Application of polymeric materials for abating the environmental impact of mine wastes

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Abstract. Insulation methods, helping to prevent the negative environmental impact of mine dumps, tailings and other waste storages, are considered and their drawbacks are revealed. The proposed two ways of environmentally sound and cost-effective preserving are described. The first approach is to form polymeric screens over the waste surface, as well as under a storage facility. The conducted experiments included the investigation of changes in physical and mechanical properties of polymers depending on their processing temperature. To study the suitability of low-density polyethylene, high-density polyethylene and polypropylene, the damage to the coating structure integrity as a result of normal load application is assessed. The second approach is to cover slopes of the dumps with a three-dimensional erosion control mat. The subsequent hydroseeding allows ensuring complete coverage and high strength of the slope surface in a short time and at the lowest cost. In order to prevent mine dump erosion and minimise associated costs, the analysis of key properties was performed. It was revealed that polypropylene and polyester used as a geonet are characterised by the lowest volume of fertile soil needed to cover.

1. Introduction

The necessity to investigate possible ways to cover the dumps was revealed according to the notion of landscape disturbance under the impact of mining and processing industry [1, 2, 16, 17]. The assessed methods of abating the environmental impact of mine wastes were determined by the local factors of chemical element migration and accumulation: geomorphological structures of urban area and types of land use [26-36]. Monitoring research in Novorossiysk city revealed that the change of these factors had caused a significant redistribution of chemical elements and their maximal accumulation in soils of residential areas [8]. Pollutants are brought into the soil directly from the source of contamination, as well as due to the migration from landscapes located hypsometrically above [11, 18, 20, 21]. Due to the listed conditions, the need to indicate a long-term, commercial, and environmentally-friendly dump reclamation and insulation technique emerged. Secondary granulated polyethylene of low density (LDPE) and high density (HDPE), as well as polypropylene (PP), were used as the studied materials. Thus, two methods of applying polymeric materials were tried: insulation by LDPE, HDPE and polypropylene plastic wastes and soil stabilisation by a three-dimensional erosion control mat [5, 9, 13, 15, 22, 24].

The choice of materials is determined by both economic (cost of polymers, market saturation and availability) and environmental factors (safety for the natural environment) [3, 6, 10]. The cost of one kilogram of granular polymers is in the range of 30–40 rubles.

Low-density polyethylene (LDPE) is a colourless wax-like material, which is industrially obtained by polymerisation of gaseous polyethylene. LDPE is a thermoplastic polymer with a density of 910-930 kg/m³. According to the published data, such polyethylene has a relatively high tensile strength, strength at multiple bending, impact strength and resistance to low temperatures.

High-density polyethylene (HDPE) is a less wax-like material characterised by high resistance to fats and oils, low resistance to shock load and strength at multiple bending. Resistance to compression and stretching is comparable to the levels of LDPE; the density is 940–960 kg/m³.
Polypropylene (PP) is a linear polymer obtained by polymerisation of propylene in the presence of catalysts. The density of polypropylene is 900–920 kg/m$^3$. It is characterised by high resistance to shock load, low strength at multiple bending; PP becomes brittle at negative temperatures.

2. Methods

Physical and mechanical properties of polymer materials and their products are a set of properties that characterise their behaviour under the influence of external mechanical loads. Such properties of polymers are determined in the course of tests, the result of which is the revealed dependence of stresses on deformation (e.g. a tensile diagram). Analysing these dependencies, the main characteristics of elasticity, strength and plasticity (modulus of elasticity, fracture resistance, ultimate strength) are found.

Compared with non-plastic materials, the physical and mechanical properties of polymers have a number of features [19]:

- the ability to develop large reversible deformations, reaching hundreds or even thousands of percent;
- relaxation properties, i.e. the dependence of strains and stresses on the duration of an external action;
- the dependence of the physical and mechanical properties of the polymer on the conditions of its production, processing and pre-treatment, which is determined by the existence of various supra-molecular forms with the long adjustment time in polymers;
- the ability of polymers to acquire a sharp anisotropy of properties under mechanical action due to the orientation of macromolecules;
- the ability to undergo chemical transformations under the mechanical impact, e.g. the development of destruction processes.

In all cases, it is necessary to know what requirements the finished product must meet when producing insulation coatings from polymeric materials. The insulation coating for mine waste must have a number of very specific properties:

- the created coating should have high strength characteristics since the mass of the ore stack is over 300 thousand tonnes, which determines the high static load on the polymer material laid in the base;
- the polymer coating must be resistant to aggressive media, as it is exposed to an alkaline solution under the process of leaching;
- the strength of the coating, under the influence of a significant temperature difference (from $-30$ to $+30$ °C), should remain unchanged.

After analysing a number of research outcomes [2, 7, 14, 23], it can be concluded that the structure of polymeric materials is determined by two main levels: molecular and supra-molecular.

At the stage of polymer synthesis, its molecular structure is formed. By varying the polymerisation conditions (pressure, temperature, etc.), it is possible to regulate the molecular weight of the polymer. The supra-molecular structure is formed at the stage of semi-finished product processing into the finished one. Types and sizes of supra-molecular formations are determined by the method of polymer processing, temperature, pressure, cooling mode, etc.

As already mentioned, two types of polyethylene (low and high density) and polypropylene were chosen as the study objects. Samples of the material were produced by extrusion of granular polymers in the shape of sheets of 200×600 mm, followed by cooling at speeds that simulate real field conditions.

During the sample preparation for each polymer, three sheets with varying thickness (1.0, 3.0 and 6.0 mm) were produced to determine the dependence of the strength characteristics of the formed coating on the thickness of the formed layer. Based on the literature data [2, 14, 25], the melting temperatures of polymers are different and lie in the range from 105 to 175 °C.

It was experimentally found that for the studied polymers the temperature of transition from the highly elastic state to the viscous one is 120 °C for LDPE, 135 °C for HDPE and 170 °C for PP. Based
on the established melting temperatures, the range from 120 to 220 °C in increments of 10 °C was studied to determine the dependence of the physical and mechanical characteristics of the polymer samples on the coating formation temperature. Thus, the total number of specimens to determine the tensile strength of the studied materials was 60.

In the course of the research, the following indicators characterising the strength of the polymer product were determined:

- breaking stress $\sigma_b$;
- tensile yield stress $\sigma_y$;
- breaking elongation $\varepsilon_b$;
- tensile yield elongation $\varepsilon_y$.

The determination of indicators characterising the strength of polymeric materials was carried out on a universal testing machine H75K-S for static testing of materials for tension, compression and bending. The tensile strength of the samples was tested in accordance with the GOST 11262-80 Plastics. Tensile test method.

For the tests, samples with a double-edged blade (dumbbell-shaped) with the following parameters were used:

- the total length $L_1 = 250$ mm;
- the distance between the marks determining the position of the clips on the sample $L_2 = 170$ mm;
- the length of the working part $L_3 = 80$ mm;
- the sample head width $b_1 = 25$ mm;
- the working part width $b_2 = 10$ mm;
- The thickness of the sample (d) varies from 1 to 6 mm.

The rupture rate was also determined on the basis of the GOST and was 200 mm per minute. The specimens were prepared by mechanical cutting of the sheets produced by extruding. The transformation of the polymer material takes place phase-by-phase.

At the first stage, the raw material is loaded. Feedstock supplied to the hopper can be presented in the form of tapes or powders or granules. Granular polymers are the best raw material for obtaining a marketable product. Processing of tapes and powders is complicated by the fact that these raw materials are prone to caking, and, consequently, they form "plugs" in the hopper. Therefore, when processing powder and tape materials, stirrers are often placed in bins. In addition, the flowability of materials depends on the humidity: the higher the humidity, the less the flowability. Therefore, materials must be dried before feeding into the hopper [19].

The loading of the inter-turn space under the hopper funnel takes place on the screw segment of (1–1.5)×D, where D is the screw diameter.

At the second stage, the material is compacted in the feeding zone. The granules move due to the difference in the friction force created by the friction of the polymer on the inner surface of the cylindrical body and friction on the surface of the working body, i.e. the screw. Since the friction force of the granules on the surface of the working body is higher than the surface of the cylinder, the granulate ceases to move along the axis of the screw and rotates with it. The solutions to this problem are (i) the increase of the cylinder wall temperature and (ii) the parallel screw cooling in the first zone. Under optimal temperature conditions in the feeding zone, the processed polymer is pressed and compacted, forming a dense "plug" in the interturn space. Typically, the length of the load zone is (2–10)×D.

In the third zone, the granular compacted polymer is melted and plasticised. This process occurs both due to the heating of the cylinder surface and due to the heat released by the viscous friction of the material in the thin layer of the melt. When the polymer is rubbing against the cylinder wall, intense shear deformation occurs, resulting in the subsequent plastification. This process is graphically shown in Figure 1.
3. Results
Damage to the formed coating can occur during its production, as well as during subsequent installation, but the largest number of fractures is most often observed during the insulation of a mine dump. Damage consists of punctures, disruptions and deformations (dents). Damage is caused by the presence of inhomogeneities on the insulated surface or non-compliance with the construction technology of a mine dump. Waterproofing base in the process of filling the stack and subsequent operation is subjected to loads leading to the violated integrity of the polymer material.

The determination of the strength of the material and its resistance to damage is performed in two ways:
- semi-production tests, by forming the coating and applying appropriate loads to it;
- laboratory experiments, by determining the strength parameters of the materials.

During the formation of a mine dump, the waterproofing coating undergoes tension, compression and shear stresses, caused by the displacements that occur between a polymer coating and a drainage layer. Compressive and tensile loads depend on the mass of the waste to be stored, the particle size distribution of a drainage layer and the term of dumping.

The stability of polymeric materials to load application vary significantly depending on several internal and external factors [4, 12, 19]. LDPE films with a thickness of not more than 0.2 mm were normally considered. Studies of polymer coatings based on LDPE and PP have been carried out as well. The method of determining the degree of damage by the number of defects per 1 m² of the test sheet sample is quite widespread in the study of polymer waterproofing materials. The experiment was conducted to determine the strength of the studied polymeric materials.

When conducting the research, the studied material was placed in a container with dimensions appropriate to the subject sample, simulating the conditions of laying the polymer coating, and brought to the destruction by the load generated by a metal stamp. The experiment tank was made of stainless steel with a wall thickness of 3 mm, thus, the tests exclude the possibility of expanding the model and the movement of sand on the surface of the polymer sheet. The proposed loading scheme characterises the stage of construction and operation of a waterproofing layer. Sands with an average particle size of 0.58 mm were used for testing.
The studies were carried out using a hydraulic press D2430B; Figure 2 schematically shows the installation for testing the sheet polymer material. A steel container (3) is filled with a 60 mm-thick layer of sand (2), which presence simulates a protective layer under the test sample. Sand is compacted, and the prepared polymer sheet (4) is laid on the surface. Sand covers the polymer sheet with a layer of the same thickness, simulating drainage. Dimensions of the tank are 400×200×150 mm. After that, the stamp (390×190 mm) is placed on the model to generate pressure on the sample. The container is installed between press plates (5) and (1), and the model is subjected to pressure at a constant speed of 3 mm/min.

![Figure 2. Design diagram of the installation for punching sample testing of polymer sheets](image)

According to the state requirements, the thickness of the waterproofing material, based on the conditions of ensuring the continuity, will be determined by the formula (1):

\[
\sigma = 0.1 \cdot d_{\text{grain}} \cdot \frac{q}{E_f} = 0.1 \cdot 2 \cdot 0.71 = 0.15 \text{ mm (1)}
\]

Where \( \sigma \) is the calculated film thickness; \( d_{\text{grain}} \) is the minimum diameter of the largest fraction of the soil scattered with the use of standard sieves, mm; \( E_f \) is the efficiency factor of additional protective fillers. \( q \) is the load taken for the screen as the greater of the two values calculated for the construction period and the operating period.

For the construction period, the load on the waterproofing layer depends on the pressure of the machines transmitted by the protective soil layer; for the operating period, it depends on the pressure of a dump. In our case, the pressure of the operating period will be determined by the mass of a dump and the area of its base.

When calculating the film thickness, the \( E_f \) is taken to be equal to one, since the dominating particle diameter is less than 10 mm and the use of an additional geotextile filler is not required. Based on the calculation, the studied insulation coating thickness (1.0, 3.0 and 6.0 mm) will meet the conditions of continuity of the formed layer in accordance with regulatory instructions. The value of the load created by loading machines depends on air pressure in tires. In the calculation, we take the value \( q = 0.71 \text{ MPa} \), as the largest at a tire pressure of 0.6 MPa. The estimated load generated by a dump per unit of base area is 0.2 MPa. The load was calculated in accordance with the state requirements. The pressure varies from 0.2 to 2.5 MPa; such value exceeds the range of real loads created by construction mechanisms, the application time of the created load is 4 min.

The other considered option is to cover the dumping sites – especially the slope surfaces – with geosynthetics subsequently topped with soil layer. In order to prevent soil erosion and minimise associated costs, the analysis of key properties was performed (Table 1). The data show the market prices for the year 2018.
Table 1. Comparative characteristics of geosynthetics

| Cover type                  | Polypropylene and polyester | Polypropylene | Polyester  |
|----------------------------|-----------------------------|---------------|------------|
| **Properties**             |                             |               |            |
| Tensile strength, kN/m     | 50                          | 20            | 20         |
| (avg., min.-max.)          | (20–200)                    | (18–28)       | (30–150)   |
| Elongation, %              | 13                          | 30–50         | 15         |
| Thickness, mm              | 13–15                       | 50–100        | 12         |
| Permissible operating      | -30…+100                    | -60…+55       | -15…+250   |
| temperature, °C            |                             |               |            |
| Surface density, g/m²      | Not less than 550           | Not less than 570 | Not less than 300 |
| Necessity of backfilling   | 25–50                       | 100–150       | 80–100     |
| with soil, mm              |                             |               |            |
| Weight, g/m²               | 400–800                     | 320–1520      | 250–950    |
| Price, rubles/m²           | 80–155                      | 70–358        | 50–124     |

As it can be seen from the data presented, polypropylene and polyester used as a geonet are characterised by the lowest volume of fertile soil needed to cover it; the other properties allow using this type of material for covering unstable slope surfaces to halt the fugitive dust emission from the studied dumps.

4. Conclusion

According to the results of the research on mine dump insulation and stabilisation, the following conclusions can be drawn:

- polymer coating manufacturing is accompanied by a non-linear strength change at different temperatures;
- the values of the tensile strength of polymer samples obtained at temperatures close to the melting point are not maximum, due to incomplete homogenisation of the melt and the presence of excess moisture and volatile impurities at 96–98%;
- the optimum temperature values for the processing of polymer granulate lie in the found range of 180–200 °C;
- the decrease in the strength characteristics of the studied samples at temperatures above 200 °C is determined by thermal and thermo-oxidative destruction;
- the considered approach to stabilising the slope surfaces of dumping sites with geosynthetics subsequently topped with soil layer can prevent soil erosion and minimise associated costs;
- polypropylene and polyester used as a geonet for mine dump stabilisation are characterised by the lowest mass of fertile soil required and acceptable expenses.

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References

[1] Aleksandrova T N, Talovina I V and Duryagina A M 2019 Gold–sulphide deposits of the Russian Arctic zone: Mineralogical features and prospects of ore beneficiation Chemie der Erde DOI: 10.1016/j.chemer.2019.04.006

[2] Alekseenko V A, Maximovich N G and Alekseenko A V 2017 Geochemical Barriers for Soil Protection in Mining Areas Assessment, Restoration and Reclamation of Mining Influenced Soils 255–274

[3] Aman A, Yaacob M M, Alsaedi M A and Ibrahim K A 2013 Polymeric composite based on waste material for high voltage outdoor application International Journal of Electrical Power and Energy Systems 45(1) 346-352

[4] Azimi E A, Al Bakri Abdullah M M, Ming L Y, Hussin K and Aziz I H 2015 Review of geopolymer materials for thermal insulating applications Key Engineering Materials 660 17-22

[5] Benkreira H, Khan A and Horoshenkov K V 2011 Sustainable acoustic and thermal insulation materials from elastomeric waste residues Chemical Engineering Science 66(18) 4157-4171

[6] Chen L, Han W, Li Z, Wei T and Xiao C 2011 Preparation and properties of alkali stimulated geopolymer and its application in thermal insulation coating Advanced Materials Research 233-235 2443-2446

[7] Chen L, Wang Z, Wang Y and Feng J 2016 Preparation and properties of alkali activated metakaolin-based geopolymer Materials 9(9) 767

[8] Datta J and Włoch M 2017 Recycling of Polyurethanes Polyurethane Polymers: Blends and Interpenetrating Polymer Networks 323-358

[9] Goldfein M D and Kozhevnikov N V 2014 A commentary on the concepts of the physical chemistry of polymers in technologies and environment protection Chemical and Biochemical Technology: Materials, Processing, and Reliability 175-186

[10] Jittabut P 2017 The study on physical and thermal properties of geopolymer pastes Key Engineering Materials 751 KEM 538-543

[11] Jordán M M, Bech J, García-Sánchez E and García-Orenes F 2016 Bulk density and aggregate stability assays in percolation columns Journal of Mining Institute 222 877-881

[12] Kalužová A, Pěnčík J and Matějka L 2013 Analysis of environmental impacts on thermal conductivity of insulation block from secondary raw materials Advanced Materials Research 649 223-226

[13] Kamseu E, Mohamed H, Sofack J C, Chaysuwan D, Tchakoute H K, Djobo J N Y, Rossignol S and Leonelli C 2018 Moisture Control Capacity of Geopolymer Composites: Correlation of the Bulk Composition–Pore Network with the Absorption–Desorption Behavior Transport in Porous Media 122(1) 77-95

[14] Łach M, Korniejenko K and Mikula J 2016 Thermal Insulation and Thermally Resistant Materials Made of Geopolymer Foams Procedia Engineering 151 410-416

[15] Lv X, Guo P, Liu H, Cui L and Cui X 2018 Preparation of paraffin-based phase-change microcapsules and application in geopolymer coating Journal of Coatings Technology and Research 15(4) 867-874

[16] Nagornov D O and Kremchee E A 2018 Framework to evaluate efficiency of peat processing using roller-disc grinding machines Journal of Physics: Conference Series 1118(1) 012028

[17] Nagornov D O and Kremcheeva D A 2017 Assessment of gravity component of moisture flow in raw peat in conditions of convective and radiative-convective heat input Journal of Industrial Pollution Control 33(1) 749-752

[18] Nagornov D O, Kremcheev E A and Kremcheeva D A 2019 Research of the condition of regional parts of massif at longwall mining of prone to spontaneous ignition coal seams International Journal of Civil Engineering and Technology 10(1) 876-883

[19] Pashkevich M A, Petrova T A 2017 Reclamation by Containment: Polyethylene-Based Solidification Assessment, Restoration and Reclamation of Mining Influenced Soils 235–253
[20] Perminova T, Sirina N, Laratte B, Baranovskaya N and Rikhvanov L 2016 Methods for land use impact assessment: A review Environmental Impact Assessment Review 60 64-74

[21] Robertus Y V, Udachin V N, Rikhvanov L P, Kivatskaya A V, Lyubimov R V and Yusupov D V 2016 Indication by environmental components the pollutant transboundary transfer to Gorny Altai Bulletin of the Tomsk Polytechnic University, Geo Assets Engineering 327(9) 39-48

[22] Su Z, Guo L, Zhang, Z and Duan P 2019 Influence of different fibers on properties of thermal insulation composites based on geopolymer blended with glazed hollow bead Construction and Building Materials 203 525-540

[23] Wongsa A, Sata V, Nematollahi B, Sanjayan J and Chindaprasirt P 2018 Mechanical and thermal properties of lightweight geopolymer mortar incorporating crumb rubber Journal of Cleaner Production 195 1069-1080

[24] Zhang Z, Provis J L, Reid A and Wang H 2015 Mechanical, thermal insulation, thermal resistance and acoustic absorption properties of geopolymer foam concrete Cement and Concrete Composites 62 97-105

[25] Yusupov D V, Bolshunova T S, Mezhibor A M, Rikhvanov L P and Baranovskaya N V 2017 The use of Betula Pendula R. Leaves for the assessment of environmental pollution by metals around tailings from a gold deposit (Western Siberia, Russia) International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM 17(41) 665-672

[26] Bushuev Y Y, Leontev V I and Machevariani M M 2018 Geochemical features of Au-Te epithermal ores of the Samolazovskoye deposit (Central Aldan ore District, Yakutia) Key Engineering Materials 769 KEM 207-212

[27] Krasotkina A O, Machevariani M M, Korolev N M, Makeyev A B and Skublov S G 2017 Tytoporphic features of niobium rutile from the polymineral occurrence Ichetju (the Middle Timan) Zapiski Rossisskogo Mineralogicheskogo Obshchestva 146(2) 88-100

[28] Beloglazov I I and Kuskova Y V 2017 Simulation of Roasting Metallurgical Concentrates in Fluidized Bed Using CFD-DEM IOP Conference Series: Materials Science and Engineering 221 012017

[29] Raupov I R and Korobov G Y 2018 Research of polymer compositions rheological properties for oil production Acta Technica CSAV (Ceskoslovensk Akademie Ved) 63(3) 493-500

[30] Rogachev M and Kondrashev A 2015 Experiments of fluid diversion ability of a new waterproofing polymer solution Petroleum Exploration and Development 42(4) 554-559

[31] Raupov I R and Shagiakhmetov A M 2019 The results of the complex rheological studies of the cross-linked polymer composition and the grounding of its injection International Journal of Civil Engineering and Technology 10(2) 493-509

[32] Alabyev V R and Korshunov G I 2017 Improving methods for calculating air temperature in mine workings equipped with cold water pipelines Ecology, Environment and Conservation 23(1) 444-450

[33] Ponomarenko T V, Nevskaya M A and Marinina O A 2017 Project-based approach to the implementation of low-waste technology at the mining companies International Multidisciplinary Scientific GeoConference Surveying Geology and Mining Ecology Management, SGEM 17(43) 163-170

[34] Limanskiy A V and Vasilyeva M A 2016 Using of low-grade heat mine water as a renewable source of energy in coal-mining regions Ecological Engineering 91 41-43

[35] Nevskaya M A and Marinina O A 2015 Regulatory aspects of mining waste management in the Russian Federation Biosciences Biotechnology Research Asia 12(3) 2619-2628

[36] Moradi S S T, Nikolaev N I and Leusheva E L 2018 Improvement of cement properties using a single multi-functional polymer International Journal of Engineering, Transactions A: Basics 31(1) 181-187