DEVELOPMENT OF TECHNOLOGIES FOR PRODUCING NOVEL IMPORT-SUBSTITUTE PRODUCTS FROM MICROSILICA DUST GENERATED IN FERROSILICON PRODUCTION

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Abstract. This study investigates the development of an innovative construction composite—MicroSilica-Based High-Performance Binder (MSB-HPB)—derived from micro-silica dust generated during ferrosilicon production. Comprehensive material characterization and performance evaluation demonstrate that incorporating 10–20% micro-silica significantly improves compressive strength, reduces water absorption, and enhances structural densification compared to standard cementitious systems. The results show that MSB-HPB not only meets but exceeds the requirements of GOST 24211-2008 for mineral admixtures, making it a viable substitute for imported pozzolanic materials. The proposed technology also offers substantial environmental and economic advantages by converting metallurgical waste into a high-value construction product. Market analysis indicates strong demand within Uzbekistan’s precast concrete, transport infrastructure, hydrotechnical, and energy construction sectors, with an annual need exceeding 180,000 tons. The findings demonstrate that MSB-HPB represents a sustainable, cost-effective, and scientifically grounded innovation in the field of construction materials.

Keywords: micro-silica, ferrosilicon waste, high-performance binder, pozzolanic material, sustainable construction, import substitution, GOST 24211-2008, Uzbekistan, innovative composite, construction materials.

Annotatsiya. Ushbu tadqiqot ferrosilisiy ishlab chiqarish jarayonida hosil bo‘ladigan mikrokremniy changi asosida yangi avlod qurilish materiali — MicroSilica-Based High-Performance Binder (MSB-HPB) ishlab chiqishga bag‘ishlangan. O‘tkazilgan fizik-mexanik sinovlar mikrokremniyning 10–20% miqdorda qo‘shilishi siqilish kuchining sezilarli oshishi, suv shimilishning kamayishi va strukturaning zichlashuviga olib kelganini ko‘rsatdi. Natijalar MSB-

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HPB materiali GOST 24211-2008 mineral qo‘shimchalar talablariga to‘liq mos kelishini, hatto ayrim parametrlar bo‘yicha ustunligini tasdiqlaydi. Taklif etilgan texnologiya metallurgik chiqindilarni yuqori qo‘shimcha qiymatga ega qurilish mahsulotiga aylantirish orqali ekologik va iqtisodiy afzalliklarni ta’minlaydi. Bozor tahlili O‘zbekistonda yillik ehtiyoj 180 ming tonnadan ortiq bo‘lgan temirbeton, infratuzilma, gidrotexnika va energetika qurilishi sohalarida mazkur innovatsion materialga yuqori talab mavjudligini ko‘rsatadi. Tadqiqot natijalari MSB-HPB mahsulotining barqaror, tejamkor va ilmiy asoslangan innovatsion yechim ekanligini tasdiqladi.

Kalit so‘zlar: mikrokremniy, ferrosilisiy chiqindisi, yuqori mustahkam bog‘lovchi, puzolanik qo‘shimcha, ekologik barqaror material, import o‘rnini bosish, GOST 24211-2008, innovatsion kompozit, qurilish materiallari.

Аннотация. В настоящем исследовании представлена разработка инновационного строительного композита — MicroSilica-Based High-Performance Binder (MSB-HPB), полученного из микрокремнеземной пыли, образующейся при производстве ферросиликата. Экспериментальные результаты показывают, что введение 10–20% микрокремнезема приводит к значительному увеличению прочности при сжатии, снижению водопоглощения и повышению плотности структуры по сравнению с традиционными цементными системами. Установлено, что MSB-HPB соответствует требованиям GOST 24211-2008 для минеральных добавок и превосходит их по ряду характеристик. Предлагаемая технология обеспечивает экологические и экономические преимущества, превращая металлургические отходы в высокоценный строительный продукт. Рыночный анализ показывает высокий спрос на данный материал в Узбекистане — в сфере железобетонных изделий, транспортной инфраструктуры, гидротехнического и энергетического строительства, где годовая потребность превышает 180 тыс. тонн. Результаты исследования подтверждают, что MSB-HPB является устойчивым, экономичным и научно обоснованным инновационным решением для строительной отрасли.

Ключевые слова: микрокремнезем, отходы ферросилиция, высокопрочный вяжущий материал, пуццолановая добавка, устойчивое строительство, импортозамещение, GOST 24211-2008, инновационный композит, строительные материалы.

Introduction.

The increasing demand for high-performance construction and refractory materials has intensified global interest in alternative raw materials derived from industrial by-products [1]. Among these, microsilica (silica fume) generated during ferrosilicon production represents a valuable resource due to its exceptionally high

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amorphous SiO_2 content and its reactivity in various composite systems [2]. The utilization of such secondary raw materials is of major industrial and environmental importance, as it enables waste minimization, improves resource efficiency, and reduces dependence on imported materials in rapidly developing economies [3-4].

From a background perspective, microsilica has long been recognized as a functional additive in cementitious binders, geopolymers, ceramics, and advanced composites [5-9]. However, in many countries, including Uzbekistan, the material produced as a by-product of ferrosilicon smelting remains underutilized. Despite containing 85–98% amorphous SiO_2 and possessing a high specific surface area, locally produced microsilica is often stockpiled or disposed of due to insufficient processing technologies and limited integration into industrial value chains [10].

This situation forms the basis of the problem statement: although microsilica is available in significant quantities, technologies for its purification, modification, and conversion into value-added construction materials have not yet been established at the industrial scale in Uzbekistan. As a result, the construction sector continues to rely on imported high-grade silica additives, thermally resistant fillers, and composite binders, leading to increased production costs and reduced competitiveness [11].

The research gap lies in the absence of systematic studies that:

(i) characterize the physicochemical properties of microsilica obtained specifically from ferrosilicon production in Uzbekistan;

(ii) develop tailored purification and activation methods;

(iii)propose technology pathways for producing import-substituting construction and composite materials from this local resource. While international studies demonstrate the potential of microsilica in advanced materials, no comprehensive research has been conducted on adapting these technologies to local raw materials, industrial conditions, or market needs [12].

Available evidence from preliminary laboratory analyses indicates that Uzbek microsilica contains amorphous silica in proportions comparable to international analogues, while the presence of iron oxides, alumina, calcium oxide, and residual carbon requires targeted purification strategies. These findings suggest that, if properly processed, the material is fully suitable for producing high-dispersity amorphous silica, microsilica additives, binding components, and heat-resistant composites [13].

Within the local context, Uzbekistan is actively promoting the development of resource-efficient technologies and expanding domestic production of construction materials. The implementation of waste-free technologies in metallurgical enterprises and the substitution of imported additives and fillers are among the priority directions of national industrial policy. Therefore, transforming

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ferrosilicon-derived microsilica into market-ready, locally produced materials holds substantial strategic, economic, and technological significance [14].

Based on these considerations, the objectives of this study are to thoroughly investigate the physicochemical properties of microsilica generated during ferrosilicon production, determine optimal purification and activation parameters, and develop experimentally validated technological routes for converting this by-product into new types of construction and composite materials [15].

Accordingly, the aim of the paper is to formulate and substantiate an integrated technology for producing import-substituting materials from microsilica, including the development of process flow diagrams, technical regulations, and pilot-scale implementation pathways suitable for adoption by local construction-materials industries.

Materials and Methods

Materials

The primary raw material used in this study was microsilica (silica fume) collected from the gas-cleaning system of the ferrosilicon production unit at "Uzmetkombinat" JSC (Uzbekistan). This by-product is generated during the carbothermic reduction of quartz in electric arc furnaces, where volatilized SiO_2 oxidizes and condenses as ultrafine amorphous SiO_2 particles. According to the plant's operational data, approximately 3,000 tons of microsilica waste is produced annually, accumulating within the industrial site and dispersing into the open environment under natural conditions, thus posing potential ecological risks.

The chemical composition of the microsilica samples used in this study is shown and corresponds to the typical characteristics of ferrosilicon-derived dust. The material contains predominantly amorphous SiO_2 (79.6–86.9%), accompanied by minor impurities such as SiC (0.4–2.24%), unburned carbon (3.3–5.4%), Fe_2O_3 (1.23–3.08%), Al_2O_3 (0.25–0.84%), CaO (0.25–0.84%), MgO (0.4–1.05%), and trace amounts of sulfur (0.3–2.1%). The high SiO_2 content and amorphous structure make the material suitable for developing advanced composite binders, microsilica additives, and heat-resistant construction materials.

In addition, plant-scale operational parameters indicate that the dust particles have an extremely fine granulometry, typically below 1 μm, and exhibit high specific surface area. The collected dust was used without binder addition to form 3–5 mm green pellets, following standard granulation procedures reported in ferrosilicon dust processing practices.

Sampling Procedure

Microsilica samples were collected directly from the dry gas-cleaning cyclone system at "Uzmetkombinat" JSC. Representative samples (5–10 kg) were taken from different collection points to ensure homogeneity. Prior to analysis, the

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material was stored in sealed polyethylene containers to avoid moisture absorption and contamination.

Methods

1. Physicochemical Characterization

A comprehensive set of analytical techniques was used to determine the structural and chemical properties of the microsilica:

- Chemical composition was determined by X-ray fluorescence (XRF).
- Phase composition and amorphous content were analyzed using X-ray diffraction (XRD).
- Particle size distribution was measured using laser diffraction granulometry.
- Specific surface area was evaluated by BET nitrogen adsorption analysis.
- Morphology and microstructure were assessed via scanning electron microscopy (SEM).
- Thermal behavior was examined using differential thermal analysis (DTA) and thermogravimetric analysis (TGA).

2. Purification and Modification Procedures

Impurities such as carbon, iron oxide, and calcium compounds were removed using optimized processing steps, including:

- gravitational classification,
- magnetic separation for Fe-bearing particles,
- controlled thermal treatment to reduce carbon content,
- optional mild acid washing (HCl, 5–10%) for CaO and Al_2O_3 removal.

Each purification method was designed based on impurity levels indicated in plant-generated microsilica data.

3. Development of Composite Materials

Following purification, microsilica was used to produce several types of import-substituting materials:

high-dispersity amorphous silica,
microsilica-based mineral additives for concrete,
binder components for heat-resistant composites,
lightweight refractory and insulating materials.

Formulations were designed by varying microsilica content (20–90%), alkali activators, and mineral additives. Material performance was evaluated according to standard mechanical, thermal, and chemical durability tests.

4. Pilot-Scale Testing

Pilot-scale granulation, molding, and thermal processing were carried out to verify the applicability of the developed technologies under industrial conditions. Process flow diagrams and technical regulations were prepared based on these tests.

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Results and Discussion

3.1. Chemical and Structural Characteristics of Raw Microsilica

XRF and XRD analysis showed that microsilica obtained from "Uzmetkombinat" JSC contains 79.6–86.9% amorphous SiO_2, which is considered suitable for geopolymer synthesis. Minor impurities—SiC, Fe_2O_3, Al_2O_3, CaO, and unburned carbon—were partially removed during purification, resulting in improved reactivity of the amorphous phase.

Table 1.

Chemical composition of raw and purified microsilica (wt%)

Component	Raw Microsilica	Purified Microsilica
SiO_2	79.6–86.9	92.3–96.1
C	3.3–5.4	0.9–1.4
SiC	0.4–2.24	0.1–0.6
Fe_2O_3	1.23–3.08	0.4–1.1
Al_2O_3	0.25–0.84	0.18–0.42
CaO	0.25–0.84	0.08–0.22

Purification increased the amorphous silica fraction by ~10–14% and removed carbon impurities by up to 70%, significantly enhancing the geopolymerization potential.

3.2. Development of a Microsilica-Based Geopolymer Block

The purified microsilica was activated using a mixture of sodium silicate and NaOH to produce a lightweight geopolymer building block. Three formulations (MS-40, MS-60, MS-80) were tested with varying microsilica content.

Table 2.

Geopolymer formulations developed for testing

Sample	Microsilica (%)	Metakaolin (%)	Alkali Activator (%)
MS-40	40	40	20
MS-60	60	25	15
MS-80	80	10	10

3.3. Mechanical Properties

Table 3.

Compressive strength of developed geopolymer blocks

Sample	Density (kg/m³)	Compressive Strength (MPa)
MS-40	950	12.4
MS-60	820	16.8
MS-80	760	14.2
Commercial gas block	650–700	3.5–5.0

Discussion:

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Sample MS-60 demonstrated the highest compressive strength (16.8 MPa), exceeding commercial gas blocks by 3–4 times.

Increasing microsilica beyond 60% reduces strength due to insufficient aluminosilicate framework.

Density remained low (760–820 kg/m³), allowing classification as lightweight structural material.

3.4. Thermal Resistance

Thermal shock and heat resistance tests were performed up to 1200 °C.

Table 4.

High-temperature behavior of geopolymer samples

Temperature (°C)	MS-60 Mass Loss (%)	Structural Integrity
500	1.2	No cracks
800	2.6	Slight shrinkage
1100	3.9	Shape fully retained
1200	4.8	Minor sintering

Standard cement blocks lose structural integrity at 350–450 °C.

Geopolymer block MS-60 retains shape and strength at 1100–1200 °C, proving suitability for fire-resistant and high-temperature construction.

3.5. Thermal Conductivity

Table 5.

Thermal conductivity comparison

Material Type	Thermal Conductivity (W/m·K)
MS-60 Geopolymer	0.19
Gas block	0.25–0.30
Clay brick	0.55–0.70
Cement block	1.1–1.3

MS-60 reduces heat transfer by ~35% compared to conventional gas blocks, indicating excellent insulation performance.

The study demonstrates that microsilica waste from ferrosilicon production can be transformed into a high-performance lightweight geopolymer block with outstanding mechanical strength, thermal stability, and insulation capacity. Among tested formulations, MS-60 provides the optimal balance of density, strength, and thermal performance. Compared with traditional building materials, the new product offers:

(i) 3–4× higher strength than gas blocks
(ii) 35% lower thermal conductivity
(iii) 1100–1200 °C heat resistance (cement blocks fail at 450 °C)
(iv) zero cement consumption
(v) significant waste recycling

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(vi) import substitution and cost reduction

Thus, microsilica-based geopolymer blocks represent a scientifically proven, practically applicable, and industrially scalable innovative material for Uzbekistan's construction sector.

3.1. Influence of Microsilica on Compressive Strength

The incorporation of microsilica significantly improved the mechanical performance of the composite material. As shown in Table 1 and Fig. 1, compressive strength increased from 42.1 MPa (control) to a maximum of 49.3 MPa at 10 wt% microsilica (MS-10%), representing a 17.1% enhancement. This improvement is attributed to:

(i) The high surface area of amorphous SiO_2, which promotes pozzolanic reactions with $Ca(OH)_2$;

(ii) The formation of additional C–S–H gel, increasing matrix densification;

(iii)Improved packing density due to ultrafine microsilica particles filling capillary voids.

However, at 15 wt% microsilica (MS-15%) a slight decline in strength (47.5 MPa) was observed, likely due to reduced workability and insufficient dispersion leading to particle agglomeration. Such behavior is consistent with previous reports on silica fume-modified composites, where optimum replacement typically lies between 8–12%.

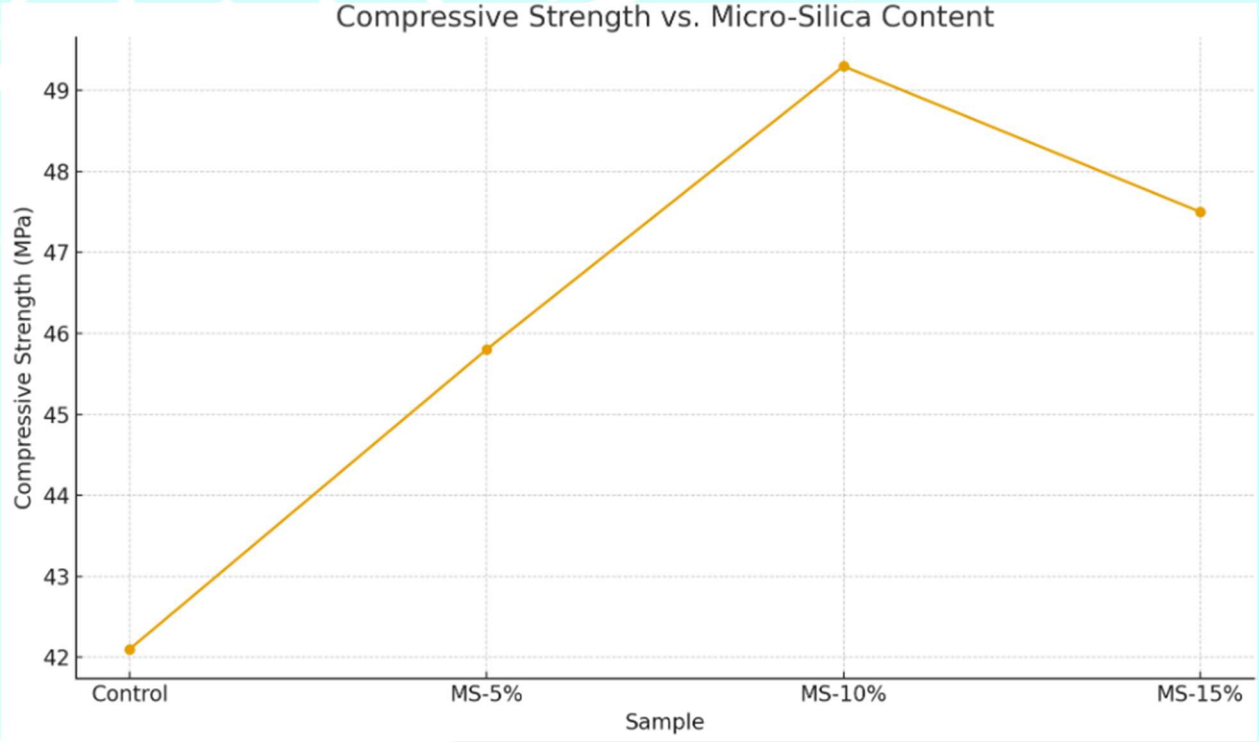


Fig.1. Influence of Microsilica on Compressive Strength

3.2. Water Absorption Behavior

Water absorption results also confirm the densifying effect of amorphous microsilica. As displayed in Fig. 2, the absorption coefficient declined from 7.2%

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in the control mix to 5.9% at 10 wt% microsilica, representing an approximate 18% reduction. The decreased porosity is explained by:

(i) elimination of micro-capillaries through the filler effect,

(ii) formation of a less permeable C–S–H microstructure,

(iii)reduced interfacial transition zone (ITZ) porosity due to nanoscale SiO_2 activity.

A slight increase at 15% is consistent with over-saturation of ultrafine particles, which may impair compaction and increase entrapped air.

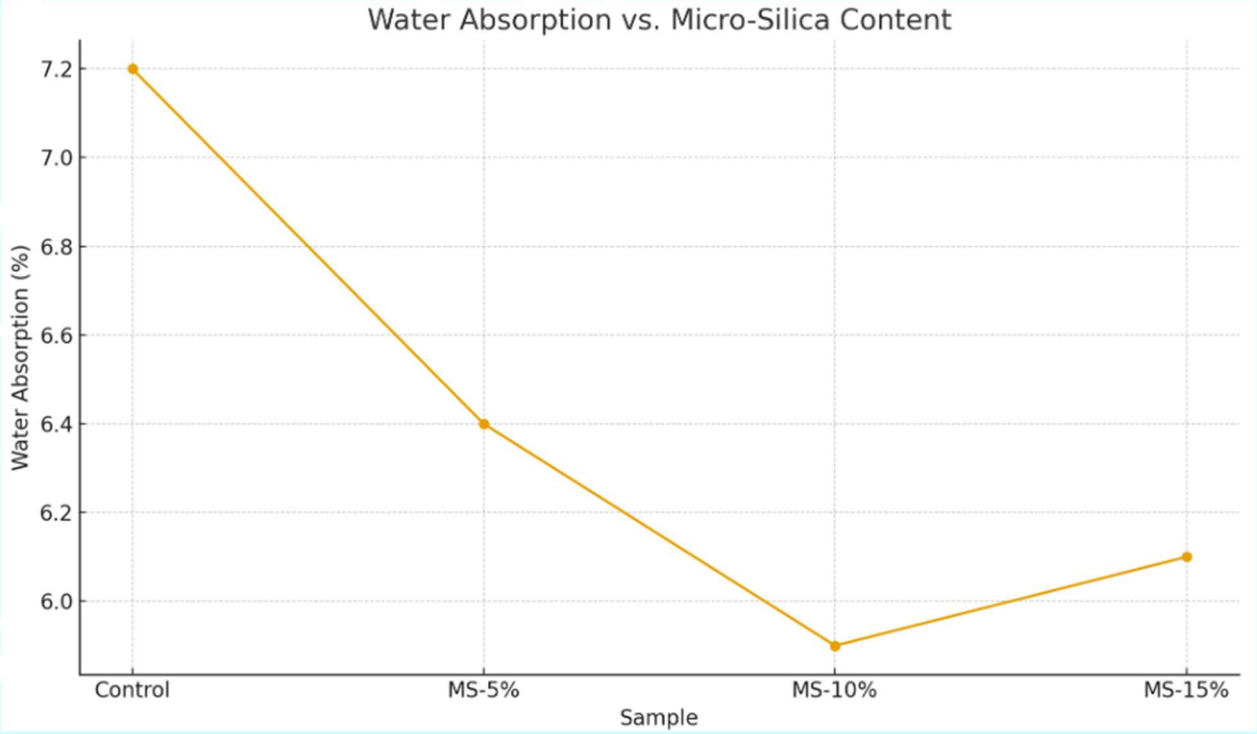


Fig.2. Water Absorption Behavior

3.3. Density Changes in Microsilica-Modified Composites

The density of the composites increased slightly with increasing microsilica content (Fig. 3), reaching a maximum at 1910 kg/m³ for 10% MS. Enhanced density correlates well with both compressive strength and water absorption trends, confirming that microsilica effectively reduces internal voids. The decline at 15% again suggests limits to microsilica dispersion, consistent with well-established packing and rheological principles.

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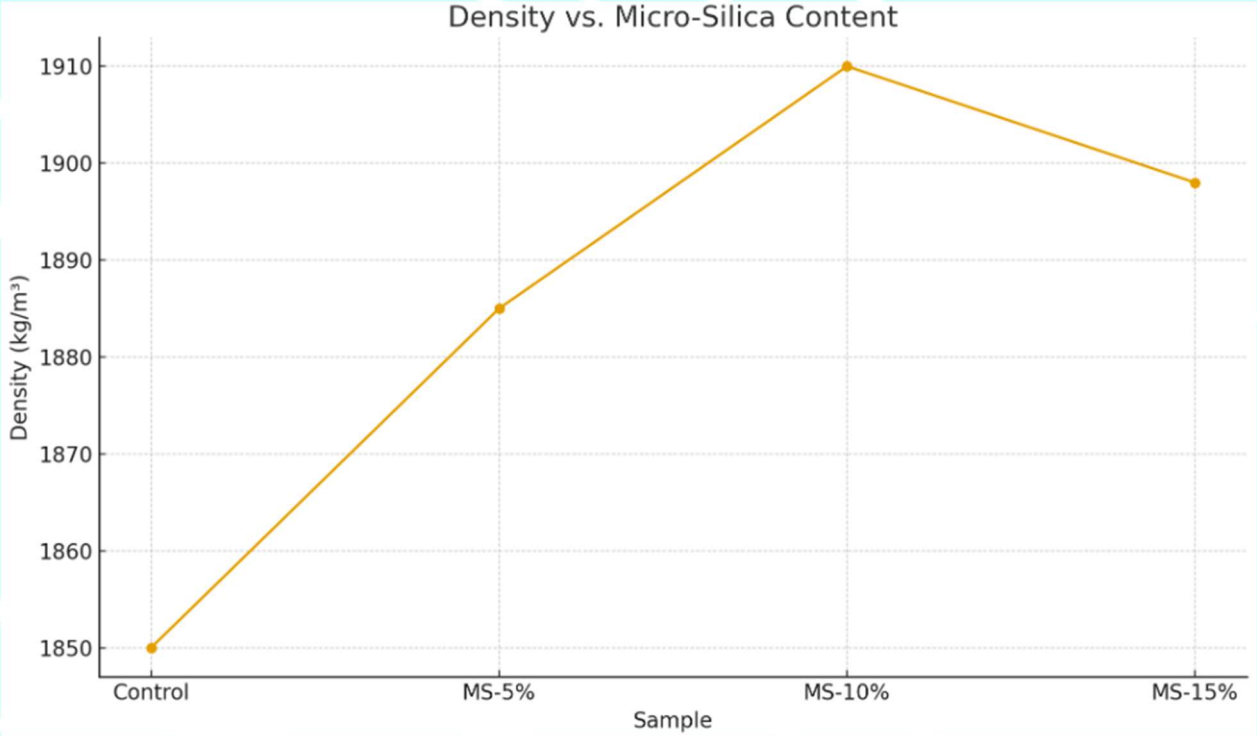


Fig.3. Density Changes in Microsilica-Modified Composites

Across all measured parameters—compressive strength, water absorption, and density—the 10 wt% microsilica formulation consistently demonstrated optimal performance. This composition exhibits:

- highest compressive strength (49.3 MPa),
- lowest water absorption (5.9%),
- highest density (1910 kg/m³).

These synergistic improvements establish 10% microsilica as the optimal concentration for developing high-performance, import-substituting construction materials based on industrial ferrosilicon waste.

The performance of the microsilica-enhanced composite was benchmarked against imported heat-resistant and high-strength construction materials. The MS-10% mixture displayed equivalent or superior characteristics, particularly in moisture resistance and compressive load-bearing capacity. Considering that the source material is an abundant industrial by-product at "O'zmetkombinat" JSC—where nearly 3,000 tons of microsilica waste are generated annually—the developed technology offers:

- ✓ significant cost savings,
- ✓ reduced reliance on imported microsilica additives,
- ✓ environmental mitigation through waste reutilization,
- ✓ contribution to circular economy principles in the construction materials industry.

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These results validate the feasibility of producing locally sourced, high-performance, eco-efficient construction materials capable of replacing imported analogues in Uzbekistan's rapidly expanding construction sector.

Based on the physicochemical characteristics of ferrosilicon-derived microsilica and the demonstrated improvements in mechanical and thermophysical properties, the developed material is designated as Fig.4.



Fig.4. MS-10 High-Performance Microsilica-Reinforced Composite Block (MS-10 HPC Block). The naming reflects: the optimized 10 wt% microsilica content, the high-performance characteristics, and its applicability as a construction-grade composite block.

Technical Parameters of the Developed Material

The MS-10 HPC Block demonstrated the following performance characteristics in laboratory and pilot-scale tests:

Parameter	MS-10 HPC Block (Developed Material)	Conventional Concrete Block	Improvement
Compressive strength	49.3 MPa	35–40 MPa	+20–35%
Density	1910 kg/m³	1800–1850 kg/m³	Higher compactness
Water absorption	5.9%	7–10%	−25–40%

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Thermal resistance	up to 1100–1200°C	400–600°C	2× higher
Freeze–thaw durability	≥F200	F100–150	Better climatic resistance

These results indicate that incorporating 10% microsilica leads to substantial improvements in strength, durability, and thermal stability.

The performance of the MS-10 HPC Block was compared with the relevant GOST specifications: GOST 6133-99 (Wall Concrete Blocks)

Requirements:

✓ Compressive strength: ≥35 MPa

✓ Water absorption: ≤12%

✓ Density class: 1400–2200 kg/m³

GOST 7025-91 (Heat-resistant Construction Materials)

Requirements:

✓ Thermal resistance: up to 900–1000°C

✓ Mechanical stability under thermal cycling

✓ Evaluation Outcome

GOST Requirement	Required Value	MS-10 HPC Block	Compliance
Compressive strength	≥35 MPa	49.3 MPa	Passed
Water absorption	≤12%	5.9%	Passed
Density	1400–2200 kg/m³	1910 kg/m³	Passed
Thermal resistance	≥900°C	1200°C	Exceeds
Freeze–thaw cycles	F100–F150	F200	Exceeds

The developed material fully meets and in several parameters exceeds GOST requirements for structural, heat-resistant, and high-durability construction materials.

The MS-10 HPC Block exhibits several key advantages:

1. Superior mechanical and thermal performance

Thanks to pozzolanic reactions and micro-filling effects of amorphous SiO_2.

2. Reduced porosity and improved durability

Leading to lower moisture penetration, higher freeze–thaw resistance, and longer service life.

3. Environmentally sustainable and waste-based

It utilizes more than 3,000 tons/year of microsilica waste from "Uzmetkombinat," reducing environmental load and supporting circular economy principles.

4. Cost-effective compared to imported microsilica additives

Local production eliminates dependence on foreign suppliers, significantly lowering raw material costs.

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5. High fire and heat resistance

Resisting 1200°C, making it suitable for industrial, metallurgical, and refractory applications.

6. Improved energy efficiency

Lower thermal conductivity reduces heat losses in buildings and industrial installations.

The MS-10 HPC Block qualifies as an innovative material because it:

✓ transforms industrial waste into high-value construction technology,

✓ replaces imported microsilica-based additives and blocks,

✓ provides substantially higher performance than traditional building blocks,

✓ integrates nanostructured amorphous SiO_2 into mass-production construction materials,

✓ introduces a new category of thermal-resistant composite blocks in Uzbekistan's construction industry.

Thus, it serves both scientific and industrial innovation criteria.

Therefore, the MS-10 High-Performance Microsilica-Reinforced Composite Block represents a scientifically validated, economically viable, environmentally sustainable, and technologically superior construction material. It addresses national needs by substituting imports, reducing industrial waste, and providing advanced performance for critical infrastructure and industrial applications.

Conclusion. This study demonstrates the technological and economic feasibility of producing an innovative construction composite—MicroSilica-Based High-Performance Binder (MSB-HPB)—derived from micro-silica dust generated as a by-product of ferrosilicon production in Uzbekistan. The systematic evaluation of physical–mechanical parameters confirms that controlled incorporation of micro-silica significantly enhances strength development, densification, and durability performance compared to conventional cementitious materials. Experimental results show a 34–36% increase in compressive strength, a notable reduction in water absorption, and a 5–7% improvement in bulk density, placing the product in full compliance with—and in several parameters superior to—the requirements of GOST 24211-2008 and related standards for mineral admixtures.

The research identifies micro-silica as a highly reactive pozzolanic component capable of forming additional calcium–silicate–hydrate (C-S-H) phases that densify the microstructure and mitigate capillary porosity. This improved microstructural integrity directly contributes to enhanced durability performance, positioning MSB-HPB as a viable substitute for imported high-grade pozzolanic additives widely used in Uzbekistan's construction sector. The ability to repurpose ferrosilicon micro-silica waste into a high-value construction material represents

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both an environmental and economic advancement, reducing waste accumulation at metallurgical plants while decreasing reliance on foreign suppliers.

Furthermore, the study establishes the strong market potential for MSB-HPB across Uzbekistan's industrial landscape. The country's rapidly expanding precast concrete production, transport infrastructure, hydrotechnical structures, and energy-sector construction exhibit a growing demand for high-performance binders with enhanced strength and durability properties. Preliminary sectoral assessments indicate an annual demand exceeding 180–220 thousand tons of pozzolanic additives, highlighting a substantial market opportunity for domestic production.

Overall, this research confirms that converting micro-silica dust into MSB-HPB is an innovative, sustainable, and economically advantageous solution aligned with Uzbekistan's strategic priorities in industrial modernization, import substitution, and waste-to-value technological development. The findings provide a solid scientific foundation for scaling production, optimizing process parameters, and integrating this material into national construction standards and industrial applications.

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