ENVIRONMENTAL AND RESOURCE EVALUATION OF SMELTER SLAG

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Abstract. The gross emission of harmful substances (dust) while unloading the smelter slag of PJSC "Mariupol Iron and Steel Works" into the waste heaps from the dump truck body and during their storage was calculated. The expediency of restoration of blast furnace slag as a siliceous component in cellular concrete was proved. The optimal compositions of cellular concrete mixtures (including the addition of TLS plasticizer – technical lignosulfonate) were determined based on the following criteria: average density of cellular concrete in the dry state and its compressive strength.

Key words: smelter slag, dust, recovery of blast furnace slag.

Fig. 1. "Panorama" of the metallurgical plant OJSC "Arcelor Mittal Kryviy Rih"

Fig. 2. Emissions of PJSC "Mariupol Iron and Steel Works"

1. Introduction

The metallurgical sector is one of the most polluting sectors of the economy. Emissions from its stationary sources of pollution reach 38 % of the total amount of pollutants. Ferrous metallurgy enterprises account for about 15 % of all industrial dust emissions, 8–10 % for sulfur dioxide emissions, 10–15 % for total water consumption [1]. A huge amount of solid waste should be added to that: slag, sludge, etc. Most slag contains contaminants of toxic elements such as As, Pb, Cd, Co, Cr, or Ni, and the like. (Fig. 1, Fig. 2).

The waste of the metallurgical enterprise is of the following types [2]: slag – 57–63 %; mineral wastes (scrap of refractories and input components) – 4–6 %; scrap metal – 15–17 %; saw, sludge, scale – 9–13 %; others – 2–4 %. The bulk of this waste is slag, which is a multi-component system consisting of the products of high-temperature interaction of iron ore, hollow rock, fluxes, fuels, and artificial minerals; containing oxides (SiO_2, CaO, FeO, MgO, Al_2O_3 and (rarely) ZnO of variable composition; they are unstable under physicochemical conditions of the earth's surface. On average, the annual slag amounts to 4.4 million tons of blast furnace slag, 2.6 million tonnes of steelmaking slag, 0.829 million tonnes of ferroalloy slag. According to [3], 240 million tonnes of slag have been accumulated at metallurgical enterprises of Ukraine, 128 million tonnes of which are the slag from steelmaking.

Slag is metallurgical melt (after hardening it is a stone or glassy substance), which covers the surface of the liquid metal during metallurgical processes − melting of raw materials, processing of molten intermediates and refining of metals. The slag is formed from iron-ore impurities, fluxes, fuel ash, products of oxidation of the processed materials, lining of the melting units.

Environmental hazards in the waste heaps of metallurgical plants are as follows:

– air pollution (emissions of pollutants into the air, dusty slag particles are spread by wind in the surrounding area);

– pollution of the water basin (change of hydrological regime; water with a high concentration of sulfides, a sharp increase in pH in reservoirs, pollution of groundwater);

– disturbance of the landscape (disturbance of the equilibrium of the geological state, removal of large territories from agricultural land bank, violation of the physical and mechanical condition of the land cover);

– soil pollution (emissions of pollutants into the soil, chemical and radiation contamination of soil);

– changes in biodiversity (oxygen content in sulfide reservoirs becomes zero and this leads to the death of living organisms) [4];

– occurrence of man-made accidents (explosions, fires).

Up to 40 % of the territory of the enterprise is used for storage of waste. The leaders of accumulated slag in Ukraine are PJSC "ArcelorMittal Kryviy Rih" and PJSC "Mariupol Iron and Steel Works" (MISW).

In Ukraine, the waste from metallurgical enterprises is added to the already existing waste heaps (Fig. 3), which is 80–100 million tonnes on average a year (blast furnace slag of cast iron is 0,6–0,7 tonnes per tonne [5], [6].

a   b

Fig. 3. Fragments of slag dumps of the Ilyich MISW (Grekovat gulch):
a − near the residential area
b − close to the detached houses

About 200 thousand hectares of fertile land are buried under the dumps of slag. Therefore, the task is to recover metallurgical waste, the level of its utilization is still not very high.

The national and international practice shows that most of waste can be recycled and used efficiently in metallurgy [7], production of building materials [8], etc.

Depending on the speed of cooling, the slag can be of two types: granular and dump ones. Granular slag

contains substances in an amorphous state; it has a vitreous structure; it is not stable; it has a large supply of internal chemical energy, resulting in high chemical and hydraulic activity (which is why it is used in the production of building materials). The slow-cooled slag is of crystalline type (most often having low chemical activity).

In [8] it is stated that fraction > 10 mm of blast furnace slag of JSC "ArcelorMittal Kryviy Rih" can be

recommended for practical use in two directions of binder production: as a raw material component for the production of portland cement clinker and in the production of slag portland cement. clinker and slag.

The studies [9] of the basic physical, mechanical and chemical properties of blast-furnace granular slag of PJSC "Dniprovsky Metallurgical Plant" have shown that in the designed compositions of fine-grained cement concrete, it can serve not only as a filler but also as a substitute for the part of the binder. In order to obtain high quality durable fine-grained concrete, it is advisable to perform a blast furnace slag treatment, for example, a mechanical activation.

In the research work [8], the main criteria to use slags as sorbents for water purification were also determined: absence of toxic elements, presence of calcium and magnesium aluminosilicates, amorphous state of substances, compliance with the requirements of radiation safety standards. Fraction > 10 mm of blast furnace slag of OJSC "ArcelorMittal Kryviy Rih" meets the specified criteria. The investigated slag is non-toxic and does not violate the sanitary and hygienic requirements for drinking water during prolonged operation, which is proved by the lack of desorption from the slag of toxic compounds. The mode of optimal chemical activation of slag is selected depending on the nature of the sorbate (for blast furnace slag of JSC "ArcelorMittal Kryviy Rih" − pre-treatment with water).

The purpose of the work is to perform calculations of the level of surface concentrations of pollutants (dust) in the air near the slag dump and substantiate the raw material value of the blast furnace slag of PJSC "Mariupol Iron and Steel Works" for the production of porous concrete.

2. Methodology and materials

The gross dust emission was determined (following the procedures [10]) near the industrial waste heaps of PJSC "Mariupol Iron and Steel Works" (MISW), located in the Grekovata gulch (waste heaps have been in operation since 1972). The largest volume is blast furnace slag (up to 75 % of annual volume) and steelmaking slag recycled at the plants of the slag processing plant and the production of AMCOM-1 and AMCOM-2 (up to 15 % of the annual volume). All other types of waste make up 10 % of annual waste. The AMCOM-1 and AMCOM-2 units are separation and sorting ones with a capacity of up to 2 million tonnes of slag per year for the extraction of metallic components from the blast furnace slag, with their subsequent use as secondary raw materials.

The area of waste heaps within the land allotment is 154.9486 ha. The dumps occupy an area of 115 hectares. 5 ha belong to the marginal protection strip of the existing pond. The wetland occupies 16.8 hectares. 20 ha is a reserve area for the expansion of the dump.

The planning marks at the sites of the existing dumps range from 31.19 m to 77.84 m in the absolute value. The natural relief of the site within the floodplain of the gulch is 13.0–15.0 m; within the slope of the gulch, it is 35.0–45.0 m. The absolute marks of the technogenic relief of the industrial waste heaps reach 80,0 m (with an average value of about 50.0 m).

According to geodetic measurements, as of September 2019, the volume of waste was 17.116 million m^3. Dumps are formed with the help of a bulldozer. Dump trucks are used for the transportation of waste.

The areas and volumes of the accumulated waste are calculated on three separate contours (Fig. 4, Table 1).
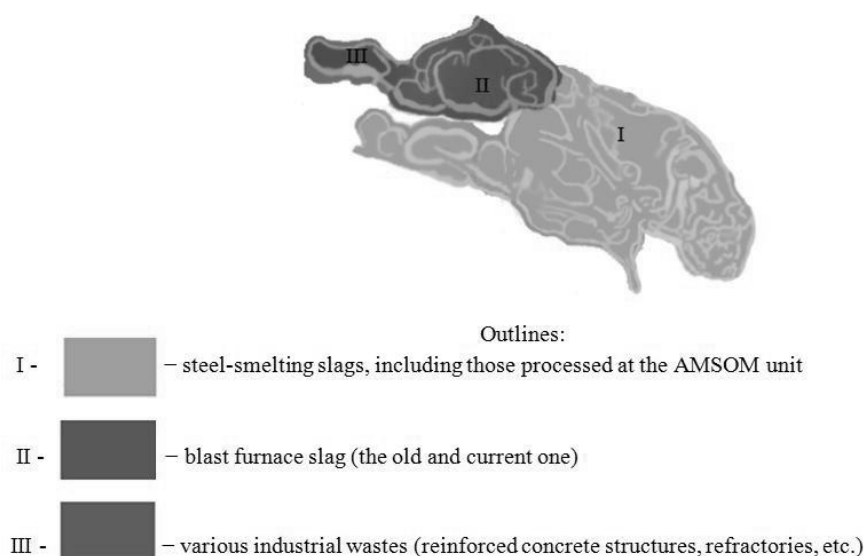

Outlines:

I - − steel-smelting slags, including those processed at the AMSOM unit

II - − blast furnace slag (the old and current one)

III - − various industrial wastes (reinforced concrete structures, refractories, etc.)

Fig. 4. The scheme of waste heaps of "Mariupol Iron and Steel Works" in the Grekovat gulch

Further storage of waste at the area of the existing waste heaps is possible within contour I and partially contour II by increasing the height of the waste heaps by 5–20 m. The specified volume can contain 6 million 375 thousand tons of waste.

Table 1

**Areas and volumes
of accumulated waste of MISW**

	Area of contour, m²	Volume of wastes, m³	Types of wastes
I	662034	6190478	Slag steel smelting (including processed at AMKOM-1,2 units)
II	193000	2914193	Blasting slag (old and current)
III	66745	675957	Miscellaneous industrial wastes (reinforced concrete structures, refractories, etc.)

The resource value of metallurgy waste − blast furnace slag of PJSC "Mariupol Iron and Steel Works" (hazard class IV [7]) − was determined by the physical and chemical properties of the criteria of non-autoclaved aerated concrete (its average density in aerated concrete in a dry type and the margin of its hardness).

Blast granulated slag is a fine-grained bulk multicomponent material, mainly vitreous, obtained by rapid cooling of liquid hot slag formed during melting of cast iron in a blast furnace (Fig. 5). In the State Classifier of Waste DK-005-96, the qualification grouping "Slag blast furnaces for construction, others" refers to the waste of production of basic metals (group 27, code 2711.2.9.11).

The following materials were used to prepare the cellular concrete mixture:

1. Milled blast furnace granulated slag of PJSC "Mariupol Iron and Steel Works" which met the requirements of UNSS Б B.2.7-302:2014 [11] was used as a siliceous component.

2. Portland cement of PJSC "Ivano-Frankivsk cement" PC II/A-W-500 (II cement type − portland cement with mineral additives from 6 % to 35 %; A − cement subtype (differs in the content of the components), AC – 80–94 % of Portland cement clinker with the addition of blast furnace granulated slag from 6 to 20 %, 500 − brandcement strength (kgf/cm²), which meets the requirements of UNSS B B.2.7-46:2010 [12].

3. Calcium lump quicklime of Collective enterprise "Azovbudmaterialy" (Mariupol, Donetsk region) meets the requirements of UNSS B B.2.7-90:2011 [13].

4. Gas-forming agent − aluminum powder PAP-1 (pigment) (Fig. 6), which meets the requirements of UNSS 5494-95 Aluminum Powder. Producer − LLC Scientific-Production Company "Ukrtorresource", Rivne).

5. Surfactant – detergent

6. Additive-plasticizer LST − technical lignosulfonate is a waste product of cellulose sulfite production and is a mixture of sodium salts of lignosulfonic acids, with the admixture of reducing and mineral substances. Producer is Limited Liability Company«Limass Industrial Company (Zaporozhzhia).It is a dark brown homogeneous binding fluid (Fig. 7).

Fig. 5. The blast furnace granulated slag

Fig. 6. Aluminum powder

Fig. 7. Liquid ignosulfonate

LST is non-toxic; it does not irritate the skin, mucous membranes of the eyes, and does not cause allergic reactions.

Due to the loss of validity of the State sanitary rules and regulations of the DSANPiN 2.2.7.029-99 "Hygienic requirements for the management of industrial waste and determination of their class of danger to public health" and the inability to determine the hazard class of LST by a known method, the latter can be accepted (with some assumptions) based on the existing Maximum Permissible Concentrations of chemical and biological substances in the atmospheric air of the inhabited places, approved by Protas S. V., Chief State Sanitary Doctor of Ukraine on March 15, 2015, as "sodium sulfite-sulfate salts" of III hazard class (line 322 in the list of substances [14]). It is this class of hazard (third) that is specified in the Chemical Product Hazard Passports (technical lignosulfonate) provided by Limas Industrial Company LLC [15] for its products.

The water complied with the requirements of UNSS B B.2.7-273:2011 [16]. The composition of the porous concrete was calculated according to the method described in [17]. The components of the aerated concrete mixture were dosed in a mixing bowl in the following order − water, milled blast granular slag and lime, cement M 500 and aluminum suspension (aluminum powder + washing powder + water). Water (60 °C), ground granulated slag and lime were first mixed. The mixture was then mixed with cement and an aluminum slurry, after which it was poured into metal molds for three future cubic samples with an edge of 10 cm. After reaching the necessary strength and cutting "hunchback", the forms were disassembled.

When forming specimens of porous concrete, in one case, calcium lump quicklime in the amount of 5 % was used in the composition of the porous concrete mixture, and in the other sample, the effect of lime was replaced by the structure-forming additive LST - technical lignosulfonate (liquid).

The additive of LST was dosed in a cellular concrete mixture in the amount of 0.1; 0.15; 0.2; 0.25; 0.3 % of the weight of dry components. The studies of the effect of the additive on the physical and mechanical properties of the cellular concrete have shown that its optimal amount in the mixture is 0.2 % of the weight of dry components.

Before testing the $10 \times 10 \times 10$ cm cubes for medium density in the dry state and their compressive strength, they were dried in an electric cabinet at the temperature (105 ± 10) °C to constant mass (paragraph 3.1.13 [18]).

The average concrete density ρm was determined by the formula:

$$\rho_m = \frac{m}{V}, \qquad (1)$$

where m is the sample weight, kg; V is the sample volume, m^3.

The strength of cellular concrete (MPa, kgf / cm^2) was calculated to the nearest 0.1 MPa (1 kgf / cm^2) according to the formula [19]):

$$\sigma_{\text{ст.}cube} = \frac{\alpha \cdot F \cdot K_w}{A}, \qquad (2)$$

where F is the destructive load, H, (kgf); A is the area of working section of sample, mm^2 (sm^2); α is the scale factor for bringing concrete strength to concrete strength in specimens of basic size and shape (for specimens cubes with ribs 100 mm long $\alpha = 0.95$, Note 2 Table 5 [19]);

K_w is the correction factor for cellular concrete which takes into account the humidity at the time of the test (for humidity 0 % − the samples are dried to constant mass − $K_w = 0.8$, Table 6 [19]).

3. Results and Discussion

Intense unorganized sources of dust formation are material overloading, loading into open wagons and gondola cars, material loading by a grapple into the hopper, filling of the material by an open jet into the warehouse, etc. The volume of dust removals for gross emissions from the dumping of metallurgical slag from the car body into the dumps was calculated by the formula [10]:

$$\Pi_{ae} = K_1 \cdot K_2 \cdot K_3 \cdot K_4 \cdot K_5 \cdot K_7 \cdot K_8 \cdot K_9 \cdot B \cdot G_a, \qquad (3)$$

where Π_{ae} is the annual estimated volume of dust, t/year; K_1 is the weight fraction of the dust fraction in the material (Table 1 [10]). It is determined by washing and sieving the sample with the extraction of a dust fraction of size from 0 to 200 μm; K_2 is the proportion of dust (from all weight dust) that passes into the aerosol (Table 1 [10]). Checking the actual dispersed composition of the dust and clarifying the value of K_2 is performed by sampling dusty air within the dusty object (warehouse, tailing, etc.) at a wind speed of 2 m/s blowing in the direction of the sampling point; K_3 is the coefficient taking into account local weather conditions (Table 2 [10]); K_4 is the coefficient taking into account local conditions, degree of protection of the node from external influences, conditions of dust formation (Table 3 [10]); K_5 is the coefficient taking into account the humidity of the material; determined in accordance with the data in the table. 4 [10]. The humidity of a material is understood as the humidity of its dust and fine-grained fractions (particle diameter d < 1 mm); K_7 is the coefficient taking into account the size of the material; taken according to table. 5 [10]; K_8 is the correction factor for different materials depending on the type of grapple (Table 3 [10]); when using other types of reloading devices $K_8 = 1$. K_9 is the correction factor for a powerful salvo discharge of material during unloading of a dump truck. $K_9 = 0,2$ at discharge of material up to 10 tons and $K_9 = 0,1$ – more than 10 tons. For the rest of unorganized

sources the coefficient $K_9 = 1$; K_9 is the correction factor for a powerful salvo discharge material during dumping of the dump truck. $K_9 = 0.2$ at discharge of material up to 10 tons and $K_9 = 0.1$ − more than 10 tons. For the rest of unorganized sources the coefficient $K_9 = 1$; B is the coefficient taking into account the height of the overflow; taken as a table. 7 [10]; G_a is the total amount of material processed during the year, t/year. It is defined by the chief technologist of the enterprise on the basis of actually processed materials or planned for a year.

For slag $K_1 = 0.05$, $K_2 = 0.02$.

According to the Doctor of Geographical Sciences, Professor Vishnevsky VI [20] The average wind speed * in Mariupol is 5,4 m/s (Table 2).

Table 2

Wind speed in Mariupol by months, m/s

I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII	Average per year
6.3	7.1	6.1	5.5	5.0	4.4	4.2	4.4	4.8	5.4	5.8	5.9	5.4

* Gross emissions for the period under consideration are determined by the average values of wind speed and humidity of that period [10]

Due to the fact that the slag dumps are open on four sides, K_4 is equal to 1.0 when reloading sawing materials without using the loading sleeve.

When storing metallurgical slag in an open way, their moisture fluctuates widely (depending on weather conditions). In the paper we take the average humidity of slag up to 10 %. Therefore, $K_5 = 0,1$.

According to the data of [21] (authors Kravchenko V. P., Taranina O. V., Gankevich V. F.) the maximum particle content of blast furnace slag of MISW refers to fractions of 500-800 microns. Thus, $K_7 = 1.0$.

Due to the fact that the dumps of metallurgical slag of MISW in Grekovat gulch are formed by a bulldozer, then $K_8 = 1.0$.

The industrial wastes of JSC "Mariupol Iron and Steel Works" are disposed into dumps by KAMAZ dump trucks, whose mass of the material in the body is more than 10 tons. Accordingly, $K_9 = 0.1$.

At the height of falling slag from the body of KAMAZ-55111 dump truck of 1m (the distance from the ground to the bottom of the body is 1 m [22]) $B = 0.5$.

The estimated monthly amount of all MISW industrial wastes that is taken to waste heaps is 250.0 thousand tonnes (90 % of this volume is metallurgical slag (blast furnace and steel smelting). The total amount of recycled slag during the year G_a will be $0.9 \cdot 250000 \cdot 12 = 2700000$ t.

Therefore, the volume of dust removals for gross emissions from dumping of metallurgical slag from the body of KAMAZ-55111 dump truck into the dumps will be:

$$\Pi_{ae} = 0.05 \cdot 0.02 \cdot 1.4 \cdot 1.0 \cdot 0.1 \cdot 1.0 \cdot 1.0 \times$$
$$\times 0.1 \cdot 0.5 \cdot 2700000 \text{ t/year} = 18.9 \text{ t/year}.$$

The gross emission of Π_{se} (estimated) harmful substances (dust, t / year) during the storage of metallurgical slag of JSC "Mariupol Iron and Steel Works" in waste heaps (Grekovat gulch) was calculated according to the formula [10]:

$$\Pi_{se} = 0.11 \cdot 8.64 \cdot 10^{-2} \cdot K_4 \cdot K_5 \cdot K_6 \cdot K_7 \cdot q \times$$
$$\times F_{pl} \cdot (1-\eta) \cdot (T-T_s-T_r), \qquad (4)$$

where K_6 is the coefficient taking into account the surface profile of the assembled material; defined as the ratio F_{max}/F_{pl}; F_{pl} is the surface of dust removal in plan, m²; determines the chief technologist for the general plan of the enterprise; F_{max} is the actual surface area of the piled material at maximum filling of the warehouse, m²; is determined by the chief technologist of the enterprise on the basis of material characteristics; q is the maximum specific dust blown, mg / (m² · s); obeys the law of the degree;

$$q = a \cdot v^b, \qquad (5)$$

where v is the wind speed, m/s; a i b are empirical coefficients that depend on the type of material being overloaded (Table 8 [10].

The results of mathematical processing of q for several types of reloading material are given in Table. 9 [10].

η is the degree of solid particle trapping in the dust trap unit; the fraction of − is determined from actual measurements. If there are no means stop dust, then take the coefficient η as 0;

T is the total shelf life of the material for the period, days;

T_s is the number of days with a constant snow cover, days;

$T_r = 2T^o_s$ (hour.)/24 is the number of days with rain,

where $2T^o_r$ (hour.) is the total rainfall over the period considered in hours.

The number of days with snow and hours with rain is requested from the territorial body of the State Committee for Hydrometeorology or determined according to the climate directories.

Since the specific blow-off decreases over time due to the depletion of the surface layer of the material by the dust fraction (which is a natural phenomenon) and leads to a decrease in dust removal, a correction factor of 0.11 is made in the gross emission formula.

From formula (4): $K_4 = 1.0$; $K_5 = 0.1$; $K_7 = 1.0$.

Conditionally taking the surface of the slag dumps horizontal, then $K_6 = F_{max}/F_{pl} = 1,0$.

The empirical coefficients for slag (as for rubble) are as follows: $a = 0.0135$; $b = 2.987$. The average wind speed $v = 5.4$ m/s (Table 2). By using these values in the formula (5), we obtain:

$$q = 0.0135 \cdot 5.4^{2,987} = 2.08 \text{ mg/(m}^2 \cdot \text{s)} =$$
$$= 0.000208 \text{ g/(m}^2 \cdot \text{s)}.$$

The dust removal surface Fpl is equal to the sum of the contours of circuits I and II (Table 1), which are occupied by steel and blast furnace slag, namely: F_{pl} = 662034 + 193000 = 855034 m^2.

The degreeof trapping solid dust particles η = 0 (no duststopping means).

The total shelf life of the material is T = 365 days (we consider one year).

In Mariupol, the length of the period with a constant snow cover is T_s = 60 days [23].

For Donetsk region, the average annual duration (in hours) of precipitation (rain) T^o_r = 1000 hours (Table 4,32 [24]). Then T_r = 2·1000/24 ≈ 84 days.

Therefore, the annual gross emission of dust Пsc (t/year) from metallurgical slag in the waste heaps (Grekovat gulch) is:

$$\Pi_{sc} = 0.11 \cdot 8.64 \cdot 10^{-2} \cdot 1 \cdot 0.1 \cdot 1 \cdot 1 \cdot 0.000208 \times$$
$$\times\ 855034\ 1 \cdot (365\text{-}60\text{-}84) = 37.4 \text{ t/year.}$$

In the calculations of ground-level concentrations of pollutants, the emission power attributed to the 20-minute time interval should be used [10]. This requirement applies to pollutant emissions with the duration T (s) of less than 20 minutes (T < 1200 s). For such emissions, the power values M (g/s) are determined as follows:

$$M = Q/1200, \text{ g/s,} \tag{6}$$

where Q is the total mass of pollutants released into the atmosphere from the considered source of atmospheric pollution during its operation.

In this case, the total mass of pollutants Q will be equal to the sum of gross emissions from the metallurgical slag of PJSC "Mariupol Iron and Steel Works" during their discharge from the car body into the waste heaps Пac and during the storage of the slag in the waste heaps. That is, the power of gross dust emissions:

$$M = (\Pi_{ac} + \Pi_{sc})/1200 = [(18.9 \cdot 10^6 +$$
$$+\ 37.4 \cdot 10^6)/365 \cdot 24]/1200 = 5.4 \text{ g/s.}$$

To determine the average density of porous concrete in the dry state and its tensile strength, sample cubes were formed from the porous concrete mixtures of such formulations (Table 3). In all the mixtures under consideration, water consumption is equal to 55 % of the weight of dry components. In the mixtures of the series of samples I-IV, a constant amount of lime is 5 % of the weight, and in the mixtures of the series of samples V–VIII, a constant amount of LST (technical lignosulfonate) additive is 0.2% of the weight. The addition of LST was dosed in the cellular concrete mixture in the amount of 0.1; 0.15; 0.2; 0.25; 0.3 % of the weight of dry components. The studies of its effect on the physical and mechanical properties of cellular concrete have shown that the optimal amount of it in mixtures is 0.2 % of the dry components. The concentration of aluminum powder within each series of samples changes equally and is 0.06 %; 0.065 %; 0.07 %.

The main difference between cellular concrete and other types of concrete is its high thermal insulation properties. When developing compositions of such concrete, one should try to obtain the greatest strength at its lowest average density. The cellular concrete of all the structures studied has the values of the average density from 690 kg / m^3 to 740 kg / m^3, and the values of compressive strength range from 1.8 MPa to 2.7 MPa (Fig. 8–11). Thus, according to UNSS B B.2.7-45:2010 [25], they all have a D700 brand by the average density (Table 1 [25]), and classes B1.0 and B1.5 by strength (Table 2 [25]).

As can be seen in Fig. 8, the concrete density of 700 kg/m3 (at an aluminum powder concentration of 0.065%) have the concrete of two series of specimens: Series I, compositions No. 1-3 (Table 3) and Series II, compositions No. 4- 6 (Table 3). The compressive strength of the concrete of composition No. 5 (–□– 30 % C + 65 % S + 5 % L + 0.065 % A.p. + 55 % W) is significantly higher than that of the concrete of composition No. 2 (–O– 25 % C + 70 % S + 5 % L + + 0.065 % AP + 55 % W), namely: 2.3 MPa versus 1.9 MPa (Fig. 9). Therefore, composition No. 5 of cellular concrete is optimal among the compositions of concrete with lime without the addition of LST (although there are kinds of concrete with higher strength, but they have an average density of more than 700 kg / m^3).

Table 3

Compositions of cellular concrete mixtures based on ground blast granular slag

No of series of samples	No. of composition of the mixture	The compositions of the mixtures, % by weight						Mark on graph
		Cement, C.	Grindable components in a ball mill		Aluminum powder, A,p,	Additive, LST	Water (from dry components), W	
			Slag, S	Lime, L				
1	2	3	4	5	6	7	8	9
I	1	25	70	5	0.07	–	55	–O–
	2	25	70	5	0.065	–	55	
	3	25	70	5	0.06	–	55	

1	2	3	4	5	6	7	8	9
II	4	30	65	5	0.07	–	55	
	5	**30**	**65**	**5**	**0.065**	**–**	**55**	
	6	30	65	5	0.06	–	55	
III	7	35	60	5	0.07	–	55	
	8	35	60	5	0.065	–	55	
	9	35	60	5	0.06	–	55	
IV	10	40	55	5	0.07	–	55	
	11	40	55	5	0.065	–	55	
	12	40	55	5	0.06	–	55	
V	13	25	75	–	0.07	0.2	55	
	14	25	75	–	0.065	0.2	55	
	15	25	75	–	0.06	0.2	55	
VI	16	30	70	–	0.07	0.2	55	
	17	**30**	**70**	**–**	**0.065**	**0.2**	**55**	
	18	30	70	–	0.06	0.2	55	
VII	19	35	65	–	0.07	0.2	55	
	20	35	65	–	0.065	0.2	55	
	21	35	65	–	0.06	0.2	55	
VIII	22	40	60	–	0.07	0.2	55	
	23	40	60	–	0.065	0.2	55	
	24	40	60	–	0.06	0.2	55	

I – ○ – 25 % C + 70 % S + 5 % L + 55 % W;
II – □ – 30 % C + 65 % S + 5 % L + 55 % W;
III – △ – 35 % C + 60 % S + 5 % L + 55 % W;
IV – ◇ – 40 % C + 55 % S + 5 % L + 55 % W;

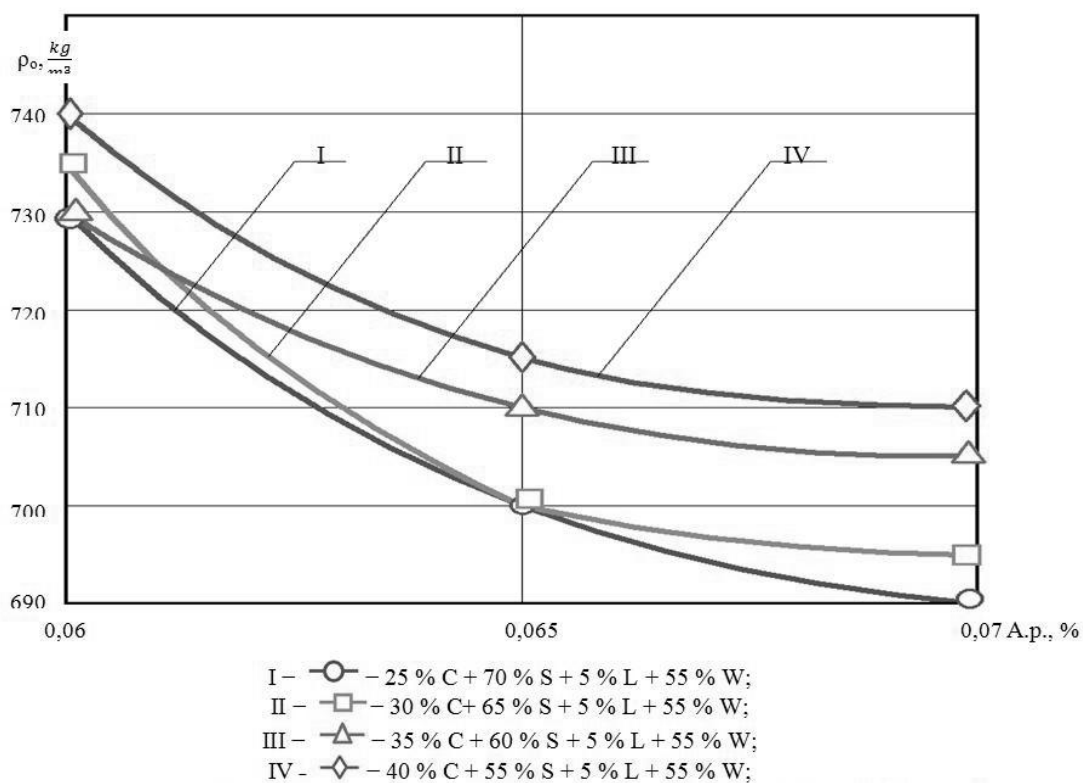**Fig. 8.** Dependence of average density of cellular concrete
(with lime without additive LST) on the concentration of aluminum powder

I – ⬡ – 25 % C + 70 % S + 5 % L + 55 % W;
II – ⬜ – 30 % C + 65 % S + 5 % L + 55 % W;
III – △ – 35 % C + 60 % S + 5 % L + 55 % W;
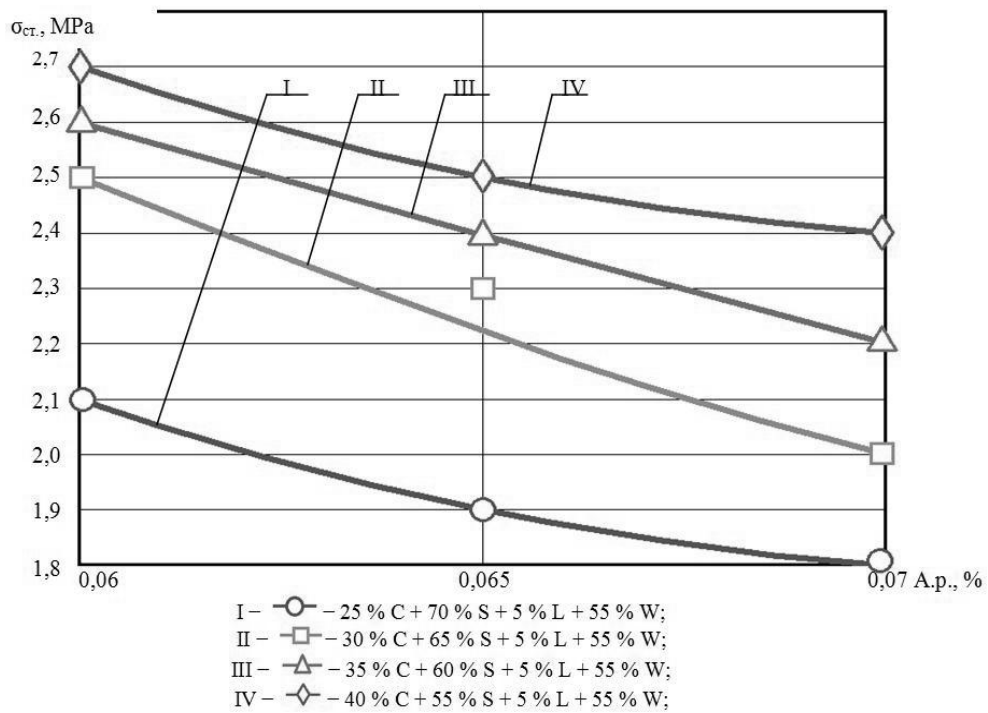IV – ◇ – 40 % C + 55 % S + 5 % L + 55 % W;

Fig. 9. Dependency of compressive strength of cellular concrete
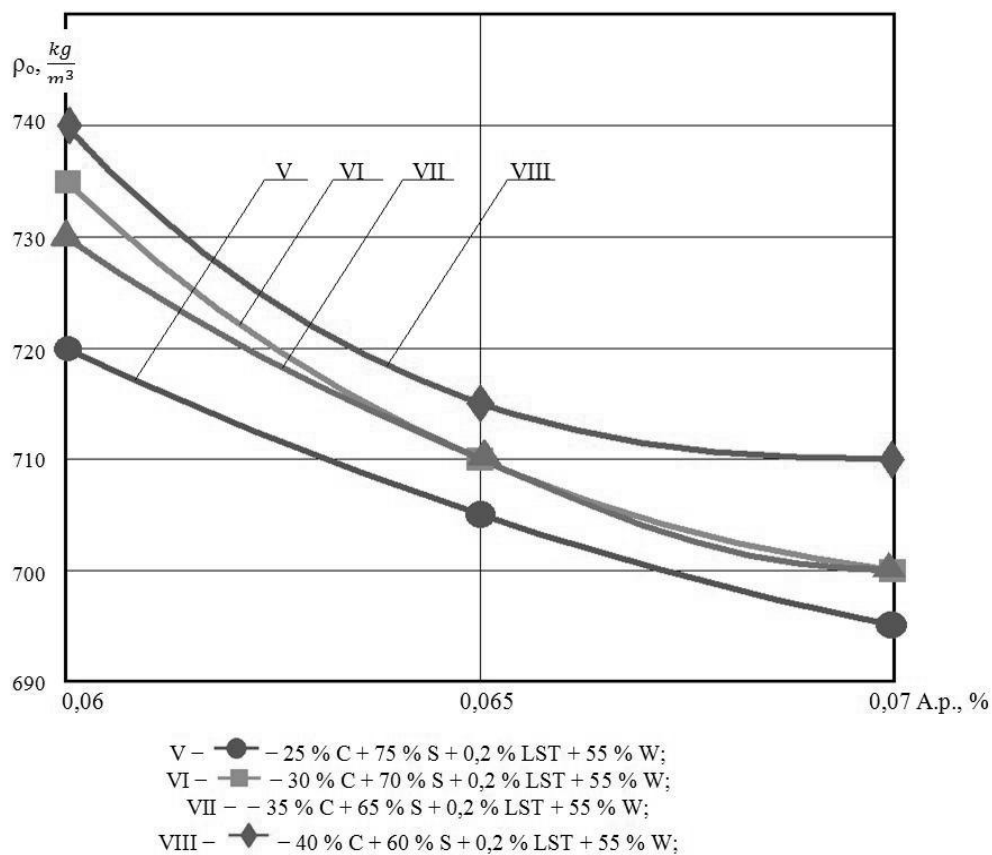(with lime without additive LST) on the concentration of aluminum powder

V – ⬤ – 25 % C + 75 % S + 0,2 % LST + 55 % W;
VI – ⬛ – 30 % C + 70 % S + 0,2 % LST + 55 % W;
VII – – 35 % C + 65 % S + 0,2 % LST + 55 % W;
VIII – ◆ – 40 % C + 60 % S + 0,2 % LST + 55 % W;

Fig. 10. Dependence of average density of cellular concrete
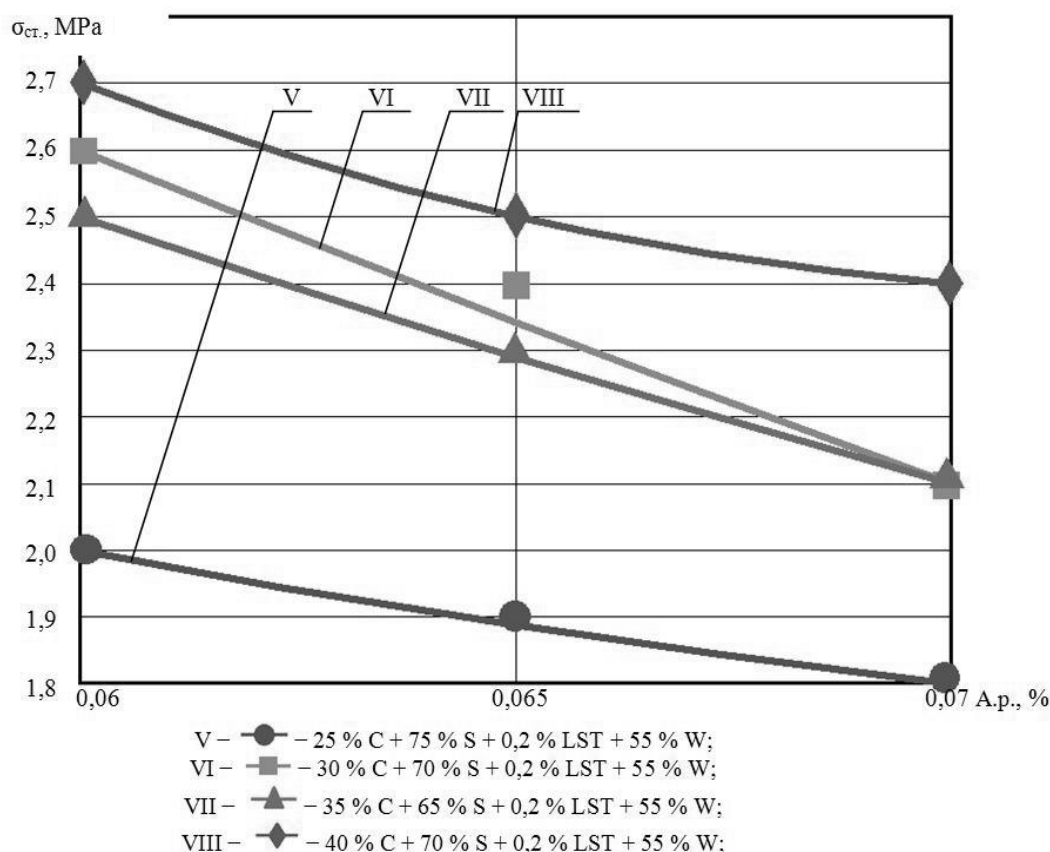(with additive LST without lime) on the concentration of aluminum powder

Fig. 11. Dependency of compressive strength of cellular concrete (with additive LST without lime)
from the concentration of aluminum powder

As can be seen in Fig. 10, at the same as the previous concentration of aluminum powder (0.065 %), the two series of concrete specimens have the same average density: series VI - compositions No. 16–18 (Table 3) and series VII - compositions No. 19–21 (Table 3). Concrete No. 17 has higher compressive strength (■ − 30 % C + 65 % S + 0.065 % AP + 0.2 % LST + 55 % W) (this is why it is optimal for concrete concentrations with the addition of LST without lime) – 2.4 MPa (Fig. 10). Concrete of composition No. 20 (▲ − 35 % C + 65 % S + 0.2 % LST + 55 % W) has a compressive strength of 2.3 MPa (Fig. 11).

Cellular concrete of optimal concentrations (No. 5 and No. 17) belong to a structural and thermal insulation type (Table 3 [25]).

Based on the Protocol of radiation quality prepared by the Laboratory of Electromagnetic Fields and Other Physical Factors of the Department of Physical and Chemical Factors Research (Mariupol), the blast furnace slag of PJSC "Mariupol Iron and Steel Works" [26] belongs to Class I [26]. According to the content of natural radionuclides, the total specific activity of the investigated samples does not exceed 370 Bq/kg, which

meets the requirements of paragraph 8.5.1 of the "NRBU-97 Radiation Safety Standards of Ukraine". Therefore, this material can be used in construction without any restrictions.

Conclusion

The ecological efficiency of the production of blast furnace granulated slag instead of blast furnace dump slag contributes to the elimination of slag dumps and releases the areas of useful land (thereby reducing the environmental burden in metallurgical production regions). For the conditions of the enterprise of JSC Mariupol Metallurgical Plant, the absence of dumps reduces gross dust emissions into the atmosphere by tens of tons per year.

The advantages of using blast-furnace slag (BFS) in the field of environmental protection are the possibility of restoring BFS in the production of cellular concrete and the low cost of materials based on this waste.

By the negative impact on the environmental objects, blast furnace slag belongs to hazard class IV (low-risk); by the content of natural radionuclides in it, it belongs to class I (use in construction without restrictions).

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