ISSN 2411-3336; e-ISSN 2541-9404

JOURNAL OF MINING INSTITUTE
Zapiski Gornogo instituta
Journal homepage: pmi.spmi.ru



Research article

Lightweight ash-based concrete production as a promising way of technogenic product utilization (on the example of sewage treatment waste)

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How to cite this article: Litvinova T.E., Suchkov D.V. Lightweight ash-based concrete production as a promising way of technogenic product utilization (on the example of sewage treatment waste). Journal of Mining Institute. 2023. Vol. 264, p. 906-918. EDN LMZCWZ

Abstract. The study is devoted to the development of a method for the technogenic raw materials utilization. Special attention is paid to the prospect of involving products based on them in the production of new building materials. The results of Russian and foreign studies on the reuse of wastes, such as phosphogypsum, metallurgical slag, waste from municipal and industrial wastewater treatment, etc., in the building materials industry are considered. It has been established that the use of incinerated sewage sludge ash in construction is a promising direction in terms of environmental and economic efficiency. The research confirmed the compliance of the lightweight ash-based concrete components to the regulatory documentation requirements for a number of indicators. As a result of the research, the composition of the raw mixture for the lightweight concrete production with incinerated sewage sludge ash as a replacement for a part of the cement has been developed. In terms of parameters, the developed concrete corresponds to standard lightweight concrete, marked in accordance with the regulatory documents of the Russian Federation as D1300 (density not less than 1.3 g/cm^3), Btb2 (flexural strength not less than 2 MPa), M200/B15 (compressive strength not less than 15 MPa). Lightweight ash-based concrete is suitable for use in construction, repair of roads and improvement of urban areas.

***Keywords*:** secondary material resources; incinerated sewage sludge ash; lightweight ash-based concrete; wastewater treatment; building materials; technogenic raw materials; waste utilization

Received: 31.10.2022 ***Accepted: 02.03.2023*** ***Online: 22.05.2023*** ***Published: 25.12.2023***

Introduction. To organize waste disposal facilities, new areas of land have to be withdrawn from economic circulation. The scale of accumulated industrial waste in Russia can be estimated at about 80 billion tons. Also, the disposed waste is a complex source of environmental pollution [1-3]. The issue of the need to utilize of large-tonnage industrial waste is an urgent environmental problem in Russia and the world. This is due, among other things, to the fact that the operation of disposal facilities is associated with the formation of the lands withdrawn from economic circulation and accompanying pollution [4, 5].

The use of industrial waste has significant prospects for the most material-intensive branch of industry, namely the construction industry. In the context of increasing consumption of building materials, new resources are needed for their production. According to the Russia's Socioeconomic Development Initiatives Until 2030[1], there is a trend towards a shortage of non-metallic building materials that act as inert fillers, such as sand, gravel, crushed stone, etc. Compensation for this deficit is possible due to the involvement in the processing of low-grade off-balance technogenic raw materials. Primarily, this is large-tonnage waste, in the utilization of which the Russian industry is

[1] Decree of the Government of the Russian Federation dated October 6, 2021 N 2816-r.

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interested. In addition, the properties of some wastes allow them to be used not only as inert fillers, but also to replace binders or multifunctional additives that improve product quality. The following types of waste have a high potential for beneficial use: waste from the mineral resource complex (for example, phosphogypsum); metallurgical slag; fly ash from thermal power plants; waste of pulp and paper complexes; hydrocarbon-containing waste; waste from municipal and industrial wastewater treatment. The involvement of these groups in the resource cycle of the construction industry will significantly expand the range of raw materials and finished goods, as well as reduce the amount of disposed waste. At the same time, it is important to ensure their compliance with industry standards and regulatory requirements for building materials components. When using industrial waste in the construction industry, the main directions of its utilization can be classified into two groups:

• the use of industrial waste (or its individual components with prior treatment and (or) decontamination) to replace natural raw materials similar to waste in composition and properties;

• the use of industrial waste (or its individual components with prior treatment and (or) decontamination) as binders, neutralizers, sorbents, antiseptic or coloring components of building materials if the waste has special properties that allow their physical and chemical activity to be used effectively [6].

Analysis of the prospects for using available industrial waste in construction. In assessing the potential use in the building materials production, industrial wastes are divided into inorganic (mineral) and organic substances. Most of the solid inorganic industrial wastes (ash, slag, etc.) can act as a binder, e.g. replacing part of the cement without reducing the strength properties of the product. In particular, steelmaking slags contain calcium, silicon, aluminium and iron oxides. The presence of these substances is necessary to calculate the composition of clinker raw mix for Portland cement production [7].

Phosphogypsum (PG) $CaSO_4 \cdot nH_2O$ is a large-tonnage waste of the wet-process phosphoric acid production phase at phosphate-based fertilizer plants. PG is used as an additive to cement clinker during its grinding in ball mills, which is necessary for regulation of time periods of Portland cement setting [8]. However, the negative aspects of PG use in Portland cement production are similar to the limiting factors of PG application in gypsum binders. A significant amount of water-soluble phosphorus- and fluorine-containing impurities found in PG reduces the degree of setting and hardening of cement. Their presence contributes to the undesirable outgassing inside the technological equipment, which indicates the need for preliminary purification of PG from such impurities.

The content of 80-98 % calcium sulphate hydrate in PG allows it to be classified as a gypsum raw material. Phosphogypsum binders can be used to produce various construction materials: dry mortars (for putties, facing tiles, etc.); structures for partitioning (panels, slabs); tiles for interior finishing (facing or acoustic); materials and structures with increased softening index (for damp rooms), etc.

The initial PG dispersity values (specific surface area 3500-3800 cm^2/g) make it possible to exclude milling from the technological process. However, the presence of up to 40 % moisture in the waste makes transportation difficult due to the need for pre-drying. The presence of water-soluble pollutants in PG, including P- and F-containing ones, makes the waste utilization less cost-effective compared to the natural gypsum use, since PG preparation should include pre-treatment stages. The strength of gypsum lime-sand materials based on old dump ("stale") PG decreases with increasing proportion of waste because of growing water absorption coefficient due to high porosity of resulting calcium sulphate hemihydrate [9].

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Studies show that PG firing without its pre-treatment leads to a reduction in binding properties due to the formation of anhydrous $CaSO_4$ under the influence of P- and F-containing compounds. If the content of anhydrous $CaSO_4$ in PG exceeds 30 %, this will lead to a sharp drop in the strength of the PG-based binder. Impurities of free phosphorus, H_2SO_4 and a number of water-soluble pollutants in PG inhibit the hardening of the binder. Also, during the firing process fluorine-containing gases are emitted, which causes severe corrosion of the equipment due to high acidity [10]. Due to such limiting factors, the beneficial use of PG in building materials requires additional waste preparation operations. Consequently, the production costs of building materials based on PG are increased and their competitiveness in comparison with their analogues is reduced. Thus, these directions of PG beneficial use still have not been implemented in full and do not allow utilizing considerable amounts of generated waste.

Some industrial wastes, e.g. wastewater sewage sludge (WSS), have multifunctional influencing the sintering and structure formation of ceramics and represent a valuable material resource. Tests have shown that bricks with 70-85 % of the incinerated mixture of municipal WSS have proper characteristics and can be effectively used as a building material [11]. The ash from co-incineration of organic waste (rice husk, wood chips and municipal WSS), pyrolysis residues from fly ash from thermal power plants and municipal WSS can act as a substitute for natural origin burn-out and nonplastic additives in expanded clay production [12].

Russian scientists also developed ceramic compositions based on various inorganic industrial wastes, in particular, ash and slag from thermal power plants as well as drill cuttings, which are added to ceramic raw materials to improve their properties and for the purpose of waste disposal and prevention of their storage in landfills [13].

The described waste additives are grouped according to their type of origin (mining waste, ore processing waste, metallurgical waste, sludge, ash, glass scrap, waste from large-scale construction and various chemical production processes) with indication of the ceramic mixture composition, molding and firing conditions, final strength, water absorption and other parameters of the final ceramic samples [14].

The use of technogenic raw materials in road construction. The requirements for road surface materials are several times lower than those for the use of industrial waste as components for reclamation of disturbed lands or fertilizers due to the high content of heavy metals in waste, which can cause significant environmental damage.

The incinerated sewage sludge ash (ISSA) with sand complies with all standards for road pavement materials. Based on the sieve analysis, it is established that the ISSA corresponds to the gravel sand in accordance with EN ISO 14688-2:2018. Consequently, the residue of WSS treatment can be considered suitable for road construction. The tested ISSA mixed with sand in a volume ratio of 3:7 meets the standard for by-products using for road pavement. The ash from grate furnaces is a more promising product than ash from fluidized bed furnaces due to lower content of heavy elements and larger particle size [15].

Ash-and-slag mixtures are actively used as an aggregate for repair of damaged road sections abroad. However, due to the necessity to specify mechanical properties of ash-and-slag wastes as a technogenic soil in Russia the use of these wastes is not widespread enough [16]. Hydrocarbon-containing industrial waste represented by used motor oil and used rubber can act as a component of waterproofing compositions [17, 18].

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One of the directions of PG utilization is its use for construction and repair of road pavements. However, the composition, properties and origin of the waste should be evaluated when using it for any purpose (in particular for road construction) due to a large number of impurities belonging to hazard classes I and II in PG. Thus, some of the phosphate ore deposits are characterized by an increased content of uranium-thorium-type radionuclides. Thus, some of the deposits of phosphate ores, which are raw materials for the production of the wet-process phosphoric acid (and, as a result, the source of PG formation), are characterized by an increased content of uranium-thorium series radionuclides, which are concentrated in the waste. Increased radioactivity is not typical for phosphorite deposits in the European-Asian zone (Kovdor and Khibiny deposits in Russia). Nevertheless, the level of radiation safety remains one of the most important factors regulating the possibility of waste application in construction.

The efficiency of the autoclave technology for concrete production is proved by practical experience of its application for production of wall construction materials. In this case numerous studies have substantiated the possibility of using various industry wastes (slag, ash, sludge, mining waste, glass scrap, etc.) as additives in the production of autoclaved building materials.

The use of mineral industrial wastes as an inert aggregate for heavy- and lightweight concrete allows significant saving of natural raw materials without deteriorating the concrete strength properties. For ecological and sanitary safety purposes it is possible to recycle the ISSA of different origin: water treatment plants; municipal sewage treatment plants; industrial effluents, in particular those from electroplating production (with obtaining high-quality ash-based concrete). This area has a huge potential according to scientists of Poland [19], China [20], Thailand [21], South Korea [22], Malaysia [23]. Joint studies of the researchers from Croatia and Great Britain [24], works of scientists of the Hong Kong Polytechnic University [25] and the University of Birmingham [26] are devoted to the choice and justification of methods of ash-based concrete production.

There is a practice of including the ISSA in the composition of autoclaved noise-proof foam concrete. This product is characterized by high strength and resistance to weathering, has optimal acoustic characteristics and does not adversely affect human health [27].

The incinerated ash of municipal WSS can partially replace cement in the concrete mixture. To confirm the assumption a number of experiments have been carried out, according to the results of which the similarity of the chemical composition of the oxide components of the ISSA and cement mixture was established: silica (SiO_2), calcium oxide (CaO), alumina (Al_2O_3) prevail both in the ISSA and cement. At the same time, it was found that the ISSA has a significant effect on the concrete technical properties. The conducted water absorption and compression tests when replacing 10 % by the weight of cement with the ISSA showed the best results [28].

Based on the review of Russian and foreign studies, it can be concluded that the construction materials industry may be a major consumer of waste in the future, given that the share of raw materials in the cost of construction products reaches 50 %. It is established that the use of waste in the construction industry can help expand the range of raw materials used. It can be reached by reduction of the following materials use during their replacement by wastes: inert aggregates, nonmetallic building materials or common minerals (sand, crushed stone, gravel); binding components (lime, cement, and gypsum).

Taking into account low cost of waste as a secondary material resource (or zero cost, when organizing production by a waste-generating enterprise), the cost of manufacturing building materials can be reduced by 10-30 %. At the same time, the resulting building materials and products will have characteristics not lower than similar ones produced with the use of natural raw materials. The main areas for building materials production using available waste are as follows: manufacturing of cement, gypsum,

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and gypsum based products; concrete mixes and products (using waste materials as additives, binders or aggregates), bricks and ceramic building materials, road pavement materials. All the areas are relevant in view of the current development strategy of the Russian economy.

As demonstrated by studies, including those tested in industrial conditions, virtually all basic building materials can be manufactured using a variety of industrial wastes. It is important to establish beforehand that these wastes meet all the necessary environmental, health and other regulatory requirements for building materials components.

Since the beginning of the 21st century, the Russian and world scientific communities have been actively engaged in research on sewage treatment wastes, their impact on environmental components, and potential methods of their utilization, however, the issue of its beneficial use has not yet found a satisfactory solution.

The relevance of the issue under consideration is also reflected in its compliance with Russia's National Projects 2019-2024. For example, as part of the National Project "Ecology", it is planned to build and reconstruct wastewater treatment facilities with an increase in the amount of wastewater treated, which will be accompanied by an increase in solid, liquid, and semi-liquid sewage treatment waste. In conjunction with measures to introduce new waste management facilities as part of the Integrated Solid Waste Management System National Project, these measures will lead to a predictable increase in WSS and products of its processing and utilization.

In Russia, the management system for sewage treatment waste, represented primarily by WSS of municipal wastewater treatment plants (WWTP), in most cases consists of their dewatering and subsequent disposal at landfills (sludge pits) [29, 30]. The negative impact of waste on the environment is the withdrawal of land for waste dumps and the associated pollution of the atmosphere, soil, and water bodies [31, 32].

Incineration as a promising method of waste utilization is increasingly used in various industries, including the management of WSS. Thermal destruction using furnaces of different designs (multiple hearth, cyclone and fluidized bed furnaces) provides disinfection of waste and recovery of its combustion heat for use as an energy source or for heating plant rooms.

The effectiveness of using such incinerators is confirmed by the experience of their use in other sectors: roasting of ore or its concentrates; incineration of municipal solid waste and agricultural waste; operation of thermal power plants. One of the disadvantages of using incineration for WSS utilization is the formation of combustion products that contain a number of pollutants (SO_x, NO_x, CO, As, Hg, Cd, Pb, dioxins, furans, etc.). Purification of furnace emissions of these pollutants is an important and complex part of the recycling cycle, but the air load can be reduced already at the stage of selecting the incinerator hardware design. Thus, high temperature in fluidized bed incinerators (up to 1200 °C) makes it possible to destroy dioxins and furans and to prevent their secondary formation during gas cooling without the necessity to equip the incinerator with an afterburner of exhaust gases [33]. Application aspects of this technology are reflected in developments of the Centre for Environment and Sustainable Development of the University of Surrey in the United Kingdom [34]. WSS incineration is one of the common methods of its utilization successfully implemented in St. Petersburg [35], it is used by state unitary enterprise (SUE) "Vodokanal of St. Petersburg" to reduce the volume of waste. But the amount of the produced ISSA is constantly increasing and reaches ~50 thousand tons/year at ash content of WSS of 30-42 %[2]. Continuous growth of waste generation, which is accompanied by a shortage of available space for its storage, confirms the need for an active solution of the ISSA utilization issue. Possible recycling options are agricultural or reclamation. However, the valuable organic com-

[2] Decree of the Government of St. Petersburg dated December 11, 2013 N 989 "St. Petersburg water and wastewater master plan up to 2025 with an outlook to 2030".

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ponents present in WSS are completely degraded by incineration. In addition, when the ISSA is exposed to an acidic environment, heavy elements concentrated on it as a product of thermal destruction may transfer to a soluble form and migrate into the environment. All this complicates the registration of this waste as a fertilizer [36-38].

On the basis of the analysis carried out, it was established that for environmental and sanitary safety purposes it is possible to recycle the ISSA to produce high-quality ash-based concrete. The use of waste for the production of building materials has a number of features. The initial chemical composition of the waste can vary within a wide range depending on the characteristics of production processes, which should be considered when assessing the possibility of its use. Important aspects of the use of any building materials are their long service life and the presence of direct contact with humans and the environment. The pollutants in the waste can change their properties due to environmental factors [39, 40]. For example, building structures are affected by the humidity and the acidity of the environment contributing to erosion processes. The leaching of pollutants contained in the ISSA, combined with an increase in their solubility and reactivity can lead to the migration of pollutants into the environment. Atmospheric precipitation, surface and ground waters in this case may act not only as a driving force of erosion and leaching processes, but also as a carrier medium in which pollutants are transported over significant distances [41-43]. Thus, in order to prove the possibility of the ISSA beneficial use, like any waste, it is necessary to first establish its hazard to the environment, specifically, to determine the waste hazard class [44]. In the case of municipal sewage treatment waste, namely the ISSA, the main pollutants are heavy elements [45]. When hazard classes I-IV are assigned to waste, any activity related to its disposal must be carried out only on the basis of a license, taking into account the provisions of federal legislation of Russia[3,4]. Thus, the study is aimed at solving the urgent issue of beneficial utilization of sewage treatment waste with the justification of the prospects of its use in the construction industry as one of the most material-intensive ones of the national economy.

Methodology. The research is implemented on the basis of laboratory and experimental facilities of the accredited Scientific and Education Center of the St. Petersburg Mining University using unique equipment of the Center for Collective Use, the Scientific Centers "Assessment of Technogenic Transformation of Ecosystems" and "Issues of Mineral and Technogenic Resources Processing".

The ISSA sampling has been carried out taking into account the requirements for waste sampling [46]. The structure of experimental studies carried out to assess the possibility of using the ISSA as a concrete component with information about the equipment used and the regulatory and methodical documentation is presented in Table 1. Assessment of the degree of contamination and establishment of the hazard class of industrial waste was performed in accordance with the current requirements of the Russian environmental protection legislation[5]. The hazard class was confirmed by biotesting of the ISSA water extract using test culture of algae *Chlorella vulgaris Beijer*. X-ray fluorescence (XRF) analysis was used to obtain information about the qualitative composition of the waste. The quantitative content of heavy elements selected on the basis of qualitative analysis was determined by atomic absorption spectroscopy (AAS) [47].

[3] Federal Law of the Russian Federation N 89-FZ of June 24, 1998 "On production and consumption waste" (as amended on July 14, 2022).

[4] Federal Law of the Russian Federation N 99-FZ of May 4, 2011 "On licensing of certain types of activities" (as amended on December 30, 2021).

[5] Order of the Ministry of Natural Resources and Ecology of the Russian Federation N 536 dated December 4, 2014 "On approval of criteria for assigning waste to hazard classes I-V according to the degree of environmental impact" (registered with the Ministry of Justice of the Russian Federation on December 29, 2015 N 40330).

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Table 1

The structure of experimental studies to assess the possibility of using ISSA as a component of concrete

Experimental studies	Equipment and materials	Regulatory and methodological documentation
The ISSA sampling	–	PND F 2.1:2:2.2:2.3:3.2-03
Determination of characteristics of the ISSA as a component of concrete	–	GOST 25818-2017 GOST 25820-2014 GOST 31108-2003 GOST 9758-2012 RD 34.09.603-88
Humidity	Infrared thermogravimetric moisture analyzer MOC-120H (Shimadzu, Japan)	GOST R 54232-2010
Density (true and bulk)	Sand bath, laboratory scales	GOST 12536-2014
Hazard class establishment (biotesting)	Cultivator KVM-05 (Russia), optical density meter IPS-03 (Russia)	PND F T 14.1:2:4.10-04 Order N 536 dated December 4, 2014
Radiological measurements	Gamma radiometer RKG-AT1320C (Atomtech, Belarus)	GOST 30108-94
Particle size distribution	Laboratory sieves, laboratory scales, laser diffraction particle size analyzer LA-950V2 (Horiba, Japan)	GOST R 55566-2013
Chemical composition:		
heavy element content (qualitative and quantitative composition)	Portable metal analyzer Niton XLt 898 (USA), atomic absorption spectrophotometer AAS-7000 (Shimadzu, Japan)	GOST 5382-2019 M-MVI-80-2008
content of SiO_2, Al_2O_3, Fe_2O_3, CaO, MgO, SO_3, P_2O_5	Wavelength dispersive X-Ray fluorescence spectrometer LabCenterXRF-1800 (Shimadzu, Japan)	GOST 5382-2019
free lime CaO_{free} content	–	GOST 5382-2019
Preparation of concrete mix and ash-based concrete samples	Standard Vicat Apparatus, collapsible molds	GOST 10180-2012 GOST 310.4-81 GOST 310.3-76
Determination of ash-based concrete characteristics:		
Density	Laboratory scales	GOST 12730.1-2020
Flexural and compressive strength	Compression and bending test plant ToniPRAX (Germany)	GOST 10180-2012 GOST 310.4-81 GOST 25820-2014

On the basis of the established waste hazard class, the method of the ISSA utilization has been considered, the use as a component of building materials. It has been established that the ISSA meets the requirements of regulatory and reference documentation, which are put forward for similar raw materials. Depending on the component of building material, which is planned to be replaced by the waste (in the framework the study it is cement in the mortar (cement-sand) mixture), the main indicators of the waste studied by the appropriate methods include: particle size distribution; density; content of oxide forms SiO_2, MgO, CaO (including CaO_{free}); radiological characteristics.

The obligatory stage of testing of building material samples obtained using industrial waste is to determine their compliance with the following characteristics: density, flexural and compressive strength (depending on the requirements for a particular type of construction materials). According to the test results, the samples of the ISSA-based building material are assigned a class or grade according to the mentioned parameters in accordance with the Russian industry-specific legislation. On the basis of these parameters, the possibility of using building goods based on industrial waste in various fields of construction is confirmed.

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Results. The hazard class of the ISSA was calculated based on the contamination of the sample with heavy elements in order to confirm the possibility of using the waste. Based on data on qualitative composition of the ISSA obtained by XRF analysis a list of elements was selected for quantitative analysis by AAS: Pb, Zn, Mn, Cu. The following excesses of maximum permissible (MPC) and approximate permissible (APC) concentrations of chemical substances in soil have been fixed in accordance with Sanitary Rules and Norms SanPiN 1.2.3685-21: Zn (7.9 APC); Pb (6.3 MPC); Cu (3.7 APC) (Table 2). In Table 2 elements for which there is an excess of standards MPC or APC (corresponding concentration ratio greater than 1) are marked in bold. The total pollution index is 15.9 (low pollution). Assignment of the ISSA to hazard class IV is confirmed by the software "Calculation of waste hazard class 2.0" and the results of biotesting of water extraction [48].

Table 2

The content of heavy elements in the ISSA [48]

Heavy elements	Gross concentration, mg/kg			Concentration ratio	Heavy elements	Gross concentration, mg/kg			Concentration ratio
	C_i	MPC_i	APC_i			C_i	MPC_i	APC_i	
Zn	1740	–	220	**7.9**	**Cu**	492	–	132	**3.7**
Pb	200	32	–	**6.3**	Mn	965	1500	–	0.6

In the course of tests it was established that the ISSA as a component of concrete mixture meets a number of requirements of regulatory and reference documentation. As a component of building materials, the ISSA corresponds to Class I (specific activity of naturally occurring radionuclides (NORs) $a \leq 370$ Bq/kg). Thus, the material can be used in construction of any objects, including housing. The content of certain radionuclides also does not exceed permissible norms according to GOST 30108-94. The results of the assessment of the specific activity of NORs, Bq/kg: Ra-226 73±12; Th-232 60±10; K-40 670±110; Cs-137 3.7±1.5; *a* 211±20. The general results of experimental studies to assess the compliance of the ISSA with the normative requirements for concrete components are presented in Table 3.

Table 3

Establishing the compliance of the composition and properties of the ISSA with regulatory requirements

Index	Value	Regulatory requirement
C_i, wt.%		
SiO_2	34.66	≥ 25
Fe_2O_3	13.93	$SiO_2 + Fe_2O_3 + Al_2O_3 \geq 65$
Al_2O_3	13.28	
CaO	8.69	< 10
MgO	3.53	≤ 5
SO_3	1.86	≤ 5
Na_2O	1.35	≤ 3
P_2O_5	17.5	–
Humidity, %	0.46	≤ 1
Sieve N0045 residue, %	60.00	> 40
Acidity modulus	1.83	> 1
CaO_{free}, %	0.56	≤ 1
True density, g/sm^3	2.64	> 2
Bulk density, g/sm^3	0.62	< 0.8 ≤ 1.3
Specific activity of NORs *a*, Bq/kg	211±20	≤ 370

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Test results characterized the ISSA as siliceous (GOST 31108-2003 "General Construction Cements. Technical Specification") lightweight ash with transport humidity $W = 0.56$ %. The coefficient of heterogeneity $K_h = 0.45$, which indicates the homogeneity of the waste, consisting mainly of fine particles. Dispersity corresponds to Class III by the sieve N0045 residue (GOST 25818-2017 "Fly ash from thermal power plants for concrete. Technical conditions"). The ISSA also meets the basic requirements for use as a component of concrete in terms of content (%) of oxide forms MgO, SO_3, Na_2O (GOST 25818-2017), as well as the content of free lime (CaO_{free}) (GOST 31108-2003). The CaO content (GOST 25818-2017) and the value of the acidity modulus allow to classify the ash as acidic. The determined value of total $SiO_2 + Fe_2O_3 + Al_2O_3$ (61.87 wt.%) is slightly below the requirements of the corresponding indicator for acidic ashes (≥ 65 wt.%). As the XRF analysis is semi-quantitative, it can be considered as satisfying the requirement. The ISSA falls within the permissible range of values of true and bulk density as a dense aggregate for lightweight concrete (GOST 25820-2014 "Lightweight Concretes. Technical Conditions").

According to research data, the presence of phosphorus (V) oxide P_2O_5 in concentrations of more than 1-2 % in cement can negatively affect the hydration activity of the binder (decreasing the strength characteristics of concrete, increasing the time of setting). The recorded content of P_2O_5 (17.5 wt.%) in the ISSA is much higher than this value. However, the basic requirements for the chemical composition of cement in the current regulatory documents do not regulate the maximum content of P_2O_5 (GOST 31108-2003). Thus, the use of the ISSA as a component of building material is acceptable, if the required indicators of ash-based concrete will be provided during the strength tests.

Based on the analysis of Russian and foreign researches the following composition of concrete mixture was proposed – cement:sand:water = 1:3:0.5 (taken as a control sample). In the experimental samples a part of cement (up to 50 wt.%) was replaced by the ISSA. The required amount of mixing water for each of the test samples was set with regard to the normal density of the cement mortar.

The strength characteristics of the test samples were established in the course of flexion and compression tests after ash-based concrete reached its design age of 28 days. According to the results of measurements in accordance with the regulatory legislation, the samples were assigned a class or grade according to the parameters presented in Table 4. In Table 4, the test samples with strength characteristics (class or grade), which are maintained at a level not lower than that of the control sample, are highlighted in bold.

Table 4

Results of strength characterization of ash-based concrete

Sample	Cement replaced by the ISSA, wt.%	Density, g/cm^3	Grade D	Flexural strength, MPa	Class Btb	Compressive strength, MPa	Class B	Grade M
Control	**0**	1.35		2.16		19.50		
1	**5**	1.33	**1300**	2.05	**2**	16.84	15	**200**
2	**10**	1.31		2.00		15.69		
3	15	1.28		1.42	1.2	10.25	10	150
4	20	1.28	1200	1.23		9.40	7.5	100
5	25	1.25		1.17	0.8	7.29	5	75
6	30	1.20		1.11		7.25		
7	50	1.10	1100	0.73	0.4	3.74	3.5	50

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It was found that the ISSA of the municipal WWTPs complies with the requirements for lightweight concrete components. The ash-based concrete tests results show a decrease of strength characteristics when adding the ISSA compared to the control sample. This may be due to increased P_2O_5 content in the waste. Nevertheless, the preservation of the strength properties of lightweight concrete, when replacing cement with ISSA up to 10 wt.% was confirmed. Ash-based concrete are assigned grade D1300 (density not lower than 1.3 g/cm^3); class Btb2 (flexural strength not less than 2 MPa); class B15 and grade M200 (compressive strength not less than 15 MPa).

In prospect, the building material based on the ISSA can be used to produce various concrete goods: building blocks (solid and hollow) for walls of industrial and power buildings; elements of landscaping (lawn grates, gutters, trays, pillar stones); paving tiles of various shapes; curb blocks; elements of railway infrastructure (fence panels, kilometer and picket poles with their sockets, etc.). Depending on the type of concrete products, it is necessary to carry out additional research to establish the values of characteristics regulated by the normative documents, in particular indicators of frost and water resistance of the developed ash-based material. In the course of research, the strength characteristics of exactly lightweight ash-based concrete (on the basis of cement-sand mixture) are confirmed. Depending on the requirements of the ash-based concrete consumers, higher strength properties can be achieved by adding coarse aggregate (e.g. crushed stone, gravel, etc.). Further research will be aimed at clarifying the ash-based concrete characteristics and developing of new waste-based concrete mixtures.

The raw mix for the lightweight ash-based concrete production and materials based on it can be successfully sold by developers, road builders, companies engaged in improvement of industrial and urban areas, and other organizations interested in concrete goods. These areas are especially relevant in the context of metropolises and expanding urban-industrial agglomerations. Sales of concrete goods to the municipal department will contribute to improving the quality of life through the development of a favorable urban environment.

The profitability of ash-based concrete production can be evaluated using the example of a concrete block production vibropressing line. Replacing part of the cement reduces the cost of production. When working in the most promising season for product sales (since May to October), the payback period of production will be less than a year. More than 16 tons/year of the ISSA or other incinerated waste can be utilized with using 30 % of production capacity of vibropressing equipment. Production volume will reach 250 thousand concrete products per year.

The Russian market is competitive due to a large number of manufacturers of building products. Considering that prices of materials purchased by construction companies are increasing every year, the production of building materials based on available industrial waste will achieve a reduction in the cost of the goods. The rising cost of brick and panel construction leads to an increased demand for self-build residential and industrial structures, with concrete blocks and wall stones being a popular building material in this area. The commercial activities of building materials companies are subject to seasonal sales. Demand peaks occur between May and October, i.e. during construction season, while the difference between sales during the peak season and the decline season can be as high as 30 %.

Statistics show a strong demand for building materials based on available industrial waste in the Russian Federation. Sales are possible through various channels: retail sales from the company's warehouse; contracting with construction organizations; deliveries to the building markets, etc. The prospects of using the proposed waste-based product are confirmed in the Strategy of Building Materials Industry Development.

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Conclusion. The development of the method of recycling sewage treatment waste as a component of building materials (ash-based concrete) contribute to the solution of the following issues:

• complex using of sewage treatment waste as a multi-component technogenic raw material;

• recycling of waste in the building material production as a secondary material resource;

• reducing the negative impact on the environment from waste disposal facilities by freeing up space and preventing the storage of waste in the future;

• expanding the raw material base of the construction industry by obtaining a raw mix for the production of concrete based on incinerated waste for civil engineering;

• reducing the use of natural raw materials for the production of similar quality concrete.

Reduction of the concrete products cost compared to peers is achieved by the number of factors. First, reducing the amount of raw materials (cement) is achieved by its replacing up to 10 % with incinerated waste. Second, waste recycling prevents waste being directed to disposal. It saves the company from paying for the negative impact on the environment (as of 2023, the fee rate for disposal of hazard class IV waste is 835.38 rubles per ton) and from waste transportation costs. All this increases the competitiveness of both products and technological solution.

As a result of scientific research a patent was received (Patent for invention of the Russian Federation N 2738072 “Raw mix for the production of lightweight ash-based concrete” from May 13, 2020), which indicates the novelty of development. Also, recommendations for the development implementation were prepared for SUE “Vodokanal of St. Petersburg”, OAO “Russian Railways”, the Committee for City Improvement of the Government of St. Petersburg and the Ministry of Construction, Housing and Communal Services of the Russian Federation.

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The authors declare no conflict of interests.

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