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EFFECTIVE STRENGTHENING SOLUTIONS FOR FRACTURED ROCK MASSES USING TAILINGS

The authors develop effective solutions for strengthening and reinforcement of disturbed rocks in underground mines using tailings. The object of research is tailings and backfill mixtures with and without additives, and the research subject is the physical and mechanical properties as well as hardening of backfill mixtures in conditions of natural humidity. The standard methods were used to determine characteristics of initial materials, backfill mixtures composition and their physical and mechanical properties. The studies included Akzhal mine tailings used as an aggregate of backfill mixtures for strengthening fractured rocks in the open pit mine, as well as damaged rib pillars and roofs in underground excavations. The results can be used for the expansion and reproduction of the building materials supplies, for the enhancement of industrial safety in mines and for the minimization of the environmental impact of mining.

Keywords: *mineral mining, open pit, mine, concentration plant, damage, fractures, rock mass failure, strengthening, mining waste, building materials, solutions, tailings, cement, superplasticizer, compressive strength and cohesion, X-ray and spectrophase analyzes*

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Introduction

Utilization of mineral processing tailings open up new prospects for the production of backfill and reinforcing mixtures for the industry of building materials. The drop in extraction and processing of mineral raw materials because of the economic system modification hampered the metallurgical industry supplies.

The way out can be involvement of mining and metallurgy waste in operation. The mining and metallurgical sector (MMS) of the Republic of Kazakhstan has accumulated large volumes of overburden rocks, tailings and slags for many years of operation. Millions of tons of harmful substances are released into the atmosphere and hundreds of millions of cubic meters of contaminated wastewater are discharged into water bodies. All this leads to serious economic, social and environmental problems.

Expansion of supplies of the building materials industry with feedstock can be ensured not only by finding for new deposits of non-metallic minerals, but also by involving non-metallic mineral mining waste into production. Mining waste or manmade raw materials, as a rule, require industrial processing and assessment using effective methods and technologies to ensure their full use at the maximum environmental preservation.

Industrial processing of manmade raw materials (tailings waste, overburden and gangue), which have similar composition as natural raw materials and are used in traditional spheres, is practically the same as industrial processing of natural mineral raw materials. Therefore, the use of mining waste for production of building materials is undoubtedly an urgent task of top priority. Researchers of Kazakhstan carry out ample studies in this regard.

Comparative analysis

Growth in construction in Kazakhstan requires significant amounts of minerals for the building materials industry. Intensification in this direction is associated with the use of industrial waste instead of primary natural resources in order to reduce cost of building materials. The use of solid mining waste in the building materials industry is more economical in comparison with the building materials production based on special extraction of mineral raw materials [1, 2].

The review of existing scientific works in this area shows that significant research on the use of manmade raw materials has been implemented worldwide. For instance, in the far abroad, mining waste is used to produce bricks [3], concrete [4] and glass ceramics [5].

The use of various industrial waste in production of building materials is of great importance abroad. This is evidenced by the fact that three review articles devoted to this problem were published in the journal *Construction and Building Materials* [6–8]. A large number of publications address involvement of mining and metallurgical waste in production of building materials: various tailings, screenings, slags, sludge from the chemical and metallurgical industries. Chinese researchers studied the use iron ore concentration tailings in production of building materials [9, 10].

The similar studies of the mining waste use in production of building materials and goods are carried out in the neighboring countries [11, 12]. Effective binders for grouting are developed using waste of nonconventional raw materials mining and processing [13]. Building materials are manufactured from overburden of the Tatar rare-metal deposit in the Krasnoyarsk Krai, where concentrates as used as an aggregate for lightweight concrete, for preparation of plaster solutions and in environmental protection [14].

According to modern estimates, over 50 billion tons of industrial waste accumulated at the facilities of the mining and metallurgical sector in Kazakhstan occupy vast areas (more than 150 square kilometers). The amount of industrial waste increases annually by about 1.5 billion tons, while, at the same time, the level of use of solid waste is currently low. Accumulated waste causes significant environmental and economic damage to the nature and people, amounting to tens and hundreds of millions of dollars per year [15, 16].

The largest accumulations of waste are tailings dumps. Involvement of tailings in production is dictated by the following circumstances:

- operation terms of tailings dumps are limited, and many tailings dumps are already filled ore are going to be filled in full in the nearest years;
- tailings occupy vast areas and, being a finely dispersed and easily blown off material, they are the source of the increased environmental risk in the regions of mineral mining and processing [17].

Tailings are finely ground products which need no additional grinding before use, which allows reducing expenses. Furthermore, tailings already have homogenous chemical and mineralogical compositions after processing.

Akshatau Mining and Processing Plant JSC supplied with raw materials by Akzhal mine produces much barren rocks, tailings and wastewater. The relevant and top-priority are of using this waste is manufacture of building materials.

Research methods

Physicochemical research. Identification of initial raw materials was carried out in accordance with requirements of physical and chemical analysis.

X-ray diffraction patterns were taken on modernized DRON-3M diffractometer using Cu-Kα radiation. X-ray diffraction patterns of materials (samples) were obtained in the 2θ range (angles) from 10 to 70°. The radiography preparation procedure included the following subsequent stages: the sample was ground in agate mortar down to powder; then the powder was placed in plexiglass cuvette pre-lubricated with petroleum jelly and was pressed a little; the excess powder was removed using blade.

IR spectra were recorded on Specord M-80 spectrophotometer (Germany) in the frequency range 4000–200 cm^{-1} and on Fourier spectrometer TENSOR-2 manufactured by BRUKER. The analysis used tablets with tungsten concentrate (KVG).

Physical and mechanical research. Cement tests were carried out in accordance with technical requirements of relevant standards. Granulometric composition—fineness modulus and grain size composition, and physical properties of tailings was determined in accordance with GOST 8736-2015 Construction Sand.

Specific effective activity of natural radionuclides was determined in accordance with the requirements of GOST 30108-94 Materials and building products. Determination of effective activity of natural radionuclides.

Physical and mechanical properties of backfill were determined according to GOST 28013-98: Mortars. General specifications and GOST 5802-86 Mortars. Test methods.

Research results

Examination of surface and underground openings at Akzhal mine showed that the largest number of falls take place in fractured rocks, and volumes of falls increase with age of the openings. The observations in excavations driven in fractured rocks revealed that they were stable for a month. After two to three months, flaws up to 10–15 cm in size are formed. Fracturing and falls develop within six months, and roof collapses occur in the form of domes. This dramatically increases the volume and labor intensity of tunneling, as well as the costs of mine support and repairing.

To prevent collapses in underground openings in fractured rocks, rockbolting with reinforcement metal meshing and shotcreting is used. However, roof rock exfoliation in haulage drift and rock failures indicate that this support design fails to ensure stability of roadways and to prevent deformation. As result, after 2–3 years of service life of the roadways, the support breaks and needs overhaul. Therefore, effective ground control and support is of high concern both in surface and underground mining in fractured rock mass [18].

In this regard, the main characteristics of waste from concentration factory at the Akzhal deposit were investigated. The analysis of geological conditions of the deposit and the inspection of roadways driven in fractured rocks exhibits essential impact exerted on the stability by systems of steep dip cracks. The cracks vary from smooth, wavy to uneven and splintered in nature. The crack opening is not wider than 3 mm and is 1.5–1.8 mm on average. Based on the studies performed on the samples of fractured rocks, it is found that rocks have different degrees of fracturing. In this respect, they are grouped into extremely, highly and partially fractured rocks (**Table 1**).

Table 1. Rocks classification, physical and mechanical properties, structure and texture

Group No.	Fracturing	Rock	Sample No.	Compressive strength, MPa	Hardness on Prodyakonov's scale, ƒ	Structure	Texture	Roughness
I	Extremely fractured	Diorites	9	43.4	6	Finely grained	Schistocity	Rough
			10	44.8	6			
			11	65.5	6			
	Average		12	51.2	6			
II	Highly fractured	Limestones	2	84	7	Finely grained	Massive	Rough and splintered
			4	103.6	8			
			14	106.4	8			
	Average			62.7	8			
III	Partially fractured	Massive limestones	3	140.0	10	Finely grained	Massive	Rough and splintered
			5	154.0	11			
			7	162.4	12			
	Average			152.1	11			

Different strength characteristics of rocks in and the drop in strength of rocks when exposed or contacting air and water dictate a differentiated approach to ground control in fractured rock mass. One of the common methods is shotcreting of damaged rock areas, i.e., injection of cement solution until rocks get completely saturated [19, 20].

Shotcrete reinforcement has following advantages over traditional methods:

- during applying mixture under pressure, fine particles of tailings are hammered into cracks in rocks, restoring the damaged rock layer. As a consequence, a restored rock envelope is included in the system of forces counteracting stratification of rock mass. This extra shell works as a single system with shotcrete, equalizes stresses and increases stability;
- shotcrete thin lining reliably protects rocks from destruction, as a result of which rocks retain their properties unchanged for a long time. Under normal conditions, rock strength in the vicinity of mine loses up to 60–70% of the initial value with time;
- shotcrete flow in pipes under high-speed pressure of air increases both dispersion and number of hydrating grains. This enhances shotcrete strength. Moreover, shotcrete activity increases due to constant ramming force of jet;
- high level of mechanization of the strengthening process of damaged surfaces ensures the increased labor productivity of tunneling operators by 2–3 times;
- shotcrete lining increases safety of mining operations and can warn in advance about hazard. This is due to the fact that deformations in the shotcrete lining appear in the form of cracks gradually, while high adhesion to rocks keeps the damaged concrete shell and separated rock pieces from falling out. Repairs, rebuilding and strengthening are very easy to do by re-spraying.

To strengthen damaged and fractured rocks in underground openings, we recommend effective shotcrete solution. Technical result is utilization of mining waste (tailings), achievement of high fluidity of solution, adhesion to rocks and strength of resultant solution.

To achieve this result, we investigated raw materials: Portland cement PC 400-D0 (M400) produced by Central Asia Cement JSC (Karaganda Region, Kazakhstan), tailings of Akzhal Concentration Plant, functional additive Reparatur manufactured by Ading (North Macedonia) and polycarboxylate additive Neolit 400 (Russia).

Choice justification of initial materials

The use of Portland cement PC 400 produced by Central ASIA Cement JSC is due to the plant location at the Balkhash city, not far from Akzhal mine.

Tailings of Akzhal Concentration Plant (hereinafter referred to as ACP) are chosen with a view to improving ecological situation in the region through their complete utilization at the environmental and economic efficiency, and for using carbonate composition of tailings for development of special cement solutions for more efficiently reinforcement of fractured rocks in underground mines.

The choice of dispersion polymer powder (DPP)—Reparatur additive of Ading Company (North Macedonia) is governed by its properties, namely, increased adhesion to the surface of cracks.

The use of dry superplasticizing (SP) additive Neolit 400 (Russia) in the composition of cementitious solutions is due to its high water-reducing properties. With a decrease in the water/binder ratio, durability and density of the solution increase with simultaneous decrease in shrinkage and creep deformations during development of strength.

Table 2. X-ray pattern of Portland cement

θ	d, Å	I	Main phases	θ	d, Å	I	Main phases
12.2	7.18	10.0	C_4AF	33.01		14.4	C_3S, aluminate phase
14.9	5.94	0.3	C_3S	34.20		18.0	C_3S, C_2S
21	4.23	3.2	Gypsum	34.50		100.0	C_3S, C_2S
23.2	3.83	11.3	C_3S	37.80		11.3	C_2S
26.8	3.32	15.4	C_2S	39.00		17.5	C_2S
29.6	3.03	72.0	C_3S	41.40		45.3	C_2S, C_3S
30.2	2.94	18.5	3_2S	47.40		17.5	C_4FF
31	2.86	10.3	C_2S, gypsum	51.80	1.76	51.5	C_3S
32.4	2.76	64.9	C_3S, C_2S	56.60		25.7	C_3S
33	2.73	46.4	C_3S, C_2S	60.20		20.6	C_3S

Comment: θ—angle of X-ray reflection; d, Å—interplanar distance, Å (1 Å = 0.1 nm); 1— intensity on a ten-point scale or the number of intensity, imp/s

Characteristics of Portland cement PC 400 D0 (M400)

It is seen in **Table 2**, that Portland cement is represented by alite (C_3S–$3CaO{\cdot}SiO_2$, or rather $54CaO{\cdot}16SiO_2{\cdot}Al_2O_3{\cdot}MgO$), belite ($C_2S$–$2CaO{\cdot}SiO_2$), celite ($4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$) and felite ($3CaO{\cdot}Al_2O_3$). Alita content is about 50% by weight, C_2S—20%, C_3A—7%, C_4AF—about 15%, and the rest is glass phase.

The chemical composition of ACP tailings is, wt. %: CaO—54.30; CaO_2—40.50; SO_3—2.30; SiO_2—1.50; MgO—1.40; $Fe[S_2]$—0.13.

The X-ray patterns of these tailings is shown in **Fig. 1*a***. It is seen that it mainly shows reflections (peaks) characteristic of calcium carbonate (CaCO3), with interplanar distances d, Å: 3.8665; 3.3498; 3.0404; 2.8446; 2.496; 2.2847; 2.0952; 1.9127; 1.77; 1.6287; 1.60; 1.5236; 1.4393. **Figure 1*b*** depicts the DTA analysis where endothermic effect is recorded at 950 °C, showing limestone dissociation.

- the granulometric composition, physical properties and the specific effective activity of natural radionuclides and concentration tailings are described in **Tables 2** and **3** and in Fig 1, from which it follows that:
- the fineness modulus of sand is 0.83, therefore, it belongs to very fine sand which is suitable for preparation of plaster mixtures;
- the bulk density is 1515 kg/m^3, the true density is 2.74 g/cm^3, and the voidness reaches 44.7%;
- the specific effective activity of radionuclides meets regulatory requirements of GOST 30108-94–120.0 Bq/kg as against the standard value of 370 Bq/kg.

The analysis of the mineral and chemical composition of nonmetallic rock of the Akzhal lead–zinc deposit shows that it mainly consists of calcite $CaCO_3$ (about 95–97%) and silica SiO_2 (about 2.5%); among them there are also impurities of magnesium, iron, aluminum, zinc, lead, barium, etc., which are not of industrial interest, since their total content is under 1%.

The concentration tailings of Akzhal CP mainly consist of calcite and silica, oxide chemical composition of which

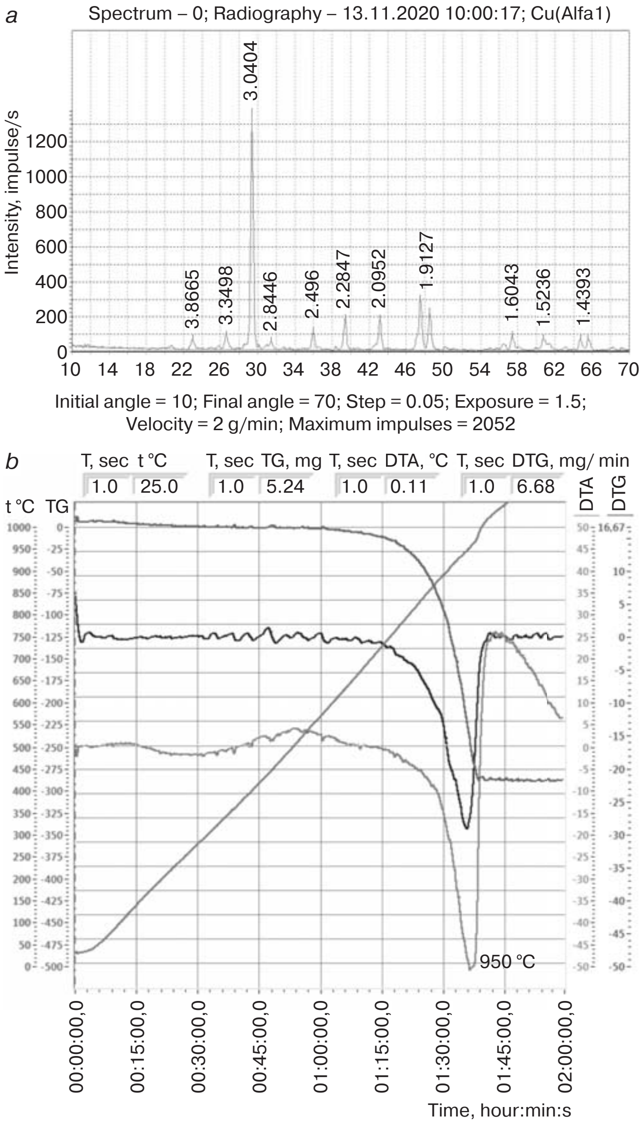

Fig. 1. X-ray pattern — *a* and derivatogram — *b* of ACP tailings

Table 3. Granulometric composition ACP tailings

Indicator, unit of measure	Total oversize, %
Grain composition:	
2.5 mm	2.5
1.25 mm	4.7
0.63 mm	7.6
0.315 mm	17.0
0.16 mm	51.4
Content of grains by size, %:	3.26
>10 mm	1.96
>5 м mm	46.3
< 0.16 mm	Sand class—II
Fineness module	0.83 Sand group—fine

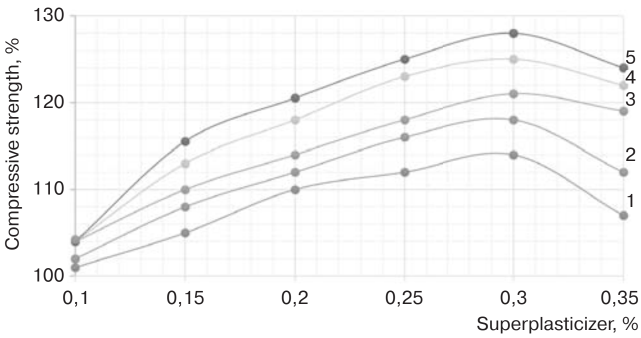

Fig. 2. Strength of test samples versus input of SP Neolit 400 at Portland cement consumption of:
1—69; 2–92; 3—140; 4—191; 5—219

includes: CaO—54.3; CO2—40.5; SO_3—2.3; SiO_2—1.5; MgO—1.4 and Fe[S_2]—0.13%.

The mine and used process water, respectively, have following characteristics: alkalinity—0.45 and 0.8; hardness—11 and 12; pH—7.5 and 8.3. Moreover, mine water is transparent, and the process water is turbid and includes concentration tailings consisting mainly of calcite $CaCO_3$.

Figure 2 illustrates the effect of SP Neolit 400 on the sample strength. It is seen that introduction of SP increases the strength of the samples by 3–27% in comparison with their strength without additive. At the same time, with more cement in the composition of mortar mix, the positive effect SP on the strength is greater; for example, at the cement consumption of 69 kg/m^3 and optimal content (0.3%), the increase in the strength of the samples reaches 11%, and at the cement consumption of 265 kg/m^3, the sample strength grows by 30%.

Thus, the composition of the strengthening solution for fractured rocks in underground roadways was selected as follows: Portland cement PC 400 up to 18%, tailings up to 71.2%, Reparatur additive 1.5%; superplasticizer Neolit 400 0.3%; water 9% at a water/cement ratio of 0.5.

After dosing cement, tailings and additives are fed into concrete mixer and thoroughly mixed. Then, water is added, and the mixture is stirred again. The finished mix is delivered to underground roadways and injected into cracks in damaged roadways.

For the strength tests, specimens 7×7×7 cm were molded from the mixture and compacted on a vibrating platform for 45 seconds. After a day, the specimens were removed from the molds and stored in humid conditions for 28 days. The physical and mechanical testing data are given below:

Physical and mechanical properties of resultant mixture
Composition, %:

Portland cement	18.0
Tailings	71.2
Reperatur	1.5
Neolit-400	0.3
Used water of concentration plant	9.0
Ultimate compressive strength, MPa	1.5
Fluidity, cm	100.0

The technical novelty of the created solution was confirmed by patents of the Republic of Kazakhstan for invention [21].

The shotcrete strengthening technology was tested in fractured rock sites of underground roadways in Akzhal and Saryoba mines in Kazakhstan. The test data analysis shows that the highest technological and economic performance of mine support using the shotcrete method are achieved owing to the correctly selected composition of the concrete mixture, with regard to the specifics of the local geological geotechnical and hydrogeological conditions.

The implemented studies prove that the strength of the resultant solution is 1.5–2 times higher and the adhesion to rock is 6 times higher. Furthermore, the solution based on Neolith 400 features the increased elasticity, fracture toughness, water resistance, adhesion to rocks and strength.

Conclusions

1. The solution has been developed for strengthening fractured rocks using the mining and metallurgical waste with polymers SP and DPP. The solution features the low cost, sufficient fluidity, compressive strength and adhesion after curing. The technical novelty of the solution is confirmed by the patent of the Republic of Kazakhstan for invention.

2. The use of tailings as fine-grained aggregate enables waste-free mineral processing, production of effective building mortars and solution of the environmental and economic problems.

3. Each component of the mixture, given efficient combination, fulfills its function:

- portland cement meets the technical requirements of the standard;
- tailings act as a structural element and plays a positive role of frame of hardened backfills;
- SP increases mobility and strength of mortar;
- DPP significantly increases strength of adhesion to the basis.

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