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Water Quality Management at the Tailings Storage Facility of the Gaisky Mining and Processing Plant

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1. Introduction

Industrial enterprises of the commodity sector are the growth points that contribute to the economic and technological development (Litvinenko 2020). However, the environmental issues require detailed study (Bonotto et al. 2019, Safiullin et al. 2019, Végsöová et al. 2019) as the areas affected can become hotspots of engineering concern (Koptev et al. 2017, Nikolaevna et al. 2020). Extractive and processing industries produce mineral waste, stored in the dumps and tailings. Their long-term operation can result in the pollution of environmental components and cause additional spending on the elimination of the negative impact (Bazhin et al. 2016, Kruk et al. 2018, Nedosekin et al. 2019, Semyachkov et al. 2012).

The studied metallurgical enterprise performs underground mining of copper ore and its flotation concentration. Flotation is based on the differences in physicochemical properties of mineral surfaces (Abramov 1984, Krasotkina et al. 2017). The studied tailings of *the Gaisky Mining and Processing Plant* (Gaisky GOK) include a tailings pond, a pond of clarified water, and a pond of acid mine waters. Depleted pits of the Gai deposit are considered too, as one of the quarries is being reclaimed by filling with beneficiation waste (Aleksandrova et al. 2019). Enrichment tailings are mixed with acid mine waters in the main building of the factory and then pumped to the abandoned quarry and partly to the tailings storage. The tailings storage of the Gaisky GOK is a hydraulic-fill hill-type dam, put into operation in 1966 (Recommendations 1986). Its total area is approximately 190 hectares, the maximum storage capability is 52.5 million m^3.

The chief research objectives are assessment and reduction of the adverse impact of enrichment waste on natural waters as well as prevention of the loss of potential raw materials of technogenic deposits with the infiltration through dams and bases of waste storage.

2. Materials and methods

The waste of copper ore enrichment at the Gaisky GOK consists of ca. 315 mm-sized particles of waste rock in a mixture with water, which are being transported through the slurry pipeline and stored in the quarry No. 2, with a capacity of ca. 70 million m^3, and partially in the tailings storage. The composition of the liquid phase of the enrichment waste is presented in Table 1. The mineral composition of the tails is represented by pyrite, chalcopyrite, sphalerite, quartz, feldspar, chlorite, and sericite. Chemical composition: Fe_2S, $CuFeS_2$, ZnS, SiO_2, aluminosilicate mixtures, and hydrochloric acid salts.

Table 1. Alkalinity level and composition of the liquid phase of tailings, mg/dm^3

Parameter	Value	Parameter	Value
Solids	5096-5230	Sodium	450-650
Suspended matter	up to 300	Potassium	45-68
Petroleum products	0.25-4.15	Magnesium	2-848
Chlorides	468.9-587.6	Iron	0.01
Sulphates	1777.2-2559.0	Copper	0.04-4.65
Hydrocarbonates	14.48	Zinc	11.8
pH up to 11.95			

In accordance with the Goldschmidt geochemical classification of elements, tailings contain mainly chalcophile elements that are being washed out of the tailings and quarry can lead to pollution of natural waters (Brysiewicz et al. 2019, Bushuev et al. 2018, Zubala 2019). In order to confirm or refute this, samples of groundwater and surface water in the area of the tailings pond, recycled water at the concentrator, and from the sedimentation pond and the acid mine pond were taken and analyzed. The sampling points are shown on the schematic map (Fig. 1).

Surface water was taken from the bordering Yalangas watercourse, 1 km North-West of the tailing dump. In total, two samples were taken: 500 m upstream from the tailing dump (sample A) and 500 m downstream (sample B). Samples were also taken from 3 observation wells. Sampling conditions were chosen in accordance with the GOST 31861-2012. The samples were analyzed in the laboratory of the Saint Petersburg Mining University. The cationic composition was determined using the Shimadzu ICPE-9000 analyzer; anions were found with the DR-5000 spectrophotometer.

Fig. 1. Schematic map of the study area

3. Results and discussion

The presented graphs (Fig. 2a and 2b) show that the concentrations of Fe, Mg, Mn, and Na exceed the MPC according to the GN 2.1.5.1315-03 in the samples taken downstream of the tailing dump. The specific combinatorial pollution index was calculated for the Yalangas river as well. The value of 5.84 characterizes the water quality as "low" (class 4A) in accordance with the RD 52.24.643-2002.

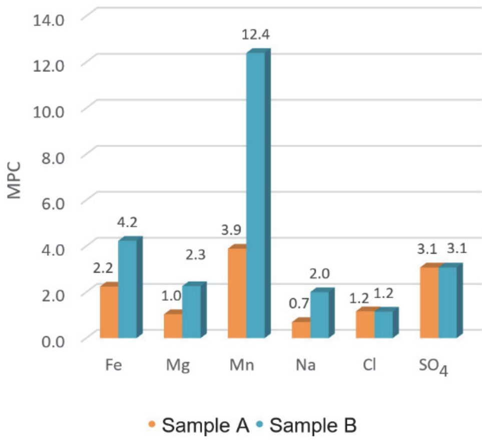

Fig. 2a. Surface water composition

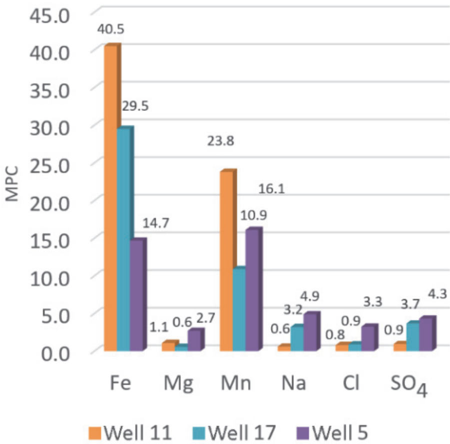

Fig. 2b. Groundwater composition

Based on the data presented, it was concluded that the operation of the tailing dump harmed surface and groundwater in its vicinity (Bolshunova et al. 2017, Gałuszka et al. 2018, Sliti et al. 2019, Yusupov & Karpenko 2016). The research conducted by A.G. Talalay, A.B. Makarov, and B.B. Zobnin, allow considering the tailings of copper ores as technogenic deposits (Makarov 2000).

Processing wastes were sampled; particle-size distribution and chemical composition were determined. Following the storage scheme at the enterprise, it was decided to take samples at the tailings dump site, as they have the average composition. First of all, particle-size distribution was analyzed by the sieve method, the results of which identified 4 grades (Fig. 3.)

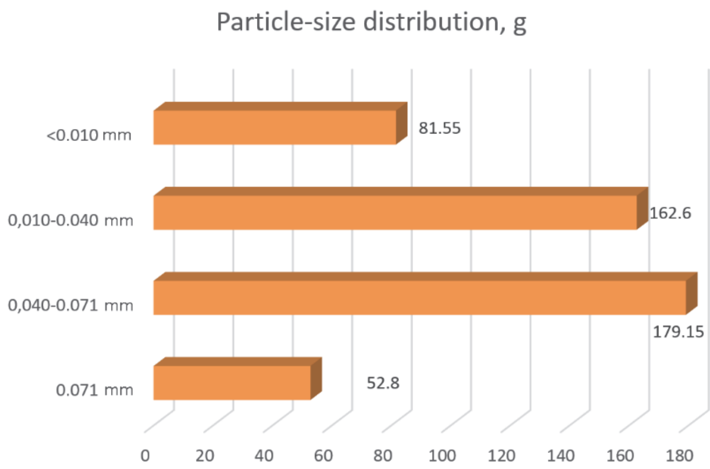

Fig. 3. Particle-size distribution of the studied tailings samples

The graph shows that the predominant size grade is 0.071-0.040 mm, its weight in the sample of 500 g is 179.15 g (35.83%), followed by a class of 0.040-0.010 mm – 162.6 g (32.52%), < 0.010 mm – 81.55 g (16.31%) and > 0.071 mm (10.56 %).

The X-ray fluorescence analysis was carried out for each size grade, in order to determine the component composition of the tails. The results are presented in Table 2.

The gross content of the components (Table 3) was consequently determined using an emission spectrometer with inductively coupled plasma Shimadzu ICPE-9000.

Table 2. Chemical composition of the tailings by size grades, %

Particle-size grade, mm							
>0.071		0.071-0.040		0.040-0.010		<0.010	
Component	%	Component	%	Component	%	Component	%
SiO_2	52.8516	SO_3	31.8341	SO_3	42.2181	Fe_2O_3	29.2247
SO_3	16.9446	Fe_2O_3	30.9487	Fe_2O_3	37.5378	SO_3	28.8020
Fe_2O_3	15.0397	SiO_2	28.4495	SiO_2	14.6119	SiO_2	27.4349
Al_2O_3	8.1800	Al_2O_3	4.4016	Al_2O_3	2.7871	Al_2O_3	8.4635
MgO	2.2164	MgO	1.2698	MgO	0.9711	MgO	2.5597
CaO	1.6646	Na_2O	0.9910	Na_2O	0.7139	Na_2O	1.3656
Na_2O	1.5894	CaO	0.9005	ZnO	0.2994	K_2O	0.6664
K_2O	0.6667	ZnO	0.2948	CaO	0.2564	CaO	0.3963
TiO_2	0.4314	K_2O	0.2627	CuO	0.1996	ZnO	0.3454
ZnO	0.1370	TiO_2	0.2460	TiO_2	0.1655	TiO_2	0.3317
CuO	0.0871	CuO	0.2288	K_2O	0.1351	CuO	0.2081
P_2O_5	0.0810	P_2O_5	0.0479	P_2O_5	0.0538	P_2O_5	0.1008
MnO	0.0656	PbO	0.0403	BaO	0.0282	MnO	0.0460
BaO	0.0340	MnO	0.0327	As_2O_3	0.0224	BaO	0.0338
As_2O_3	0.0109	BaO	0.0305			As_2O_3	0.0210
		As_2O_3	0.0212				

Table 3. Bulk concentrations of major polluting elements

Particle-size grade, mm	Component						
	Cu	Fe	S	Zn	Pb	Au	Ag
	kg/t					g/t	
<0.010	5.3565	284.9950	255.9624	3.3500	0.4315	n. d.	3.95
0.040-0.010	5.4065	437.9950	462.9624	3.0300	0.1925	0.0766	2.84
0.040-0.071	4.9565	356.9950	377.9624	2.3400	0.1385	0.0541	1.88
>0.071	1.9665	179.9950	174.9624	2.0800	0.0990	0.0313	1.04

As a result of moisture infiltration into the aquifer, such valuable components as copper, zinc, silver, and gold, and such dangerous as sulfur can migrate (Bonotto & Garcia-Tenorio 2019, Kasimov et al. 2016, Yusupov et al. 2017, Zhang et al. 2018). It should be taken into account that tailing dumps are the facilities designed for storing industrial waste, while quarries are not specially prepared for that (Kremcheev et al. 2018, Nagornov et al. 2019). This is a relatively new trend. The sides of the quarry are composed of different-sized rocks, which is a factor of increased filtration. It is necessary to conduct observations of groundwater and surface water in the quarry area, taking into account the peculiarities of the existing natural and man-made geosystem (Pochechun et al. 2014). As a result of this work, it was concluded that the waterproofing insulation of the tailings is feasible for two reasons (Bortnikov et al. 2014, Coulombe et al. 2012, Krzaklewski & Pietrzykowski 2002, Wang et al. 2017, Zhao et al. 2011):

- reduction of negative load on groundwater and surface water,
- preservation of useful components for future use of enrichment waste as a technogenic deposit.

In this regard, in order to preserve the technogenic deposit of the Gaisky Mining and Processing Plant (Gaisky GOK) and reduce the environmental load on underground and surface water, a waterproofing technology was developed. As of today, various waterproofing techniques are used, the choice of which depends on the set of waste parameters and materials used (Dos Santos & Gardoni 2014, Lee & Shang 2013, Weishi et al. 2018, Zhu et al. 2015). Analysis of methods of waterproofing allows us to identify the main of them, applied to increase the groundwater protection efficiency:

- based on natural materials (clay, loam),
- based on polymeric materials (geomembranes, geomats),
- based on waste oil products.

Application of natural clays as a waterproof layer is extremely time-consuming: the volume of the applied material should be from 0.35 to 1.0 m^3/m^2; pre-treatment is required before application. Clays of the protective layer are exposed to infiltrating aggressive waste. As a result of the impact the structure of a protective layer changes with the further dissolution of argillaceous minerals both in an acid and alkaline environment. The initial clay strength is reduced, and the risk of waste infiltration into the groundwater increases.

Waterproofing of constructions using geomembranes is a very laborious method, as well as expensive: the price per square meter of a geomembrane can reach ca. 12 USD in Russia. Moreover, the stitching of finished sheets creates seams that pose a threat to the coating integrity, which is absolutely unacceptable. Toxicity and destruction under the influence of aggressive media are the disadvantages of insulation with waste oil products.

Following the review results, granules of secondary polyethylene of low and high pressure and polypropylene were chosen as the materials for the study.

Low-density polyethylene (LDPE) is a waxy material of unexpressed color, obtained industrially by the polymerization of gaseous polyethylene. LDPE is a thermoplastic polymer with a density of 910-930 kg/m^3. The literature review shows that this polymer has relatively high reliability at the break, resistance to multiple bending, impact, and low temperatures.

High-density polyethylene (HDPE) is a less waxy polymer than LDPE, resistant to fats and oils, but subjected to impact and bending. The values of resistance to compression and stretching of LDPE and HDPE are comparable. The density of HDPE is 940-960 kg/m^3.

Polypropylene (PP) is a linear polymer obtained during the propylene polymerization in the presence of catalysts. The density of polypropylene is 900-920 kg/m^3. It is highly resistant to the impact but can be destroyed by multiple bending and under low temperatures.

Secondary polyethylene and polypropylene pellets are products of recycling of used polymers. The physical and mechanical properties of these polymeric materials and their products determine their behavior as a result of external loads. The determination of these properties on a trial basis allows identification of the dependence of stresses on deformation (tensile diagram). The dependence analysis allows finding the main parameters of elasticity, strength, and plasticity (modulus of elasticity, fracture resistance, and ultimate strength). Physical and mechanical properties of polymers have a number of features as compared to non-plastic materials (Lyamkin 2000):

- ability to develop large reversible deformations (hundreds or even thousands of percent),
- relaxation patterns, i.e. the ratio of strain and stress for the impact duration,
- dependence of physical and mechanical properties on the conditions of its manufacture, processing, and preliminary changes (due to the different types of supramolecular structure with a long period of rearrangement).

To determine the dependence of the physical and mechanical properties of the materials on the manufacturing temperature, a step equal to 10°C and an interval from 160 to 230°C were chosen. The total number of plates for finding strength under tensile loads of polymers was 63. Figures 4a, 4b, and 4c reflect the dependence of changing polymer strength on the temperature. The results of this experiment allow us to draw the following conclusions:

- the strength of samples processed at different temperatures does not change linearly,
- the value of the tensile strength of polymers at temperatures commensurate with the melting point is not the greatest. This is due to incomplete homogenization of the material, the presence of excessive moisture and volatile impurities,
- the temperature range of 185-195°C for polymeric material processing is the optimal,
- the decrease in the strength of the test samples at temperatures above 200°C is determined in connection with thermal and thermo-oxidative destructive processes.

The developed waterproofing technology suggests applying the polymer granules processed by melting to the prepared surface. The surface is anticipatorily prepared by cleaning from large rock debris, roots, etc. The prepared layer is consequently leveled with a layer of clay, 20-40 centimeters-thick. Then sand of medium particle-size with a thickness of 15-20 centimeters is applied, this minimizes the load on the clay horizon during the laying of the polymer material.

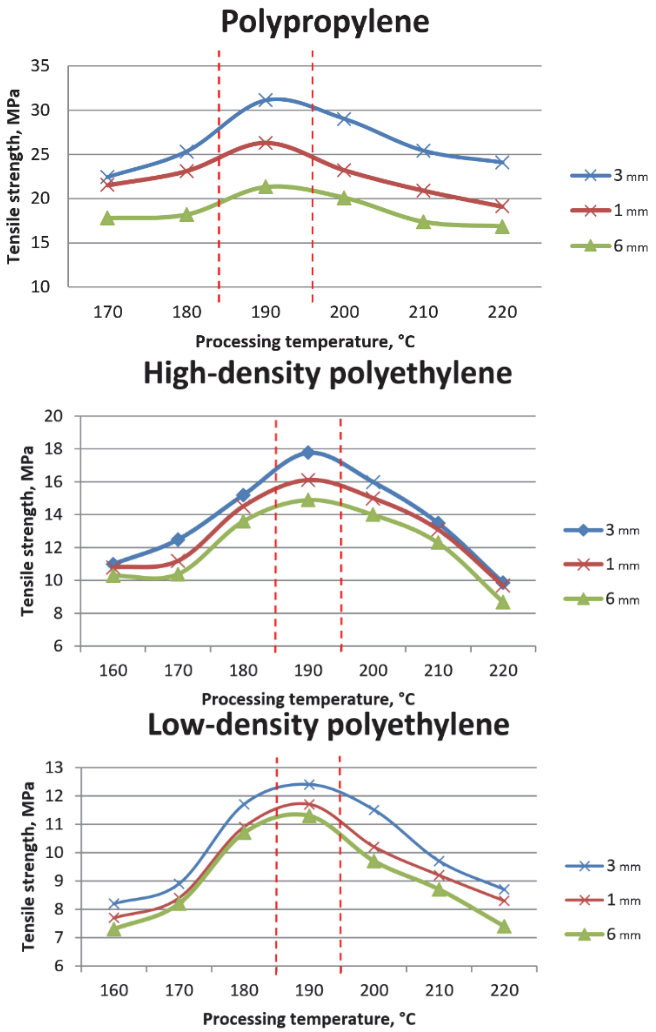

Fig. 4 (a, b, c). Dependence of strength properties of polymer samples on the ambient temperature

The mixture of polymers is extruded onto the prepared layer at a temperature of 185-195°C, after cooling the surface, a drainage layer of coarse-grained material (sand) with a thickness of 10-15 centimeters is applied. The drainage layer of the collecting and irrigation systems is developed afterward. The mixture is prepared at the place of its application, loaded into the hopper of the extrusion machine, where it is subjected to electro-thermal heating to a melting point of 185-195°C. After that, the molten mixture is applied to the prepared surface in strips of 2.0-2.5 m, with a mutual overlap of 0.15-0.20 m by means of screw feeding to the extruder. Overlapping of the stacked polymer mixture strips will improve the integrity of the entire coating, as well as eliminate the need for the coating stitching, as in the case of geomembranes.

The main operation issue of such a screen is the impact of static and dynamic loads and aggressive environment (acidic or alkaline), which leads to fairly rapid, within few years, deterioration of the strength properties of polymer screens, and their consequent destruction. The blending of additives into the polymer, as well as the application of a coarse sand layer, are the relevant solutions since the layer distributes the load from the tailings body and does not violate the integrity of the polymer material properties.

4. Conclusions

The conducted research has confirmed that the long-term operation of the tailings leads to contamination of groundwater and surface water. The study of enrichment waste samples showed that the concentration of useful elements allows considering the tailings as a technogenic deposit. The physical and mechanical properties of secondary polymers under tensile loads were determined. The tested protective approach suggests applying the polymer granules processed by melting to the prepared surface. The developed waterproofing technology reduces the negative impact on natural waters, as well as preserves raw materials for potential further secondary extraction.

The analyses were performed using the equipment of the Common Use Centre of the Saint Petersburg Mining University. Author Contributions: Babenko D.A. – resources, methodology, investigation, writing – original draft preparation; Pashkevich M.A. – supervision, project administration, writing – review and editing; Alekseenko A.V. – translation, data curation, conceptualization, validation, formal analysis, visualization, software.

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Abstract

The paper justifies the waterproofing technology for waste storage conservation. The paper presents the results of full-scale monitoring of the quality of surface and groundwater affected by the tailings of the Gaisky Mining and Processing Plant. The determined chemical composition of enrichment waste is described. The existing methods of waste storage waterproofing are reviewed. The studied residuals of copper ore enrichment can be insulated with a mixture of processed secondary polyethylene and polypropylene pellets. The physical and mechanical properties of recycled polymers are investigated. The proposed technology of covering with a waterproofing coating can be applied to preserve technogenic deposits aiming at their future secondary extraction, as well as to ensure the environmental safety of newly designed facilities. The implementation of this technique will improve the regional environmental situation and reduce the migration of potentially hazardous substances as a result of seepage, thus reducing the pollution of natural waters.

Keywords:
ore dressing waste, tailings storage, adverse impact, secondary polymers, waterproofing