



DOI: 10.58224/2618-7183-2025-8-3-5



Investigation properties of microsilica to assess the possibility of its use as an additive in concrete production

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Abstract. A comprehensive study of the composition, structure and properties of microsilica from the sludge field of JSC Kremniy was conducted. It was shown that the capture of microsilica during gas purification with a soda solution and its storage under a layer of water on the sludge field for many years contributed to the formation of agglomerates of particles with an average size of 7-16 μm , consisting of nanosized amorphous silica particles of spherical shape. It was found that microsilica has a relatively low pozzolanic activity, and agglomerates of its particles formed during capture during gas purification and long-term storage on the sludge field reduce the efficiency of using microsilica as an active mineral additive. To increase the activity of microsilica and destroy agglomerates, intensive mechanical action is required during the processing of microsilica as part of various building materials. The laboratory studies have confirmed the possibility of using microsilica in the construction industry as an active mineral additive to cements, including as a substitute for part of the clinker, as an "acidic" component of unfired hydraulic and autoclave hardening binder, and as a silica-containing additive to raw sludge for clinker firing. It has been shown that the use of microsilica from JSC "Kremniy" in the construction industry will improve the environmental situation in the region, and the experience of using waste described in the work can be extended to other metallurgical enterprises.

Keywords: microsilica, agglomerates of amorphous silica, pozzolanic activity, microporosity, active mineral additive, raw sludge

Please cite this article as: Kulikov B.P., Tarasov I.V., Bezrukikh A.I., Konstantinov I.L., Voroshilov D.S. Investigation properties of microsilica to assess the possibility of its use as an additive in concrete production. *Construction Materials and Products*. 2025. 8 (3). 5. DOI: 10.58224/2618-7183-2025-8-3-5

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1. INTRODUCTION

One of the types of waste from metallurgical production in the production of technical silicon is microsilica (MS) obtained during high-temperature processing of silica-containing raw materials in ore-thermal furnaces. The formation of MS occurs during condensation of the cooling dust-gas mixture passing through bag filters or electrostatic precipitators of a number of metallurgical enterprises. The material is particles of amorphous silica, the size of which is approximately 100 times smaller than the average particle of cement, and the average specific surface is 17-20 m²/g. Condensed MS is classified as a highly reactive pozzolanic material and is used as an active mineral additive for obtaining a wide range of concretes and cement mortars [1-3]. This is explained by the fact that the smallest spherical silica particles fill the voids between the particles of cement components, and also compact and strengthen the cement mortar with hydration products. It is noted that MS additives improve the main characteristics of concrete, including compressive strength, wear resistance, frost resistance, chemical resistance and significantly reduce permeability. Therefore, due to its advantages, MS is in great demand in the construction industry.

According to information from the source [4], it is predicted that until 2029, the global MS market will grow by an average of 4.7% per year.

In the work [5], it is noted that MS dust is usually supplied in three forms: ultrafine powder in its original state, compacted or in the form of a suspension. At the same time, as the authors claim, this difference in states should not affect the pozzolanic behavior of MS in the cement matrix.

In the article [6], the main attention is paid to the development of a technology in which a system has been developed that uses MS powder and a specially designed package of dispersants to ensure fluidity and control the behavior of cement during setting. In silicon production, one of the methods for removing industrial waste is to capture it by gas cleaning using a weak soda solution. The resulting MS suspension is dumped onto a sludge field, where a huge amount of waste often accumulates, which, despite the valuable elements they contain, has a harmful effect on the environmental situation in the region of the enterprise. The specifics of capturing MS with a soda solution and the peculiarity of storing it under a layer of water require a detailed study of the structure and properties of MS to assess its use in the construction industry.

Therefore, the works devoted to the study of the possibility of using metallurgical production waste as raw sludge for cement production should be considered relevant. The results of the work will also help to improve the environmental situation in the areas adjacent to these enterprises and provide enterprises engaged in cement production with raw materials. The purpose of the work was to study the composition, structure and properties of microsilica to assess the possibility of its use in the construction industry.

To achieve this goal, the following tasks were solved in the work:

- study of the structure and properties of microsilica;
- determination of the optimal content of microsilica in the composition of cement;
- study of the properties of clinker containing microsilica and their comparison with the properties of clinker made from cement obtained using standard raw materials.

2. MATERIALS AND METHODS

The following instrumental methods and equipment were used to achieve the goal set in the work.

For X-ray phase analysis (XPA), a Shimadzu XRD-7000 X-ray diffractometer was used in Cu K α radiation. X-ray patterns were recorded in the 2 θ angle range from 5 to 70° with a step of 0.03 degrees at a scanning speed of 1.5 degrees/min. The X-ray pattern analysis was performed according to the program of the information retrieval system using the PDF₂ database of X-ray phase standards of minerals for phase identification and quantitative X-ray phase analysis using the multi-reflex method of "corundum numbers" [7].

Electron microscopic studies were carried out according to GOST R ISO 22309-2015 on a Tescan Vega III SBH scanning electron microscope equipped with an Oxford X-Act integrated energy-dispersive microanalysis system. Ancillary equipment included a Quorum Q150RES sample

preparation system and a PFEIFFERDUO 6M forevacuum pump. The standard samples used were Co (MAC, reg. no. 9941 Co) and a standard sample cassette (MAC, reg. no. 11192).

During the studies, fragments of MS samples were placed on double-sided conductive tape and covered with a carbon layer of about 20 nm thickness. Each sample was examined using an electron microscope at two magnifications. At high magnifications, the search for and identification of major and impurity minerals was carried out, including determination of their sizes, morphological characteristics, and features of intergrowths. At low magnifications (with a field of view of 100-200 μm), the chemical composition of MS particles was determined to study their general characteristics. In addition, the samples were placed in a cylindrical form, filled with epoxy resin and kept under vacuum until the compound hardened. The resulting samples were ground, polished, and then examined using an electron microscope. The dispersed composition of the MS was determined by laser granulometry using an Analysette-22 NanoTec Plus particle analyzer. The analysis procedure was carried out as follows. The sample in the form of an aqueous suspension in which the MS was suspended was fed into the measuring cell. The light scattered proportionally to the particle size was focused using a lens and directed to the detector. The particle size distribution was calculated from the distribution of the scattered light on the detector plate, according to the Fraunhofer theory [8].

To analyze the surface area and study the porous structure of the MS, the automated ASAP 2020 V4.00 system was used. For this purpose, a MS sample weighing 200 ± 20 mg was loaded into a 250 ml test tube in a liquid nitrogen environment. Then the test tube with the sample was placed in the degassing station, and the maximum degassing temperature was set to 250 °C. The degassing time after reaching the maximum temperature and the final pressure in the test tube equal to 5 μm of mercury was 1 hour. The completeness of the component removal was estimated by the pressure sensor readings. After degassing, the test tube was filled with nitrogen, removed from the degassing station and began measuring the sample surface, for which an adsorption-desorption isotherm was plotted at 56 points at a temperature of 77 K. Each point was measured upon reaching adsorption equilibrium in automatic mode. After completion of the analysis and reaching room temperature by the sample, the sample was weighed. The change in mass was taken into account when recalculating the surface.

The total specific surface of the MS was measured using the desorption curve at a relative pressure of 0.995. The surface was measured using the BET method at 56 points. By summing up the calculated values for all pores in the studied range of relative pressures (0.01–0.99), the cumulative (total) specific surface was obtained. The specific surface area of the MS was calculated using the value of the monolayer capacity, which was determined based on the processing of experimental data using the linear form of the BET equation [9-11].

The microporosity of the MS was determined using the De Boer t-method as the average statistical thickness of the adsorption film. Each value of the relative pressure corresponded to a certain value of the adsorption film thickness. According to the De Boer dependence, the relative pressure values were recalculated into the values of the adsorption film thickness. The De Boer method also allowed the calculation of the external specific surface area [12].

The pore size distribution was calculated using the Barrett-Joyner-Halenda (BJH) method [13]. The pore volume was determined using the values of the pore wall surface area and pore length. Models of slit and cylindrical pores were used for the calculation. Porosity was determined automatically using the above methods using licensed software from Micromeritics (USA). Before taking samples, the correct operation of the device was checked by measuring the surface of a standard aluminum oxide sample. The degree of pozzolanic activity of MS was determined using the technique [14, 15] based on the amount of CaO absorbed from a saturated solution of calcium hydroxide by one gram of MS when the solution was heated to 85-90°C and held for 12 hours. The decrease in the concentration of CaO in the saturated solution due to the absorption of MC was determined by titration with hydrochloric acid with a concentration of 0.05 mol/dm³ in the presence of a methyl orange indicator. The amount of CaO absorbed by 1 g of the additive in 12 hours was calculated based on the difference between the values of the CaO content in the initially poured saturated solution and the amount of CaO contained in the solution at the time of titration.

The construction and technical properties of clinkers with active mineral additives in the form of fly ash from the Novo-Irkutsk Thermal Power Plant (Russia, Irkutsk Region) and microsilica from

JSC Kremniy (Russia, Irkutsk Region) were studied using laboratory-ground cements with the addition of gypsum in the amount of 2.03-2.17% (mass.) in terms of SO_3 . Clinker from the Angarsk Cement Plant (Russia, Irkutsk Region) was used in the experiments. The fineness of grinding of cements was estimated by the residue on a 0.08 mm sieve and by the specific surface. To obtain a non-fired binder, a mechanical mixture of MS and carbide silt (CS) from the sludge field of the oxygen-acetylene plant (Russia, Krasnoyarsk Territory) and CS from the sludge field of the Usolye-Khimprom plant (Russia, Irkutsk Region) were used. The mixture was mixed with a certain amount of water and samples were molded from it. The samples were kept in air-humid conditions, in water for 14 days, after which their mechanical characteristics were determined. Then, after 1 day of hardening in air, autoclave treatment of the samples was carried out at 180 °C for 2 hours under a pressure of 0.8 MPa. Physicomechanical tests of the obtained cements were carried out in accordance with the requirements of GOST 310.1–76 (EN 197–1), GOST 310.4–81 (EN196–1) and GOST 30744-01 using an Instron 3369 desktop testing machine.

The use of MK as a component of raw sludge for clinker firing was considered using the example of raw materials from the Belgorod Cement Plant (Russia, Belgorod). In the plant raw sludge, the main silica-containing component, crushed stone, the content of which in the sludge is 8.09% (mass.), was replaced with MS. The raw sludge with the addition of MS was fired in a laboratory resistance furnace at 1430 °C for 45 min. The resulting clinker was compared with the plant clinker in terms of composition, modular characteristics and physical and mechanical properties of cement stone. The research results were subjected to statistical processing with a confidence level of 0.95.

3. RESULTS AND DISCUSSION

The general appearance of the MS sample in backscattered electrons is shown in Fig. 1. The sample is an agglomerate of spherical and irregularly shaped particles cemented with amorphous silica.

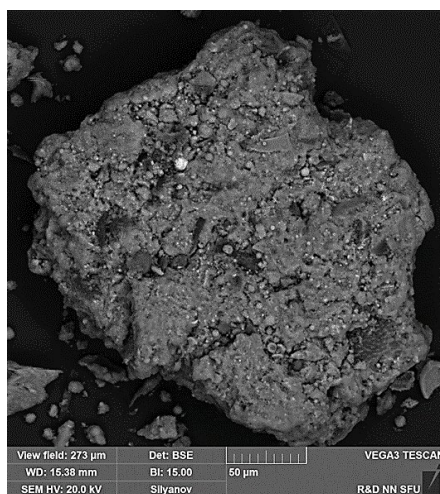


Fig. 1. Appearance of a microsilica sample.

The microstructure of the sample is shown in Fig. 2. The sample under study consists mainly of amorphous silica, which binds slag particles of spherical and irregular shapes.

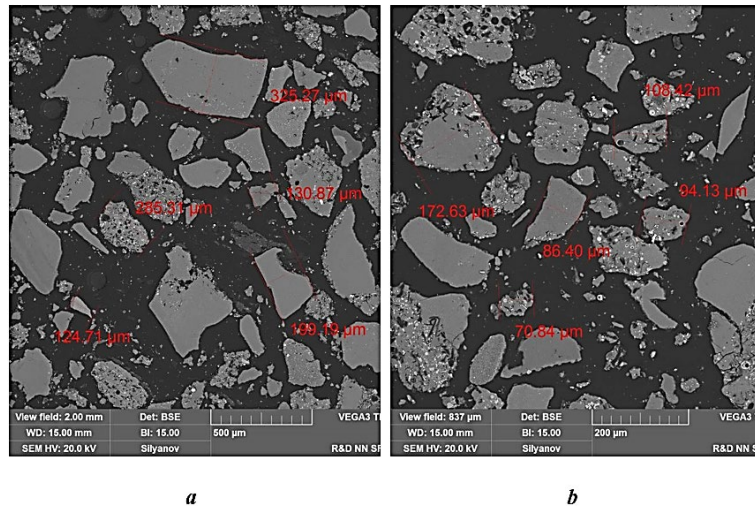


Fig. 2. Microstructure of microsilica particle agglomerates at two magnifications.

When studying the MS structure, it was found that in one part of the agglomerates, submicron MS particles predominate (Fig. 2*a*), while in the other part, MS binds slag and silicon carbide particles of spherical morphology (Fig. 2*b*). Also, in the dusty part of the sample, there are individual spherical slag particles covered with submicron MS grains. Among the slag particles, calcium and iron oxides are noted, sometimes with an admixture of chromium, nickel, copper, as well as silicon carbide SiC.

Fig. 3 shows two types of MS, made at different magnifications. Fig. 3*a* shows an MS agglomerate of 45-50 μm in size. Figure 3*b* shows an enlarged image of its surface, which shows that the agglomerate consists of rounded nanosized particles.

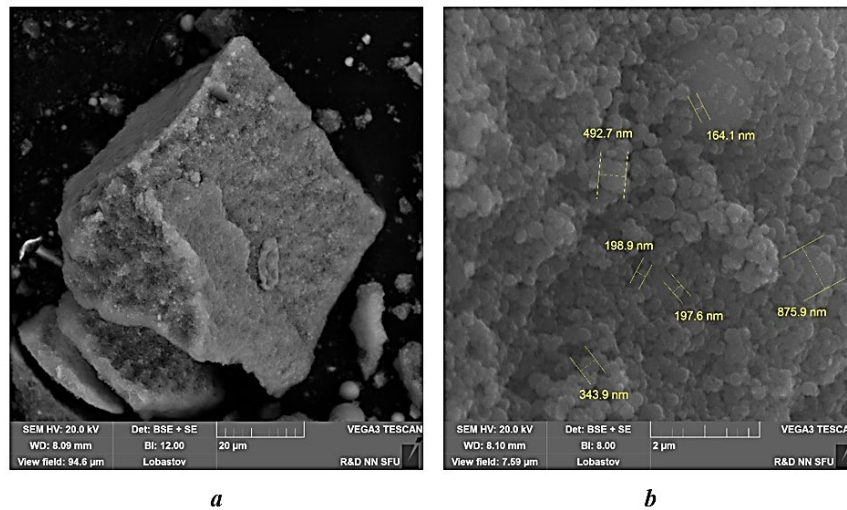


Fig. 3. Agglomerate of microsilica particles from JSC “Kremniy” at two magnifications.

Using a soda solution with a calcined soda concentration of about 2.5 g/dm³ in gas cleaning of JSC “Kremniy” waste also promotes the agglomeration of the smallest MS particles. Apparently, the soda solution and the products of its interaction with gases promote the unification of micron and nanosized MS particles into agglomerates.

Fig. 4 shows an X-ray diffraction pattern of MS from JSC “Kremniy”.

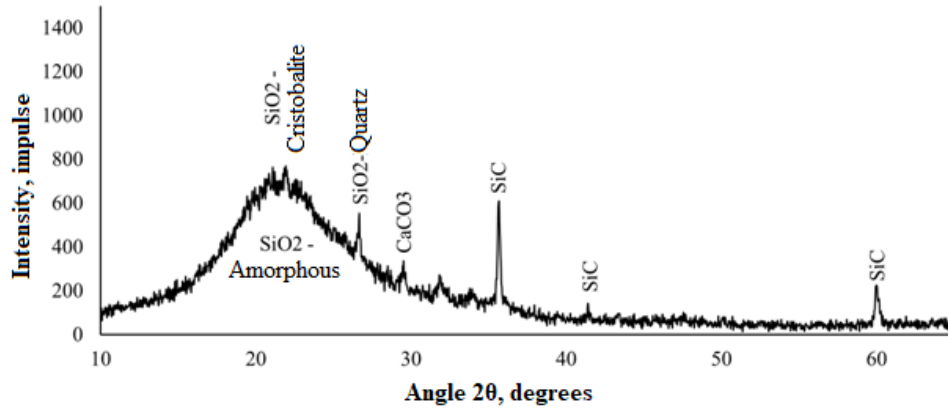


Fig. 4. X-ray diffraction pattern of microsilica from JSC “Kremniy”.

According to X-ray phase analysis, the basis of MS is amorphous silicon oxide with an admixture of silicon carbide, quartz, cristobalite and calcite. A significant amorphous ring (halo) complicates the examination of the MS composition, covering small peaks of impurity compounds [16].

To clarify the composition of MS, including the content of impurities in it, 40 measurements were performed on 10 samples using the method of micro-X-ray spectral analysis (MSA). The averaged results of the analyses in terms of elemental oxides are given in Table 1.

Table 1. Composition of microsilica according to MSA data.

Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	P ₂ O ₅	SO ₃	CaO	Fe ₂ O ₃	Other
0.8	0.3	0.6	93.7	0.3	1.4	1.8	0.5	0.6

The impurity concentration in the MS was clarified by X-ray spectral analysis (XRSA) (Table 2). In general, the impurity content in the MS, determined by XRSA and XRSA, are in satisfactory agreement. Carbon, the concentration of which in the MS is about 5% (mass), is represented by silicon carbide and amorphous carbon.

Table 2. Impurity content in microsilica of JSC "Kremniy" according to XRSA data, % (mass).

K	C	P	Fe	Na	S	Al	Ca	Mn
0.4	5.2	0.1	0.2	0.6	0.5	0.2	1.0	0.04

Fig. 5 shows the fine structure of the MS agglomerates with the points where the spectra were recorded. According to the analysis, silica and slag inclusions, including those based on iron oxide with an admixture of silicon carbide, predominate in the agglomerates.

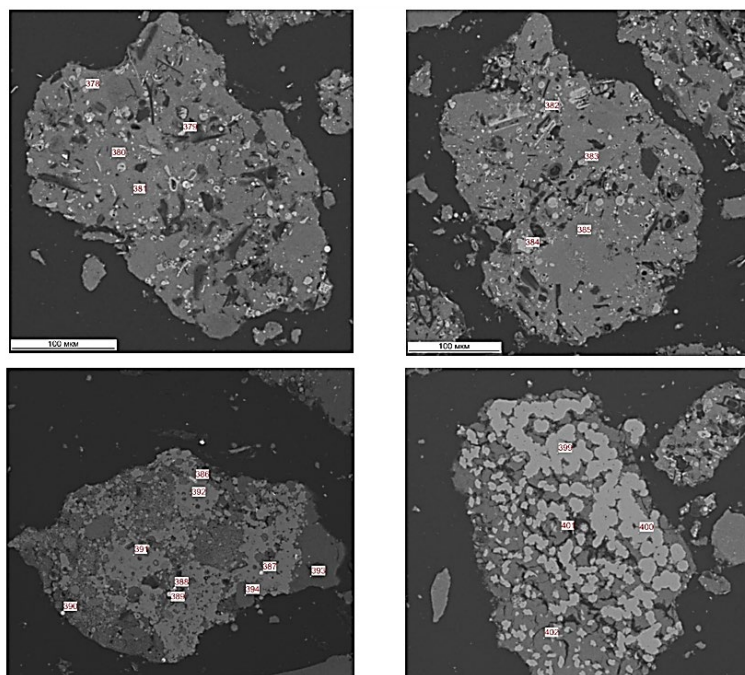


Fig. 5. Fine structure of microsilica agglomerates with MRSA areas.

Table 3 shows the chemical composition of the main structural components of MS according to MRSA data (the numbers in Figure 5 correspond to the spectral numbers in Table 3).

Table 3. Results of spectral analysis of microsilica agglomerates from the sludge field of JSC “Kremniy”.

Spectrum	O	Na	Mg	Al	Si	P	S	K	Ca	Fe	Mineral
378	54.0				45.4				0.6		Silica
379	56.2	0.8			9.5				33.5		Slag
380	48.2	0.7			48.6		1.3	0.4	0.7		Silica
381	47.6	1.0			51.5						Silica
382	48.2			23.1	24.0			4.7			Slag
383	52.4				47.6						Silica
384	51.8	1.7	0.9						45.7		Slag
385	49.1	0.7			50.2						Silica
386	42.3			0.5	2.5	0.3	0.5		2.5	50.8	FeO
387	33.3				2.2				2.2	62.3	FeO
388	5.3				4.0				2.7	88.0	FeO
389	29.7				0.9				0.8	68.7	FeO
390	29.5				1.6				0.6	68.3	FeO
391	54.4		0.8		9.8	1.0	0.6		33.5		Slag
392	52.0				46.3				1.7		Silica
393	49.1	0.8			43.0	2.0			5.2		Silica
394	50.4				48.6				0.9		Silica
395	2.5				96.8				0.8		SiC
396	51.4				46.3				2.2		Silica
397	56.7				23.8				19.6		Slag
398	49.7				50.3						Silica
399	58.8	0.3	0.3		17.2	0.9			22.6		Slag
400	60.7	0.6	0.3		14.8	0.9	0.3		22.4		Slag
401	48.7				51.3						Silica

Fig. 6 and Table 4 show the results of granulometric analysis of MS JSC “Kremniy”, including those carried out with ultrasound treatment.

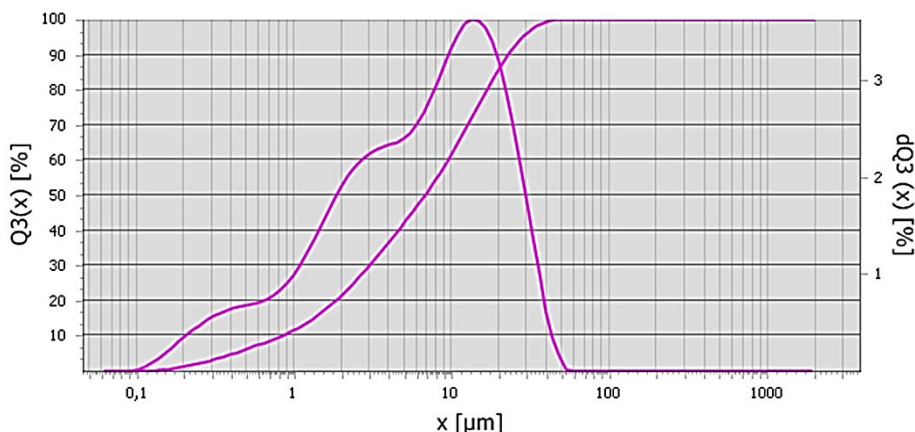


Fig. 6. Distribution of microsilica particle agglomerates by size without ultrasound treatment.

Table 4. Distribution of MS particle agglomerates by fractions.

Without ultrasound treatment		With ultrasound treatment	
Q3(x) in %	x in μm	Q3(x) in %	x in μm
5	1.4	5	0.4
10	2.2	10	0.8
25	5.7	25	2.4
50	15.8	50	6.9
75	28.8	75	14.7
90	42	90	23
95	50.3	95	28.6
99	65.4	99	38.8

According to laser granulometry, the average size of MS particle agglomerates without ultrasound treatment was 15.8 μm , and with ultrasound treatment 6.9 μm . The maximum size of MS agglomerates did not exceed 40 μm .

An important characteristic of MS, which determines its possibility of use in concrete and mortar mixtures, is the specific surface area of the particles. This indicator depends on the particle size, the presence of pores, microcracks and particle defects. The specific surface area is also affected by the heat capacity, porosity and internal moisture in the MS. The surface area was determined from the adsorption curve using the Brunauer-Emmett-Teller method [17]. The adsorption curve shown in Fig. 7, refers to the type IV isotherm (according to the Brunauer classification) with a hysteresis loop H3 in the range of relative adsorbate pressure values P/P_0 0.45–1.0, which indicates that MC is a predominantly mesoporous structure with slit-shaped pores. The surface area, which was calculated based on points lying in the range of relative pressures from 0.06 to 0.30, was 17.05 m^2/g (Table 5).

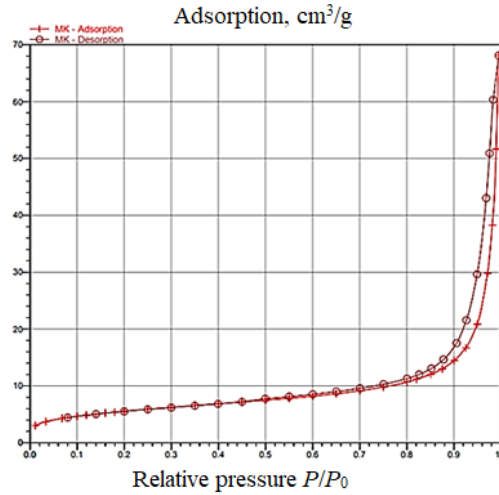


Fig. 7. Isotherm of nitrogen adsorption-desorption by micros silica at 77 K.

Table 5. Surface area of micros silica particles of JSC “Kremniy”, m²/g.

Surface area at a point $P/P_0 = 0.30$	Surface area BET	External surface area	Total adsorption surface area of BJH with pore width from 1.7 to 300.0 nm	Total desorption surface area of BJH with pore widths from 1.7 to 300.0 nm
18.9	17.0	19.3	15.7	15.9

Note – P/P_0 is the relative pressure of the adsorbate (P is the pressure of the adsorbate, P_0 is the saturated vapor pressure of the adsorbate).

Table 6 shows the results of determining the volume and size of pores in MS particles obtained by the BJH method. The calculated pore volume was approximately 0.1 cm³/g.

Table 6. Volume and size of pores of micros silica of JSC "Kremniy".

Pore volume, cm ³ /g			Pore size, nm		
Total volume of pores with width less than 399.5 nm at point $P/P_0 = 0,30$	BJH adsorption. Total volume of pores with width from 1.7 to 300.0 nm	BJH desorption Total volume of pores with width from 1.7 to 300.0 nm	Average adsorption pore width (BET)	Average adsorption pore width (BJH)	Average pore width during desorption (BJH)
0.1	0.1	0.1	24.7	26.3	26.1

MS contains virtually no micropores, since their total volume calculated using the De Boer method does not exceed 1.1×10^{-4} cm³/g. The external specific surface area determined using the same method was 19.3 m²/g. The difference in the surface area calculated using the BET method and the De Boer method indicates that adsorption occurs both on the external surface and in the micropores. The pore size distribution was determined using the BJH model. The average pore width was about 26 nm. Determining this characteristic using the BET model gives a comparable result (24.7 nm).

The average particle size determined using the analysis results was 351.9 nm. The difference between the particle sizes determined using laser granulometry (6.9 μm) and the BJH method (0.35 μm) is probably due to incomplete destruction of micros silica particle agglomerates by ultrasound in the laser particle analyzer. The scientific and patent literature has covered solutions for using condensed MS in the production of various building materials [18-20] quite widely, and the GOST R 58894-2020 standard has been developed, which classifies the types of MS. This document includes

MS quality indicators, methods for their control, and instructions for the use of MS in the production of concrete and building mortars. The MS captured at JSC “Kremniy” using the wet gas cleaning system can also potentially be used for the manufacture of building materials, since GOST R 58894-2020 allows the use of condensed MS in the form of a suspension (paste). The MS suspension is obtained by mixing condensed MS, water, and a stabilizing component, and, if necessary, a plasticizing additive. Table 7 shows the requirements for the MS suspension according to GOST R 58894-2020. Comparison of the standardized quality indicators of MS brand MKS-85 (condensed microsilica for concrete and mortars, Table 7) with the studied composition of MS of JSC “Kremniy” (Tables 1, 2) shows that in terms of impurity content, the latter meets the requirements of GOST R 58894-2020.

Table 7. Standard value of quality indicators for suspension (paste) MKS-85.

Name of the indicators	Value of the indicators
1 Appearance	Dark gray fluid
2 Mass fraction of moisture, %, not more than	60
3 Mass fraction of silicon oxide (SiO ₂), %, not less than	85
4 Mass fraction of loss on ignition (Δ), %, not more than	5
5 Mass fraction of free alkalis (in terms of Na ₂ O), %, not more than	2
6 Mass fraction of calcium oxide (CaO), %, not more than	3
7 Mass fraction of sulfur oxide (SO ₃), %, not more than	2
8 Mass fraction of chloride ion (Cl ⁻), %, not less than	0.1
9 Density of suspension (paste), kg/m ³ , not less than	1280
10 Activity index of hydrogen ions (pH) of aqueous suspension (paste) of microsilica, not less than	7

To assess the possibility of using MS of JSC “Kremniy” as an active mineral additive to cements and mixtures based on it, the degree of its pozzolanic activity was determined. The amount of CaO absorbed by 1 g of MS from a saturated solution of Ca(OH)₂ for 12 hours at 85–90°C was 98.7 mg. According to this indicator, MS is classified as an active mineral additive of medium activity.

To assess the possibility of using MS as an active mineral additive in grinding clinker of JSC “Angarskcement”, Portland cement grade CEM-I/42.5 of the Angarsk Cement Plant was selected. MS from the sludge field of JSC “Kremniy” and fly ash supplied to the cement plant by “Irkutskzoloprodukt” were used as an active additive to cement. In this experiment, fly ash should provide the maximum degree of cement replacement while observing the main criterion - maintaining the quality characteristics of the cement stone of the specified grade. In this work, the change in the physical and mechanical characteristics of the cement stone was assessed, depending on the amount of added active mineral additive. MK and fly ash were introduced into the composition both separately and in various combinations with each other. The work was carried out in the laboratory of the Angarsk Cement Plant (Russia, Angarsk) using standard methods and equipment.

The chemical composition of the cement after replacing the fly ash with MS is presented in Table 8.

Table 8. Chemical composition of cement after replacing fly ash with MK % (mass.).

Charge % (wt.)	Δ	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	Mg O	Na ₂ O	K ₂ O
Clinker-100% + gypsum	-	20.7	5.3	4.2	63.8	4.5	-	-
82% clinker + 18% fly ash	1.1	27.2	8.1	4.5	52.4	4.4	0.2	0.6
82% clinker + 18% MS	2.3	30.8	43	3.6	51.8	4.2	1.1	0.4

Continuation of Table 8

82% clinker + 12% fly ash + 6% MS	1.7	28.6	6.7	4.5	51.8	4.3	0.5	0.6
82% clinker + 6% fly ash + 12% MS	2.0	30.1	5.6	3.9	52.7	3.9	0.9	0.5

From Table 8, the sample of 82% clinker + 18% MS stands out, in which 18% (mass.) of clinker is replaced by MS. The compressive strength of the samples of this sample, compared to the control samples (clinker-100% + gypsum) without an active mineral additive, at the age of 28 days increased by 4.5% from 45.0 to 47.0 MPa, the bending strength increased by 11% from 6.0 to 7.0 MPa. This can be explained by an increase in the specific surface area of cement from 2860 to 5185 cm²/g due to the addition of MS. At the same time, the setting time and other characteristics of the cement remained virtually unchanged.

The composition of the cement stone from clinker with a composition of 82% clinker + 18% MS, calculated based on the results of X-ray phase analysis, is given in Table 9. In this table, the absence of silica in the sample is a consequence of its amorphous structure.

Table 9. Phase composition of clinker composition according to X-ray fluorescence analysis.

Formula	Compounds	Content of compounds
Ca ₃ (SiO ₄)O	Hatrurite	50.6
Ca ₂ FeAlO ₅	Brownmillerite	15.3
Ca(OH) ₂	Portlandite	15.2
Ca ₆ Al ₂ (SO ₄) ₃ (OH) ₁₂ ·26H ₂ O	Ettringite	7.4
MgO	Periclase	4.7
SiO ₂	Quartz	6
CaCO ₃	Calcite	4.7
SiC	Silicon carbide	0.4

Fig. 8 shows the microstructure of cement stone obtained on the basis of clinker of JSC “Angarskcement” and MS of JSC “Kremniy”. The microstructure is characterized by large fragments of silica and calcium silicates.

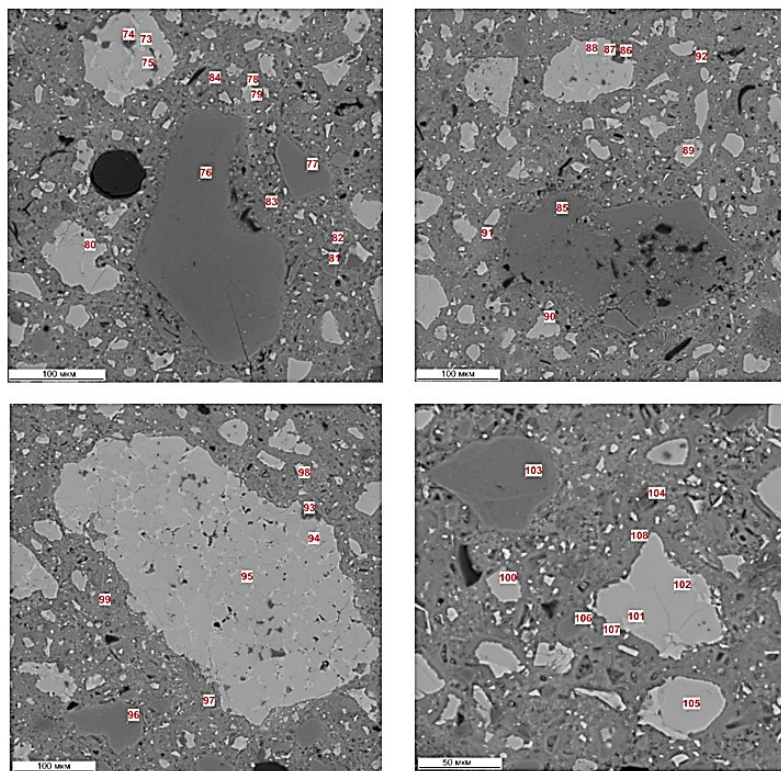


Fig. 8. General view of sample No. 3 in a polished block.

Table 10 provides a decoding of the spectra presented in Fig. 8.

Table 10. Chemical composition of cement based on clinker from JSC “Angarskcement” and MS from JSC “Kremniy”, % (mass.).

Spectrum	Mineral	O	Na	Mg	Al	Si	S	K	Ca	Ti	Fe
73	Brownmillerite	35.8		1.4	9.6	1.7			33.3	0.6	17.5
74	Periclase	37.8		60.7					0.9		0.6
75	Larnit	34.6		0.4	4.7	10.6		0.9	45.5		3.3
76	Silica	51.3	0.5			40.2		1.4	6.6		
77	Silica	51.5	0.8			37.7		1.6	8.5		
78	Brownmillerite	34.0		1.4	9.1	1.5			34.3	0.5	19.1
79	Larnit	38.3			0.7	15.2			45.2		0.7
80	Hatrurite	35.4		0.8	0.4	12.4			50.6		0.5
81	Si-Ca-O	51.4				35.8		0.5	12.3		
82	Slag	49.1				42.6			0.4		7.9
83	Si-Ca-O	48.2	0.4			35.9		0.7	14.9		
84	Si-Ca-O-S	47.4		1.0	1.06	13.6	1.9		34.0		0.7
85	Silica	51.0	0.7			40.2		1.9	6.3		
86	Periclase	36.4		61.9					0.9		0.8
87	Brownmillerite	31.6		1.6	9.75	1.9			36.6		18.6
88	Hatrurite	34.3		0.9		12.2			52.6		
89	Hatrurite	35.4		0.7	0.4	11.9			51.7		
90	Hatrurite	34.8		0.7	0.76	11.7			52.1		
91	Si-Ca-O-S	45.1		1.1	0.79	13.8	0.7		37.7		0.9
92	Si-Ca-O-S	46.0		1.2	0.67	13.5	0.7		37.1		0.8
93	Periclase	38.5		60.5					0.5		0.4

Continuation of Table 10

94	Brownmillerite	34.3		1.9	9.45	2.0			34.8	0.5	17.1
95	Larnit	35.9		0.4	0.67	15.5			46.7		0.9
96	Silica	50.8				37.4		0.8	10.9		
97	Silica	50.8				35.4			13.8		
98	Si-Ca-O-S	46.8		0.9	2.93	7.6	2.4		34.3		5.1
99	Si-Ca-O-S	45.2		1.1	1.08	14.5	1.2		36.1		0.9
100	Hatrurite	35.5		1	0.32	11.9			50.9		0.4
101	Brownmillerite	33.9		1.4	9.53	1.7			34.5	0.8	18.2
102	Hatrurite	35.5		1.0		11.9			51.6		
103	Si-Ca-O	48.5		2.4		26.3			22.8		
104	Periclase	38.7		58.7					1.5		1.1
105	Si-Ca-O	36.0		1.1	0.4	11.8			50.7		
106	Si-Ca-O	50.8				33.0		0.9	15.3		
107	Si-Ca-O	49.3				24.6	0.6		25.5		
108	Si-Ca-O	45.1				27.1	0.7		27.1		

The results of the sample study (Fig. 8 and Table 10) show that it consists of fragments of MS, calcium, iron and aluminum silicates (brownmillerite) and calcium silicates (larnite, hatrurite). Calcium silicates, as well as calcium, iron and aluminum silicates, are found in tight intergrowths, where calcium silicates significantly predominate.

The intergrowths also contain periclase and calcite segregations. Calcite is represented by newly formed crystals, brushes, druses, and porous (microgranular) formations (Fig. 9).

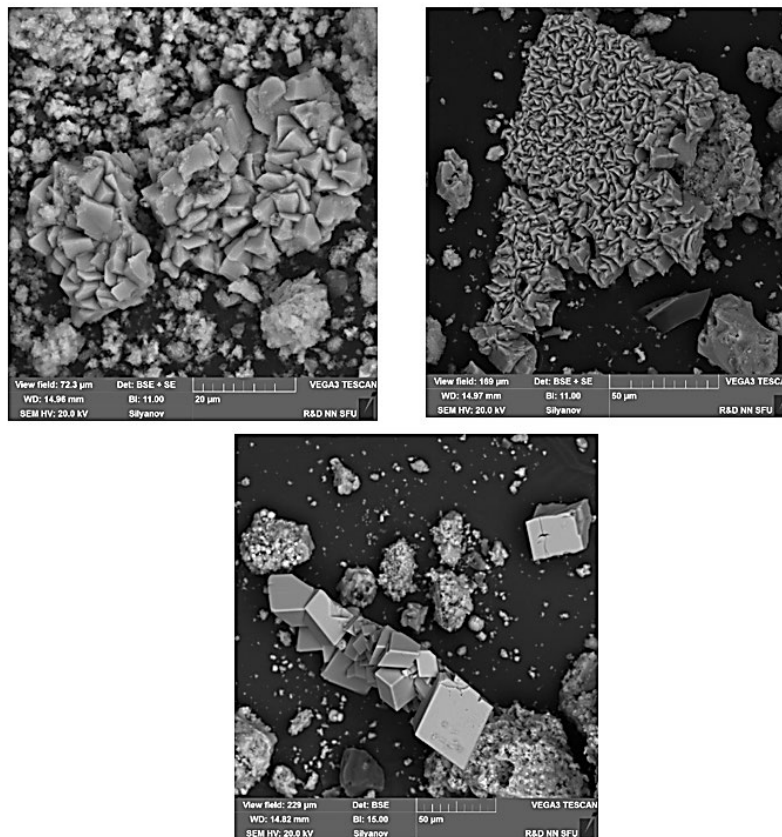


Fig. 9. Newly formed calcite.

Additional tests of concretes made on the basis of cement with the addition of MS confirmed an increase in water resistance, frost resistance of the cement stone, as well as an increase in the rheological properties of the cement mortar (Table 11).

Thus, laboratory tests have shown the possibility of replacing up to a concentration of 18% (mass.) of Portland cement MS of JSC "Kremniy" while maintaining the quality parameters of cement grade CEM-II/A-Mk 42.5N at the level of CEM-I/42.5 indicators. There is also reason to believe that autoclave treatment of products based on Portland cement with MS will significantly enhance the modifying effect of the latter due to a significant increase in the specific surface area of cement (from 2860 to 5185 cm²/g).

Table 11. Results of laboratory tests of cement after replacing fly ash with MS.

Charge,% (wt.)	Probe No.	grinding time, min	additive, %	SO ₃ , %	fineness of grinding, +0.08, %	specific surface area, cm ² /g	normal density, %	W/C	uniformity of volume change	Setting time, hours: min	
										start	end
Clinker-100% + gypsum	1		-	2.2	12.0	2860	24.3	0.5	0	03:20	04:20
82% clinker + 18% fly ash	2	25	16	2.2	12.0	3136	27.0	0.5	0	05:10	06:10
82% clinker + 18% MS	3	35	17	2.0	28.0	5185	28.0	0.5	0	03:00	04:30
82% clinker + 12% fly ash + 6% MS	4	27	15	2.2	27.0	4398	27.0	0.5	0	04:00	04:45
82% clinker + 6% fly ash + 12% MS	5	30	17	2.1	22.0	4955	27.3	0.5	0	03:20	04:45

Note W/C – water-cement ratio.

The mechanical properties of cement after replacing fly ash with MS are given in Table 12.

Table 12. Mechanical properties of cement after replacing fly ash with MS.

Charge,% (wt.)	Ultimate tensile strength, MPa			
	Bend		Compression	
	2 s	28 s	2 s	28 s
Clinker-100% + gypsum	2.4	6.4	10.1	45.2
82% clinker + 18% fly ash	2.1	5.6	9.5	34.8
82% clinker + 18% MS	2.7	7.1	12.8	47.3
82% clinker + 12% fly ash + 6% MS	2.4	6.5	10.0	43.1
82% clinker + 6% TPP ash + 12% MS	2.4	6.6	11.0	47.0

Important tasks in the production of construction materials include expanding the raw material base, improving their consumer properties and reducing their cost. One way to solve these problems is to replace expensive components with cheaper ones, reduce transportation costs and expand the raw material base of the construction industry through regional raw material resources of both natural and man-made origin [21-25].

An example of expanding the raw material base is the production of low-activity unfired binders, in which MS JSC "Kremniy" is used as the "acidic" component. The main principle of designing unfired binders from waste and products of various industries is to prepare a balanced composition containing free, active lime and active aluminosilicate components. Moreover, the ratio of active lime and active acidic components should be as close as possible to the stoichiometry of the resulting calcium hydrosilicates and aluminates.

For experiments on developing compositions of unfired binders, MS of JSC "Kremniy" and CS of the "Usolye-Khimprom" plant (Russia, Irkutsk region) and the oxygen-acetylene plant (Russia, Krasnoyarsk region) were used.

Table 13 shows the results of laboratory tests of unfired binder samples kept in air-dry conditions and in water for 14 days. Of the two tested compositions, the best strength characteristics were demonstrated by a mixture of the composition % (mass.): 30% CS + 70% MS.

Table 13. Properties of samples CS (Usolye) + MS JSC “Kremniy”.

Content of components, % (mass.)		W/C	Test time, days	Sample No.	Density, kg/m ³	R_{compr} , MPa
CS	MS					
30	70	0.55	Air-dry environment			
			3	1	1061	4.72
				2	1067	4.68
			7	1	1045	4.12
				2	1041	3.99
			14	1	1021	3.62
				2	1015	3.43
			Water			
			3	1	1459	3.57
				2	1462	3.64
			7	1	1475	4.57
				2	1479	4.76
			14	1	1499	6.35
				2	1502	6.49
40	60	0.58	Air-dry environment			
			3	1	1070	4.62
				2	1067	4.63
			7	1	1056	3.54
				2	1048	3.39
			14	1	1032	2.75
				2	1041	2.82
			Water			
			3	1	1459	3.11
				2	1460	3.12
			7	1	1465	3.78
				2	1468	3.89
			14	1	1478	4.52
				2	1482	4.54

It should be noted that the obtained lime-pozzolan binder is slow-hardening and gains strength over a long period of time (weeks and months).

Table 14 shows the molecular composition of the binder composition % (mass.): 30% CS + 70% MS after 14 days of hardening in water, calculated based on the results of X-ray phase analysis. Compared with the initial composition of the mixture of CS and MS, ettringite, larnite and calcium carbonate were identified in the composition of the interaction products. The insignificant concentration of hydration products is associated with short hardening times of the sample.

Table 14. Molecular composition of unfired binder.

SiO ₂	Ca ₆ Al ₂ (SO ₄) ₃ (OH) ₁₂ ×26 H ₂ O	Ca(CO ₃)	Ca ₂ (SiO ₄)	Ca(OH) ₂	SiO ₂
2.2	2.7	6.8	2.4	14.6	71.1

A series of laboratory experiments were conducted to assess the impact of heat and moisture treatment on the hardening efficiency of lime-pozzolan binders based on technogenic waste. CS from “Usolye-Khimprom” and the oxygen-acetylene plant, as well as MS from JSC “Kremniy”, were used as binder components.

The amount of added water was determined by the rheology of the mixture. Table 15 shows the results of mechanical compression tests of samples of two compositions. The first composition, % (mass.): 33 CS + 33 MS + 33 water was tested for compression after 1 day of hardening in air and subsequent autoclave treatment at 180 ° C for 2 hours and under a pressure of 0.8 MPa. The second composition % (mass.): 36 CS +36 MS +28 water +1 ReoMAX was tested after hydration in air for 4 days (first mode) and after hydration in air for 24 hours followed by autoclave treatment for 2 hours (second mode).

Table 15. Results of compressive strength tests of two cement compositions conducted before and after autoclave treatment.

Cement composition, % (mass.)			
33 CS + 33 MS + 34 water		36 CS +36 MS + 28 water + 1ReoMAX	
Compressive strength, MPa			
Before processing	After processing	Before processing	After processing
1.5 \pm 0.3	13 \pm 0.5	6.5 \pm 0.5	27 \pm 0.5

As follows from the results of Table 15, autoclave treatment of the samples of the first composition leads to an increase in compressive strength by about 9 times. It is known that polycarboxylate hyperplasticizers can increase the fluidity (workability) of the mixture and due to this reduce the amount of water added to it [26]. In the work, we used the ReoMAX hyperplasticizer, which made it possible to reduce the amount of water in the mortar mixture by about 15%. The reduction in moisture led to a significant increase in strength. The results of testing the compressive strength of samples for the second composition containing 1% (mass.) ReoMAX before and after autoclave treatment showed that a decrease in the amount of water in the binder from 34% to 28% leads to an increase in strength from 1.5 \pm 0.3 to 6.5 \pm 0.5 MPa before autoclave treatment and from 13 \pm 0.5 to 27 \pm 0.5 MPa after treatment. This result can be explained by the fact that excess moisture in the system leads to an increase in porosity and, as a consequence, to a decrease in the strength of the samples.

From the analysis of the microstructure of the sample with the composition % (mass.) 50 CS + 50 MS (Fig. 10) it follows that its structure consists of large fragments of MS and portlandite of various sizes. Slag and SiC spherical particles of silicon carbide SiC are also noted, which, as a rule, are in the form of inclusions in the fragments of MS.

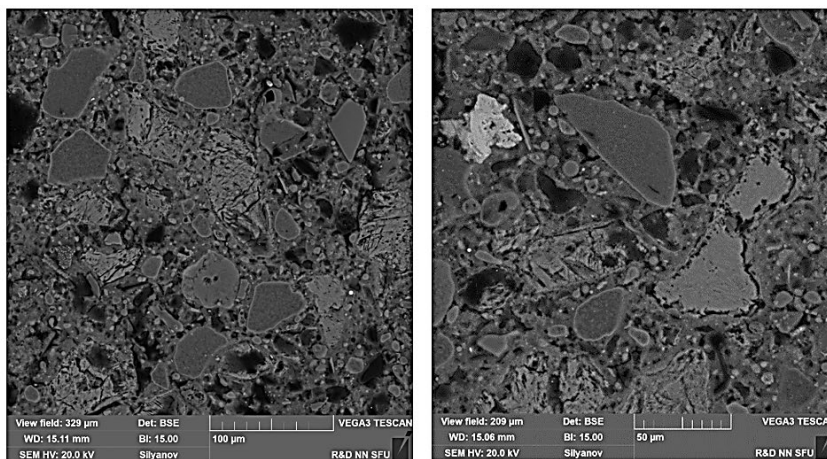


Fig. 10. Microstructure of the 50% CS + 50% MS sample at two magnifications.

MS and portlandite fragments are cemented by a fine-grained mass, which also consists of MS and portlandite (Fig. 11, Table 16), as well as by a newly formed fine mass, which in chemical composition consists of Si, Ca, O (Fig. 12, Table 17). According to the MRSA data, the finely dispersed mixture of a sample of this composition is represented by silica, calcite, alite and belite.

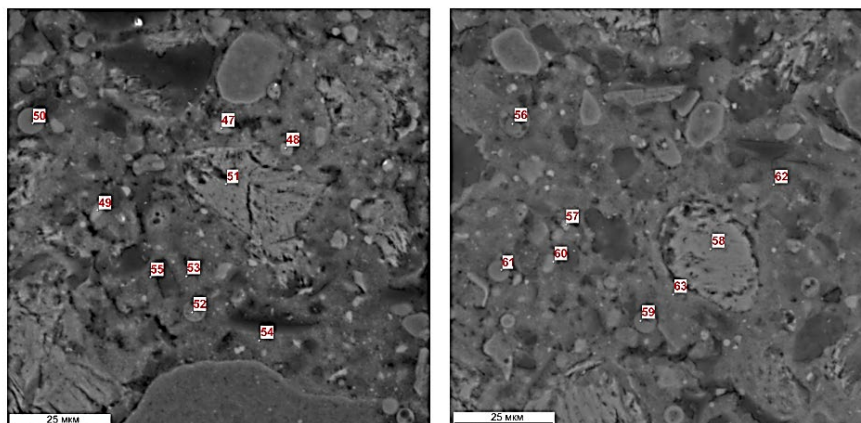


Fig. 11. Fine, cementing, sample fraction. The numbers in the photo correspond to the spectra numbers in Table 16.

Table 16. Chemical composition of the cementing fraction of the sample, % (mass.).

Spectrum No.	Mineral	O	Mg	Al	Si	S	Ca
47	Slag	53.5			18.5	0.4	27.6
48	Slag	51.2		8.3	10.8	0.7	29.0
49	Silica	58.6	0.8		13.4	0.3	26.7
50	Portlandite	58.3			39.3		2.4
51	Silica	43.1			1.3		55.6
52	Silica+calcite or belite-alite	34.7			55.9		7.2
53	Silica+calcite or belite-alite	44.5		0.6	21.3	0.4	33.2
54	Silica+calcite or belite-alite	46.6			22.8	0.3	30.3
55	SiC	42.3		0.5	20.1	0.6	36.5
56	Carbonate	8.1			90.7		1.2
57	Portlandite	56.1			9.6	0.3	34.0
58	Silica	43.5			0.6		55.9
59	Slag	53.3		0.6	38.6		7.5
60	Silica	57.0			22.3		20.7
61	Silica+calcite or belite-alite	51.4	0.4	0.9	44.3		2.2
62	Silica+calcite or belite-alite	49.9		0.4	19.4	0.5	29.9
63	Mineral	45.8			26.0	0.4	27.7

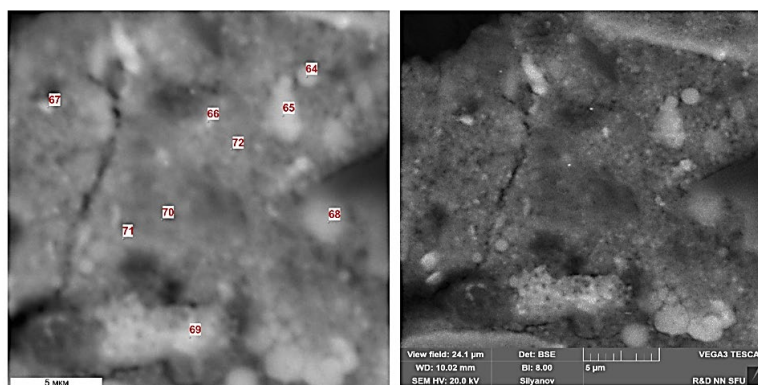


Fig. 12. Cementing fine-grained aggregate of alite-belite, or a mixture of calcite and MS. The numbers in the photo correspond to the numbers of the spectra in Table 17.

Table 17. Chemical composition of fine cementing mass particles, %, (mass.).

Spectrum No.	Mineral	O	Mg	Al	Si	S	K	Ca
64	Slag	57.5		0.4	23.3			18.8
65	Slag	51.3			21.7			27.1
66	Slag	54.3		0.4	16.2	0.4		28.7
67	Slag	56.8		0.4	12.9	0.4		29.5
68	Silica	52.3	0.5	1.4	34.1		0.4	11.2
69	Silica+calcite, belite-alite	47.9			37.8			14.3
70	Silica+calcite, belite-alite	39.0		0.5	22.2	0.5		37.7
71	Silica+calcite, belite-alite	44.8			21.4	0.4		33.4
72	Silica+calcite, belite-alite	50.9	0.2	0.4	19.4	0.5		28.6

The obtained low-activity unfired binder can be used as:

- dry grouting mixture for dry and wet operating conditions;
- hydraulic binder in building masonry mortars of grade 50;
- binder for the production of lightweight concrete wall stones and large blocks with strength class B3.5 of natural hardening and B5 after 10-hour hardening in a steam environment at a temperature of no more than 90°C;
- substitute for Portland cement in composite gypsum binders used for the production of partition stones and panels;
- independent binder in the production of autoclaved aerated concrete.

To study the possibility of using MS of JSC "Kremniy" as a silicate component of raw sludge for clinker firing, raw sludge of the Belgorod Cement Plant (Russia, Belgorod) was used, the composition and modular characteristics of which are given in Table. 18.

Table 18. Composition of raw sludge of JSC “Belgorod Cement”.

Components	% (mass.)	Mass fraction, % (mass)							
		Δ	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	R ₂ O
Limestone	70.8	38.9	7.7	4.4	0.9	46.7	0.9	-	0.1
Slag	5	12.0	12.2	3.4	54.1	6.0	3.2	1.4	1.5
Crushed stone	8.1	1.2	92.7	1.0	3.8	0.7	0.2	0.2	0.2
Chalk	17.6	43.6	1.8	0.5	0.2	53.3	0.4	0.1	0.2
Raw material mixture		35.6	13.7	3.4	4.4	42.7	0.9	0.1	0.3

Note – Saturation coefficient SC = 0.94; silicate modulus $n = 2.2$; alumina modulus $p = 1.2$.

In the raw sludge of JSC “Belgorod Cement”, crushed stone was replaced with MS of JSC “Kremniy”, since the concentrations of SiO₂ in these components are close and amount to 92–93% (mass). The chemical composition of MS adopted in the calculation is presented in Table 1. Taking into account the adjustments made to replace crushed stone with MS, an experimental chemical composition of the raw sludge was obtained (Table 19).

Table 19. Experimental composition of the raw mix of JSC “Belgorod Cement” with MS.

Components	% (mass.)	Mass fraction, %							
		Δ	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	CaO	MgO	SO ₃	R ₂ O
Limestone	69.8	38.9	7.7	4.4	0.9	46.7	0.9	-	0.1
Slag	3.5	12.0	12.2	3.4	54.0	6.0	3.2	1.4	1.5
Microsilica	9.1	-	93.7	1.2	0.5	2.8	0.2	0.4	0.5
Chalk	17.6	43.6	1.8	0.5	0.2	53.3	0.4	0.1	0.2
Raw material mixture	-	35.3	14.7	3.3	2.6	42.4	0.8	0.1	0.2

Note – Saturation coefficient SC = 0.90; silicate modulus $n = 2.5$; alumina modulus $p = 1.3$.

Based on the results of firing tablets from raw sludge, clinkers of the following composition were obtained (Table 20).

Table 20. Composition of clinker of JSC “Belgorod Cement”, factory and experimental, % (mass.).

Clinker	C ₃ S	C ₂ S	C ₃ A	C ₄ AF
Factory	63.4	11.0	6.6	13.6
Experimental	52.4	23.4	6.7	12.1

Fig. 13 shows the microstructure of the experimental clinker obtained with the addition of MS. In the structure, alite is represented by individual crystals and intergrowths ranging in size from 7 to 70 μm . The shape of the crystals is tabular, prismatic, hexagonal, and round.

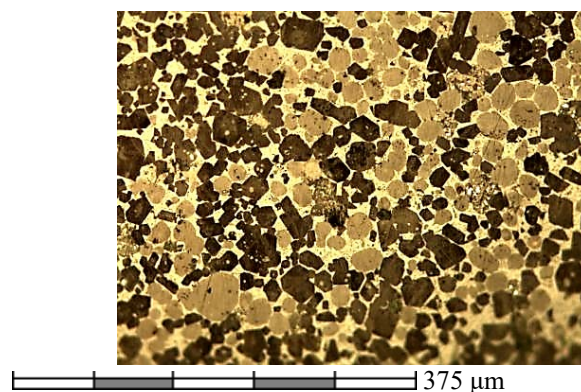


Fig. 13. Microstructure of clinker with MS.

Belite is represented by individual crystals, small clusters and belite fields. The shape of the crystals is oval. The size of the crystals is from 5 to 100 μm . The limits of variation in the size and content of alite and belite crystals in the clinker are given in Table 21.

Table 21. Characteristics of alite and belite in the experimental clinker.

	Alite		Belite	
	% (mass.)	Grain size, μm	% (mass.)	Grain size, μm
Minimum	33.2	7.6	9.1	4.9
Maximum	72.5	70.4	52.2	99.8
Average	55.6	26.6	24.4	23.0

The results of the assessment of water demand, setting time, hydration activity of clinkers based on the raw mix of JSC “Belgorod Cement” with the replacement of crushed stone with MS are given in Table 22.

Table 22. Comparative characteristics of raw sludges and clinkers.

Raw mix	Specific surface area, cm^2/g	Fineness of grinding, sieve 0.08	W/C ratio	Setting time, h		Ultimate tensile strength at 28 days, MPa	
				Start	End	Bend	Compression
Belgorod	3190	8.8	0.4	2:55	4:20	6.7	51.5
Experiment	3350	10.3	0.4	3:25	4:55	6.4	50.9

The obtained results confirmed the possibility of using MS JSC "Kremniy" as a silica-containing component of raw sludge while maintaining the quality indicators of the final product – clinker.

4. CONCLUSIONS

The article presents the results of a comprehensive study of the composition, structure and properties of microsilica from the sludge field of JSC “Kremniy”. Specific conditions of microsilica capture during gas purification with a soda solution and its storage under a layer of water on the sludge field for many years contributed to the formation of agglomerates of particles with an average size of 7-16 μm , consisting of nanosized amorphous silica spheres. Despite the significant specific surface area (17.05 m^2/g) and nanosized particle sizes, microsilica has a relatively low pozzolanic activity (98.7 mg CaO per 1 g of MS). Agglomerates of spherical microsilica particles formed during capture during gas purification and long-term storage on the sludge field reduce the efficiency of using microsilica as an active mineral additive. To increase the activity of microsilica and destroy

agglomerates, intensive mechanical action is required during the processing of microsilica in the composition of various building materials.

The laboratory studies confirmed the possibility of using microsilica in the construction industry. It was shown that microsilica from JSC “Kremniy” is effective as an active mineral additive to cements, including as a substitute for part of the clinker, as an "acidic" component of unfired hydraulic and autoclave hardening binder, and as a silica-containing additive to raw sludge for clinker firing.

The use of microsilica from JSC “Kremniy” will improve the environmental situation in the region, and the experience of using waste in the construction industry described in the work is recommended for dissemination to other metallurgical enterprises.

5. ACKNOWLEDGEMENTS

The work is performed as a part of the state assignment for the science of Siberian Federal University, project number FSRZ-2023-0009.

REFERENCES

1. Potapov V.V., Gorev D.S. Physico-Chemical Characteristics of Nanosilica (Sol, Nanopowder-Shock) and Microsilica. *Fundamental’nye Issledovaniya = Fundamental Research*. 2018. 6. P. 23 – 29.
2. Ahmad Sh., Mohaisen K.O., Adekunle S.K., Al-Dulaijan S.U., Maslehuddin M. Influence of admixing natural pozzolan as partial replacement of cement and microsilica in UHPC mixtures. *Construction and Building Materials*. 2019. 198. P. 437 – 444.
3. Sánchez de Rojas M.I., Rivera J., Frias M. Influence of the microsilica state on pozzolanic reaction rate. *Cement and Concrete Research*. 1999. 29 (6). P. 945 – 949.
4. Microsilica Market Increases Demand from Construction Industry. <https://exactitudeconsultancy.com/ru/blog/2023/05/06/silica-fume-market-growth/>, 2024 (accessed 11 Dec 2024)
5. Lee N.K., Koh K.T., Kim M.O., Ryu G.S. Uncovering the role of micro silica in hydration of ultra-high performance concrete (UHPC). *Cement and Concrete Research*. 2018. 104. P. 68 – 79.
6. Peng, Hong. Recent progress in microsilica-gel bonded no-cement castables. *Ceramics International*. 2023. 49 (14). P. 24566 – 24571.
7. Bulakh A.G., Zolotarev A.A., Krivovichev V.G. Atlas of crystal structures, chemical substitutions, formulas, classification of minerals, first ed. Publishing House of Saint Petersburg State University. St.Petersburg, 2014.
8. Budak V.P., Efremenko D.S., Smirnov P.A. Fraunhofer Diffraction Description In The Approximation Of The Light Field Theory. *Light & Engineering*. 2020. 28 (5). P. 55 – 59.
9. Walton K.S., Snurr R.Q. Applicability of the BET Method for Determining Surface Areas of Microporous Metal-Organic Frameworks. *Journal of the American Chemical Society*. 2007. 129 (27). P. 8400 – 8670.
10. Ambroz F., Macdonald T.J., Martis, V., Parkin I.P. Evaluation of the BET Theory for the Characterization of Meso and Microporous MOFs. *Small methods*. 2018. 2 (11). 1800173.
11. Zhang D., Ma Y., Feng Hu., Wang Y., Hao Y. Preparation and characterization of the carbon-Microsilica composite sorbent. *Advanced Powder Technology*. 2023. 23 (2). P. 215 – 219.
12. Zeng Q., Zhang D., Li K. Kinetics and Equilibrium Isotherms of Water Vapor Adsorption/Desorption in Cement-Based Porous Materials. *Transport in Porous Media*. 2015. 109. P. 469 – 493.
13. Villarroel-Rocha J., Barrera D., Sapag K. Introducing a self-consistent test and the corresponding modification in the Barrett, Joyner and Halenda method for pore-size determination. *Microporous and Mesoporous Materials*. 2014. 200. P. 68 – 78.

14. Zyryanov M.S., Akhmetzhanov A.M., Manushina A.S., Potapova E.N. Determination of pozzolanic activity of metakaolins. *Advances in chemistry and chemical technology*. 2016. 30 (7). P. 44 – 46.
15. Van Lam T., Tung Lam N.Z. Pozzolanic activity of finely dispersed mineral components of various nature in Vietnam. *Technique and technology of silicates*. 2021. 28 (1). P. 7 – 12.
16. Poddubny V.I., Lavrentiev V.K. On the shape of the amorphous halo on the diffraction pattern of amorphous-crystalline polymers. *High-molecular compounds. Chemical sciences*. 1990. 32 (5). P. 354 – 356.
17. Sinha P., Datar A., Jeong Ch., Deng X., Chung Yo.G., Lin L.-Ch. Surface Area Determination of Porous Materials Using the Brunauer-Emmett-Teller (BET) Method: Limitations and Improvements. *J. Phys. Chem. C*. 2019. 123 (33). P. 20195 – 20209.
18. Gurinenko N.S., Batyanovskiy E.I. Polyfunctional additive with ultradispersed microsilica for cement concrete. *Contemporary Issues of Concrete and Reinforced Concrete*. 2018. 10. P. 135 – 154.
19. Kakharov Z.V., Islomov A.S. Application of micro silica in concrete productions. *Bulletin of Science*. 2023. 4. P. 371 – 375.
20. Kononova O.V., Smirnov A.O. Almost self-compacting concrete with microsilica strength forming investigation. *Fundamental research*. 2017. 9 (2). P. 327 – 331.
21. Dahhou M., Hamidi A., Moussaouiti M., Arshad M. Synthesis and characterization of belite clinker by sustainable utilization of alumina sludge and natural fluorite (CaF₂). *Materialia*. 2021. 20. P. 101204.
22. Kulikov B.P., Vasyunina N.V., Dubova I.V., Samoilo A.S., Balanov R.O., Ivanova I.K., Sysoeva Ya.S. An effective additive based on synthetic fluorite and graphitized carbon from aluminum production waste for the synthesis of clinker compounds. *Cement and its application journal*. 2023. 2. P. 74 – 78.
23. Kulikov B.P., Vasyunina N.V., Dubova I.V., Samoilo A.S., Merdak N.V. Obtaining and using synthetic fluorite for Portland cement clinker production. *Magazine of Civil Engineering*. 2024. 17 (3). P. 12703.
24. Kulikov B.P., Vasyunina N.V., Dubova I.V., Samoilo A.S. Processing of finely dispersed fluorocarbon-containing waste from aluminum plants to produce synthetic fluorite and caustic alkali solution. *News of higher educational institutions. Chemistry and chemical technology*. 2024. 67 (4). P. 90 – 100.
25. Lazarevich E.V., Nikitenko N.E., Gilevich A.A., Orlov A.A. Development of nonfired materials by serpentine. *Architecture, urban planning and design*. 2017. 2 (12). P. 15 – 19.
26. Murtazaev S.-A.Y., Salamanova M.Sh., Bisultanov R.G., Abukhanov A.Z., Alaskhanov A.Kh. Multicomponent Binders with Organic Mineral Additive Based on Volcanic Ash. *Proceedings of the International Symposium Engineering and Earth Sciences: Applied and Fundamental Research*. 2018. P. 359 – 362.

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