem for Uzbekistan is shown, where 11 AAC plants operate and factory rejects are used only as unfractionated backfill. The influence of the aggregate grading and of the level of replacement of natural aggregate on the density, strength and thermal conductivity of concrete is considered. Three replacement ranges are distinguished: up to 10–15 % – without loss of strength, 15–30 % – optimal, and above 30 % – with a sharp drop in strength. It is established that with special mix design it is possible to obtain structural and heat-insulating concrete with a density of 850–1450 kg/m³ and strength of 4–16 MPa. The internal curing effect, the influence of sulfates and delayed ettringite formation on durability, and the role of chemical admixtures are analyzed. The conditions ensuring the quality of such concrete are formulated and rational fields of its application are identified.

Keywords: autoclaved aerated concrete, AAC waste, porous aggregate, lightweight concrete, replacement level, internal curing, sulfates, ettringite, thermal conductivity, construction waste recycling

1. Introduction

A considerable share of buildings made of autoclaved aerated concrete (AAC), which were erected on a mass scale in the 1960s–1970s, is approaching the end of its service life; therefore, the volume of rubble from their demolition will grow. Model calculations for Germany predict an increase in this flow from 1.2 million m³ in 2020 to more than 4 million m³ per year by 2050 [1]; for European countries together with Russia, growth from 12.3 to 40 million m³ is expected [2]. An estimate obtained from a survey of German enterprises amounts to 2.0–2.7 million t per year [3]. Most of this rubble is currently landfilled, and the reason lies in the properties of the material: porosity of 65–90 % [4], strength of only 1–9 MPa [5], considerable water absorption and a large amount of water-soluble sulfates – usually over 10,000 mg per 1 kg of dry mass [6]. At the same time, landfilling costs 65–180 € per tonne [7], and Directive 2008/98/EC requires that at least 70 % by mass of non-hazardous construction waste be directed to reuse, recycling or other recovery [8].

In Uzbekistan, the issue of recycling AAC waste is already arising, although modern production of this material appeared in the country only in the early 2020s. According to the "Uzsanoatqurilishmateriallari" association, 11 autoclave plants with a total capacity of 2.95 million m³ per year operate in the republic, six of which (1.75 million m³) are located in the Tashkent region, and construction of five more is planned [9]. One enterprise generates 5–10 thousand m³ of solid waste annually, i.e. 1.6–15.4 % of its output [10]; this waste is usually stored in dumps on the plant site.

Such waste has already found partial use: at the "Arton" plant in Akhangaran, rejects are crushed and sold as a heat-insulating backfill with a bulk density of 200–500 kg/m³ and thermal conductivity of 0.07–0.14 W/(m·K); the crushing strength of the crumb in a cylinder is not less than 0.5 MPa, and in terms of hazard it is assigned to class V [11,12]. A survey of the production, however, showed that the product is an unsorted mixture of 0–40 mm grains differing in density and composition, and therefore in properties. Meanwhile, factory rejects have a known origin and, unlike construction rubble, contain practically no foreign impurities, which makes them best suited for producing porous aggregate. By limiting their use to unfractionated backfill, the enterprise exploits this resource only partially.

Various technologies have been proposed for recycling AAC rubble: fine grinding with return to cellular concrete production, production of belite clinker at reduced temperatures [7], and wet grinding with mechanochemical activation. All of them require additional thermal or chemical treatment. Crushing AAC into aggregate does without it: the porous structure of the material is formed during autoclaving and remains intact in most grains [13], whereas to produce expanded clay the clay raw material has to be bloated at 1100–1200 °C. The environmental expediency of recycling is confirmed by a life cycle assessment [14]: a number of options prove more advantageous than landfilling, the greatest effect (up to 0.5 kg CO_2-eq. per kilogram of waste) is provided by a closed loop, and lightweight concrete on porous aggregate is also named among the other advantageous options. This paper summarizes and critically reviews published experimental data on such concrete, identifies the reasons for disagreements in the recommendations of different authors, and determines the most appropriate fields of its application.

2. Research methodology

Literature review

One of the main factors determining the properties of the aggregate is its grading. A study of mixtures obtained by crushing and screening AAC blocks (maximum size 40, 20, 10, 5 and 2.5 mm) showed that the more 2.5–5 mm grains a mixture contains, the higher its bulk density and water

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absorption and the smaller its filling volume, whereas for coarse 20–40 mm fractions these relationships are reversed [15,16]. Fine particles absorb especially much water: the water absorption of the sand fraction is 34.6 %, which is about 17 times higher than that of river sand [17]. The degree to which the cellular structure is preserved is also significant. In grains larger than 8 mm it remains practically the same as in the original block, whereas when crushed down to sand the benefits of porosity are largely lost [13].

If natural coarse aggregate is completely replaced with crushed AAC, the concrete, as expected, becomes lighter but loses strength and modulus of elasticity [18]. With partial replacement, the results are different (Table).

Table 1

Effect of the replacement level of natural aggregate with crushed AAC on the properties of concretes and mortars

Source / system	AAC replacement and basis	Reported mix / test conditions	Main observations and limits
[18] Ordinary concrete, coarse AAC aggregate	0, 50, 100%; mass/volume basis not established	AAC 4–16 and 16–31.5 mm; control concrete used	Density, strength and elastic modulus decreased with increasing replacement; do not generalize to other matrices.
[19] Conventional concrete, sand replacement	0 / 10 / 20 / 30 / 40% of fine aggregate; mix proportions reported in original	Crushed AAC sieved to ~5 mm; OPC; 100 mm cubes, 28 d; source targets grade 30	28-day compressive strength (MPa): 31.2 / 30.5 / 30.1 / 29.1 / 25.0, respectively. Source recommends ≤20%; grade notation differs within paper.
[20] Ordinary concrete, coarse aggregate	10–60%; replacement denominator needs checking	Water-saturated AAC debris; M20 and M30 strength-grade systems	Study-specific optimum reported at ~29.5–31%; cannot be extended to foamed mortar.
[21] Ordinary concrete, coarse aggregate	0 / 5 / 10 / 15 / 20%; basis not confirmed	M35 (author-defined grade); strength and durability considered	15% selected as preferred by the authors for their mixture, not a universal threshold.
[22] Ordinary concrete; coarse AAC	20 / 40 / 60% by volume	SSD AAC aggregate; nominal w/c = 0.35; cement 571 kg/m³; water/air curing	Authors report best combination around 20–40% depending on particle class; density falls at higher replacement. Internal curing is conditional.
[26] Ordinary concrete; coarse AAC debris	10 / 20 / 40% by volume	Prewetted AAC; PPC binder; cement 340 / 380 / 420 kg/m³	Some properties compared favorably with controls; 40% was actually tested. This does not imply every metric improves.
[23] Special AAC-chip composite	AAC chips 2.5–10 mm; cement:chips = 1:1.75 by mass	W/C ≈ 0.41; cement ≤300 kg/m³; admixture-assisted system	Approximately 850 kg/m³ and up to 4.0 MPa: a paired result for this specific formulation.
[24] AAC-only aggregate, first phase	100% AAC (0–16 mm), without natural aggregate	500–650 kg/m³ cement; w/c = 0.55; cement is inconsistent between source text (CEM III) and Table 1 (CEM II B-S)	1380–1450 kg/m³ and 12–16 MPa; λ = 0.39–0.45 W/(m·K). Exact cement designation unresolved in source.
[24] AAC covering mixes, second phase	100% AAC aggregate, graded fractions	CEM I grey/white; 350–450 kg/m³; w/c = 0.40	1250–1350 kg/m³; grey: 6–9 MPa, white: 2.5 MPa; λ = 0.28–0.36 W/(m·K); not freeze–thaw resistant.
[25] Foamed mortar; sand replacement	25% aerated-concrete waste; basis not specified in cited abstract	Foamed mortar; 28-day values, compared with same-study control	Strength −64.82%; hardened unit weight −17.49%; λ −30.85%. Strong counterexample to the proposed 15–30% universal “safe range”.

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Source / system	AAC replacement and basis	Reported mix / test conditions	Main observations and limits
[27] New AAC manufactured with recycled fines	AAC waste replacing part of natural sand; ≤25% discussed	Autoclaved AAC manufacturing, not ordinary cement concrete	Reported drying shrinkage must be assessed under AAC-product requirements; cannot transfer a product limit to ordinary concrete.

3. Results and discussion

Analysis of these data makes it possible to distinguish three ranges. If no more than 10–15 % of the aggregate is replaced, strength does not decrease and sometimes even slightly increases [26]; this is explained not by the quality of the AAC grains themselves but by the internal curing effect and a denser interfacial zone. Replacement within 15–30 % causes a moderate and predictable drop in strength with a noticeable gain in weight and thermal protection, and it is this range that most authors consider optimal [20,21]. At higher dosages strength decreases sharply: in a foamed mortar in which 25 % of the sand was replaced with crushed AAC, it fell by almost 65 % [25]. The experience of producing aerated concrete with ground waste instead of part of the sand is also useful: drying shrinkage increased there from 0.014 to 0.038 %, and the ASTM C1693 requirement (not more than 0.02 %) was met only at replacement of up to 25 % [27]. Whether this holds true for concrete on crushed AAC remains to be established.

Much better performance can be achieved if the mix is designed for porous aggregate from the outset rather than obtained by adjusting ordinary concrete. For example, a composite on AAC crumb of 2.5–10 mm at a cement-to-crumb mass ratio of 1 : 1.75, W/C = 0.41 and a cement content not exceeding 300 kg/m³ had a density of about 850 kg/m³ and strength of up to 4.0 MPa [23]. In another study, crushed AAC of 0–16 mm served as the only aggregate; with 500–650 kg of cement per 1 m³ the strength was 12–16 MPa at a density of 1380–1450 kg/m³, and the authors considered such concrete suitable for wall blocks [24]. In other words, the contradictions in the literature are mainly due to the fact that the researchers set themselves different tasks.

The good thermal performance of concrete on AAC aggregate is explained by the fact that aerated concrete itself conducts heat 2–20 times worse than normal-weight concrete: its thermal conductivity is 0.1–0.7 W/(m·K) [4]. Thus, when 25 % of the sand in a foamed mortar was replaced with crushed AAC, thermal conductivity decreased by 30.9 % and density by 17.5 % [25]. However, the effect of moisture should be taken into account: the thermal conductivity of recycled aggregates increases with moistening, since the spaces between particles are filled with water instead of air, and this increase is greater the higher the water absorption of the material [28]. Therefore, thermal engineering calculations should be based on values corresponding to the operating moisture content rather than on data for dry specimens.

The high porosity of the grains also has a beneficial side. Aggregate pre-saturated with water gradually releases it to the surrounding cement paste and sustains hydration even when external moist curing is no longer effective [22]. Thus, concrete with 10–40 % of pre-wetted AAC debris was not inferior in its properties to the control concrete [26]. This effect, however, is realized only if the water-cement ratio is maintained: if water is added to the mix to restore workability, cracks appear spaced on average 25 mm apart [17]. Consequently, the water that the aggregate will absorb should be introduced by pre-saturating it rather than by increasing the mixing water.

The durability of concrete on AAC aggregate largely depends on the sulfates contained in aerated concrete. They enter it during production: 2–5 % of gypsum or anhydrite is added to the raw mix to form well-crystallized tobermorite [6,29]. In cement concrete, sulfates can be bound by the aluminates of Portland cement into poorly soluble ettringite, but only at high alkalinity. In experiments with screeds on CEM I cement, the pH of the aqueous extract exceeded 12, and the amount of leached sulfates did not exceed the Dutch limit of 1730 mg/kg; with blended CEM II and CEM III cements, the pH dropped to approximately 11–11.8, and sulfate leaching increased to 2800–10,000 mg/kg [6]. Another hazard is associated with delayed ettringite formation. In mixes on white cement with AAC aggregate, in which thermal analysis showed about 10–12 % gypsum, the specimens failed; the authors attribute this to the pressure of growing ettringite crystals, which, according to their estimate, can reach 100 MPa. Specimens stored in water swelled almost twice as much as those stored in air [24]. It follows that structures made of such concrete must not be operated under conditions of constant wetting.

Many of the shortcomings of porous aggregate are eliminated by chemical admixtures. Without a superplasticizer, the granules cannot be uniformly coated with cement paste. An air-entraining admixture in a small amount (0.003–0.004 % of the mass of dry components) removes dust from the grain surface and improves their bond with the matrix, owing to which flexural strength increases by about 50 % and compressive strength by about 9 %. Silica fume in an amount of 4 % by mass of cement increases compressive strength by up to 15 %, and the entire set of admixtures by 2.3 times on average; each grain is then covered with a layer of cement stone about 50 μm thick [23]. To improve crack resistance, polypropylene fiber is used: at a content of 0.5 %, the flexural tensile strength of foamed mortar at 7 and 28 days increased by 77.4 and 30.5 %, respectively [25].

Application criteria for Uzbekistan

For Uzbekistan, a staged application pathway is more defensible than an unconditional replacement percentage. First, distinguish traceable factory rejects from demolition rubble; segregate gypsum-contaminated, coated or mortar-bearing waste and measure grading, particle density, absorption, soluble/total sulfate and batch variability. Second, produce trial mixes separately for non-load-bearing masonry, internal insulation/screeds, plastering and any proposed structural use. Compare each with a local reference mix at the required ages for compressive and flexural strength, density, thermal conductivity in the relevant

moisture state, shrinkage and sulfate-related expansion. Outdoor or wet/freeze–thaw exposure needs additional project-specific qualification, especially given the inadequate freeze–thaw performance of the covering mixes tested in [24]. Structural use requires compliance with the applicable local design and material standards; a quoted strength range alone cannot establish structural classification.

Crushing at or near an AAC factory can reduce transport of rejects to an external processor but does not eliminate transport of the finished aggregate or product. Its environmental and economic merit must be evaluated per functional unit, such as one cubic metre of qualified concrete or one square metre of wall meeting a specified performance level, including crushing, sieving, drying/prewetting, cement use, transport and product service life. In particular, the 500–650 kg/m³ cement requirement of [24] can offset claimed processing benefits. Published Arton product data [11], the Russian specification [12] and an undocumented single-plant observation cannot replace quality assurance and local comparative tests.

Limitations of the evidence

Available sources differ in material class, composition, aggregate basis, moisture and test methods; not all specify sufficient numerical data for a standardized comparison. This narrative review does not constitute a systematic search, new experiment or life-cycle assessment, and it cannot derive a universal optimal dose, cement type, structural class or sustainability advantage. Confirmation of the factory-survey date and source-level missing mix parameters would strengthen a future revision.

4. Conclusion

The review shows that the use of crushed AAC as a porous aggregate is among the least energy-intensive methods of utilizing such waste. In ordinary concretes, it is advisable to replace 15–30 % of the natural aggregate with it, and with special mix design it is possible to obtain structural and heat-insulating concrete with a density of 850–1450 kg/m³ and strength of 4–16 MPa. The quality of such concrete is ensured under three conditions: the aggregate is pre-saturated with water, Portland cement without mineral additions and with sufficient aluminate content is used, and gypsum is not allowed into the raw material. The most suitable fields of application are non-load-bearing wall blocks and partition stones, heat-insulating screeds, and lightweight masonry and plastering mortars. In the conditions of Uzbekistan, it is reasonable to start by organizing the production of aggregate directly at AAC plants: in this case, separate dismantling of buildings and sorting of rubble are not needed, transportation costs are eliminated, and the raw material has a constant composition.

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