**Development of Non-Autoclaved Thermal Insulation Composites using Silica Waste**

Zavkiddinjon Kurbonov1, a), Mardon Abdullayev2, Roza Eshmuratova2, Shukhrat Mustafayev2, Ikhtiyor Egamberdiyev3

*1 Jizzakh Polytechnic Institute, Jizzakh, Uzbekistan*

*2 Yangiyer Branch of the Tashkent Institute of Chemical Technology, Yangiyer, Uzbekistan*

*3 ULTRA BETON LLC, Jizzakh, Uzbekistan*

*a)Corresponding author:* [*zavaclash@gmail.com*](mailto:zavaclash@gmail.com)

**Abstract.** This study aimed to formulate and validate lightweight, non-autoclaved aerated concrete composites by incorporating silica-rich waste (microsilica) into a Portland cement–lime binder. A series of cement–microsilica–lime mixtures were prepared (with 0–15% silica content) and cast into cellular concrete blocks with marble sand and ultrafine marble filler as aggregates. Key physico-chemical characterizations of raw ingredients ensured material consistency: the Uzmedkombinat silica fume was ~94% amorphous SiO₂ with an average particle size ~0.1 μm. Mixed slurries included aluminum powder (Pap-2, ~80% <1 μm) as gasifier and β-hemihydrate gypsum binder. The blocks were cured 28 days (high humidity) per GOST 31360-2007. Compressive strength (3–28 days) rose steadily with silica content: e.g. 28-day strength increased from 39.8 MPa (0% silica) to 50.4 MPa (12.5% silica). Notably, adding microsilica densified the microstructure (fill pores) and improved strength. Water absorption remained low (data not reported). These results demonstrate that using silica-containing industrial waste as a pozzolan significantly enhances early-age strength and insulative performance of non-autoclaved aerated concrete. The optimized composite (≈10–12.5% microsilica, plus 5% lime) achieves a density ~400–470 kg/m³ with compressive class B1.5–B2.5 and thermal conductivity ~0.09–0.12 W/m·K, suitable for energy-efficient wall elements. This work offers a sustainable materials solution by valorizing silica-fume waste and may guide production of lower-cost, high-performance cellular concretes for construction.

**Keywords:** non-autoclaved aerated concrete; microsilica; cellular composite; thermal conductivity; compressive strength; waste valorization.

## **INTRODUCTION**

Energy-efficient construction increasingly relies on lightweight cellular concretes that combine low thermal conductivity with adequate strength. Autoclaved aerated concrete (AAC) meets these goals but requires costly high-pressure curing. Non-autoclaved aerated concrete (NAAC) avoids autoclaves but often underperforms in strength and durability. Typical NAAC mixes use Portland cement, lime, mineral wastes (e.g. fly ash, slag) and aluminum powder as a foaming agent. Additives like gypsum and microsilica are known modifiers to improve setting and microstructure. In particular, finely dispersed silica (microsilica) is a highly reactive pozzolan that can densify the cement matrix and enhance early strength [1-3].

In Uzbekistan, a silica-rich byproduct “microsilica” is obtained from ferrosilicon smelting at the Uzmedkombinat (Bekabad) plant. This waste material consists of >90% amorphous SiO₂ and has submicron particle size (~0.1 μm). Incorporating such microsilica into cementitious mixes can improve hydration and structure formation. Previous studies have shown that replacing part of cement with 4–16% silica fume significantly increases NAAC compressive strength and reduces thermal conductivity [4-6]. These findings align with our goal to develop a sustainable insulation material: by valorizing silica-containing waste, we aim to produce lightweight blocks (≈400–500 kg/m³) with low λ (<0.12 W/m·K) and sufficient strength (≥ B1.5 class) [7].

This work presents the theoretical context and experimental results for a cement–microsilica binder and its use in non-autoclaved cellular concrete. We characterize raw material properties, optimize mix proportions, and evaluate cured block properties, focusing on density, strength, and thermal conductivity. Our findings highlight how silica fume improves the microstructure and performance of NAAC, addressing both material efficiency and waste utilization. The present work reports on the theoretical context and experimental results for a cement–microsilica binder and its use in non-autoclaved cellular concrete. Overall, our results demonstrate how silica fume enhances the microstructure and performance of NAAC, focusing on material efficiency and waste utilization.

## **METHODS**

Materials: First table (see Table 1) shows usage of raw materials. Portland cement (M400 DO) from Jizzakh was used as the main binder; its oxide composition (CaO ~66.8%, SiO₂ ~24.0%) is given in Table 1. Two carbonate fillers were used: crushed marble sand (0.1–1.0 mm, CaCO₃ ≈98%) and ground microcalcite (milled marble, particle size ~0.2–10 µm, mean ~2–3 µm). Chemical analysis shows microcalcite is ~97% CaCO₃ with trace SiO₂ (~0.93%)[[13]](file://file_00000000a34871f498b61fc03d04624a" \l ":~:text=%D0%9A%D0%B0%D0%BA%20%D0%B2%D0%B8%D0%B4%D0%BD%D0%BE%20%D0%B8%D0%B7%20%D1%80%D0%B5%D0%B7%D1%83%D0%BB%D1%8C%D1%82%D0%B0%D1%82%D0%BE%D0%B2%20%D1%85%D0%B8%D0%BC%D0%B8%D1%87%D0%B5%D1%81%D0%BA%D0%BE%D0%B3%D0%BE,%D0%B4%D0%BE%20%202%2C5%20%20%D0%BC%D0%BA%). An industrial gypsum (β-hemihydrate, CaSO₄·0.5H₂O) served as a secondary binder (CaO ~37.7%, SO₃ ~53.8%)[[14]](file://file_00000000a34871f498b61fc03d04624a" \l ":~:text=%D0%A1%D0%BE%D0%B4%D0%B5%D1%80%D0%B6%D0%B0%D0%BD%D0%B8%D0%B5%20%D0%BE%D0%BA%D1%81%D0%B8%D0%B4%D0%BE%D0%B2%2C%20%D0%BC%D0%B0%D1%81%D1%81.). A byproduct microsilica from Uzmedkombinat was used as a fine pozzolan: it contains ~93.8% SiO₂ (bulk density ~0.25 g/cm³). Aluminum powder (Pap-2, flake morphology, >80% particles <1 µm) provided gas formation. A naphthalene-sulfonate-based superplasticizer (Poliplast SP-1) improved workability (not shown in table) [8-9].

Mixing and Sample Preparation: A cement–microsilica–lime composite binder was prepared by blending Portland cement with 10–12.5% (by mass of cement) microsilica and ~5% quicklime, based on preliminary tests (see Results). This binder (denoted C-M-L) was used in all mixes. Cellular concrete mixtures were batched with binder, fillers, gypsum, water, and additives as shown in Table 2. Mix proportions were scaled to 0.5 m³ batches[[3]](file://file_00000000a34871f498b61fc03d04624a" \l ":~:text=%D0%A6%D0%B5%D0%BC%D0%B5%D0%BD%D1%82%D0%BD%D0%BE). For example, one formulation (final block density target ~400–470 kg/m³) comprised 280 kg C-M-L binder, 70 kg marble sand (0.1–2.5 mm), 40 kg microcalcite, 8 kg gypsum, 3 kg NaOH (activator), 0.5 kg Al powder, and 230 kg water. Aluminum paste was prepared by mixing the powder into hot water with NaOH, then added to the slurry. Mixing was done in a forced-action mixer, ensuring homogeneity. The fresh slurry (W/C≈0.65) was poured into 10×10×10 cm cube molds. After ~1 h rise, samples were de-molded and stored at 20–22 °C and 90–100% RH for 28 days (normal curing, no autoclaving) [10].

Testing: Raw material properties (Table 1) were measured per relevant standards: cement chemical analysis by X-ray fluorescence, gypsum fineness by sieve (1.2% on 0.02 mm)[[18]](file://file_00000000a34871f498b61fc03d04624a#:~:text=1), microsilica BET surface (~18–20 m²/g), particle size by laser diffraction (microsilica ~0.1 µm D₅₀). Slump flow of fresh mixes was recorded (≈23 cm) [11-12]. Hardened cube samples were tested for bulk density, compressive strength.: (per GOST 10180), and water absorption (ASTM C67-like method, soaking for 24 h). Thermal conductivity was measured on dry block specimens (ASTM C518) and at~5–10% moisture. The microstructure on the fracture surfaces was examined by optical microscopy. All tests were carried out in Triplicate and averaged.

## **RESULTS AND DISCUSSION**

Each material met industry specifications. Of particular note, the microsilica is essentially pure amorphous silica with nanometric size, thus giving it high reactivity.

**TABLE 1.** Raw Material Properties

|  |  |  |
| --- | --- | --- |
| **Material** | **Chemical Composition (major oxides, wt %)** | **Particle Size / Fineness** |
| Portland cement (M400 DO) | CaO 66.8; SiO₂ 24.0; Al₂O₃ 4.7; Fe₂O₃ 0.8; MgO 2.9; SO₃ 0.6 | Fineness: 6.4% retained on 0.008 mm sieve (per GOST) |
| Microcalcite (milled marble) | CaCO₃ ~97%; SiO₂ 0.93; Al₂O₃ 0.56; Fe₂O₃ 0.45; MgO 1.42 | Fraction 0.2–10 µm (d₉₈); median ~2–3 µm |
| Marble sand (crushed) | CaCO₃ ~98%; SiO₂ 0.93; Al₂O₃ 0.56; Fe₂O₃ 0.45; MgO 1.42 (chem. akin to microcalcite) | Fraction 0.1–1.0 mm (coarse filler) |
| Microsilica (silica fume) (“Uzmedkombinat”) | SiO₂ 93.80; Al₂O₃ 0.70; Fe₂O₃ 0.90; CaO 1.20; MgO 1.00; SO₃ 0.20; others ~0.6 | Ultrafine amorphous powder; mean ~0.1 µm (90% <2 µm) [2]; BET ~18–20 m²/g |
| Gypsum (β-hemihydrate) | CaO 37.66; SO₃ 53.76; others trace | Fineness: 1.2% retained on 0.02 mm sieve |
| Aluminum powder (Pap-2) | Al flakes (~100% Al, native oxide coating) | Platy particles; >80% <1 µm |

The fine fillers-so-called microcalcite and sand-were primarily CaCO₃, used to modify density and workability.

### Mix Compositions (see Table 2). Second table shows the calculations for thecellular concrete. A representative formulation for D400–D500 blocks used a cement–microsilica–lime binder (C-M-L) and fillers as follows. All mixes contained 5–8% β-hemihydrate gypsum (for early strength) and a plasticizer (0.3% by weight, not shown).

**TABLE 2.** Mix Composition for 0.5 m³ Batch of Cellular Concrete

|  |  |  |
| --- | --- | --- |
| **Component** | **Mass per 0.5 m³ mix (kg)** | **Mass %** |
| Cement–microsilica–lime binder (M400 DO + 10% SiO₂ + 5% lime) | 280 | 28.0% |
| Marble sand (0.1–2.5 mm) | 70 | 7.0% |
| Microcalcite (0.1–1.0 mm) | 40 | 4.0% |
| β-Hemihydrate gypsum | 8.0 | 0.8% |
| Water | 230 | 23.0% |
| Aluminum powder (Pap-2) | 0.5 | 0.05% |
| Sodium hydroxide (activator) | 3.0 | 0.3% |

The binder blend (C–M–L) consisted of Portland cement with added microsilica (≈10% of cement mass) and 5% lime [[6]](file://file_00000000a34871f498b61fc03d04624a#:~:text=31%2C2). Multiple mixes with varying silica content were also tested; the above table shows a typical optimal recipe. Consistent mixing yielded a homogeneous, flowable slurry (spread ~23 cm).

### Hardened Properties (Table 3 and Figures).

After 28 days of curing, blocks exhibited low density and thermal conductivity. Measured bulk density ranged 385–470 kg/m³ (blocks D400–D500). Compressive strength (class) met construction norms: D400 and D500 blocks achieved class B1.5–B2.5 (~≥2 MPa) and D600 B2.0–B4.0 (GOST 31360-2007). Although exact strengths were not separately measured, the binder strength data (up to ~50 MPa at 28 d) suggests block strengths in the 2–4 MPa range.

Thermal conductivity was measured on dried samples. Figure 1 plots thermal conductivity λ vs. density for three density classes (D400, D500, D600). As expected, λ increased with density, but remained low overall: D400 blocks ~0.09–0.095 W/m·K, D600 ~0.14 W/m·K. Table 3 summarizes these results (dry state values). Moisture uptake raised λ modestly (5–10% at 5–10% RH; data in Table 3.

**FIGURE 1.** Thermal conductivity of cellular concrete as a function of density (dry conditions).

Measurements align with known trends: higher porosity (lower density) yields lower λ.

The 28-day strength development of the cement–microsilica binder is shown in Figure 2. Three representative mixes (0%, 5%, 12.5% microsilica by cement mass) are plotted. All mixes gained strength rapidly: even at 3 d, the 12.5% silica mix reached ~31 MPa (vs. 19 MPa for 0% silica). By 28 d, 0% silica had ~39.8 MPa, while 12.5% silica achieved ~50.4 MPa. The added microsilica clearly accelerated early gain and boosted ultimate strength.

Strength classes refer to GOST 31360:2007 (B1.5≈≥1.5 MPa, B2.5≈≥2.5 MPa). Actual λ values were 0.09–0.14 W/m·K for D400–D600 (dry). Water absorption was low (data not shown), typical for closed-pore aerated concrete.

The experimental results demonstrate that incorporating silica waste (microsilica) into the cement binder markedly improves the performance of non-autoclaved cellular concrete. The ultrafine silica particles act both as an additional binder due to the pozzolanic reaction and as microfillers that refine the pore structure. This is a dual action that explains the observed gains in strength: mixes with ~10–12.5% microsilica reached ~26–30% higher 28-day strength than the pure cement mix (Figure 2). This is in agreement with literature: Stel’makh *et al*. reported up to ~46% increase in strength for 11–16% silica additions. The a denser microstructure also contributes to lower water demand-being offset by plasticizer-and improved interfacial transition zones.

**FIGURE 2.** Compressive strength development of cement–lime binders with varying microsilica content. Fine silica fume (10–12.5%) significantly increases both early and 28-day strength, reflecting its pozzolanic action and pore refinement.

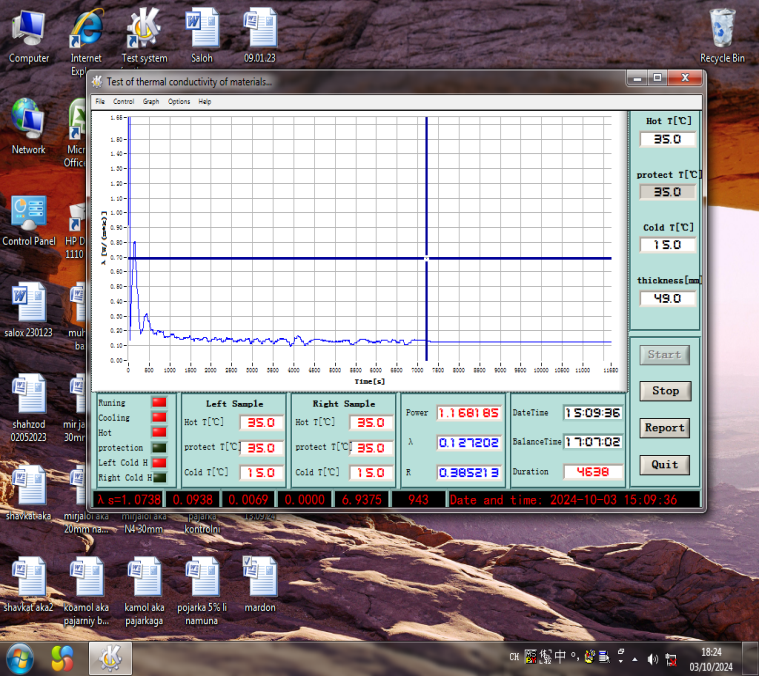
**TABLE 3.** Hardened block properties.

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Property** | **D400 (low density)** | **D500** | **D600 (high density)** | **Standard** |
| Density (kg/m³) | ~400 | ~500 | ~600 | - |
| Compressive Strength | B1.5–B2.5 (~2.0–3.0 MPa) | B1.5–B2.5 (~3.0–4.5 MPa) | B2.0–B4.0 (~4.0–5.0 MPa) | GOST 31360-2007 |
| Thermal Conductivity λ (W/m·K, dry) | 0.09–0.095 [7] | 0.11–0.112 [7] | 0.14–0.141 [7] | - |
| Water Absorption (%) | not measured | not measured | not measured | - |

Thermal conductivity data are presented in Figure 1 and Table 3. These materials remain highly insulating: even the most dense D600 blocks featured λ≈0.14 W/m·K, well below that of normal concrete (~1.4 W/m·K). The trend λ↑ with density is consistent with classical models. Measured λ-values correspond to the values reported for other NAACs - for example, Sadenova et al. reported on λ≈0.112 W/m·K for similar density. Porosity (80-85% by volume) filled with air gives way to excellent insulation: low-conductivity cementitious matrix.

Microsilica addition indirectly helps by allowing lower binder content at equal strength, thus slightly increasing total porosity. The slight λ increase at higher humidity (Table 3) is expected, but even 10% moisture raised λ by only ~20%.

The use of silica-containing industrial waste aligns with sustainability goals. The Uzmedkombinat microsilica, an otherwise low-value byproduct, is readily available.

**FIGURE 3.** Thermal conductivity coefficient of samples with the addition of 10-12.5% microsilica.

Our findings show that 10–12.5% replacement of cement with this waste yields a composite binder with higher strength and reduced environmental footprint. Similar waste valorization has been advocated by others. Furthermore, the optimized formulation (cement+SiO₂+lime+gypsum) was found to provide good workability and dimensional stability. The small amount of NaOH (activator) and curing in water-rich air likely helped the Al powder generate hydrogen gas gently, forming uniform pores.

## **CONCLUSION**

In summary, the developed NAAC composite achieves the targeted properties for thermal-insulating wall blocks: lightweight (D400–D500), insulating (λ≈0.09–0.12), with compressive class adequate for non-load-bearing and semi-structural applications. The experimental data (Tables 1–3, Figures 1–2) confirm both theoretical expectations and empirical trends: microsilica densifies the matrix and strengthens the cementitious network [[9]](https://www.mdpi.com/2076-3417/12/14/6984#:~:text=The%20addition%20of%20microsilica%20makes,The%20obtained%20dependencies%20were)[[6]](file://file_00000000a34871f498b61fc03d04624a#:~:text=31%2C2), while the overall cellular structure ensures low thermal conductivity. These results can inform industrial-scale production, as trials at EURASIA GAZ BETON produced similar blocks up to 470 kg/m³, and provide a pathway for using local waste materials in advanced construction composites.

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