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The effect of mechanical and thermal treatment on the characteristics of saponite-containing material

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Abstract

Solving the problems of modern building materials science is reduced to obtaining high-quality materials, expanding and searching for a rational raw material base, which can be carried out through the use of various industrial wastes. In this paper, the possibility of using waste from the mining industry – saponite-containing material (SCM) obtained during the enrichment of kimberlite ores from the Lomonosov diamond deposit, as an active mineral additive for cement binders and concretes is considered. The influence of mechanical and thermal treatment on a number of properties of the material selected from the tailings dump and in its initial state was studied. The study of the surface activity of SCM samples consisted in determining the sorption capacity, acid-base centers and their distribution. An increase in the activity of the surface of the material particles as a result of mechanical activation and its decrease during temperature treatment were determined. These effects are associated with phase rearrangements and structural changes in the sandy-clay rock, which was confirmed during thermal analysis. The temperature effect has no pronounced effect on the microstructure, the "smoothness" of the particles and the formation of a consolidated surface of the structural elements of the saponite-containing material are noted.

Keywords

saponite-containing material; ore dressing waste; surface activity; mechanical activation; firing

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Introduction

Construction materials science in modern conditions is focused on the production of high-quality materials while achieving effective technical and economic indicators. The search for rational solutions makes it possible to expand the raw material base, which can be carried out by using secondary products of various industries and industrial waste.

Waste of man-made origin, in particular from the mining industry, is an important source of raw materials for the construction materials industry (CMI). About 40 billion t of such waste, of which at least 30 % of overburden and tailings of enrichment, almost all metallurgical and fuel slags, are potential raw materials for the CMI industry [1]. The volume of waste increases annually, is stored and occupies huge areas. Mining waste can reasonably be considered a backup reserve of the raw material base of the Russian Federation, equivalent to the opening of new deposits. Despite the huge resource potential as a source of raw materials and the possibility of reducing pressure on the environment, they have not found the proper degree of application in our country, they are used irrationally and in small quantities.

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In foreign countries, the level of waste involvement in economic turnover is much higher and has some application experience. Many developed countries are focusing their policies on energy and resource conservation, actively implementing the practice of recycling man-made waste and developing new technological solutions through reuse in various industries. For example, the leaders in waste recycling are the USA and Japan, the share of waste in the total raw material balance of these Countries is about 26 %, in most economically developed countries this indicator ranges from 16-20 %, in the USSR it was 15 %, in modern Russia – about 10 % [1, 2]. Secondary use resources are gaining momentum in other countries [3-6] (Canada, Great Britain, South Africa, Spain, India, etc.)*.

Representatives of the M.V.Lomonosov NARFU Scientific School, together with AO Severalmaz and scientists of BSTU named after V.G.Shukhov, are actively conducting research on one of the types of waste from the mining industry – saponite-containing material (SCM), which is a secondary product of the enrichment of kimberlite ores from the Lomonosov diamond deposit of the AO Severalmaz processing plant (Arkhangelsk region), for its use in the production of building materials [7]. Technologies for the use of SCM in the manufacture of ceramic tiles, mineral wool materials, magnesia and composite binders have already been developed [8-11]. The paper proposes to expand the range of SCM applications in the building materials industry, as the largest in terms of consumed raw materials and manufactured products, through the development of an active mineral additive for cement binders and concretes.

The specificity of the composition and properties of SCM has predetermined a fairly wide range of areas of its use, in addition to CMI. Thus, this secondary product is used as a base for drilling mud [12], as a sorbent for cleaning industrial wastewater [13], for waterproofing in the construction of landfills for storing solid household waste, radioactive burial grounds and for wastewater filtration, as well as in medicine and resort business [14]. Saponite occupies a special place in agriculture as a mineral additive to feed and fertilizers, filler and granulant, is used for soil detoxification, sorption of herbicides and pesticides introduced into the soil, heavy metals, etc. [14].

Saponite-containing material is a sandy-clay rock in a watered state (with a humidity of at least 60 %) and has:

• mineralogical composition – the main component is saponite (60-70 %), the remaining mass of the rock is quartz, montmorillonite, palygorskite, phlogopite, clinochlorite, talc, dolomite;

• the chemical composition – the main oxides are SiO_2 (53 %), MgO (17 %), Fe_2O_3 (10 %), Al_2O_3 (9 %), CaO (4 %) [8].

The process of enrichment of clay rock requires a large amount of water consumption. The presence of raw materials in a suspended state makes it difficult for its further use in the construction industry, difficulties in separating the solid fraction do not allow the use of water as a circulating water due to the low degree of purification [12, 13, 15-17]. In this regard, it is necessary to select the method and parameters of processing the raw materials that allow the rational and effective use of SCM in the building materials industry.

It is known that mechanical activation affects not only the dispersion characteristics of the raw material, but also the properties of its surface [18-21], increasing the activity for subsequent interaction of the material components [22, 23].

Due to the affiliation of SCM to clay minerals, the effect of temperature treatment should be considered. The use of burnt clays as mineral additives in cement systems has a fairly long history [24-27]. This component is characterized by increased activity, which is due to the processes caused by temperature exposure and associated with the formation of primary dehydration products and the destruction of clay minerals, which leads to a restructuring of the crystal lattice. It is noted that the main clay minerals (kaolinite, montmorillonite, illite, bentonite, etc.) pass into the active form

* Cement Statistics and Information. URL: https://www.usgs.gov/centers/national-minerals-information-center/cement-statistics-and-information (accessed 08.05.2024).

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precisely at a temperature of 200±600 °C [25, 26, 28, 29]. When referring to saponite-containing material isolated from a recycled water suspension, it was found that modification transformations stop at a temperature of 900 °C, the effect of which leads to a change in a number of properties – an increase in true density, a decrease in specific surface area, porosity, and water absorption [8, 30].

The structure of saponite, which acts as the main mineral of the waste from the enrichment of kimberlite ores, is represented by a three-layer structure with an expanding crystal lattice, which allows moisture to be sorbed. Saponite has rather weak bonds between the layers, which are formed by Van der Waals forces. As a result, the process of grinding raw materials can be accompanied by modification of the resulting powder. Mechanical action contributes to the transformation of the crystal lattice of the material [22], followed by a transition to a two-layer serpentine structure [25]. Serpentine itself can also be an effective component of building materials [31, 32]. Further high-temperature treatment leads to the modification of serpentine into forsterite [30]. Thus, a chain of mineral transformations is built as a result of mechanical and thermal treatment (Fig.1). Initially, mechanical grinding of saponite-containing raw materials intensifies the stages of the chemical transformation process, and increasing the duration of the grinding unit allows increasing the quantitative yield of serpentine and, as a result, forsterite.

To determine the nature of the effect of SCM emission technology on its properties, it is necessary to investigate the effect of mechanical and thermal effects on the initial suspension selected from the tailings before the insertion of various flocculants and other substances.

Methods

The paper considers the potential possibility of using saponite-containing material as a mineral additive for concrete. The suspension was studied in the initial (i.e., watered rock of sandy-clay composition), as well as mechanically activated dried and burnt states.

The SCM was dried to a constant mass in a drying cabinet with a thermostat at a temperature of 70 °C. Next, dry grinding was carried out to a highly dispersed state in a laboratory ball mill with uralite grinding media to eliminate the possibility of milling (usually happens in metal mills). The specific surface area was measured by the PSKh-11M(SP) device, which uses the generally accepted in world practice method of Kozeni – Karman gas permeability.

The temperature treatment was carried out in a muffle furnace at 700 °C, the choice of temperature regime was consistent with the known data.

The reactivity of [33-35] saponite-containing raw materials based on:

• sorption capacity determined by the Zaporozhets method by changing the concentration of $Ca(OH)_2$ in a saturated solution due to the absorption of lime by SCM particles. The amount of $Ca(OH)_2$ in the solution was determined by titration with a solution of hydrochloric acid with a concentration of 0.05 N. The amount of absorbed calcium hydroxide (1 mg per 1 g of the test substance) from the lime solution was estimated by the difference between the initial and final concentrations. In this case, the measurements were carried out at specified time intervals (1; 3; 6; 24 and 30 h from the moment of introduction of the test material into the lime solution), selected according to the required measurement accuracy and the specifics of the samples;

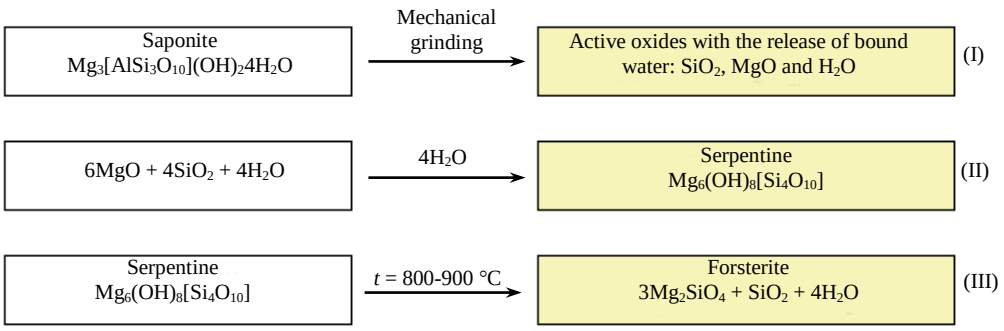


Fig.1. Schemes of mineral transformations [30]

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• acid-base properties that allow to evaluate changes in surface characteristics by using the indicator method of distribution of adsorption centers (DAC) and the theory of Bronsted – Lowry and Lewis. The point of the method is that various acidic and basic centers on the surface of a solid selectively adsorb indicator molecules. The study of the surface properties of a solid substance implies the determination of the concentration of active centers of *q*pKa, equivalent to the amount of adsorbed indicator of the acidic strength of pKa. The results obtained make it possible to regulate and predict the mechanism of physical and chemical processes on the surface of a solid.

When determining the activity, three parallel measurements of the selected samples were performed, the error between the obtained values was 2-3 %.

Using the NETZSCH synchronous thermal analysis device STA 449 F1 Jupiter, which allows combining the methods of differential scanning calorimetry (DSC) and thermogravimetry (TG), a sample of the initial SCM, dried to a constant mass, was studied in the temperature range of 25-1200 °C. The method is based on recording the difference in heat fluxes coming from the test and reference samples. The heat flow is measured as the temperature difference at two points of the measuring system at a certain point in time. Measurements of heat and mass fluxes were carried out under completely identical conditions.

The microstructure of the SCM was studied using the Mira 3 FesSem scanning electron microscope (Tescan). The shooting took place in high vacuum discharge mode.

Discussion of the results

A specific surface area of 165 m^2/kg, optimal for this type of equipment (ball mill), was determined for the dried initial SCM containing clay and sand components. The grinding time was 40 min. Longer grinding is not effective, since there is no significant increase in the specific surface area, but energy consumption increases significantly.

To determine the sorption capacity of the samples after mechanical activation, the activity and dynamics of absorption of lime $Ca(OH)_2$ from a solution of a sub-sample material were studied. In order to detail the result, SCM samples were studied at all stages of grinding – after 10, 20, 30 and 40 min.

Based on the results obtained, it can be concluded that with an increase in the specific surface area, the volume of lime absorbed from the solution ($Ca(OH)_2$) increases. The activity for samples crushed for 40 min is 69.2 mg/g, which is 6 % higher than for crushed at 10 min, and 39 % higher than for dried SCM (without grinding – 0 min). The positive dynamics is caused by mechanical activation, which is an affordable and effective way to increase the activity of mineral dispersed materials [23, 34].

Due to the obvious positive effect of mechanical activation on the value of the sorption capacity, samples of the control composition (initial sample, without grinding) and crushed within 40 min after firing were fired.

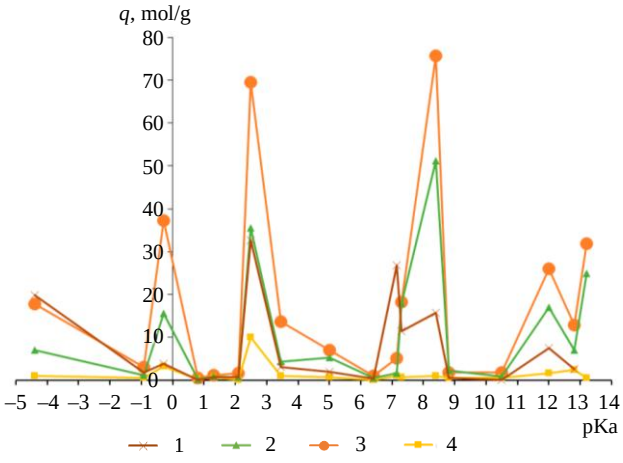


Fig.2. Distribution of adsorption centers on the surface of the SCM after mechanical and thermal exposure

1 – without grinding; 2 – grinding for 10 min; 3 – grinding for 40 min; 4 – grinding for 40 min + firing

Temperature treatment helps to reduce the activity of the material by 5.7 %, compared with the material after 40 min of grinding, which is caused by the interaction of the components during firing, the processes of destruction of the crystalline lattice of the clay fraction.

To analyze the acid-base properties of the surface, SCM samples were studied, dried and selected at different stages of grinding: control – without grinding, at the initial point of grinding – grinding for 10 min, at the final point – grinding for 40 min, as well as a sample after mechanical activation for 40 min and firing at 700 °C (Fig.2).

Over the entire range of the pKa scale, the surface of the SCM sample has the highest concentration of active centers after 40 min of grinding. Their

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predominance in the area of Bronsted centers is noted: for Bronsted acids (pKa = 2.5) – 70 mmol/g, for bases (pKa = 8.4) – 75 mmol/g. The sample after 10 min of grinding is characterized by a decrease in activity by 32 % (pKa = 8.4). This fact has a logical explanation. Mechanical activation for 10 min is not sufficient to achieve high dispersion and a highly developed surface, as at 40 min, when an optimal specific surface is reached and longer grinding is not required. The mechanically activated and fired SCM sample has a minimum number of active centers in all areas. This correlation of values is maintained when calculating the total number of adsorption centers (Table 1).

Table 1

The number of adsorption centers of different nature on the surface of the SCM particles

SCM sample	Number of adsorption centers, mmol/g, ±2			
	Lewis bases	Bronsted acids	Bronsted bases	Total number
Without grinding	25.5	39.7	64.9	130.1
Grinding for 40 min	58.3	94.6	141.9	294.8
Grinding 40 min + firing	4.9	13.0	7.8	25.6
Grinding for 10 min	23.7	47.5	98.2	169.5

Thus, an increase in the activity of the surface of SCM particles as a result of mechanical activation and its decrease during temperature treatment associated with phase rearrangements and structural changes of sandy-clay rock were noted.

A study of the reactivity of saponite-containing raw materials in the initial and pretreated state (grinding, firing) was carried out. For a detailed assessment of the results, a comparison of these indicators with traditional components of natural and man-made origin currently used as mineral pozzolan additives is presented (Table 2): natural silica-containing raw materials – quartz sand, granite, silica clay, perlite; man-made raw materials – ash of Nazarovskaya TPP (Krasnoyarsk region) and Troitskaya SDPP (Chelyabinsk region).

It should be noted that acid-base properties are presented selectively, only in the area of Bronsted acid centers, which mainly determine the growth of activity.

According to the Table 2 the studied samples of SCM have sufficiently high activity indicators comparable to the activity results for natural and man-made materials used as pozzolan additives.

Table 2

Comparison of the reactivity indicators of traditional and investigated components of mineral pozzolan additives

Raw materials components	Method of treatment	Concentration of Bronsted acid centers, mmol/g	Sorption capacity, mg/g	Source
Sand	Dry grinding	33.5	33.5	[36]
Granite		36.3	27.9	
Silica clay		22.3	53.1	
Perlite		35.3	30.2	
Ash of the Nazarovskaya TPP	–	4.4	1.0	[37]
Ash of Troitskaya SDPP		45.4	3.0	
SCM	–	39.7	49.5	Author's data
	Dry grinding (40 min)	94.6	69.2	
	Dry grinding (40 min) + firing	13.0	65.1	
	Dry grinding (10 min)	47.5	65.2	

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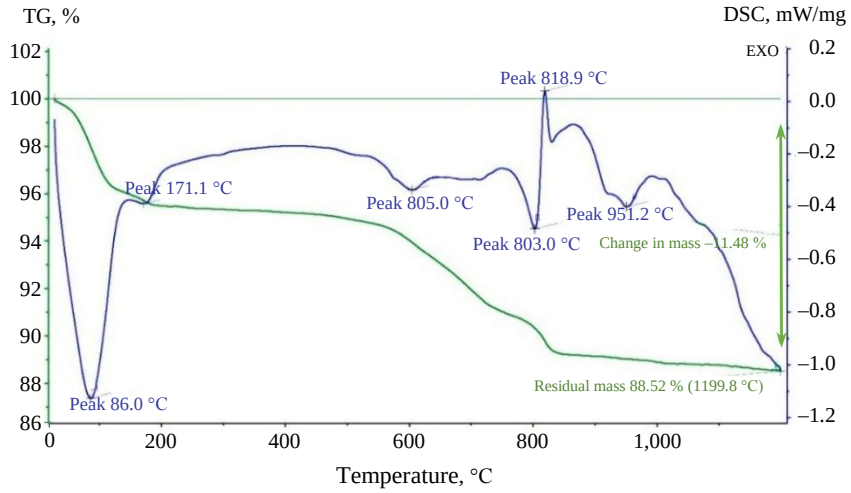


Fig.3. Thermogram of the SCM sample

Thermal analysis methods are based on the course of various chemical transformations in materials when they are heated, which are usually accompanied by a change in mass. During this type of research, the sample of the initial SCM was dried to a constant mass and tested in the temperature range of 25-1,200 °C.

The thermogram obtained (Fig.3) shows the presence of thermal effects. The course of endothermic processes occurs at peaks, the minima of which correspond to temperatures of 86; 171; 605; 803; 819 and 951 °C.

The presence of the first peak (86 °C), representing an endothermic thermal effect, is associated with the removal of adsorption-bound water. It is with this fact that the choice of the temperature value for drying saponite suspension samples is 70 °C, due to the possibility of minimizing structural changes and preserving the initial parameters and characteristics of the material. The second peak (171 °C) is also characterized by an endoeffect and corresponds to the removal of interplane/interpack water.

A small endothermic peak was noted at 575 °C (it is not indicated on the thermogram), which is associated with the transition of low-temperature α-quartz SiO_2 to high-temperature β-quartz.

Peaks of 605 and 803 °C, as well as peaks of insignificant size at a temperature of about 700 °C (not indicated in Fig.3) are endothermic effects corresponding to the dehydroxylation of serpentine, which in the form of various modifications is part of the saponite-containing material [30]. Its formation can be caused by the formation of the active form of magnesium and silicon oxides in an aqueous dispersion medium. The most pronounced peak of the exothermic thermal effect corresponds to 819 °C, associated with the formation of high-temperature forsterite from serpentine (this peak also means that the dehydration of serpentine has ended). The results obtained are confirmed by previously performed studies [8, 30]. At the end of heating, the particles of the saponite-containing material gradually sinter.

Thermogravimetric analysis records a mass loss curve depending on temperature changes. The total mass loss of the sample is 11.48 %. At a temperature range of 200-600 °C, a section of the plateau is marked, which demonstrates sufficient stability and the absence of chemical transformations. A sharp drop in the gravimetric curve indicates the chemical decomposition of the material.

The study of the microstructure of a material is one of the informative research methods that allows identifying the structural features of an object, determining the dimensional parameters of individual elements, the shape and morphology of the particle surface, observe the interaction of system components, the formation of new structures, defects, etc. With regard to raw materials for the production of building materials, these studies in combination with physical and chemical methods of substance analysis allow to make a predictive assessment of the effectiveness of using certain components in the composition of polymineral polydisperse raw materials mixtures, as well as to explain the results obtained analytically.

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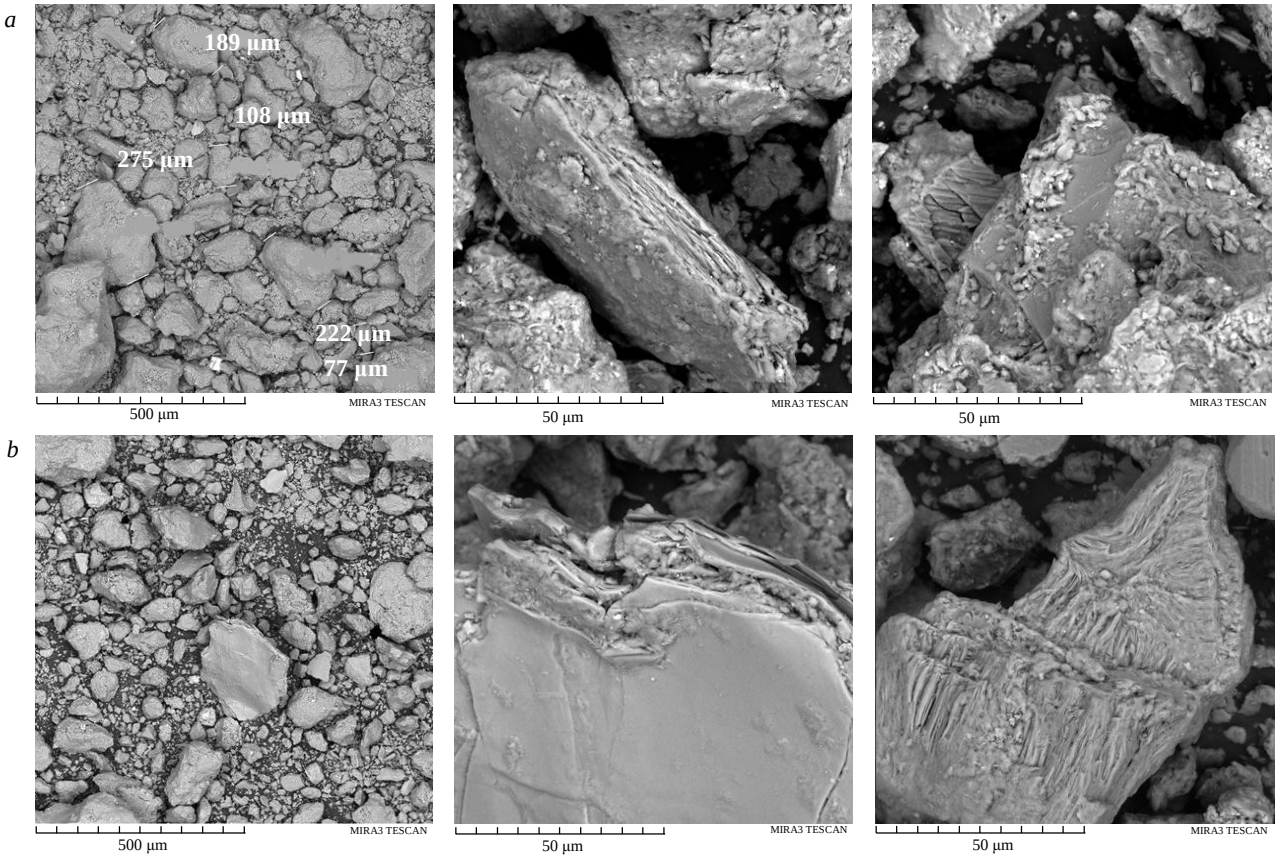


Fig.4. The microstructure of the SCM:
a – mechanically activated; *b* – mechanically activated and thermally treated

The microstructure was studied on similar samples of dried SCM after mechanical and thermal treatment. It follows from the analysis of the images that the bulk of the sample of mechanically activated SCM is composed of polydisperse particles of sandy and clay components (Fig.4, *a*). Quartz particles with a size of up to 300 μm are the largest. The morphology of the particles is angular, with a shell-like fracture typical of quartz. Quartz mineral grains have varying degrees of roughness. There is a "pouring" of clay aggregates onto quartz particles. Clay particles are well identified by their characteristic plate-like shape and layered structure. The layers of clay minerals are formed mainly by thin leaf-like structures tightly adjacent to each other.

The general character of the microstructure of the SCM samples after temperature exposure is preserved and ensured by the presence of a polydisperse system of granular quartz particles and clay aggregates of plate-like shape (Fig.4, *b*). The difference from the samples before heat treatment consists in the purchase by the material of some consolidated surface of the particles of the SCM.

Based on the microscopic analysis of the SCM samples in the form of mechanically activated and burnt dispersed powder, it was determined that the bulk of the material is composed of quartz grains with an angular fracture and plate-like particles of clay minerals with different layering.

Conclusion

The article considers the possibility of using saponite-containing material, which is a waste product of the enrichment of kimberlite ores during diamond mining at the Lomonosov deposit, as an active mineral additive for cement binders and concretes. For this purpose, the influence of mechanical and thermal treatment on a number of properties of the material selected from the tailings dump and in its initial state was evaluated.

The study of the surface activity of SCM samples was reduced to determining the sorption capacity, acid-base centers, and their distribution and allowed to determine the increase in the surface

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activity of material particles as a result of mechanical activation and its decrease during temperature treatment, which is associated with phase rearrangements and structural changes of sandy-clay rock.

As a result of the thermal analysis method, endothermic thermal effects associated with the removal of adsorption-bound and interplane water, the transition of low-temperature α-quartz SiO_2 to high-temperature β-quartz, the dehydroxylation of serpentine and the subsequent formation of high-temperature forsterite were revealed.

Microscopic analysis indicates the predominance of the bulk of the material from quartz grains and plate-like particles of clay minerals with different layering. The temperature effect has no pronounced effect, there is some "smoothing" and consolidation (sintering) of the surface of the structural elements of the saponite-containing material.

REFERENCES

1. Larichkina F.D., Knysha V.A. Rational use of secondary mineral resources in the context of Ecologization and the introduction of the best available technologies.Apatity: Izd-vo FITs KNTs RAS, 2019, p. 252.
2. Vinslav Yu.V., Lisov S.V., Lunjkin A.N. For efficient management of mineral-raw material complex in Russia: problems of subsurface use. *Russian Economic Journal.* 2017. N 3, p. 37-60 (in Russian).
3. Marrocchino E., Zanelli C., Guarini G., Dondi M. Recycling mining and construction wastes as temper in clay bricks. *Applied Clay Science*. 2021. Vol. 209. N 106152. DOI: 10.1016/j.clay.2021.106152
4. Vo T.L., Nash W., Del Galdo M. et al. Coal mining wastes valorization as raw geomaterials in construction: A review with new perspectives. *Journal of Cleaner Production*. 2022. Vol. 336. N 130213. DOI: 10.1016/j.jclepro.2021.130213
5. Benahsina A., El Haloui Y., Taha Y. et al. Substitution of natural clay by Moroccan solid mining wastes to manufacture fired bricks. *Materials Today: Proceedings*. 2022. Vol. 58. Part 4, p. 1324-1330. DOI: 10.1016/j.matpr.2022.02.211
6. Dod R.D., Dhodare S.S., Bhandari J. et al. Extraction of sand from the complex matrix of coal mining dump waste: A sustainable approach in Indian context. *Cleaner Materials*. 2024. Vol. 12. N 100243. DOI: 10.1016/j.clema.2024.100243
7. Pashkevich M.A., Alekseenko A.V. Reutilization Prospects of Diamond Clay Tailings at the Lomonosov Mine, Northwestern Russia. *Minerals*. 2020. Vol. 10. Iss. 6. N 517. DOI: 10.3390/min10060517
8. Malygina M.A., Ayzenshtadt A.M., Drozdyuk T.A. et al. Structural modification of saponite-containing material during its mechanical dispersion. *Construction Materials.* 2022. N 9, p. 32-38 (in Russian). DOI: 10.31659/0585-430X-2022-806-9-32-38
9. Buravchuk N.I., Guryanova O.V., Parinov I.A. Use of technogenic raw materials in ceramic technology. *Open Ceramics*. 2024. Vol. 18. N 100578. DOI: 10.1016/j.oceram.2024.100578
10. Migunthanna J., Rajeev P., Sanjayan J. Waste Clay Bricks as a Geopolymer Binder for Pavement Construction. *Sustainability*. 2022. Vol. 14. Iss. 11. N 6456. DOI: 10.3390/su14116456
11. Juenger M.C.G., Winnefeld F., Provis J.L., Ideker J.H. Advances in alternative cementitious binders. *Cement and Concrete Research*. 2011. Vol. 41. Iss. 12, p. 1232-1243. DOI: 10.1016/j.cemconres.2010.11.012
12. Zubkova O.S., Pankratieva K.A. Complex processing of saponite ore of the Lomonosovsky diamond deposit. *Achievements in chemistry and chemical technology.* 2021. Vol. 35. N 8 (243), p. 129-130 (in Russian).
13. Zubkova O.S., Pyagay I.N., Pankratieva K.A., Toropchina M.A. Development of composition and study of sorbent properties based on saponite. *Journal of Mining Institute.* 2023. Vol. 259, p. 21-29. DOI: 10.31897/PMI.2023.1
14. Kosareva E.N., Kabachkova N.V., Romanov E.M., Shabanova E.N. The use of saponite-containing materials as fertilizers in the cultivation of potatoes. *Bulletin of the Russian State Agrarian Correspondence University.* 2018. N 28 (33), p. 11-20 (in Russian).
15. Oblicov A.Yu. Some aspects of utilization of high-clay enrichment waste. *Mining Informational and Analytical Bulletin.* 2013. N 7, p. 390-392 (in Russian).
16. Alexeev A.I., Zubkova O.S., Polyanskiy A.S. Improving the technology of enrichment of saponite ore in the process of diamond mining. *Bulletin of Higher Educational Institutions. North Caucasus region. Technical Sciences.* 2020. N 1 (205), p. 74-80 (in Russian). DOI: 10.17213/1560-3644-2020-1-74-80
17. Jones T.R., Poitras J., Paterson D., Southam G. Historical diamond mine waste reveals carbon sequestration resource in kimberlite residue. *Chemical Geology*. 2023. Vol. 617. N 121270. DOI: 10.1016/j.chemgeo.2022.121270
18. Stroganov V., Sagadeev E., Ibragimov R., Potapova L. Mechanical activation effect on the biostability of modified cement compositions. *Construction and Building Materials*. 2020. Vol. 246. N 118506. DOI: 10.1016/j.conbuildmat.2020.118506
19. Sanchez F., Sobolev K. Nanotechnology in concrete – A review. *Construction and Building Materials*. 2010. Vol. 24. Iss. 11, p. 2060-2071. DOI: 10.1016/j.conbuildmat.2010.03.014
20. Sadique M., Al-Nageim H., Atherton W. et al. Mechano-chemical activation of high-Ca fly ash by cement free blending and gypsum aided grinding. *Construction and Building Materials*. 2013. Vol. 43, p. 480-489. DOI: 10.1016/j.conbuildmat.2013.02.050
21. Sharmin S., Sarker P.K., Biswas W. et al. Characterization of waste clay brick powder and its effect on the mechanical properties and microstructure of geopolymer mortar. *Construction and Building Materials*. 2024. Vol. 412. N 134848. DOI: 10.1016/j.conbuildmat.2023.134848
22. Ayzenshtadt A., Strokova V., Nelyubova V. Physical and chemical characteristics of the surface of powders of saponite-containing material after its mechanical dispersion. *Physics and Chemistry of Materials Treatment.* 2024. N 1, p. 53-64 (in Russian). DOI: 10.30791/0015-3214-2024-1-53-64
23. Alfimova N.I., Kalatozi V.V., Karacupa S.V. et al. Mechanical activation as a way of improving the efficiency use of raw materials of different genesis in building materials science. *Bulletin of Belgorod State Technological University named after V.G.Shukhov.* 2016. N 6, p. 85-89 (in Russian).

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24. Fernandez R., Martirena F., Scrivener K.L. The origin of the pozzolanic activity of calcined clay minerals: A comparison between kaolinite, illite and montmorillonite. *Cement and Concrete Research*. 2011. Vol. 41. Iss. 1, p. 113-122. DOI: 10.1016/j.cemconres.2010.09.013

25. Sabir B.B., Wild S., Bai J. Metakaolin and calcined clays as pozzolans for concrete: a review. *Cement and Concrete Composites*. 2001. Vol. 23. Iss. 6, p. 441-454. DOI: 10.1016/S0958-9465(00)00092-5

26. Balykov A.S., Nizina T.A., Volodin V.V., Korovkin D.I. Strength of cement stone with mineral additives based on calcined clay and carbonate rocks. *Expert: Theory and Practice*. 2020. N 4 (7), p. 26-30 (in Russian). DOI: 10.24411/2686-7818-2020-10031

27. Volodin V.V., Balykov A.S., Nizina T.A et al. The activity of a mixed cement binder with additives of thermally activated clays. Young scientists – development of the National Technology Initiative (POISK): sbornik materialov Natsionalnoi molodezhnoi nauchno-tekhnicheskoi konferentsii, 22-24 aprelya 2020, Ivanovo, Russia. 2020. N 1, p. 779-782.

28. van Jaarsveld J.G.S., van Deventer J.S.J., Lukey G.C. The effect of composition and temperature on the properties of fly ash- and kaolinite-based geopolymers. *Chemical Engineering Journal*. 2002. Vol. 89. Iss. 1-3, p. 63-73. DOI: 10.1016/S1385-8947(02)00025-6

29. Gerasimov A.M., Eremina O.V. Application microwave radiation for directional changes of layered silicates properties. *Eurasian Mining*. 2021. N 1, p. 55-60. DOI: 10.17580/em.2021.01.11

30. Drozdyuk T., Frolova M., Ayzenshtadt A. et al. Preliminary Study on the Mechanical Activation and High-Temperature Treatment of Saponite-Containing Tailings Generated during Kimberlite Ore Dressing. *Applied Sciences*. 2022. Vol. 12. Iss. 10. N 4957. DOI: 10.3390/app12104957

31. Jain A., Agrawal V., Gupta R. Using serpentine in concrete: A literature review. *Materials Today: Proceedings*. 2023, p. 5. DOI: 10.1016/j.matpr.2023.03.138

32. Zinchuk N.N. Specific features of kimberlites serpentinization. *Proceedings of Voronezh State University. Series: Geology*. 2017. N 3, p. 66-74 (in Russian).

33. Shekhovtsova J., Zhernovsky I., Kovtun M. et al. Estimation of fly ash reactivity for use in alkali-activated cements – A step towards sustainable building material and waste utilization. *Journal of Cleaner Production*. 2018. Vol. 178, p. 22-33. DOI: 10.1016/j.jclepro.2017.12.270

34. Yadykina V.V., Trautvain A.I. The influence of the active filler based on the technogenic siliceous raw materials on the strength cement systems. *Fundamental Research*. 2015. N 5, p. 174-179 (in Russian).

35. Skvortsova L.N., Chukhlomina L.N., Minakova T.S., Sherstoboeva M.V. Investigation of acid-base and sorption properties of surface of metal–ceramic composites. *Russian Journal of Applied Chemistry*. 2017. Vol. 90. N 8, p. 1246-1251. DOI: 10.1134/S1070427217080092

36. Nelyubova V.V., Strokova V.V., Danilov V.E., Aizenshtadt A.M. Comprehensive activity analysis of silicacontaining raw materials for use in mechanical activation efficiency evaluations. *Obogashchenie rud*. 2022. N 2, p. 17-25 (in Russian). DOI: 10.17580/or.2022.02.03

37. Markov A.Yu., Strokova V.V., Markova I.Yu. Evaluation of properties of fuel ashes as components of composite materials. *Construction Materials*. 2019. N 4, p. 77-83 (in Russian). DOI: 10.31659/0585-430X-2019-769-4-77-83

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