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Use of high-density paste backfill for safe disposal of copper/zinc mine tailings

Introduction

Technological advancements in mineral processing have increased the feasibility of refining low grade ores. Because of this progression and continual depletion of high grade ore deposits, much larger volumes of waste material are produced. At the same time, increasing environmental legislation and cost competitiveness dictate that these wastes must be disposed of in a manner that is both environmentally acceptable and economically viable (Scoble et al. 2003). When there is no disposal of sulfidic mine tailings, mine closure is a quite straightforward process. Buildings must be removed and openings must be sealed; tailings dams, waste rock dumps, and other tailings disposal areas must be stabilized safely (Potvin et al. 2005). Sulphidic tailings may continue to generate contaminated acid mine drainage water for several years or even centuries after the closure of the operation.

The safe disposal of mine tailings is fast becoming a key economic factor in determining the profitability of mining operations. Surface disposal of pyrite and pyrrhotite mine waste is the major cause of acidic mine water generation and of resulting environmental damages. The oxidation of sulphide minerals (e.g. pyrite) generates sulphuric acid, which then encourages the release of toxic heavy metals which run off to the surface streams and

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underground water (Hassani et al. 1994). The safe disposal of sulphidic tailings could be achieved by backfilling underground mine openings instead of surface disposal. Backfill has been an integrated part of mine designs in the past few decades and is accommodating to the requirements of deeper and/or bulk mining. There are several reasons why backfilling is used: to provide ground support, to permit utmost ore recovery and the economics of mining, and to dispose of mine tailings materials (Landriault 1995). As well, in response to reducing acid mine drainage problems, reactive tailings could be restored underground for backfilling mine voids. This placement could be part of cemented or non-cemented backfill in order to provide some structural support to the mine (Archibald et al. 1999).

There have been new approaches applied and better technologies used in the past few years in order to enable mining operations to backfill total tailings (Amaratunga, Hmidi 1998; Newman et al. 2004; Qiu, Sego 2007). One of the new approaches is the use of high-density paste backfill (HDPB), which is widely used by the modern mines all over the world, due to increasingly stringent environmental regulations on sulphur-rich mill tailings. The main advantages of HDPB are lower operating costs and a reduction of the amounts of harmful waste material sent to the tailings dams at the surface (Benzaazoua et al. 2004). This lessening of the amount of waste in tailings dams decreases the environmental impact, and postpones future capital expenditures related to the tailings dams. Many people believe that underground disposal represents the future of waste disposal in the mining industry. This significantly reduces the oxidation risk and other environmental effects. With the recent focus of attention on the environment and subsequent tightening in legislation, the possibility of using the HDPB method as a method of waste disposal is becoming economically attractive. Waste materials used as a backfill material mainly consist of waste development rock, deslimed and total tailings, quarried and crushed aggregates, alluvial sands, and metallurgical tailings (Hassani et al. 1994). However, the tailings, among other backfill materials (i.e. slurry and rock fill), are used only within HDPB systems because of environmental points of view.

This paper focuses on the potential environmental benefits of using the HDPB when mill tailings are acid generating, and it also provides examples from a case study to illustrate these benefits. Additionally, this study highlights the influence of mechanical properties of tailings and binders on mechanical strength development of HDPB used in an underground copper/zinc mine in northeast Turkey.

1. High-density paste backfill (HDPB)

In recent years, the utilization of high-density paste backfill (HDPB), a.k.a. cemented tailings mine backfill or cemented paste backfill, has evolved from an experimental tailings management method with limited application to a technically viable and economically attractive alternative. This is due to the development of dewatering and transportation

systems that allow for controlled and consistent production and delivery of paste in a cost-effective manner (Fall et al. 2005). It has also been recognized that underground backfill provides for a mechanism to safely dispose of mining wastes, which results in cost savings and reduced direct and long-term liability. Minimizing this liability through a reduction of surface disposal will have a useful effect on the feasibility of any mining venture. Several publications discuss in more details in situ and laboratory behaviour of the HDPB (Kesimal et al. 2005; le Roux et al. 2005; Sivakugan et al. 2006; Yilmaz et al. 2007). The environmental benefits of disposal of acid-generating tailings in the HDPB form are given as follows (Landriault 1995; Verburg 2002; Benzaazoua et al. 2004); (1) little free water available to generate leachate that might have detrimental effects on ground water; (2) the higher degree of saturation in the paste retarding the ingress of oxygen, which reduces the potential for generation of acidic water; and (3) co-disposal of other waste materials with paste, i.e. acid generating tailings being sent to the same waste facility to be encapsulated in tailings paste, and reducing the oxidation risk and the number of waste facilities requiring closure.

Paste backfill is a highly complex material consisting of a mix of high-density mill tailings (72–85wt% solids, depending on grain size and specific gravity), binding agent to meet fill stability requirements, and water to transport the paste to the mine stope in the desired slump (Benzaazoua et al. 2004). The paste is a granular material mixed with water to fill the interstices between the particles so that the material behaves as a fluid. The grainy matter retains all the water between the particles because of its colloidal electrical particle charge that bonds the solid particles to the water molecules. Overall, granular materials must have at least 15wt% of its particles finer than 20 µm for the colloidal properties of the material to retain sufficient water to form a paste. The colloidal properties of a material are governed not only by the size of the particles, but also by their chemical and mineralogical composition (Landriault 1995). This means that different materials will form a paste with different grain size distributions. Each granular material must be tested independently to determine its properties and its behaviour as a paste.

Moreover, due to technology advancements and public awareness of the environmental impacts of tailings disposal at the surface, tailings produced during ore processing are now being treated in various forms for industrial or environmental purposes. Some of these novel usages (Archibald et al. 1999; Kesimal et al. 2005; Zou, Sahito 2004; Gutt, Nixon 2006) are: (1) the use of total plant tailings for shotcrete as a ground support; (2) the use of tailings for blended cements (e.g., slag, fly ash) as a pozzolanic material; (3) the use of power station bottom ash as inert building fill; (4) the use of red mud from the alumina industry as a soil conditioner; (5) the use of waste materials in the construction industry; and (6) the use of power station ash for backfilling coal mining voids.

2. Test site description

A mine site selected to study the high-density backfill system for mill tailings runs an underground copper and zinc mine. The mine, currently the Turkey's largest copper and zinc producer, is situated close to the town of Cayeli, which is located about 25 km from the coastal city of Rize in northeast Turkey (Fig. 1). The underground mine, opened in 1994, is run sublevel retreat with post paste backfilling method. It produces three types of concentrates: copper (Cu), zinc (Zn), and copper and zinc bulk concentrates. In 2006, the mine proceeded about 933,000 tonnes of ore with an average feed grade of 3.9% Cu and 5.7% Zn, respectively. Copper grades, metal recoveries and tonnes of copper produced for the year were 84% and 30,400 tonnes, respectively. Zinc tonnes and recoveries, however, were 38,700 tonnes and 73%, respectively.



Fig. 1. Location map of the studied mine site

Rys. 1. Lokalizacja kopalni

The type of ore deposit is poly-metallic volcanogenic massive sulphide. The ore is primarily clastic in texture. The ore body is made of massive sulphide conglomerates, breccias and sandstones consisting of more than 90% sulphide minerals with minor dolomite and barite gangue. Mill tailings consist of pyrite and chalcopyrite, up to 20 cm in size, in a sulphide matrix containing less than 10% sphalerite. In the past, a submarine tailings disposal system was used whereby mill tailings were transported by pipeline along the river for discharge into the anoxic environment of the Black Sea. Since 2000, this system has been replaced by the HDPB in order to represent the most environmentally responsible way to dispose of highly pyritic tailings.

3. Experimental study

3.1. Material characterization

Sulphate-rich mine tailings samples were received in sealed plastic containers and kept in a humid room during the tests. A sufficient amount of the samples was oven dried to conduct the initial physical (i.e. particle size, density) and chemical/mineralogical analysis needed for characterization. The ASTM (American Society of Testing Materials) standards were used in the experiments conducted as testing procedures. The selected analyses were performed in triplicate and their average values for the represented results are reported.

The experimental results indicate that tailings samples have a moisture content of 11.42%, a specific gravity of 3.48 and a specific surface area of $2.54 \text{ m}^2\text{g}^{-1}$. The results of tailings samples grain size analysis (Fig. 2) indicate that tailings sample contained about 30% by weight of its particles finer than $20 \mu\text{m}$, having a sufficiently fine material content to produce the HDPB mixture according to Landriault (2005). Most of the particle-size distribution fell in medium to fine sand, with very limited amounts of clay-sized particles. Geochemical analyses such as hydrogen ion activity (pH), redox potential (Eh) and electrical conductivity (EC) was conducted on the mix water which is derived from as-received mill tailings. The experimental results indicated that the parameters pH, Eh and EC had a value of 6.85, 0.365 V and 0.312 mS/cm, respectively.

Chemical and mineralogical analyses were performed on mine tailings before binder addition. Tailings samples elemental composition was determined by the atomic absorption spectrometry (AAS) method. The results of AAS analysis are given in Table 1. The dominant elements are iron and sulphur due to pyrite content. Other minor elements include alumina

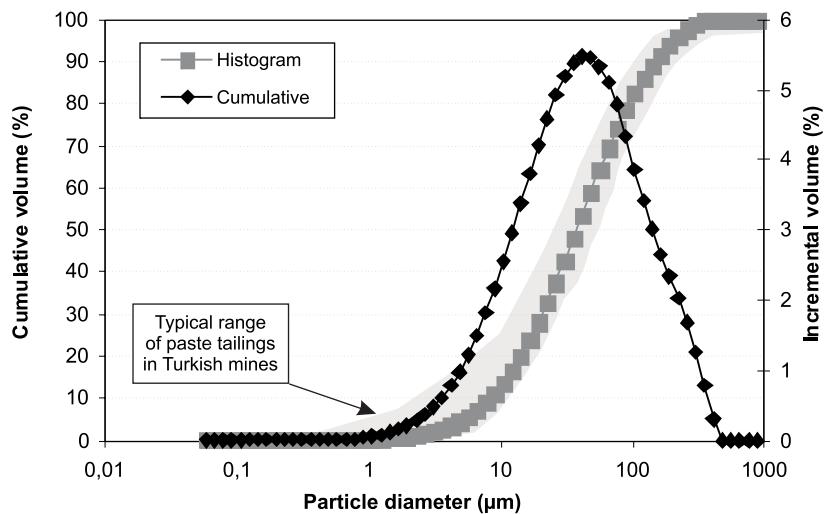


Fig. 2. Particle size distribution of the studied tailings

Rys. 2. Rozkład ziarnowy odpadów przeróbczych

Chemical composition of mill tailings

TABLE 1

Skład chemiczny odpadów przeróbczych

TABELA 1

Elements	Al ₂ O ₃	CaO	Fe ₂ O ₃	K ₂ O	MgO	MnO ₂	Na ₂ O	S	SiO ₂
Grade (wt%)	2.1	1.42	44.3	0.1	0.7	0.1	0.1	46.1	5.1

and silica. Iron and sulphide-rich tailings typically have highly variable rheological characteristics, water retention capabilities and strength gain properties.

The mineralogical analysis of tailings was also carried out by using X ray diffraction (XRD) and the results are summarized in Table 2. The tailings are characterized by fine-grained pyrite grains that were angular and irregular in shape, with minor, coarser-grained, sub-rounded to irregular silicate minerals. Other minor sulphide minerals occurred as angular to irregular grains. Minor iron oxides, limonite and goethite, occurred as blocky grains and as replaced pyrite in quartz grains, respectively. Calcite is present in trace quantities as fine ground mass and minor chlorite flakes can be observed.

Mineralogical composition of mill tailings

TABLE 2

Skład mineralogiczny odpadów przeróbczych

TABELA 2

Mineral	Formula	XRD (relative)
pyrite	FeS ₂	major
sphalerite	ZnS	
marcasite	FeS ₂	
arsenopyrite	FeAsS	
chalcopyrite	FeCuS ₂	
galena	PbS	
limonite	FeO(OH)	
goethite	FeO(OH)	
quartz	SiO ₂	trace
carbonate	CaCO ₃	
potassium feldspar	KAlSi ₃ O ₈	trace
chlorite/serpentine	(Mg,Al) ₆ (Si,Al) ₄ O ₁₀ (OH) ₈	

3.2. Binder composition

As a result of its capability of absorbing excessive water and developing high early strength, Portland composite cement (PKC) agent was used for producing a variety of high-density backfill mixes in the laboratory. This binder agent has a specific surface area of $0.356 \text{ m}^2\text{g}^{-1}$, a soundness (le Chatelier) value of 5%, and a relative bulk density between 2.74 and 3.12 with a typical particle size of 95.8% below 90 μm . Its main constituent is calcium sulphate aluminates. The binder type used in this study is “PKC/A 32.5-R type”, and was supplied by TCMB (Turkish Cement Manufacturers’ Association) research laboratory in Ankara, Turkey. The chemical composition of the cement is given in Table 3.

TABLE 3
Chemical composition of the cement

TABELA 3
Skład chemiczny cementu

Elements	PKC/A 32.5-R (%)
SiO_2	19.12
Al_2O_3	7.01
Fe_2O_3	2.68
CaO	42.50
MgO	1.08
SO_3	1.96
free CaO	0.55
insoluble residue	11.60
soluble SiO_2	9.72
loss on ignition	2.08
undetermined	1.70

3.3. Rheological properties

The rheological or flow properties of the granular materials such as high-density backfill are important for pipeline gravity flow transportation and underground placement as a fill material. Factors such as ease of placement, consolidation, durability, and mechanical strength depend on the flow properties (Amaratunga, Hmidi 1998). The test contains a set of water retention, settling and modified slump cone tests designed to assess the colloidal properties of an uncemented material and the resistance to pipeline gravity flow. In fact, a “slump test” (Fig. 3) is used to measure the ease of placing and consolidating freshly mixed concrete or paste. This is a simple standardized test which involves hand



Fig. 3. A slump test showing paste material with 7" slump

Fig. 3. Badanie konstystencji mieszanki betonowej opadu stożka; mieszanka o opadzie 7"

placing an amount of fresh concrete into a metal cone and then measuring the distance the fresh paste falls (or slumps) when the cone is removed. The slump cone was filled with fresh paste material in three layers, tamping between each layer to remove voids. The paste was levelled off with the top of the cone. When removing the cone, slump was measured.

The results of the rheological index tests are illustrated in Fig. 4. The results show that there are important differences between the 6" and 7" slump values of tailings sample. At 24 hours, the 6" slump sample kept apparently 10% more water than the paste with 7" slump. On the contrary, the amount of water separated from 7" slump tailings is ~1.4 times higher compared to 6" slump tailings. This could be mainly attributed to their mineralogical composition as the tailings' water retention generally increases in the presence of clay (calcite, kaolinite, etc.) or similar highly colloidal, high-water-retention minerals.

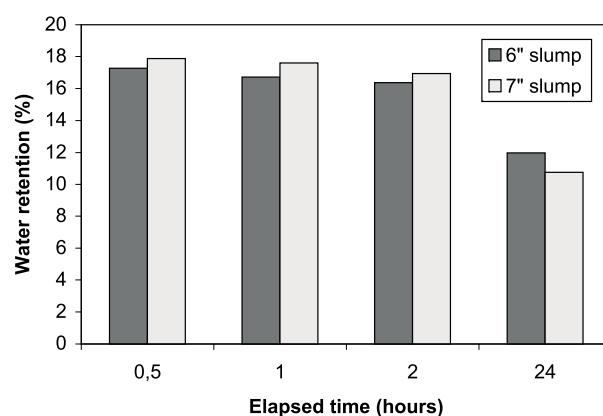


Fig. 4. Water retention versus time for uncemented tailings sample

Fig. 4. Retencja wody w funkcji czasu dla bezcementowej próbki odpadów przeróbczych

3.4. Backfill sample preparation

The constituents of the paste batch were measured in accordance with the predetermined paste backfill recipe. The tailings sample and the cement were weighed and mixed with a measured volume of water in a pail. The paste was thoroughly kneaded with a mortar and plaster mixer until a fluid slump (5–7") consistency was reached, usually after 3 min. After pouring the manufactured paste mixes into plastic moulds, they were sealed and cured in a foggy room maintained at 90% of relative humidity and a temperature of 25°C. The two ends of the samples were first rectified to get plane surfaces before running the tests.

3.5. Compressive strength tests

A series of cylindrical specimens (with a diameter of 10 cm and a height of 20 cm) were prepared to measure the samples' compressive strength. The strain rate for experiments was fixed at 0.83% per minute. The experiments were conducted in triplicate to ensure the reliability of the test results. A total of 156 cylinders were made and tested to determine the unconfined compressive strength (UCS) of the backfill samples and to establish a general trend for the strength acquisition with different treatment additives. The UCS test refers to sample's resistance to compression with increasing strain, measured under undrained conditions. In this study, the UCS tests were performed using ELE Multiplex digital press with a 50 kN load capacity. The United States Environmental Protection Agency generally considers a stabilized material as satisfactory if it has a UCS value of at least 345 kPa (US EPA 1989); however, the lowest mechanical strength should be determined from the design loads to which the material may be subjected.

4. Preliminary results and interpretation

A laboratory-scale testing study was conducted to determine the performance and quality of HDPB samples and focused on measuring UCS as a function of water-to-solid ratio, binder type, binder proportion, and tailings type based on fine particles included.

Fig. 5 shows that the water-to-solids ratio of the batch mixes strongly influence on the UCS value of HDPB. Assuming no aeration or sedimentation occurs during setting, the porosity (and hence density) of the cast is determined solely by the water-to-solids (*w/s*) ratio of the paste. Porosity in the cast leads to a reduction in the strength. Overall, UCS increases with decreased *w/s*, regardless of curing time. Also, the graph clearly shows the advantage of maximizing the backfill solids density. This increasing in UCS with tailings density as a function of *w/s* is due to higher binder consumption in unit volume.

Even a slight reduction in the cement content leads to a substantial cost saving. Thus, a series of test using different HDPB mixtures are carried out to study the effects of cement content on the strength characteristics of the backfill as a function of curing time (Fig. 6).

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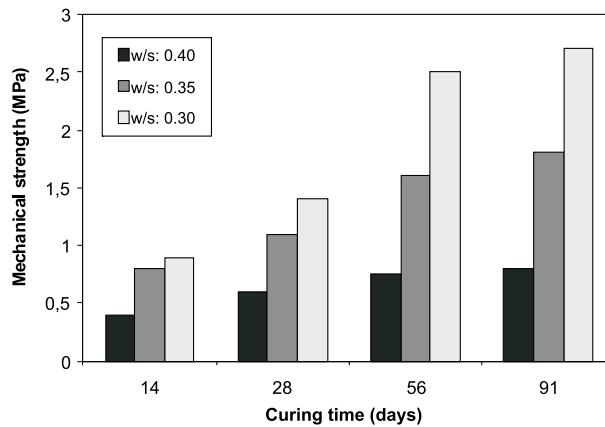


Fig. 5. Effect of water/solids ratio on the mechanical strength of HDPB samples

Rys. 5. Wpływ stosunku zawartości wody do cząstek stałych na wytrzymałość mechaniczną próbek podsadzki zestalanej

It is fairly evident from the figure above that UCS increases with increasing curing time and cement content as expected. The minimum UCS criterion for the stabilized materials, recommended by the US Environmental Protection Agency, is only provided from 6wt% binder samples at curing times of above 28 days.

Fig. 7 also demonstrates the results of UCS tests on the high-density backfills with diverse types of binder. In the tests, a constant binder content of 6% by weight was used. It was observed that the highest strength gain amongst the four binder agents used came from a mixture of ordinary Portland cement (OPC, 20wt%) and granulated blast furnace cement (GBFC, 80wt%). The binder agent consisting of pulverized fly ash (PFA, 50wt%) and OPC (50 wt%) gave low compressive strength at early ages (up to 28 days) but provided

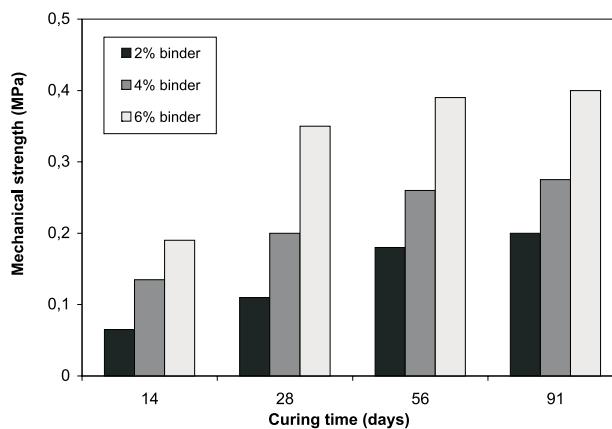


Fig. 6. Effect of cement content on the mechanical strength of HDPB samples

Rys. 6. Wpływ zawartości cementu na wytrzymałość mechaniczną próbek podsadzki zestalanej

higher long-term strengths. The Portland composite cement (PKC) produced lower UCS values than OPC agent. Overall, the reason why blended cements such as GBFC provided higher strengths could be explained by additives included as a pozzolanic material which helps to prevent sulphate attacks and secondary mineral formation during curing.

Fig. 8 shows the effect of fines fraction ($-20\text{ }\mu\text{m}$) on the strength development in HDPB. The samples were deslimed by using sedimentation method in order to prepare the coarse (15–35wt% solids), medium (35–60wt% solids) and fine (60–90wt% solids) tailings, based on classification recommended by Landriault (1995).

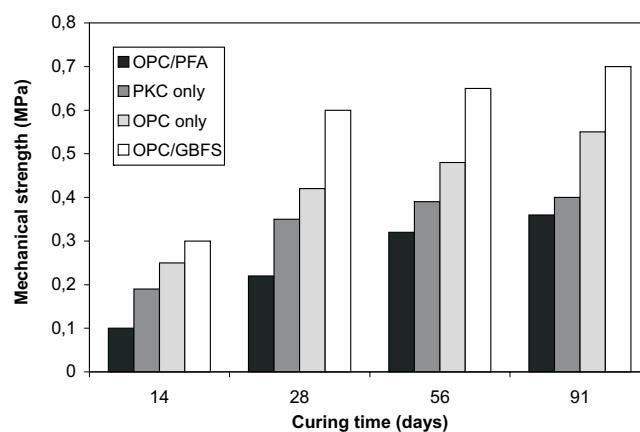


Fig. 7. Effect of binder type on the mechanical strength of HDPB samples
 OPC – ordinary Portland cement; PFA – pulverized fly ash; PKC – Portland composite cement;
 GBFC – Granulated blast furnace cement

Rys. 7. Wpływ typu spojwia na wytrzymałość mechaniczną próbek podsadzki zestalanej
 OPC – cement portlandzki zwykły; PFA – sproszkowane popioły lotne; PKC – kompozytowy cement portlandzki; GBFC – granulowany cement hutniczy

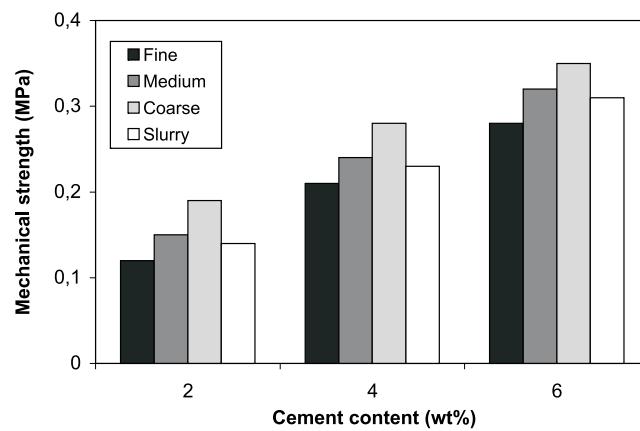


Fig. 8. Effect of tailings type on the mechanical strength of HDPB samples

Rys. 8. Wpływ typu odpadów przeróbczych na wytrzymałość mechaniczną próbek podsadzki zestalanej

It was shown that the highest strength was obtained with coarser tailings which contain 15% of –20 µm. In addition, the solids density and strength of HDPB decreases as the tailings become finer because the backfill is able to retain more water, and the water-to-cement ratio increases. The fine tailings backfills have low solids density and produce strengths which are similar to typical slurry tailings backfill.

Conclusions

When the surface disposal is mostly difficult mainly due to the geographical conditions or if mine tailings require treatment, it can become economic to use underground disposal; this is especially true when backfill is an essential part of the mining method. The challenge for HDPB is to offer a new alternative to existing waste management problems. The UCS tests and tailings characterization such as grain size distribution, mineralogical, chemical and rheological properties showed that tailings could be used for the aim of underground disposal (backfilling). Hence, the quantity of the tailings deposited at the surface would be reduced and/or eliminate the potential of environmental risk. Additionally, further detailed geochemical characterization should be done on these tailings to find out an efficient mine backfill design and disposal alternatives. In particular, the in situ tests are to become of great value in determining and predicting the environmental stability of the paste material.

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**UŻYCIE ZAGĘSZCZONEJ PODSADZKI ZESTALANEJ DO BEZPIECZNEGO SKŁADOWANIA ODPADÓW
GÓRNICHTWA MIEDZI I CYNKU**

Słowa kluczowe

Odpady przeróbcze, podsadzanie, charakterystyka, środowisko, stabilizacja, unieszkodliwianie

Streszczenie

Bezpieczne dla środowiska składowanie zasianczych odpadów przeróbczych górnictwa miedzi i cynku staje się ważnym czynnikiem ekonomicznym determinującym opłacalność działalności górniczej. W ostatnich latach stosuje się nowe podejście i opracowano nowe technologie, które pozwalają zakładom górniczym redukować i eliminować szkodliwe oddziaływanie górniczych odpadów przeróbczych na środowisko. Jednym z takich rozwiązań jest użycie zagęszczonej podsadzki zestalanej (HDPB), składającej się głównie z mieszaniny częstek

stałych (i cementu) z wodą, zawierającej między 70 a 85% wagowo suchej masy. Rosnące zastosowanie podsadzki zestalanej zwiększyło niezawodność, przy jednoczesnym zmniejszeniu kosztów produkcji i systemów transportu. Artykuł przedstawia potencjalne korzyści dla środowiska płynące z użycia podsadzki zestalanej w przypadku odpadów przeróbczych powodujących zakwaszanie. Zaprezentowano również studium przypadku podziemnej kopalni miedzi i cynku w północnowschodniej Turcji, które ilustruje uzyskane efekty.

USE OF HIGH-DENSITY PASTE BACKFILL FOR SAFE DISPOSAL OF COPPER/ZINC MINE TAILINGS**Key words**

Tailings, backfills, characterization, environmental, stabilization, disposal

Abstract

The safe environmental disposal of sulphide-rich copper/zinc mine tailings is fast becoming a major economic factor in determining the profitability of mining operations. There have been new approaches and better technologies practised in the recent years which allow the mining industries to reduce and/or eliminate the environmental impacts of harmful mine tailings. One of these approaches is the use of high-density paste backfill (HDPB) which is consisting mainly of a mix of solid particles (with the cement) and water, containing between 70% and 85% by dry weight of solids. The increased use of HDPB has improved the reliability, and has reduced the cost of the preparation and transportation systems. This paper focuses on the potential environmental benefits of using the HDPB when tailings are acid generating, and also provides a case study conducted in an underground copper/zinc mine in northeast Turkey in order to illustrate these benefits.