Geoecoprotective Screens for Road Construction and Operation in Cold Regions

Maria Shershneva, Antonina Sakharova and Ivan Kozlov

Abstract The intensive development of highways leads to the natural system pollution by hazardous substances such as heavy metals and oil products. At the same time, wastes are accumulated and stored in the metallurgical industry, which has a negative impact on environment. The purpose of the work is to study the applicability of the metallurgy waste for transport construction to minimize the negative impact of polluted roads on the environment in cold regions. The task of the work is using of the metallurgical wastes properties in geoecoprotective technological solutions in road construction and operation. Blast-furnace metallurgical slag was chosen as the object of study. IR spectrometry, atomic absorption photometry, and PQ analysis methods were used to study the properties of this slag. The article presents data on the degree of road pollution and on geoecoprotective capacity of blast-furnace metallurgical slag against heavy metal ions. The authors have proposed the technological solutions for using of blast-furnace metallurgical slag in transport construction and reconstruction, including the effective life calculation during their operation. There are two geoecological problems being solved for cold regions: utilization of metallurgical wastes and the use these wastes for soil cleanup and treatment of runoff containing heavy metal ions.

Keywords Geoecoprotective screens · Road construction · Blast-Furnace metallurgical slag · Highways · Heavy metal ions · Local treatment plants

1 Introduction

Surface runoff is the most susceptible to pollution during the construction and operation of roads. It is formed by rain and snow melting. Surface runoff contamination in cold regions depends on many factors, which can be grouped into the following groups: climatic conditions, sanitary state of the drainage area and ground-level air, and hydrogeological regularities of surface runoff movement over the land topog-

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Table 1 Pollutants concentrations in the surface runoff

Road category	Runoff type	Pollutants concentration (mg l^{-1})		
		Iron ions	Lead ions	Oil products
I	Rainfall runoff	0.90	0.28	24
	Snowmelt runoff	0.93	0.30	26
II	Rainfall runoff	0.78	0.22	19.2
	Snowmelt runoff	0.80	0.24	20.8
III	Rainfall runoff	0.56	0.16	14.4
	Snowmelt runoff	0.60	0.18	15.6
IV	Rainfall runoff	0.43	0.11	9.6
	Snowmelt runoff	0.45	0.12	10.4
V	Rainfall runoff	0.30	0.08	7.2
	Snowmelt runoff	0.33	0.09	7.8

raphy and in the catchment area [1–4]. The main pollutants of surface runoff from highways are dissolved oil products and heavy metal ions (HMI) [5–8]. Table 1 shows data on the pollution degree of surface runoff depending on the road category.

Many measures are performed for reducing pollutants concentrations in surface runoff. The main ones are as follows: the organization of regular mechanized site cleanup, timely repair of roads pavement, the fencing of landscaping zones by borders, etc. In cases, when stormwater treatment is necessary, the entire wastewater volume should be directed to local treatment plants. The efficiency of local treatment plants can be increased by applying cheap and effective materials for pollutants neutralization.

Polluted runoff from roads is collected in roadside trays, ditches and closed sewers, located in the lower roads sections. There are several methods of surface runoff diversion from road:

- runoff spontaneously flows from road surface and is discharged from the shoulders along slopes, side channels for drainage systems, or cuvettes;
- runoff flows from road pavement into special trays for water collection. A reinforced drainage ditch is a place for surface water collection and an intermediate point before the treatment plants or land topography;
- runoff is collected in open types of trays located along the curbs on opposite sides of the road in order to subsequently get into the drainage ditch;
- urban runoff flows into the municipal surface sewage collection system.

2 Objects and Research Methods

The object of the research was selected granulated blast-furnace slag, which is waste of metallurgical production in Russia including cold regions. About a ton of slag is formed for each ton of metal when smelting iron and steel. Rapid cooling (granulation) contributes to the detection of glass in the slag, the content of which is up to 80% by mass or more. The gelenite, monticellite, spinel and other silicates, aluminates, and aluminum silicates of Ca and Mg are in the crystalline component [9, 10]. The authors consider the blast-furnace granulated slag of the Cherepovet's Metallurgical Combine. This slag has an amorphous structure. It contains C_2S and a small amount of iron and manganese compounds. Table 2 presents the approximate chemical composition of the slag.

Atomic absorption method was used for investigation of the sorption characteristics of blast-furnace slag against heavy metal ions. The control over the water treatment degree from heavy metal ions was carried out on an atomic absorption spectrometer (AAS) of the Perkin–Elmer company (USA), model PE-305. It is designed for concentration determination through the monochromatic light absorption by element steam. The wavelength of the light corresponds to the center of the absorption line. AAS PE-305 allows determining more than 30 elements in the analytical laboratories conditions for solving ecology, agrochemistry, biology, medicine, geology, metallurgy, chemistry problems, and scientific research.

Laboratory infrared Fourier spectrometer (FSM) was used for investigation of the sorption characteristics of slag against oil products. It is intended for recording and studying optical spectra in the infrared (IR) region, as well as for environmental control, forensic, and other types of examinations.

PQ method was used for quality assessment of the proposed technological solutions. The PQ method allows evaluating not only the geological aspects of technological solutions, but also the economic and operational aspects, which are summarized then. The results of this method are the higher the index value, the higher the quality of the proposed technological solution.

The capacity (mg g-1) is the main value characterizing the geoecoprotective properties of slag to absorb heavy metal ions. It shows the mass of pollutants (mg) absorbed by one gram of slag [11–14].

Capacity was determined against various HMI and was calculated by the formula 1:

$$a = \frac{(C_i - C_r)V}{m} \tag{1}$$

Table 2 Chemical composition of the slag, mass%

Oxides content (mass%)					
SiO_2	Al_2O_3	Fe_2O_3	CaO	MnO	MgO
41.92	6.6	0.33	44.8	0.9	2.38

where

a	capacity, mg g^{-1};
C_i, C_r	initial and residual concentrations of HMI in specimen, mg l^{-1};
V	specimen volume, l; and
M	slag mass, g

The treatment degree corresponded to the level of maximum allowable concentration (MAC) (for fishery water) for each metal. The capacity was determined under dynamic conditions: the treatment was carried out by filtration through the slag layer.

3 Research Results

First of all, researches conducted on the choice of the optimal grain size of the slag and the filtration rate of polluted water. Table 3 presents the results.

According to the experiment results on determination of dynamic capacity of the slag, a filtration rate of 6 m h^{-1} and 0.315–0.63 mm fraction size was chosen. For such conditions, the dynamic capacity of the slag was determined against various HMI (Table 4).

The dynamic capacity of slag was determined for each metal in the presence of the other two for investigation of slag ability to sorb the several heavy metal ions simultaneously. Table 5 demonstrates the research results.

The data from Table 4 confirm that selective sorption is not observed for any selected metals during simultaneous presence of all metal ions in the solution. The capacity for each metal has significantly decreased.

Table 3 Data on the choice of slag grain size and filtration rate

Grain size, mm	Filtered solution volume before breakthrough at the MAC (l)			
	Filtration rate (m h^{-1})			
	1	3	6	9
0.114–0.315	23	22	22	–
0.315–0.630	23	22	22	21
0.630–1.25	10	6	5	5
1.25–2.5	8	5	4	3
2.5–5.0	5	3	3	2

Table 4 Dynamic capacity of the slag (mg g^{-1})

HMI					
Mn^{2+}	Fe^{3+}	Ni^{2+}	Pb^{2+}	Cd^{2+}	Cr^{3+}
0.65	0.9	0.5	0.75	0.85	1.10

Table 5 Absorption research results

Sorbent	Dynamic capacity for each metal in the presence of two other (mg g^{-1})		
	Mn^{2+}	Fe^{3+}	Cr^{3+}
Slag	0.23	0.44	0.52

Table 6 Study results of exchangeable ions in the filtrate

Sorbent	Concentration of exchangeable metal ions (mg l^{-1})					
	Background content			HMI filtration		
	Ca^{2+}	K^+	Na^+	Ca^{2+}	K^+	Na^+
Slag	2	2	0.5	9.8	2.0	0.5

There studies were conducted on identification of exchangeable ions in the filtrate to explain the sorption mechanism. It was found that during water passes through the slag, calcium ions are washed out to water (Table 6).

The strength of formed bonds between the sorbent and HMI can be determined by «washing out» the ions into the aquatic medium from its surface. For this purpose, the slag was previously saturated by iron ions. Then analysis of slag aqueous extract was carried out (Table 7).

The research results shown in Table 6 exclude the possibility of HMI elution from sorbent surface.

Study of the sorption process in the simultaneous presence of water pollutants of various nature (organic and inorganic) is important for practical purposes. Studies on determination of sorbents sorption capacity have been conducted during simultaneous presence of HMI and dissolved oil products in water, as previous experiments have shown that the tested sorbents do not have selectivity for HMI sorption. There for model solution contained ions only one metal (manganese ions) with a concentration of 10 MAC and dissolved oil products with a concentration of about 2 mg l^{-1}. The breakthrough was taken as the concentration of HMI and dissolved oil products at a level which corresponds to the MAC. The research results showed that sorbents capacity for manganese during the presence of dissolved oil products in model solution is not decreased. These results indicate that HMI sorption does not depend on presence of organic pollutants in water. The research results allow proposing technological solutions for the use of blast-furnace metallurgical slag during highway construction and reconstruction in cold regions [15–19]:

Table 7 Analysis results of aqueous extract

Waste name	Fe (III) concentration in the aqueous extract (mg l^{-1})	Ca (II) concentration in the aqueous extract (mg l^{-1})
Slag	–	0.5–0.8

- firstly, granulated blast-furnace slag can be part of earth roadbed. In this case, HMI entering through surface runoff from road pavement will be neutralized in the earth roadbed;
- secondly, blast-furnace granulated slag can be used in gabion construction, which is applied in road construction for slope reinforcement or in treatment facilities.

The calculation of granulated slag effective life in the earth roadbed or gabion constructions was made on 5 km of category I road for conditional pollution by HMI with 10 MAC concentration.

Average width of this category road is up to 22.5 m, taking into account shoulder width (3.75 m), which is also subject of HMI pollution. The total pollution area of 5 km of the road is calculated by the formula (2):

$$S_p = l \cdot m, \tag{2}$$

where

S_p pollution area, m^2;
L road segment length, m;
M road segment width, m; and

$$S_p = 5000 \cdot 30 = 150,000\,\text{m}^2$$

The average annual rainfall for the North-West region is 500 mm per year. The precipitation volume, discharged on average per year from the surface of road segment, can be calculated by the formula (3):

$$V = S_p \cdot 0.5, \tag{3}$$

where

S_p pollution area, m^2;
0.5 average annual rainfall, m/year

$$V = 150,000 \cdot 0.5 = 75,000\,\text{m}^3/\text{year}$$

It was chosen the MAC for lead (0.001 mg l^{-1}) for effective life calculation. Lead ions concentration in runoff was taken 0.28 mg l^{-1} (0.28 g m^{-3}) from Table 1.

The total mass of pollutants discharged from the estimated road segment per year is calculated by the formula (4):

$$m = V \cdot 0.28, \tag{4}$$

where *m*—the lead ions mass in runoff from the estimated road segment, g/year.

$$m = 75,000 \cdot 0.28 = 21,000\,\text{g/year}$$

Rains with an intensity of 7–12 l s^{-1} per 1 ha for 20 min almost completely flush all pollutants from catchment surface. Also, taking into account the snow removal during the winter period, the mass of lead ions entering gabion constructions can be up to 10% of the calculated (2100 g/year).

The lead mass that can be neutralized by blast-furnace metallurgical slag is calculated by the formula (5):

$$m_{\text{Pb}^{2+}} = a \cdot m_{\text{III}}, \tag{5}$$

where

$m_{\text{Pb}^{2+}}$ lead ions mass, g;
a slag capacity, g kg^{-1}; and
m_{III} slag mass, kg

The weight of the used slag per 5 km will be 45,000 kg with 900 kg m^{-3} average density using up to 1 m^3 of blast-furnace metallurgical slag for every 100 m of road segment. The slag capacity for lead is 0.75 g kg^{-1} (Table 4).

$$m_{\text{Pb}^{2+}} = 45,000 \cdot 0.75 = 33,750\,\Gamma$$

Geoecoprotective material effective life can be calculated by the formula (6):

$$T = \frac{m_{\text{Pb}^{2+}}}{m}, \tag{6}$$

where T—geoecoprotective material effective life, years

$$T = \frac{33,750}{2100} = 16\,\text{years}.$$

The following factors should be taken into account when calculating the effective life:

- first, the slag volume can be significantly increased (up to 10–20 m^3 for every 100 m of the road). This can significantly increase geoecoprotective material effective life;
- second, the presence of other HMI will be reducing slag capacity (Table 5), which can decrease material effective life;
- third, the presence of suspended solids and film oil products in the surface runoff will be reducing the slag filtering capacity.

Therefore, the real effective life can only be determined on the results of monitoring the HMI concentrations in the surface runoff from specific road segment.

PQ method was used [20–24] to compare the proposed technological solutions for the application of granulated blast-furnace slag for surface runoff treatment from

Table 8 PQ index calculation results

Technological solutions	PQ indexes
Surface runoff purification in local sewage treatment plants	0.58
Surface runoff treatment using the slag in gabion constructions of road	0.73
Surface runoff treatment using slag in the composition of the earth roadbed	0.88

highways. The assessment was carried out on such aspects as geoecoprotective, technological, and operational. Technological solutions were compared with the applied technology for surface runoff purification in local sewage treatment plants. Table 8 presents the results.

A higher PQ index for the technological solution with the use of slag in the composition of earth roadbed is explained by the simplicity of this solution in the implementation. The low PQ index for the technological solution with the use of local sewage treatment plants is explained by the high cost of 1 m^3 surface runoff purification.

4 Conclusions

1. The use of granulated blast-furnace slag having geoecoprotective properties against heavy metal ions for highways construction in cold regions is proposed. It will allow simultaneously solving the problems of slag utilization and surface runoff treatment from highway.
2. Studies have shown that calcium ions are washed out from slag into the filtrate during HMI absorption. There is no leaching of absorbed metals into an aqueous solution from a saturated slag. There is no selectivity against various HMI, and there is no impact of organic pollutants on the slag capacity.
3. Granulated blast-furnace slag can be used for surface runoff treatment from the highway as part of the earth roadbed or in gabion constructions.
4. The approximate effective life of the blast-furnace granulated slag can be calculated using the formulas proposed in the article. The real effective life can be determined by monitoring the surface runoff composition near roads in cold regions.
5. The quality assessment of the proposed technological solutions using the PQ method has shown the advantage of using granulated blast-furnace slag as part of the earth roadbed.

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