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Structural and phase features of ceramics from loam and incinerated sewage sludge ash

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Abstract. The relevance of the work is due to the need to expand the raw material base of the construction industry and develop an effective technology for the disposal of waste from water treatment plants. The purpose of the work was to establish the features of the phase composition and structure of loam ceramics and incinerated sewage sludge ash. The work used differential thermal and X-ray phase analysis, electron microscopy. It has been established that the enrichment of loam by the addition of ash from the incineration of domestic sewage sludge (DSS) ensures the connection of aggregates and individual particles into a single system reinforced with anorthite crystals. In this case, an increase in the amount of the anorthite phase and the mechanical strength of ceramics occurs with an increase in the proportion of ash from the incineration of DSS in the charge to more than 20 %. It is shown that the structure of ceramics made from loam with the addition of ash from the combustion of DSS is characterized by a spatial frame, which is a kind of a matrix that combines filler particles according to the "core-shell" type, and an increase in the number of reserve pores, which favorably affects the frost resistance of ceramics.

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1. Introduction

Currently, facade ceramics are widely used both in civil and industrial construction. The demand for such ceramics is due to their high performance properties: strength, durability, fire and environmental safety. However, the limited reserves of high-quality clays hinder the growth in the production of facade ceramics. Therefore, the development of technological processes for obtaining competitive facade ceramics from low-grade clay raw materials and man-made waste is of particular relevance.

In the production of building materials, one of the most popular secondary sources of raw materials is the ashes of thermal power plants [1–7]. The Russian enterprise's experience indicates that the addition of ashes and slags from thermal power plants into the composition of the charge contributes to a decrease in the firing temperature, an increase in the strength and frost resistance of products, and a decrease in fuel consumption [8–10]. The mineral particles contained in their composition and unburned coal form a ready-made additive for emaciated purpose. The use of ash, especially fine-grained ash, as a lean additive helps to reduce the crack resistance of ceramic products during drying [11–14]. The moisture conductivity of ash-clay masses of optimal compositions is 5 times higher than the moisture conductivity of clay raw materials, and shrinkage during drying decreases by 4–5 times [15–18].

Nowadays, recommendations have been developed on the selection of the composition of the raw mixture, taking into account the main patterns of the influence of TPP ash on the properties of clays and loams. The recommended amount of ash added into the charge (vol%) are: 10–20 for clays of low plasticity, 20–30 for moderate plastic, 30–40 for medium plastic [19]. Low-melting ash from coal combustion has an advantage over ash from brown coal. The brown coal, in the production of wall ceramics, as a rule, adversely affects the properties of the clay mass and finished products.

Among the promising secondary sources of raw materials for the production of building ceramics, along with the ashes from thermal power plants, are ashes from the incineration of domestic sewage sludge (DSS). The properties of such ashes and the possibility of their use in composition with clay raw materials from the construction industry have been studied in a number of works [20–29].

The addition of ash from the incineration of DSS into the composition of the clay charge, which, according to the authors of [22] refers to complex polymineral systems with low-symmetry crystalline modifications, reduces shrinkage during drying of products, promotes the intensive formation of the crystalline structure of ceramics, and also leads to the intensive formation of a melt that binds magnesium and calcium oxides into aluminosilicates. The melt, evenly distributed at the grain boundaries, dissolves silica and prevents the process of its cristobalitization. This leads to the formation of a dense structure of the shard and, as a result, increased strength and frost resistance of products [27].

The water absorption of specimens with an ash content of 50 % DSS, obtained by firing them at a temperature of 1000 °C, was about 20 %, but decreased (down to 12–15 %) with an increase in the firing temperature to 1100 °C [23].

According to the results presented in [24], intensive sintering of ash from the incineration of DSS, accompanied by an increase in the density of the shard, occurs in the temperature range of 1050–1100 °C. After roasting, the samples of the DSS ash reached, on average, a maximum density of 2.25 kg/m^3. The discrepancy in the maximum densities achieved is quite low (in the range of 2.09 to 2.36 kg/m^3 the coefficient of variation was 4.7 %). Although it is assumed that the compaction initiation temperatures show much higher variability. Density growth seems to start at temperatures between 900 and 1150 °C, and the optimum conditions, i.e. the peak density point, range from 1050 to 1200 °C. The water absorption of specimens with an ash of the DSS content of 50 %, obtained by firing at a temperature of 1000 °C, was about 20 %, but decreased (down to 12–15 %) with an increase in the firing temperature to 1100 °C.

It was noted in [25, 26, 30] that ceramics made with the use of DSS ash do not always have stable strength characteristics, even in the presence of a dense structure. According to the authors of these studies, this is due to the unstable chemical composition of the ashes. In this regard, the study of the physical and chemical patterns of the formation of the phase composition of a ceramic shard during the production of facade ceramics using ash from the incineration of DSS has scientific and practical interest. It can expand the raw material base of enterprises for the production of ceramic materials and ensure the disposal of environmentally hazardous waste, thereby reducing the load on the environment.

The purpose of the work was to identify the relationship and patterns in the "composition – structure – property" system, which allow optimizing the formulations of compositions from loam and incinerated sewage sludge ash to achieve the required levels of technological, physical and mechanical characteristics.

To achieve this goal, the following tasks were solved:

- the dynamics of phase transformations occurring during the firing of ceramics from loam and incinerated domestic sewage sludge ash in the temperature range up to 1100 °C was studied;
- the features of the phase composition and structure of the ceramic shard of samples of different compositions were studied;
- the properties of ceramic products made from a mixture based on loam and incinerated sewage sludge ash were determined.

2. Materials and Methods

To obtain samples of clay-ash ceramics, representative technological samples of loam from the Kamyshensky deposit of the Novosibirsk region were used. The chemical composition of loams is given in Table 1. According to the chemical composition, the raw material is acidic, with a low content of water-soluble salts, coarse and dusty, moderately plastic and sensitive to drying.

Table 1. Composition of the mineral part of loam.

Charge Component	Oxide content, wt%						Total LOI above 100%
	SiO_2	$A1_2O_3$	Fe_2O_3	CaO	MgO	K_2O	
Loam	68.70	11.78	4.10	4.76	1.68	3.60	5.62

As an additive to the loam, ash obtained from the incineration of domestic sewage sludge was used. Municipal enterprise "Vodokanal" (Novosibirsk) provided a mixture of mineral and organic substances in the form of a colloidal solution (humidity 95–97 %) during settling at a water treatment plant. Before incineration, sewage sludge was preliminarily dried at 120 °C. The sludge was burned for an hour in a laboratory furnace SNOL 6,7/130 at a temperature of 800 °C.

According to the chemical composition, ash is an acidic raw material with a high content of coloring oxides (Table 2).

Table 2. Chemical composition (wt%).

MgO	Al_2O_3	SiO_2	P	K_2O	CaO	TiO_2	MnO	FeO	Cu	Zn	O
1.9	10.6	53.9	6.1	3.1	6.2	6.3	0.2	7.5	0.12	0.3	47

The effect of domestic sewage sludge incinerated ash on the nature of physical and chemical processes during firing, the phase composition, physical and mechanical properties of clay ash ceramics was studied on samples with a diameter of 20 mm and a height of 20 mm, which were prepared from charges of different composition (Table 3) in the following order.

Table 3. Compositions of charge and structural and mechanical characteristics of samples

Composition No.	Component content, wt%		Structural and mechanical characteristics of samples	
	Loam	Ash of DSS	Average density, g/cm^3	Compressive strength, MPa
1	100	0	2.08	3.3
2	80	20	2.07	10.2
3	50	50	2.08	27.0
4	20	80	2.08	31.6
5	0	100	2.11	30.2

For the preparation of ceramic samples, samples of loam and ash were dried to a constant weight at a temperature of 110 °C in an oven. Prepared raw materials were dosed by weight, thoroughly mixed. The resulting mixture was moistened and aged for a day to evenly distribute moisture throughout the volume of the molding masses. Samples with a diameter of 20 mm and a height of 20 mm were molded on an Across MP15 press at a pressure of 1.5 MPa and dried at a temperature of 110 °C in an oven to constant weight. The samples were fired in a muffle furnace SNOL 6,7/1300. The temperature rise rate was 5–10 °C/min with holding at the maximum firing temperature equal to 1100 °C for two hours. Cooling of the samples to 30 °C was carried out together with the oven for 18 hours.

The dynamics of phase transformations in the studied compositions was evaluated based on the results of X-ray phase and thermal analyses. X-ray phase analysis (XPA) was carried out on a Bruker D8 Advance diffractometer using Cu-Kα radiation. The obtained diffraction patterns were identified using the PDF2 database with the Search-Match shell.

Differential thermal analysis was carried out on a Netzsch STA 449C setup. The values of exo- and endoeffects were determined in the temperature range of 20–900 °C at a rate of 10 deg/min in a closed crucible and a helium flow.

The determination of the frost resistance of ceramics was carried out on sample tiles with dimensions of 150×100×8 mm. The samples were saturated with water for 48 hours at a temperature of 20 °C. The samples saturated with water were placed in a freezer maintaining the temperature no less than –18 °C. The test cycle included:

- freezing for 2 hours;
- defrosting for 1 hour under water at a temperature of 20 °C.

Electron micrographs and elemental analysis were obtained on an electron microscope Hitachi TM-1000 equipped with a TM1000 EDS energy dispersive detector.

3. Results and Discussion

The DTA, TG, and DTG curves shown in Fig. 1 indicate that a number of endothermic and exothermic effects are observed when the ceramic mass is heated.

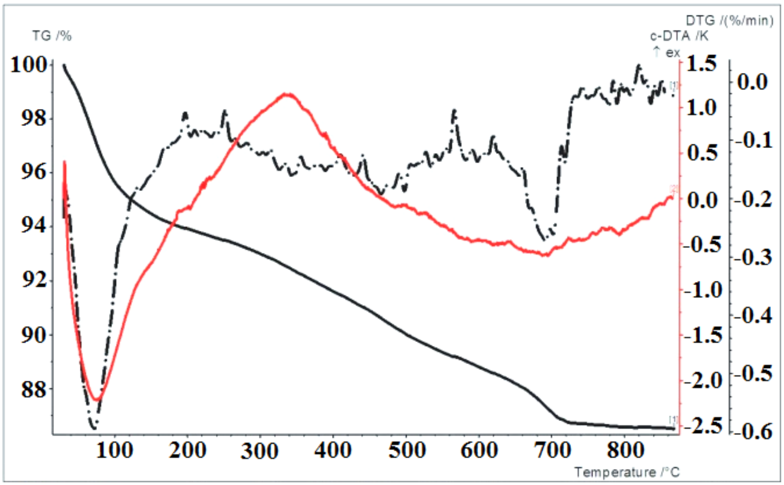


Figure 1. Thermogram of ceramic composition No. 3.

The weight loss of 3.04 % and the endo-effect in the temperature range of 50–220 °C are due to the removal of interpacket and interplanar water from clay minerals. Further reduction in mass when the material is heated to 680 °C occurs at a much lower rate.

In the temperature range of 340–550 °C, the processes of magnetite oxidation and polymorphic transformation of quartz, accompanied by an exothermic effect, occur: the transition of β-quartz to α-quartz.

The endo-effect at 700 °C is associated with the destruction of the kaolinite lattice: kaolinite loses water of crystallization and turns into metakaolinite, which decomposes into oxides at 800–900 °C [31]. A low-intensity exothermic effect at 830 °C can be identified with the oxidation of the remaining magnetite to Fe_2O_3.

The processes occurring in the temperature range of 770–950 °C are quite diverse. In addition to the oxidation of iron, this is the dissociation of carbonate inclusions in the clay raw material [32], as well as the formation of new crystalline phases: in ceramics after firing at a temperature of 1000 °C according to XRD data (Fig. 2), quartz (3.35 Å) anorthite (3.10; 4.05 Å), and hematite (2.7 Å) are identified.

It should be noted that there is no free calcium oxide (CaO) in the shard, which indicates complete involvement of the dispersed carbonate additive in the physicochemical reactions during the firing process.

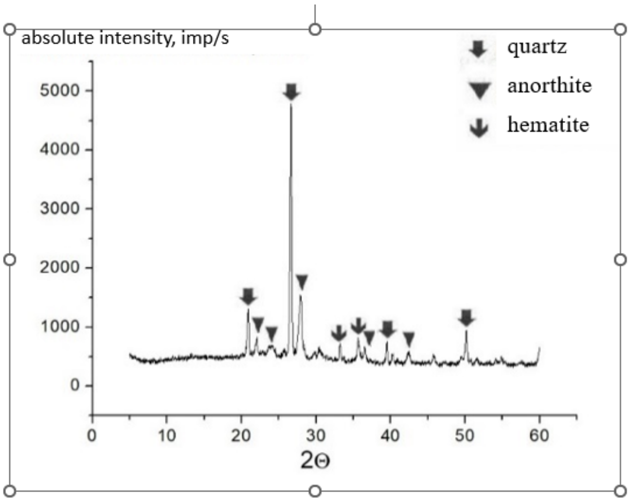


Figure 2. X-ray patterns of ceramic samples from the charge of composition No. 3.

Processing the results of X-ray phase analysis using the corundum number method made it possible to estimate the content of anorthite in the crystalline phase of ceramics from loam with the addition of incinerated DSS ash. The data obtained (Table 4) show that with an increase in the ash content of DSS in the charge above 20 %, the amount of the anorthite phase increases.

Data on the amount of anorthite correlate with data on the strength of ceramic samples (Table 3): a high anorthite content makes it possible to reinforce the ceramic structure more strongly and thereby increase its mechanical strength. This character of the influence of the anorthite phase on the physical and mechanical properties of ceramic materials was previously noted in a number of studies [33–36].

Table 4. Results of quantitative X-ray phase analysis of ceramic samples using the corundum number method.

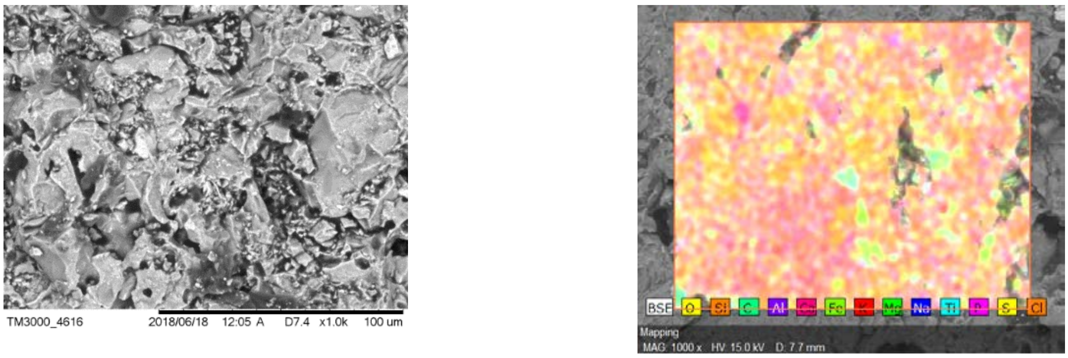
Composition No. according to Table 3	Phase composition
2	64% anorthite $CaAl_2Si_2O_8$ + 34% quartz SiO_2 + 2% hematite Fe_2O_3
3	68% anorthite $CaAl_2Si_2O_8$+ 29% quartz SiO_2 + 3% hematite Fe_2O_3
4	69% anorthite $CaAl_2Si_2O_8$+ 29% quartz SiO_2 + 2% hematite Fe_2O_3

A possible mechanism for the formation of anorthite may be related to the reaction involving amorphous silica and calcium oxide. According to studies [28, 37–39], the process of crystallization of anorthite in clays with a high content of calcite begins with an exothermic effect at a temperature of 840 °C. The process is activated by the exothermic oxidation of iron FeO => Fe_2O_3. Moreover, the released heat contributes to the dissociation of calcium carbonate. The following reaction takes place:

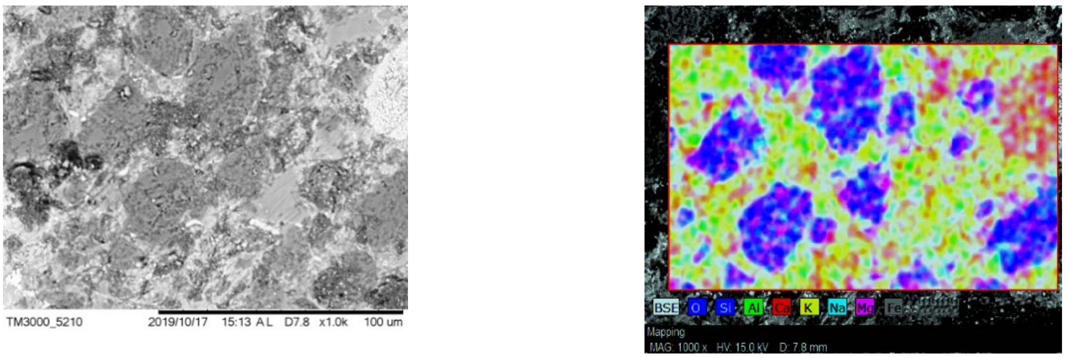
$$Al_2O_3\ 2SiO_2 + CaCO_3 = CaO\ Al_2O_3\ 2SiO_2 + CO_2.$$

Thus, the amount of anorthite formed during the sintering of the clay ash charge is limited by the amount of newly formed CaO and metakaolinite.

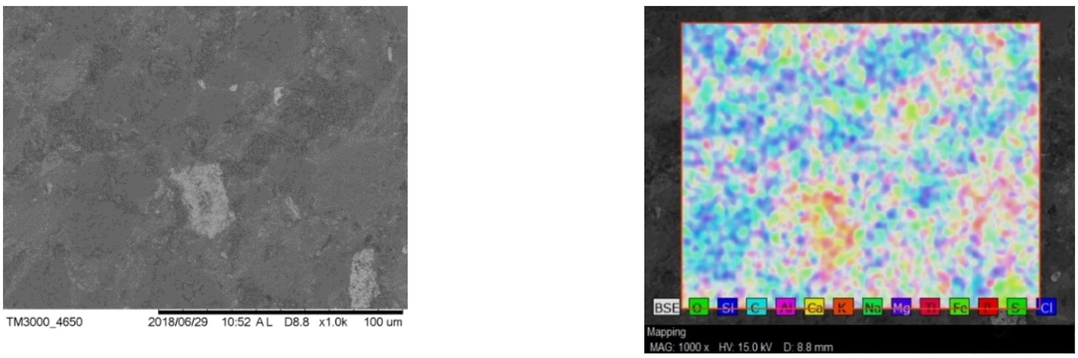
Studies of the surface relief and distribution of the main chemical elements in ceramic samples of different compositions have shown that a feature of ceramics from loam with the addition of ash is the structure characterized by a spatial frame, which is a kind of a matrix that combines filler particles in a "core-shell" type. The organization of the ceramic shard structure according to this principle is confirmed by the electron microscopy data presented in Fig. 4.



a)



b)



c)

Figure 4. Electron microscopy of ceramic samples: a – composition No. 4; b – composition No. 3; c – composition No. 2.

A feature of the structure of the newly obtained clay-ash ceramics is also the organization of the pore space. The study of the porous-capillary structure of the samples by mercury porosimetry showed a difference in the size distribution of pores in ceramics with and without ash additives.

The integral curves presented in Fig. 5 indicate that the introduction of ash into the mixture leads to an increase in the number of pores with a diameter of 10^{-4}–10^{-5} m. According to [40], pores of this size are reserve, since they are not filled when water is saturated, and allow water to expand when it freezes, thereby minimizing hydrostatic pressure, which is a favorable factor for increasing the frost resistance of newly developed ceramics.

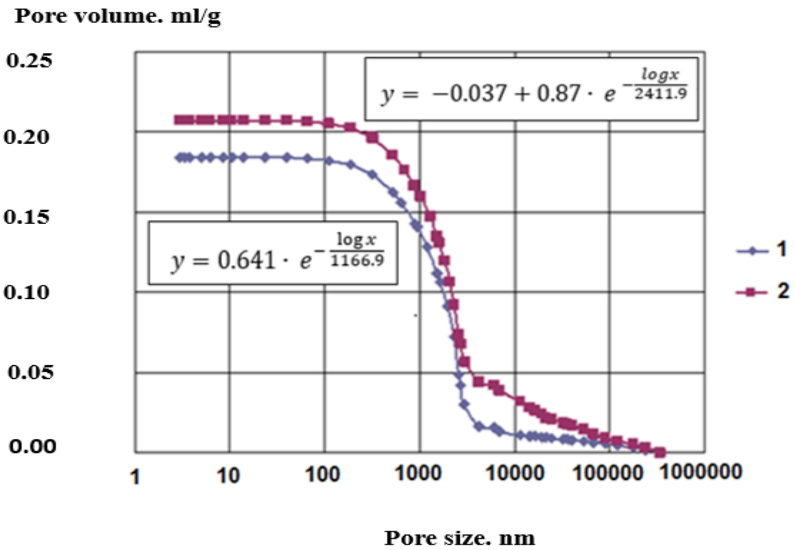


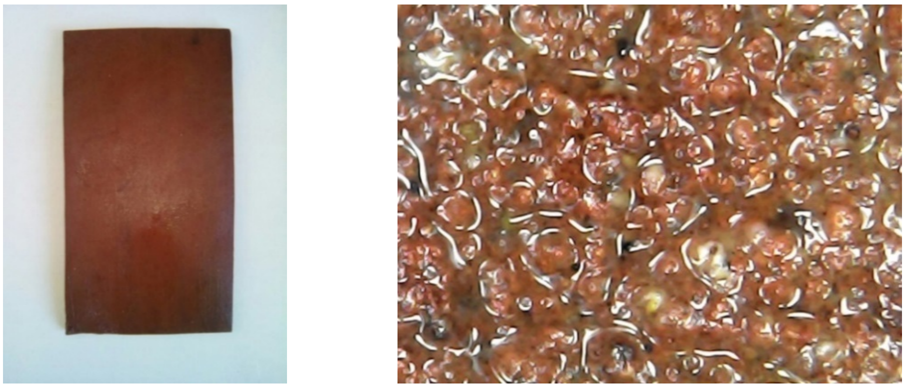
Figure 5. Integral curve of pore size distribution: 1 – composition No. 1; 2 – composition No. 3.

The structure of porosity largely determines the performance properties of wall ceramics. Taking into account the presence of changes in the pore structure of the clay-ash ceramics, the tiles of the experimental batch were additionally tested for frost resistance.

The results of the tests showed the absence of damage and weight loss. During 100 freeze-thaw cycles, no damage, chips, cracks, delaminations were observed both from the front and from the mounting surfaces (Fig. 6), which meets the requirements of Russian State Standard GOST 13996-2019 “Ceramic tiles. General specifications".

Thus, the research results allow us to conclude that the higher strength of the walls of pores and capillaries, due to the composition of the crystalline phases, in particular, the increased content of anorthite, provides resistance to the destructive effect of water freezing in the pores of the material under conditions of changes in the porous-capillary structure of the shard of clay-ash ceramics.

a)



b)

Figure 6. Appearance and macrostructure of ceramic tiles (composition No. 3) before and after frost resistance tests: a – 0 cycles; b – 100 cycles.

To confirm the results of laboratory studies on the development of the charge composition, an experimental batch of facade tiles was made from the newly developed charge composition.

Products were molded on a Ural-M3 vibropress (vibration frequency 65 Hz, pressure 12 MPa). The molded products were kept in the drying chamber for 24 hours. Roasting was carried out at a temperature of 1100 °C. The results of tests of ceramic products are presented in Table 5.

Table 5. Table 5. Properties of facade ceramic tiles from clay-ash mixture.

Charge composition	Sample No.	Flexural Strength (MPa)		Water absorption (%)		Frost resistance (cycles)	
		Requirement of Russian State Standard	Fact	Requirement of Russian State Standard	Fact	Requirement of Russian State Standard	Fact
Ash 50%, loam 50%	1	at least 16	19.5	no more than 9 and no less than 2	4.9	at least 40	112
	2	—‖—	19.1	—‖—	5.1	—‖—	110
	3	—‖—	18.8	—‖—	5.6	—‖—	105
	4	—‖—	18.7	—‖—	5.8	—‖—	104
	5	—‖—	19.3	—‖—	50	—‖—	110
	average		19.08		5.28		108

4. Conclusions

An analysis of the physicochemical transformations of the phase composition and structure of the ceramic shard, occurring in the studied compositions in the temperature range up to 1100 °C, allows us to conclude that:

1. Enrichment of loam with the addition of ash from the incineration of DSS provides:
   - connection of aggregates and individual particles into a single system reinforced with anorthite crystals;
   - an increase in reserve porosity, which favorably affects the frost resistance of the resulting ceramics.
2. The special features of ceramics from loam and incinerated domestic sewage sludge ash is:
   - an increase in the amount of anorthite phase with an increase in the ash content in the charge over 20 %. A higher anorthite content makes it possible to reinforce the ceramic structure more strongly and thereby increase its mechanical strength.
   - a structure characterized by a spatial frame, which is a kind of a matrix that combines filler particles according to the "core-shell" type.
3. The test results of an experimental batch of facade tiles made from a mixture of a newly developed composition confirm the positive effect of an increase in the content of anorthite and reserve porosity on the performance properties of products, established in the course of laboratory studies.

References

1. Vatin, N.I., Petrosov, D.V., Kalachev, A.I., Lahtinen, P. Use of ashes and ash-and-slad wastes in construction. Magazine of Civil Engineering. 2011. 22 (4). Pp. 16–21. (rus). DOI: 10.5862/MCE.22.2
2. Verma, A., Srivastova, D., Sing, N. A review on Partial Replacement of Cement by Fly Ash and Effect of Steel Fibers. Journal of Mechanical and Civil Engineering. 2017. 14(3). Pp. 104–107.
3. Coud, V., Soni, N. Partial Replacement of cement with fly ash in concrete and its effect. JOSP Journal of Engineering. 2016. 6(10). Pp. 69–75.
4. Kalra, T., Rana, R. A review on Fly Ash Concrete. International Journal of Latest Research in Engineering and Computing (ULREC). 2015. 3(2). Pp. 7–10.
5. Telford, T. The Properties and Use of Coal Fly Ash. London. 2001. 261 p.
6. Naik, T., Ramme, B., Kraus, R., Siddique, R. Loug-Term Performance of High-Volume Fly Ash Concrete Pavements. ACI Materials Journal. 2003. 100(2). Pp. 150–155.
7. Malhotra, V., Mechta, P. High-Performance, High-Volume Fly Ash Concrete. Supplementary Cementing Materials for Sustainable Development Inc. Ottawa. 2005. 124 p.
8. Panteleev, V.G., Melentiev, V.A., Dobkin, E.L. Ash and slag materials and ash dumps [Ash and slag materials and ash dumps]. Moscow: Energy, 1978. 295 p.
9. Kapustin, A.P., Kalykova, L.F., Stanevich V.T. Production of ceramic bricks from coal mining wastes of the Ekibastuz basin [Production of ceramic bricks from coal mining wastes of the Ekibastuz basin]. Construction Materials. 1991. 10. Pp. 13–14.
10. Beck, N.A., Pona, M.G., Shvlyud N.N. The use of fuel slag from the State District Power Plant for the production of ceramic tiles [The use of fuel slag from the State District Power Plant for the production of ceramic tiles]. Glass and ceramics. 1981. 7. Pp. 4–5.
11. Khrundzhe, A.V., Babushkin, V.I. Waste from the State District Power Plant for the production of ceramic tiles [Waste from the State District Power Plant for the production of ceramic tiles]. Glass and ceramics. 1983. 3. Pp. 5–8.
12. Abbas, S., Saleem, M.A., Kazmi, S.M.S., Munir, M.J. Production of sustainable clay bricks using waste fly ash: mechanical and durability properties. Journal of Building Engineering. 2017. 14. Pp. 7–14. DOI: 10.1016/j.jobe.2017.09.008
13. Pawar, A., Garud, D. Engineering properties of clay bricks with the use of fly ash. International Journal of Research in Engineering and Technology. 2014. 3 (9). Pp. 75–80. DOI: 10.15623/ijret.2014.0321016
14. Baykal, G., Doven, A.G. Utilization of fly ash by pelletization process, theory, application areas, and research result. Resource Conservation Recycling. 2000. 30 (1). Pp. 59–77. DOI: 10.1016/S0921-3449(00)00042-2
15. Saibulatov, S.Zh. Resource-saving technology of ceramic bricks based on TPP ash [Resource-saving technology of ceramic bricks based on TPP ash]. Moscow: Stroyizdat, 1990. 248 p.
16. Swierczek, L., Cieslik, B.M., Konieczka P. The potential of raw sewage sludge in construction industry: A review. Journal of Cleaner Production. 2018. No. 200. Pp. 342–356.
17. Bijen, J.M. Manufacturing processes of artificial lightweight aggregates from fly ash. The International Journal of Cement Composites and Lightweight Concrete. 1986. 8 (3). Pp. 191–199.
18. Kayali, O. Fly ash lightweight aggregates in high-performance concrete. Construction and Building Materials. 2008. 22 (12). Pp. 2393–2399. DOI: 10.1016/j.conbuildmat.2007.09.001
19. Danilovich, I.Yu. The use of fuel slag and ashes for the production of building materials [The use of fuel slag and ashes for the production of building materials]. Moscow: Higher School, 1988. 330 p.
20. Argunov, N.D., Vatueva, O.B., Veselov, V.M., Salomatina, N.A., Pilgun V.A. Some properties and features of sewage sludge [Some properties and features of sewage sludge]. Agrochemical Bulletin. 2013. 4. Pp. 39–43.
21. Shakhov, S.A., Rudaya, T.L. Structural-mechanical properties of loam ceramics with the addition of water treatment sludge [Structural-mechanical properties of loam ceramics with the addition of water treatment sludge]. Izvestiya TPU. 2014. 325(3). Pp. 98–105.
22. Polyakov, G.N., Svyatskaya, L.I., Levit, I.M. Introduction of technology for the production of ceramic bricks with the addition of ash from the incineration of sewage sludge [Introduction of technology for the production of ceramic bricks with the addition of ash from the incineration of sewage sludge]. Construction Materials. 2002. 10. Pp. 28–30.
23. Korenkova, S.F., Sheina, T.V. Fundamentals and concept of utilization of industrial waste chemical sludge in the construction industry [Fundamentals and concept of utilization of industrial waste chemical sludge in the construction industry]. Samara: SGASU. 2004. 208 p.
24. Lin, K.L. Mineralogy and microstructures of sintered sewage sludge ash as lightweight aggregates. J. Ind. Eng. Chem. 2006. 3. Pp. 425–429.
25. Cieslik, B.M., Namiesnik, J., Konieczka P. Review of sewage sludge management: standards, regulations and analytical methods. Journal of Cleaner Production. 2015. 90. Pp. 1–15.
26. Cusido, J.A., Cremades L.V. Environmental effects of using clay bricks produced with sewage sludge: Leachability and toxicity studies. Waste Management. 2012. 32. Pp. 1202–1208.
27. Tuani, Z., Mariana, B., Naquiele, S., Ana, M.S., Robinson, C.D., Gihad, M., Erich, D.R. Potential re-use of sewage sludge as a raw material in the production of eco-friendly bricks. Journal of Enviroment Management. 2021. 297. Pp. 113–138.
28. Shakhov, S.A., Nikolaev, N.Yu. Peculiarities of the formation of the phase composition and structure of ceramics from an ash-clay charge modified with a silicate sol [Peculiarities of the formation of the phase composition and structure of ceramics from an ash-clay charge modified with a silicate sol]. News of higher educational institutions. Construction. 2019. 728(8). Pp. 19–27.
29. Shakhov, S.A., Nikolaev, N.Yu. Mixture for the manufacture of ceramic products [Mixture for the manufacture of ceramic products]. Russian patent No. 2655868, 2018.
30. Shakhov, S.A., Nikolaev, N.Yu. High-temperature phase transformations in ash-clay mixture modified with sludge filtrate [High-temperature phase transformations in ash-clay mixture modified with sludge filtrate]. Proceedings of the II All-Russian scientific and practical conference with international participation. Novokuznetsk: publishing house of SGIU. 2019. Pp. 130–134.

31. Klepikov, M.S., Shcherbakov, A.A., Viktorov, V.V. Kaolins of the Southern Trans-Urals are a new source of high-quality raw materials [Kaolins of the Southern Trans-Urals are a new source of high-quality raw materials]. Bashkir chemical journal. 2011. 18(4). Pp. 242–245.
32. Golovanov, S.P., Zubekhin, A.P., Likhota, O.V. Bleaching and intensification of sintering of ceramics using iron-containing clays [Bleaching and intensification of sintering of ceramics using iron-containing clays]. Glass and ceramics. 2004. 12. Pp. 9–11.
33. Vlasov, V.A. Semenov, M.A., Skripnikova, N.K., Shekhovtsov, V.V. Features of the use of substandard types of raw materials for the production of anorthite ceramics [Features of the use of substandard types of raw materials for the production of anorthite ceramics], Vestnik TGASU. 2020. 5. Pp. 122–128.
34. Rozenstrauha, I., Bajare, D., Cimdins, R., Berzina, L., Bossert, J., Boccaccini, A.R. The influence of various additions on a glass-ceramic matrix composition based on industrial waste. Ceramics International. 2006. 32. Pp.115–119.
35. Sergievich, O.A., Alekseenko, I.A., Artemiev, E.A. Ceramic materials with increased wear resistance for machine-building and light industry [Ceramic materials with increased wear resistance for machine-building and light industry]. Proceedings of the Kola Scientific Center of the Russian Academy of Sciences. 2017. 5. Pp.167–172.
36. Tunalia, A., Ozela, E., Turan, S. Production and characterization of granulated frit to achieve anorthite based glass–ceramic glaze. Journal of the European Ceramic Society. 2015. 35. Pp. 1089–1095.
37. Kanygina, O.N., Chetverikova, A.G., Lazarev, D.A., Salnikova E.V. High-temperature phase transformations in iron-bearing clays of the Orenburg region [High-temperature phase transformations in iron-bearing clays of the Orenburg region]. Vestnik OGU. 2010. 112(6). Pp. 113–118.
38. Dhir, K.R., Ghataora, S.G., Lynn, C.J. Sustainable Construction Materials: Sewage Sludge Ash. Woodhead Publishing. 2017. 274 p.
39. Park, Y.J., Moon, S.O., Heo, J. Crystalline phase control of glass ceramics obtained from sewage sludge fly ash. Ceramics International. 2003. 29. Pp. 223–227.
40. Galperina, M.K., Egerev V.M. Interrelation of porous porous-capillary structure and frost resistance of facade ceramic tiles [Interrelation of porous porous-capillary structure and frost resistance of facade ceramic tiles]. Proceedings of the Research Institute of Construction Ceramics. 1985. 55. Pp. 5–15.

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