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Advances in reducing large volumes of environmentally harmful mine waste rocks and tailings

Introduction

Each year mines and mills produce large volumes of mine tailings and waste rocks. Surface mining usually causes more environmental damage than underground mining due to the use of lower grade deposits, the creation of large open voids, and the release of dangerous substances into the environment (Morin, Hutt 2001). The treatment and disposal of tailings produced by open pit and underground mining pose enormous challenges that require a multidisciplinary study approach, because they lead to environmental pollutions such as acidic water generation, tailings dam failures, and ground water contamination (Johnson, Wright 2003; Lottermoser 2007; de Andrade Lima et al. 2007). In the past, little attention was paid to either environmental management during operations or final rehabilitation, and tailings were deposited as dilute slurries. Due to disadvantages in terms of construction, use, and economics, this practice is being replaced by dry disposal techniques (Bussière 2007). Traditional wet tailings disposal has been problematic due to the risk of ground water contamination and the difficulty in rehabilitating storage sites. Tailings dams are at risk of failure due to leakage, instability, liquefaction, and poor design (Aubertin et al. 2003; Rico et al. 2008). Since 1960, there have been 77 major geotechnical instabilities of tailings dams worldwide, resulting in at least 471 human deaths, serious economical impacts, and untold environmental damage (WISE 2007).

In recent years, new approaches and technologies have been developed. These have significantly reduced dam failures and their subsequent environmental hazards and enabled

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mine operations to minimize wastes (Verburg 2002; Driussi, Jansz 2006). A common element of these techniques is that the tailings are thickened or de-watered prior to final disposal in dry form. Dry disposal using thickened, paste, or filtered tailings offer the major advantages of improved water and reagent recovery and decreased in situ tailings volumes (Bussi re 2007; Ritcey 2005). One new approach is the use of paste backfill, having the main advantages of lower operating costs and less waste material sent to tailings ponds (Benzazoua et al. 2004; Landriault 2006). Lower quantities of tailings decrease environmental hazards and defer future capital expenditures associated with tailings impoundments. However, these techniques can be costly and difficult to implement and control, and their mid- and long-term viability is in question. Improved waste management options would enable the mine industry to re-use total tailings. Hence, there is an urgent, ongoing quest for efficient tailings recycling methods.

The main goals of this review are to introduce emerging methods designed to reduce tailings and waste rock volumes stored in tailing dams or rock piles in order to minimize environmental hazards, and to present waste disposal methods that could potentially maximize tailings recycling. The specific goals are to 1) present an overview of the literature on tailings management, with a focus on tailings and waste rocks from mining operations and volume minimization; 2) discuss existing methods and approaches for efficient waste treatment and disposal; and 3) report on emerging technologies for waste minimization in the mining and mineral industry.

1. Mine waste materials

Mining and milling of metallic (e.g., Cu, Zn, and Au) and non-metallic ore deposits produce solid and liquid wastes with harmful contents. The mining industry uses various techniques to extract minerals from the earth's crust, whereas mineral processing separates valuable minerals from extracted ore (Morin, Hutt 2001; Johnson, Wright 2003; Aubertin et al. 2003). Fig. 1 presents a schematic view of a mining operation. Tailings and waste rocks discharged from mining and milling operations produce a potential source of environmental contamination. Safe disposal of mine wastes is the thorniest challenge in the mining industry. More than 90% of extracted ore is sent to waste storage facilities. These highly voluminous wastes are undesirable due to their surface toxicity, and they have no economic value for mines.

Fig. 2 presents a schematic diagram of integrated tailings management, including waste volume and environmental impact reduction. The extraction of mineral resources begins with surface and/or underground mining. Separation, ore dressing, and mineral extraction generate waste materials as well as processing wastes and discharges. Two types of mine wastes are generally produced: solids and liquids (Lottermoser 2007; Aubertin et al. 2003; Ritcey 2005). Solids include overburden, waste rock, tailings, spoils, sludge, and used equipment and tires, whereas tailings liquid or water includes mine and process waters, used

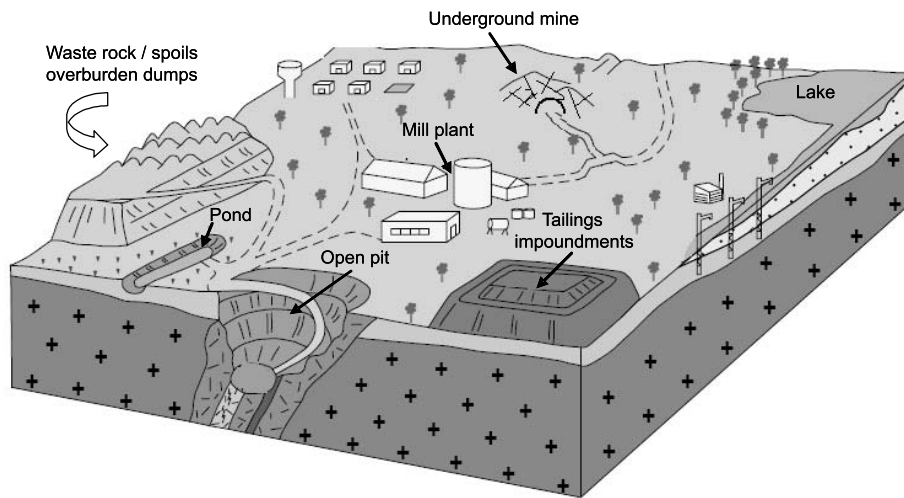


Fig. 1. A schematic diagram illustrating the various components of a mining operation

Rys. 1. Diagram przedstawiający składowe operacji górniczych

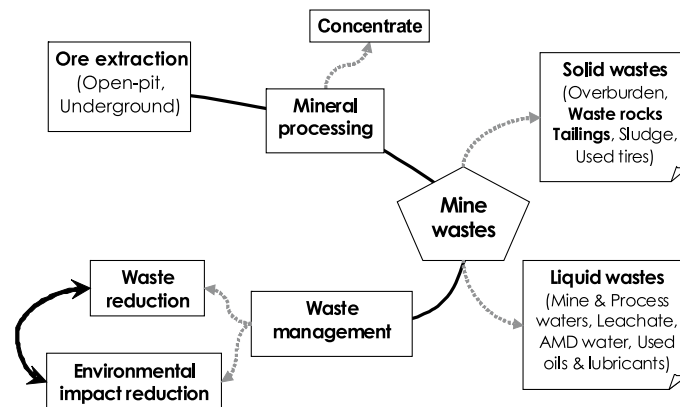


Fig. 2. Overview of an integrated mine waste management system

Rys. 2. Przegląd zintegrowanego systemu zagospodarowania odpadów górniczych

oils and lubricants, and acid mine rock drainage water. This study addresses tailings solids only, including mine tailings and waste rocks, in terms of waste minimization and environmental hazard reduction

1.1. Waste rocks

Waste rocks consist of unmineralized rocks and rocks containing mineralization that is too low grade to extract economically with existing technologies. The amount of mine-

-generated waste rocks depends largely on the shape of the ore body, the mining plan, and the total ore and waste production during the mining cycle. Many studies have examined the volume-mass relationships, geotechnical characteristics, transport properties, and geochemistry of waste rock piles (e.g., Lottermoser 2007; Bussi re 2007; Aubertin et al. 2003; Verburg 2002; Azam et al. 2007; Wickland et al. 2006). Results indicate that grain-size distribution varies greatly (uniformity coefficient C_u range: 8–650, curvature coefficient C_c range: 0.6–8). In general, water content (4–14 wt%) is relatively high in the upper 3 m of waste rock piles and lower ($3 \pm 1\%$) in subsequent benches up to 90 m. Desiccation of waste rock with depth is attributed to water escape through venting, water consumption during sulphide mineral oxidation, and low charge in a prevailing semi-arid climate. In situ dry density γ_d ranges from 1,500 kg/m³ to 2,100 kg/m³, for an average of 1,900 kg/m³. Mean temperature in the upper 3 m was found to be 30°C, decreasing gradually to about 10°C for a given waste pile (up to 90 m horizontally). Degree of saturation S_r , porosity n , and volumetric water content θ of waste rock samples were 0.26, 29.3%, and 0.08, respectively. Typical values for saturated hydraulic conductivity k_{sat} ranged from 1.9×10^{-5} to 3.4×10^{-3} cm/s, depending on porosity and grain size distribution of the studied samples. Due to the high angularity of particles, the drained angle of friction of samples is frequently greater than 30° and drained cohesion is typically close to zero. For the selected samples, saturated volumetric water content θ_s , air entry values ψ_a , residual volumetric content θ_r , and residual matrix suction ψ_r were 0.22–0.34, 0.02–3.42 kPa, 0.12–0.19, and 0.38–40.06 kPa, respectively.

1.2. Mine tailings

Tailings, made up of solids and liquids, are the products that remain after metals have been extracted from ore by physical and chemical techniques. Solids, typically in the fine sand and silt range, are discharged (at a solid content from 25% to 45%) with spent process water into tailings dams. Water present at the surface of tailings dams and in the pores of tailings solids is called tailings liquid. Tailings liquid tends to contain high concentrations of process chemicals. Depending on the material and milling process, tailings often show a grain size distribution from 0.01 to 1 mm and a particle density from 1.5 to 4. Many studies undertaken on mine tailings (Lottermoser 2007; Bussi re 2007; Aubertin et al. 1996, 2003; Shamsai et al. 2007) found that the saturated hydraulic conductivity k_{sat} of homogenized tailings varied from 10^{-4} to 10^{-6} cm/s for fine-grained tailings and from 10^{-2} to 10^{-4} cm/s for coarse-grained tailings. The angle of internal friction ranged from 27° to 41° and the void ratio e was from 0.5 to 1.7. Moreover, mine tailings showed only slight plasticity, usually with a liquid limit w_L below 40 and a plastic limit w_p from 0% to 15%. Relative density D_r of solid particles was from 2.6 to 4.5. From compaction tests, optimal water content w_{opt} was found at from 10 to 20% with an equivalent dry unit weight γ_d from 14.6 to 20.1 kN/m³. Consolidation parameters for hard rock mine tailings were also determined. Results showed that, depending on tailings type and sample, the compression index C_c varied from 0.05 to 0.3

and the recompression index C_{cr} varied from 0.003 to 0.03. The higher C_c values indicated a higher initial void ratio e_0 . Overall, the consolidation coefficient c_v for coarse-grained tailings and fine-grained tailings was from 10^2 to 10^{-1} cm²/s and from 10^{-1} to 10^{-3} cm²/s, respectively.

2. Waste minimization techniques

Each year the Canadian mining industry produces approximately 500 million cubic meters of mine tailings and waste rocks—more than enough to cover a 900 ha area (Aubertin et al. 2003). Tailings should be reduced or securely disposed of to minimize contact with the environment and promote sustainable development. Large quantities of mine wastes cannot be eliminated. However, the volumes and environmental effects of

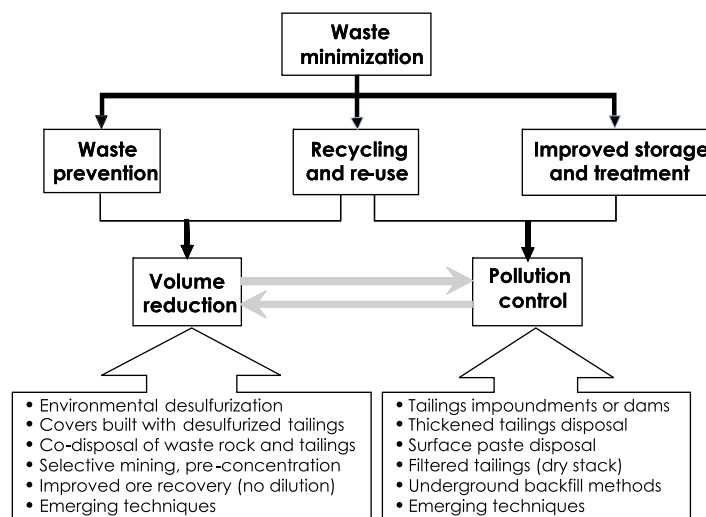


Fig. 3. Flow chart illustrating the hierarchy of waste management for volume reduction

Rys. 3. Schemat ilustrujący kolejność zagospodarowywania odpadów dla redukcji ich objętości

mine wastes can be reduced using waste hierarchy methods (Yilmaz 2007). The most efficient hierarchy method is to first reduce tailings production, then recycle and reuse tailings where possible. Fig. 3 presents a flow chart of the different components of waste volume reduction. Numerous methods have been developed to reduce tailings volume after milling, spurred by cost competitiveness and environmental legislation, changing mill practices, and the introduction of cost-effective applications. Tailings and waste rocks in various forms can be evaluated for both surface and underground mining operations. The next section presents a brief discussion of these emerging waste reduction techniques.

2.1. Waste prevention

Waste prevention is the most desirable method of volume reduction. When the amount of generated wastes is reduced through improved manufacturing methods, disposal becomes simpler.

Ore dilution: The term “dilution” refers to the any waste material within the mining block, including barren and subgrade rock and backfill. The addition of waste rock decreases ore grade and increases mined tonnage for a given geological reserve. Dilution can be divided into three general categories: internal (planned), external (unplanned), and ore loss (Henning, Mitri 2007). Ore dilution reduces the profitability of mining operations by lowering the amount of minerals or metal that can be produced from each ton of processed ore. The economic impact of dilution is due to costs associated with the mucking, haulage, crushing, hoisting, milling, and treatment of wastes or low-grade rock, which displace profitable ore and diminish processing capacity. Approximately 51% of all ore production by underground metal mines in Canada is derived directly from open stoping operations. Henning and Mitri (2007) reported that 40% of open stope operations suffered dilution, usually varies from 10% to 20%. The stages that contribute to dilution include ore body delineation, design and sequencing, stope design, drilling and blasting, and production.

Selective mining: The objective of selective mining is to obtain relatively high-grade ore. This entails the use of a much more expensive stoping system with high exploration and development costs. However, it allows operators to reduce ore loss due to waste and ore dilution. Selectivity governs mining losses and dilution. Bulk mining tends to be applied to large ore bodies where selectivity has less impact. Selective methods entail smaller volumes of ore excavation that closely follow complex ore outlines, tending to reduce productivity (Scoble et al. 2003). Fig. 4 shows the factors that control selective mining operations. Generally, opencast mining does not allow the same degree of selectivity as underground mining; there is less flexibility to change sequencing or select ore body areas to the mine. The beneficial effect of reducing dilution using selective mining is proportionately greater in narrower ore bodies. Selective mining provides opportunities to implement proactive waste management strategies.

Mineral pre-concentration: Traditionally, ore was transported from underground mines to surface mineral processing plants, where valuable minerals were separated from the tailings. However, processing the ore underground would reduce the costs of bringing ore to the plant and returning backfill waste to underground voids. As mines become deeper, cost savings from underground processing become more significant. Accordingly, integrated mining and recovery systems, such as underground ore processing/pre-concentration, can minimize the amount of acid-generating tailings along with tailings handling and transport. The most noteworthy case is the Andina Mine in Chile, where the ore processing plant was built underground due to extreme climatic conditions (Klein et al. 2002). The main pre-concentration technology is dense media separation (DMS), used to separate metal-rich sulphides from siliceous gangue particles ranging in size from 0.25 to 500 mm.

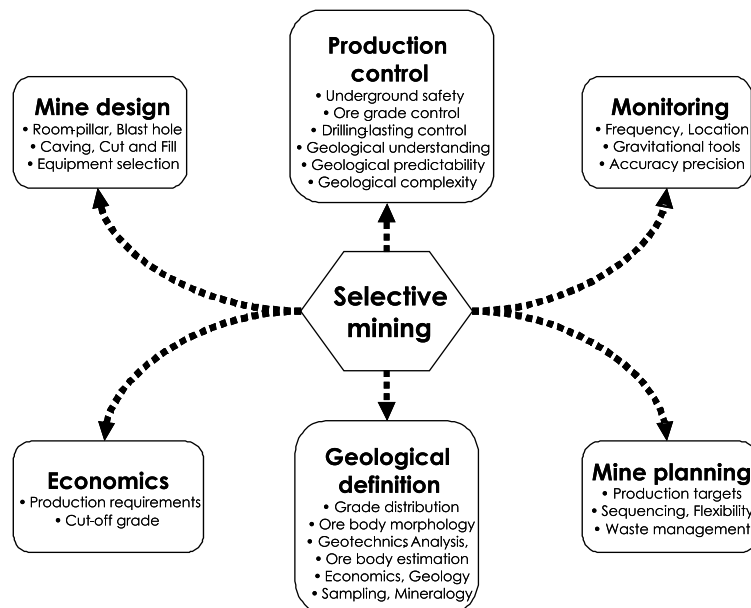


Fig. 4. Factors controlling the implementation of selective mining (modified from Scoble et al. 2003)

Rys. 4. Czynniki warunkujące wprowadzenie selektywnego wydobycia (zmodyfikowany)

The key benefits of pre-concentration are reduced environmental concerns, smaller footprint for surface processing facilities, waste minimization, and lower capital and operating costs.

2.2. Recycling and reuse

One way to minimize waste volumes and environmental hazards is to use mine back-filling. This method has led the mining industry to place greater emphasis on maximizing the return of tailings to underground openings (stopes) as backfill. The three main types of backfill used at most modern mines are rock, hydraulic, and paste. The choice among backfill types is site-specific and depends on the requirements of the mining operation. The three types of backfill have different properties and present various advantages and disadvantages (Table 1). In Canadian mines, backfills placed in underground stopes contain 64% waste rocks (36% cemented and 28% uncemented), 32% tailings (27% cemented and 5% uncemented), and 4% uncemented sand and gravel (Hassani et al. 2007).

Rock fill: For over 80 years rock fill has been used in the mining industry to provide underground support. With its ready availability at mines, rock fill provides direct benefits by improving bulk-mining practices such as pillar recovery and void-filling operations. It can be used in the form of cemented or uncemented material. Cemented rock fill (CRF) is now being used effectively in many mines worldwide (Stone 2007). The mechanical strength development of CRF materials depends on a number of factors, including the grading and

TABLE 1

Comparison of underground mine backfill methods (Landriault 2006)

TABELA 1

Porównanie metod podsadzkowych w górnictwie podziemnym

	Rock (aggregate) backfill	Hydraulic (slurry) backfill	Paste (high-density) fill
Placement state	dry	60–75wt% solids	75–85wt% solids
Transport system	raise, truck, separate cement	borehole/pipeline via gravity	borehole/pipeline via gravity
Cemented vs. uncemented	cemented or uncemented	cemented or uncemented	cemented only
Water/cement-w:c ratio	low w:c ratio, high binder UCS	high w:c ratio, low binder UCS	low w:c ratio, low binder UCS
Placement rate	100 to 400 tons/hour	100 to 200 tons/hour	50 to 200 tons/hour
Segregation	stockpile segregation	slurry settlement segregation	no segregation
Stiffness	high stiffness	low stiffness	low or high stiffness
Bulkheads	not necessary	expensive	inexpensive
Water run off	no water run off	excessive water run off	negligible water run off
Capital/operation costs	moderate / high	low / lowest for uncemented fills	high / lowest for cemented fills

angularity of backfill particles, cement content, rock type, placement methods, segregation, and water content. To produce a blended rock fill with better quality control and decreased risk of segregation, sand or tailings are added to waste rocks. CRF typically has 4–8 wt% cement content, 0.9–3.3 water-to-cement ratio, 1.9–2.5 g/cm³ grain density, 1.6–18 MPa strength, and 17–35% porosity (Hassani et al. 2007; Stone 2007).

Hydraulic fill: The hydraulic fill placement method was developed in the 1940s and has become the most widely used backfill method in the mining industry today. It consists of mixing an appropriate-sized granular material with water on the surface to produce a slurry that can be transported and distributed underground through boreholes and pipelines. Permeability and percolation rate are crucial properties for drainage and liquefaction. Researchers have attempted to numerically model hydraulic filling of mining stopes and have analyzed pore pressures, flow rates, and hydraulic gradients (Rankine et al. 2006). Hydraulic fills commonly have permeability from 1 mm/h (3×10^{-5} cm/s) to 40 mm/h (1×10^{-3} cm/s), specific gravity of 2.8–4.5, porosity of 48–70%, water content of 17–34%, and relative density of 50–80%.

Paste backfill: The use of paste backfill has gradually gained ascendancy over hydraulic and rock fills worldwide due to the major reduction (up to 60 wt%) in the amount of tailings

stored on the surface, lower rehabilitation costs, and superior environmental performance (Landriault 2006). Essentially, paste backfill is an engineered material consisting of a mixture of filtrated wet mine tailings (75–85 wt% solids), binding agent (3–7 wt%) to provide cohesion, and water to reach the desired consistency (6–10" slump) so that the paste can be transported from the backfill plant to the mine stopes. In general, at least 15 wt% of the granular material particles must be finer than 20 μm for the colloidal properties of tailings to retain sufficient water to form a paste. The preparation of any paste backfill and its corresponding intrinsic properties depend not only on binder type and content, water content, mineralogy, and grain size distribution of the tailings, but also its pore water chemistry and mineral additives. A number of scientific studies (Benzaazoua et al. 2004; Belem, Benzaazoua 2008; Fall et al. 2008; Yilmaz et al. 2009; Ercikdi et al. 2009) have investigated a number of laboratory and in situ backfill samples to determine the effects of intrinsic factors (i.e., tailings, binder, and mix water) and extrinsic factors (i.e., curing under pressure; backfill hardening conditions; stope dimensions, inclination, and geometry; boundary conditions; drainage or bleeding of excess pore water; curing temperature; self-weight; and time-dependent consolidation).

2.3. Improving storage and treatment

Another way to minimize waste volumes is to improve the final disposal and monitoring methods. If wastes cannot be recycled or reused for volume reduction, they can be treated and/or disposed of on the surface at a specific solid content. However, these methods need careful monitoring due to their potential for causing severe environmental damage.

Tailings impoundments: The great majority (almost 100%) of mine tailings is generally pumped to large surface impoundments-also called tailings dams-as slurry with a solid content of 25 wt% to 45 wt%. There are more than 3,500 tailings dams worldwide (WISE 2007). Tailings impoundments should provide safe and economical storage for the required tailings volume and enable the construction and operation of pollution control facilities. Tailings dams are generally classified into four different types: cross-valley, valley bottom, valley side, and ring, depending on the location (Lottermoser 2007; Aubertin et al. 2003). The tailings themselves, consisting mainly of the sand-size fraction, are often used to construct the embankments. Table 2 compares surface impoundment embankment (tailings dam) types. Tailings dams can have upstream, downstream, or centerline embankment types. Over 50% of tailings dams around the world are built with an upstream-type embankment, generally with 5H:1V embankment slope throughout its opening life. Each embankment construction method has different advantages and disadvantages in terms of construction, usage, economics, and seismic stability (Lottermoser 2007).

Fig. 5 presents a photo of an upstream embankment construction method. This embankment construction method uses the earlier constructed embankment material in order to construct a new containment dike on the near beach of the deposited tailings. This method of construction has supported the various methods of tailings deposition utilized over the near

TABLE 2

Comparison of surface impoundment embankment types (WISE 2007)

TABELA 2

Porównanie typów powierzchniowych składowisk odpadów

	Upstream	Downstream	Centerline
Mill tailings requirements	≤40–60% sand in tailings. Low density desirable to help segregation	suitable for any tailings type	sands or low-plasticity slimes
Discharge requirements	peripheral discharge and well-controlled beach necessary	varies according to design details	peripheral discharge of at least nominal beach necessary
Water storage suitability	not suitable for significant water storage	good	not good for stable storage. Temporary storage acceptable with proper design
Seismic resistance	poor in high seismic areas	good	acceptable
Raising rate restrictions	≤4.5–9 m/yr most desirable ≥15 m/yr can be hazardous	none	height restrictions for individual raises may apply
Embankment fill requirements	natural soil, sand tailings, or mine tailings	sand or tailings if production rates are sufficient, or soil	sand or tailings if production rates are sufficient or natural soil
Relative costs	low	high	moderate

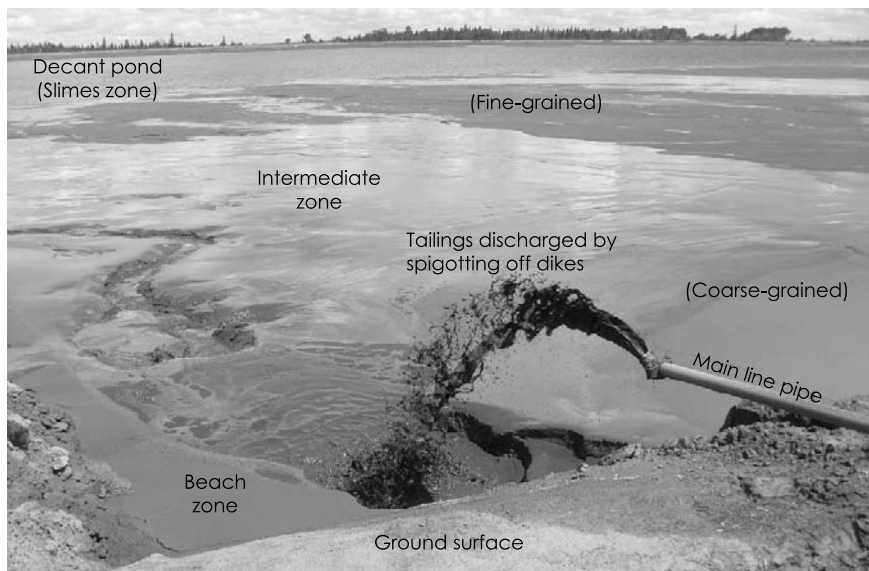


Fig. 5. View of the upstream method of tailings dam construction

Rys. 5. Metoda upstream budowy składowiska odpadów przeróbczych

100-year life of the facility. Tailings deposition in the impoundment uses a combined single point discharge with a peripheral spigotting system. The deposition of the fine-grained sands, silts, and clay-sized materials underwent some degree of segregation during deposition. The coarser grained materials (fine sands) falling out of the slurry in the near vicinity of the discharge point (the beach zone) and the finer grained silts and clay sized materials depositing within the impoundment and process water decant collection area. The tailings materials were generally deposited in a loose, saturated state, entraining substantial amounts of process waters.

The data provided by WISE (2007) indicates that over 77 geotechnical instabilities of tailings dams have occurred in the mining industry since 1960. Tailings dam failures have caused major environmental damage, high economic costs, and loss of human lives. The causes of failures include liquefaction, seismic damage, overtopping, foundation failure, rapid increase in dam wall height, excessive water levels, and seepage (Aubertin et al. 2003; Rico et al. 2008). Fig. 6 presents an aerial view of the failed Aznalcóllar tailings dam in Spain. This tailings dam enclosed an area of 200 ha and was 27 m in height, ~2 km long EW, and 1 km long SW. An estimated 1.5×10^6 m³ of tailings solids and 5.5×10^6 m³ of acidic water (pH: 2–4) were lost. The thickness of lost tailings was ~4 m near the mine site. To prevent tailings dam failures, thorough geotechnical studies of tailings sites must be conducted, including a risk assessment of local natural hazards such as earthquakes, landslides, and disastrous meteorological events (Rico et al. 2008). Monitoring of dam



Fig. 6. Photo showing the failure of the Aznalcóllar tailings dam (Rico et al. 2008)

Rys. 6. Fotografia przedstawiająca zniszczenie tamy składowiska odpadów przerobczych Aznalcóllar

structures is also vital to prevent environmental pollution and tailings dam failures and spillages.

Thickened tailings disposal: This technique was initially used at the Kidd Creek Mine to reduce the environmental risks associated with traditional tailings dykes and facilitate mine closure. It was first introduced by Robinsky (1999) with the aim of building a self-supporting ridge or hill of tailings to lessen the necessity for confining dams, thus eliminating the need for a settling pond. The thickened tailings remove a large proportion of water from the tailings prior to final storage. The tailings, which contain a high slurry density of 45–70% solids, are discharged to the disposal area from spigots on a central ramp. The tailings slurries present non-Newtonian flow behavior and have a yield stress τ_y of 10 to 300 Pa. Slope angle typically ranges from 1° to 3.5° . Table 3 presents the main advantages and uncertainties of thickened tailings. In the future, as environmental regulations tighten and the mining industry comes under increasing pressure to become more sustainable, the benefits of dry tailings disposal, including paste and dry stack, will likely outweigh the drawbacks.

Surface paste disposal: Surface paste disposal evolved from an earlier backfilling technology applied to excavated voids in underground mines. The required dewatering technology has been driven by the demand to produce lower water content tailings. Paste disposal results in the elimination of ponds, reductions in containment dams, and a significant decrease in water volumes discharged into tailings basins. The advantages and disadvantages of paste tailings are presented in Table 3. Paste is deposited as thickened tailings to form conical piles that generate slope angles of $3\text{--}10^\circ$. This system has been effectively used at the Bulyanhulu Mine in Tanzania. Tailings have shear strength of 5 to 60 kPa, average void ratio e of 0.84, and degree of saturation S_r approaching 100%. Fig. 7 depicts the relationship between pulp density and storage volume for different tailings disposal methods. Martin et al. (2005) also showed that for tailings with 75 wt% solids, the required storage volume is 2.2 to 3.7 times lower than for traditional tailings.

Filtered tailings (dry stack): Tailings can be dewatered to less than 20 wt% water content using large capacity vacuum and pressure belt filter technology. Dewatered material can be transported by conveyor or truck and placed, spread, and compacted to form an unsaturated, dense, and stable tailings stack (known as dry stack) that requires no tailings retention pond (Davies, Rice 2001). Fig. 8 presents a diagram of pumpable and non-pumpable tailings continuum. The costs of filtering and transporting filtered tailings are higher than those for traditional disposal methods. However, in very arid regions where water conservation is a major issue, or in very cold regions where water handling is very difficult in winter, this technique has significant advantages (see Table 3).

This system was first applied to the La Coipa silver/gold mine in the Atacama region of Chile. A daily tailings production of 18,000 t is dewatered by belt filters, conveyed to the storage site, and stacked with a radial, mobile conveyor system. The second implementation, the use of truck transport, was at Falconbridge's Raglan nickel operation in the Arctic region of northern Quebec. The Green Creeks mine in central Alaska recently introduced this

TABLE 3

Comparison of densified mine waste types (Bussi re 2007)

TABELA 3

Por wnanie typ w zagęszczonych odpad w g rniczych

	Thickened tailings (TT)	Paste tailings (PT)	Filtered tailings (FT)
Objective	<ul style="list-style-type: none"> improve physical and chemical stability 	<ul style="list-style-type: none"> improve physical and chemical stability 	<ul style="list-style-type: none"> improve physical stability
Principle	<ul style="list-style-type: none"> increase solid content of tailings (50% < P < 70%) elimination of the pond minimizes water handling issues and reduces pore pressures in the impoundment densified tailings eliminate the need for large retaining dikes no significant segregation occurs during deposition, which creates an homogenous disposal area greater shear strength of the tailings is achieved due to the lower initial water content 	<ul style="list-style-type: none"> increase solid content of tailings (70% < P < 85%) 	<ul style="list-style-type: none"> increase solid content of tailings (P > 85%)
Advantages and benefits	<ul style="list-style-type: none"> TT are relatively easy to pump ($10 < t_y < 300$ Pa with no measurable slump value) low k_{sat} which reduce seepage and contaminant migration high Sr reduces oxidation reactions in the stack desiccation can increase the strength of the TT 	<ul style="list-style-type: none"> fairly low k_{sat} which reduces seepage and contaminant migration high S_r reduces oxidation reactions in the stack (particularly in humid climate) hydro-geological and environmental properties can be improved by adding a binder 	<ul style="list-style-type: none"> higher strength and lower n than tt and pt techniques water management simplified (only run-off to manage) smaller footprint for a similar tailings tonnage less prone to liquefaction and settlement
Disadvantages and uncertainties	<ul style="list-style-type: none"> does not completely eliminate the AMD problem evolution of properties with time (e.g., due to oxidation and desiccation) can be complex TT are still prone to liquefaction in most climatic conditions difficult to predict the angle of repose (usually between 2 and 6%) cracking may affect physical / chemical stability of the stack 	<ul style="list-style-type: none"> more viscous than TT ($100 < t_y < 1000$ Pa with slump value between 200 and 275 mm) rheological behavior is complex deposition needs to be optimized cracking may affect physical / chemical stability 	<ul style="list-style-type: none"> higher operational costs FT have a relatively low S_r, which increases oxygen availability for oxidation reactions (compared to TT and PT)

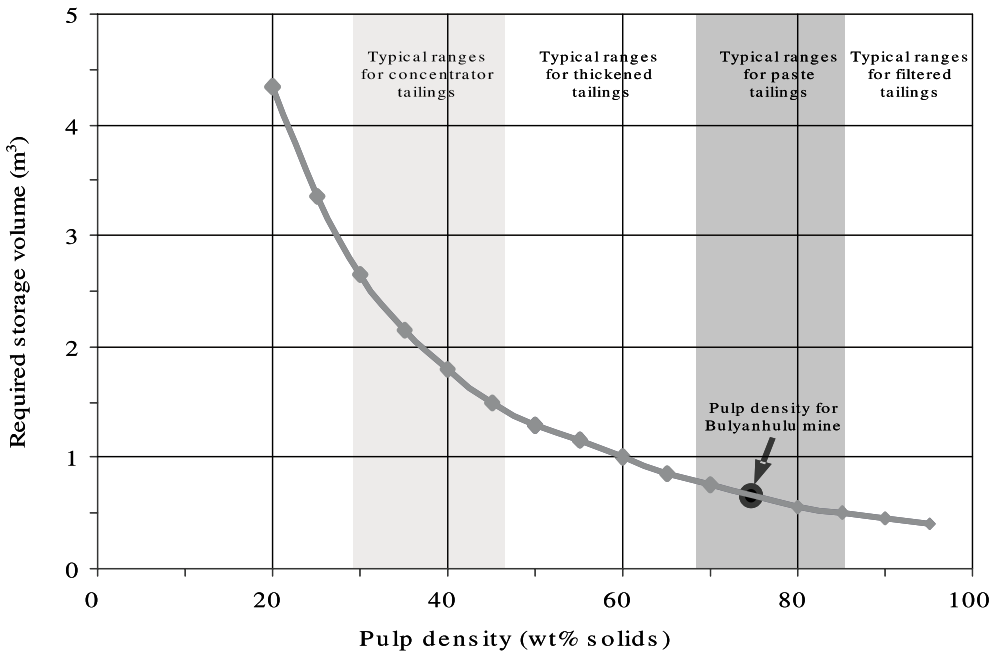


Fig. 7. Relationship between required storage volume and pulp density (modified from Martin et al. 2005)

Rys. 7. Związek pomiędzy wymaganą pojemnością a gęstością składowanej pulpy (zmodyfikowany)

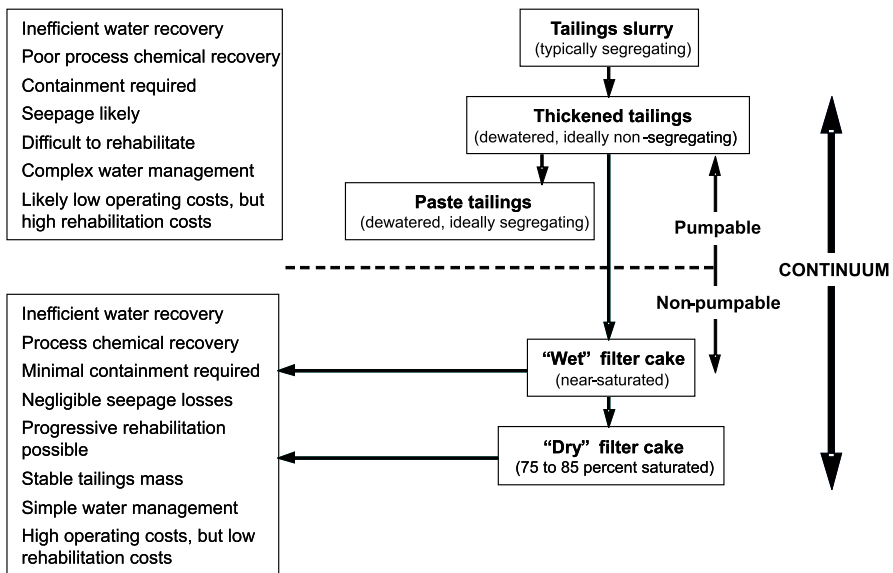


Fig. 8. Relation between pumpable and non-pumpable tailings continuum (modified from Davies and Rice, 2001)

Rys. 8. Zależności pomiędzy możliwymi do przepompowania a niemożliwymi do przepompowania odpadami (zmodyfikowany)

technology, discharging approximately 40% of its tailings into a surface storage area and using the remaining 60% for underground backfilling.

3. Emerging techniques

3.1. Environmental desulphurization

In recent years environmental desulphurization has gained popularity in the mining industry as an attractive tailings management alternative. It essentially consists of separating an adequate quantity of sulphides (based on neutralization potential) from concentrator tailings using bulk flotation (Bussi re 2007; Benzaazoua et al. 2008), in which the two different fractions (sulphide concentrate and desulphurized tailings) are generated separately. Desulphurized tailings can be used in an engineered cover to prevent acid mine drainage (AMD), while sulphide tailings concentrate, with its high acid generating potential, is employed as raw material for underground paste backfill. However, sulphide-rich tailings can negatively affect the short- and long-term strength and stability of cemented paste fill if binder types and/or combinations are not properly selected (Benzaazoua et al. 2004; Hassani et al. 2007). The use of sulphide concentrate in underground backfilling reduces the amount of tailings that must be sent to surface disposal facilities. This clearly lessens both the environmental hazards and capital expenditures of the surface tailings facility. Fig. 9 schematically illustrates the environmental desulphurization method. The technical and

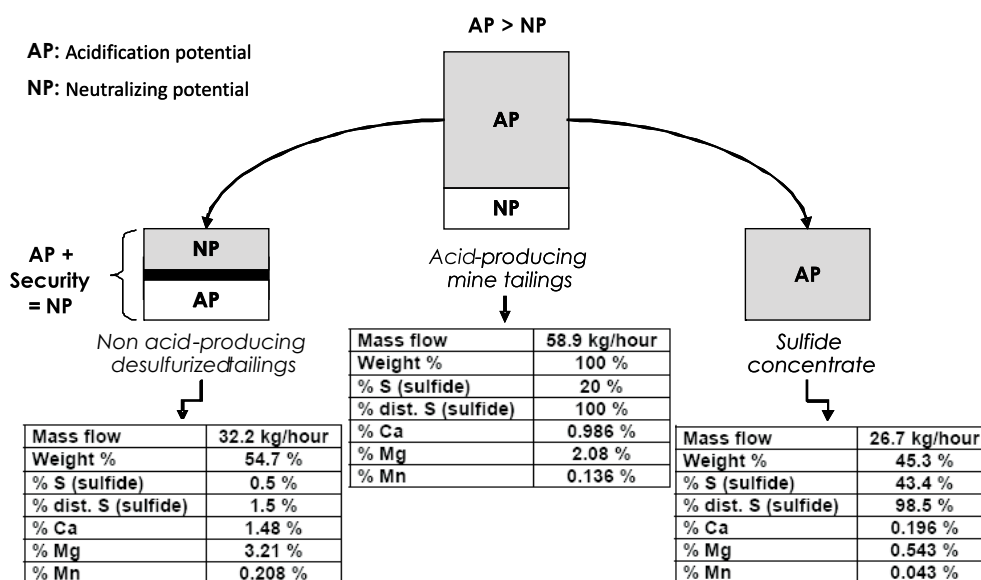


Fig. 9. Schematic view of a desulphurization system based on mass balance (modified from Bois et al. 2005)

Rys. 9. Schemat systemu odsiarczania opartego na bilansie masy (zmodyfikowany)

economic feasibility of environmental desulphurization have also been demonstrated by a number of laboratory studies on mine tailings with different sulphide contents (Benzaazoua et al. 2008; Demers et al. 2008).

This technique can be used as an integrated management method during the life of the mine and to facilitate rehabilitation at the end of mine life. A recent in situ study (Bois et al. 2004) of a mine site with a small-scale flotation plant confirmed the feasibility of desulphurized mill tailings. One of the main benefits of desulphurization is that it can increase the net neutralization potential NNP (neutralizing potential NP minus total acid generating potential AP) of low-sulphide tailings, as the removal of sulphide minerals essentially increases the relative proportion of neutralizing elements.

3.2. Covers built with sulphide-free tailings

Covers with capillary barrier effect (CCBE) have been successfully used to rehabilitate tailings dams. For instance, low-sulphide tailings can be integrated as moisture-retaining material into a multi-layer or single-layer cover, especially when the water table position can be controlled (Bussière 2007). Engineered cover systems consisting of non-acid generating tailings can isolate and control oxidation and leaching effects. Multi-layer CCBEs employ unsaturated soil properties to create capillary barrier effects that maintain one of the layers at constant high saturation. This high saturation impedes gas advection and diffusion, making the moisture-retaining layer an efficient oxygen flow barrier. By limiting oxygen flux, the cover limits AMD generation, because oxygen is a constitutive element in sulphide mineral oxidation. A detailed description of the use of desulphurized or sulphide-free tailings in both in situ and laboratory trials is given in the literature (Aubertin et al. 2003; Demers et al. 2008; Bois et al. 2005; Bussière 1999). In addition, a number of numerical modeling studies have simulated the performance of covers made with sulphide-free tailings (Bussière 1999; Fal et al. 2005). It was concluded 200in oxidation reduction by consuming a fraction of the oxygen that migrates through the cover. Finally, it is worth mentioning that the residual sulphide content in tailings used as cover material can improve its performance. However, it is critical to ensure that low-sulphide tailings do not generate AMD over time.

3.3. Co-disposal of tailings and waste rocks

As an alternative, co-disposal of mine-produced tailings and waste rocks can minimize the volume or footprint required to store the separate waste streams, and offers a considerable reduction in long-term environmental liability, land disturbance, and closure costs. Mines have used different co-disposal methods with varying mixing and placement methods: co-mixing, co-mingling, and co-placement (Bussière 2007; Aubertin et al. 2003; Wickland et al. 2006; Wilson 2001). The objective of co-disposal, in which tailings and waste rock are combined as a homogenous mix, is to acquire better mix properties than those of the materials

separately, and the greatest challenge is to design the ideal cost-effective mixing ratio. The optimal mixture ratio is based on water content, hydraulic conductivity, porosity, void ratio, saturation degree, strength, stability, density, cohesion, friction angle, consolidation, liquefaction, and compression.

Co-mixing: In this approach, tailings and waste rocks are mixed together before transport to a disposal site. In combined waste rock–tailings storage, tailings are introduced into voids of waste rocks that are dumped in thin lifts, or rock is introduced into soft, unconsolidated tailings particles. It was shown by a number of researchers (Aubertin et al. 2003; Wickland et al. 2006; Wilson 2001) that the influence of tailings and waste rocks on saturated hydraulic conductivity k_{sat} and water-retention properties for a mix ratio (waste rocks to tailings) ranged from 20:1 to 1:1. Test results showed a typical k_{sat} value of 1×10^{-5} to 2×10^{-5} cm/s for non-compacted co-mixtures and 5×10^{-6} cm/s for compacted mixtures, confirming that co-mixed materials have lower k_{sat} values (typically from 10^{-3} to 10^{-4} cm/s) than waste rocks (Martin et al. 2005).

Co-mingling: This is a form of co-disposal in which tailings and waste rocks are transported separately and allowed to mix together in the disposal site after deposition. Layered co-mingling helps to reduce oxygen flux and water infiltration, with the aim of controlling AMD production. It was shown that the effect of fine-grained tailings layers on water quality is not significant when tailings layers are horizontal (Aubertin et al. 2003; Wickland et al. 2006). However, when fine layers are inclined at 5%, water is diverted by the capillary barrier effects created at the interface between coarse waste rock and tailings. In an effort to optimize this method, various parameters of layered co-mingling are under investigation: distance between layers; thickness and properties of tailings layers; layer angles; particle size compatibility of tailings and waste rocks; and the effect of climatic conditions on performance.

Co-placement: In this type of co-disposal, tailings and waste rocks are transported separately and mixed together immediately prior to or on placement in the storage site. The physical stability of tailings dams and their drainage capability is improved by adding waste rocks to tailings. The improved drainage helps increase the consolidation rate and tailings density, which improve the geotechnical properties of the tailings dams (Aubertin et al. 2003). Other parameters to consider are tailings thickness, critical conditions induced by tailings liquefaction, and grain size compatibility of the materials. Co-placement helps reduce acidic mine waters, and can be used in underground mines to eliminate the need for waste rock piles at the surface.

3.4. Geotextile tube dewatering

Geotextile tube dewatering is an innovative system used to contain and dewater high water content waste materials in the form of slurries or sludges. These tubes have been used for the past three decades for dewatering sediments in sandbags, concrete forms, large soil and aggregate filled bags, tailings bags, and hydraulically or mechanically filled tubes

(Newman et al. 2004). A permeable tube with diameters ranging from one to several meters enables the water to drain but retains the tailings material inside. Recently more stringent environmental concerns together with a general decrease in available disposal areas have created the need for superior dewatering technologies for sustainable tailings management. Geotextile tubes or containers are an emerging technology that offers the significant advantages of rapid disposal of large volume of wastes, ease of construction, suitable placement, high efficiency, low cost, reduced environmental hazards, and labor savings. Newman et al. (2004) reported on this novel tailings management at the Stratoni Mine in

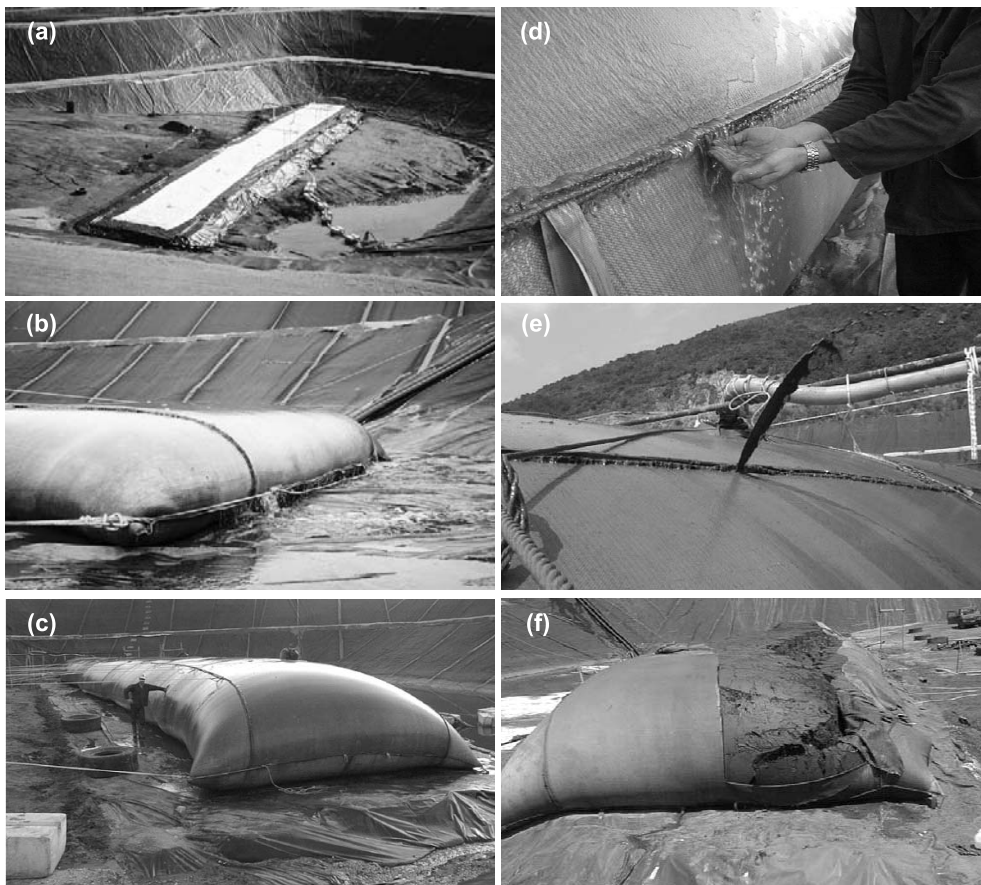


Fig. 10. A geotextile dewatering technique for tailings disposal

- (a) layout of geotextile tube; (b) dewatering in progress; (c) ongoing dewatering through a growing tube,
 (d) excellent filtrate quality from tube dewatering; (e) small hole in tube;
 (f) dewatered tailings ready for excavation (modified from Newman et.al. 2004)

Rys. 10. Technologia geowłókninowych rur odwadniających do składowania odpadów przeróbczych:

- (a) ułożenie geowłókninowej rury; (b) odwadnianie w toku; (c) proces odwadniania powiększa rurę,
 (d) doskonała jakość filtratu z rury odwadniającej; (e) mały otwór w rurze;
 (f) odwodnione odpady gotowe do wyjęcia

Greece, which uses large-scale geotextile tubes to dewater tailings fines and mine water sludge (Fig. 10). Geotextile tubes 60 m long, 14.7 m in diameter, and 2.5 m in height were used for just 10-day dewatering of tailings. After dewatering, the material contained in the tubes had a solids content of 65 wt% compared to an initial input of 27 wt%. Dewatering cost was about \$1.20 per cubic meter of slurry received from the concentrator. Another system used for tailings dewatering is electrokinetic geosynthetics (see Fourie et al. (2007) case study).

3.5. Use of tailings for shotcrete operations

Mine waste tailings can also be reused in shotcrete, which is generally used to provide structural and ground support in underground metalliferous mines. Replacing aggregates used in conventional shotcrete with tailings benefits mining operations in many ways: it provides basic ground support material, reduces operating, and more importantly, reduces the volume of mine wastes stored at the surface. From this perspective, Zou and Sahito (2004) performed a laboratory analysis of the strength properties of shotcrete made from tailings to assess their suitability as shotcrete material. Fig. 11 presents the compression and flexural testing results. In general, compressive strength does not meet the Canadian and United States required strengths of 20–30 MPa at 7 days. However, flexural strengths are very satisfactory. With 1.2~1.6% fibers by mass, a flexural strength of 7 MPa is achieved at 28 days, exceeding the commonly specified value of 5 MPa (Rispin, Brooks 2000). To improve the quality of shotcrete manufactured from tailings, further tests need to be conducted: long-term performance related to strength, flexural testing with different recipes, tailings with different sulphide contents as aggregate, and different binder types and contents.

3.6. Other techniques

A few other mine waste recycling methods are used to reduce tailings volume and storage requirements for either industrial or environmental purposes. These include 1) the use of mine tailings as an additive in Portland cement (Celik et al. 2006); 2) the use of wastes as a soil additive in road construction, as a mineral filler material, and in the manufacture of bricks and lightweight-aggregate blocks (Carpenter et al. 2007); 3) the use of coal tailings as a low-grade fuel and backfill material (Karfakis et al. 1996); 4) the use of tailings to control acid mine drainage and mining-induced subsidence (Nehdi, Tariq 2007); and 5) the use of treatment sludge in the paste backfill (Benzaazoua et al. 2006). Moreover, when ore processing and smelting operations are located within industrial regions, there may be synergistic opportunities for using waste streams from one industrial process as a valuable input to another one.

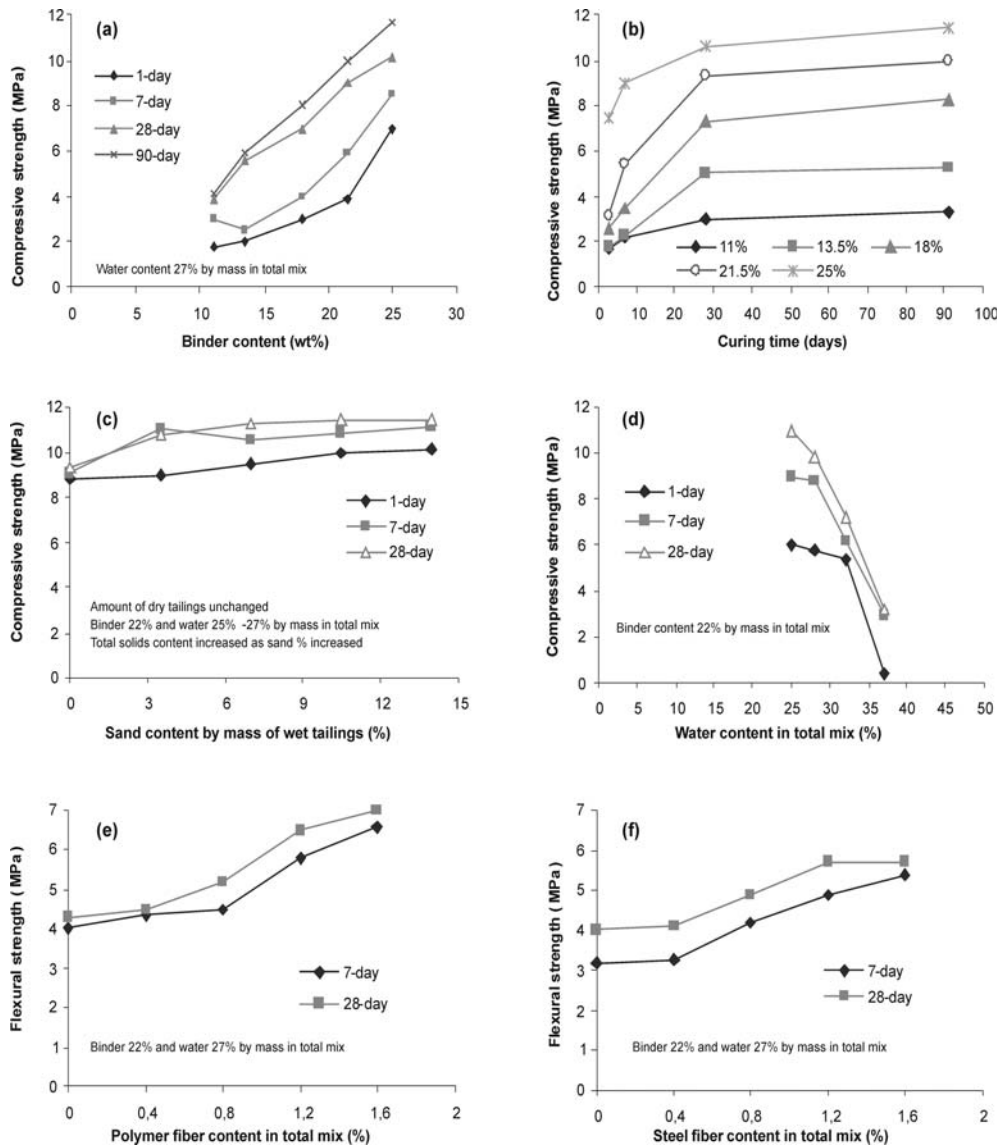


Fig. 11. Laboratory testing on tailings use as shotcrete material

- (a) compressive strength versus binder content; (b) compressive strength with curing time;
 (c) effect of sand content by mass of wet tailings; (d) compressive strength with varying water content;
 (e) flexural strength with varying polymer fiber content;
 (f) flexural strength with varying steel fiber content (modified from Zou and Sahito 2004)

Rys. 11. Badania laboratoryjne odpadów wykorzystywanych jako materiał do produkcji betonu natryskowego

- (a) wytrzymałość na ściskanie w porównaniu z zawartością lepiszcza; (b) wytrzymałość na ściskanie z czasem utwardzania; (c) wpływ zawartości piasku na masę odpadów mokrych;
 (d) wytrzymałość na ściskanie w zależności od zawartości wody; (e) wytrzymałość na zginanie dla różnej zawartości włókien polimerowych; (f) wytrzymałość na zginanie dla różnej zawartości włókien stalowych (zmodyfikowany)

Conclusion

Hard rock mining operations generate substantial amounts of solid and liquid wastes that must be properly managed to reduce environmental hazards. This study addresses tailings and waste rocks only, in terms of waste minimization. Given their detrimental impacts on the environment, these highly voluminous wastes should be stored and/or treated safely for sustainable development. Worldwide, most mass-produced tailings are pumped into large surface ponds called tailings dams. However, these tailings dams have a poor safety record, with at least one major failure annually in the last 30 years. These failures cause extensive environmental hazards in ecosystems, loss of life, and property damage. The main goals of this review paper were to document the characteristics, disposal/treatment options, emerging management techniques, volume reduction methods, and environmental hazards of tailings. The main focus is on tailings and waste rocks generated by hard rock mining. Other relevant aspects such as sulphide oxidation and geochemical processes in acidic mine waters are discussed. Desulphurization has emerged as a promising technique to prevent environmental hazards. The use of CPB as a ground support element in underground mines may provide an alternative to conventional tailings production and disposal methods in reducing large volumes of problematic tailings stored at the surface. Other techniques, including densified tailings, covers built with tailings, co-disposal of tailings and waste rocks, geotextile tube dewatering, and use of tailings for shotcrete operations, are presented. The use of integrated techniques introduces new possibilities for waste management, with considerable operational and environmental benefits.

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POSTĘPY W REDUKCJI OBJĘTOŚCI SZKODLIWYCH DLA ŚRODOWISKA
ODPADÓW GÓRNICZYCH I PRZERÓBczyCH

Słowa kluczowe

Odpady górnicze, skała płonna, minimalizacja ilości odpadów, zagrożenia dla środowiska, nowoczesne metody

Streszczenie

Duża ilość stałych i ciekłych odpadów produkowanych przez kopalnie i zakłady przemysłowe każdego roku powinna zostać zutyliзована i zminimalizowana przez zastosowanie alternatywnych metod składowania, jak na przykład zagęszczanie czy suszenie. Coraz bardziej restrykcyjne ustawodawstwo dotyczące ochrony środowiska oraz kwestia konkurencyjności nakazują z kolei zastosowanie odpowiednich technicznie, rentownych, przyjaznych dla środowiska, jak i odpowiedzialnych społecznie rozwiązań. Praca przedstawia wybrane technologie, które mogą potencjalnie zredukować duże objętości odpadów (w tym odpadów górniczych i skały płonnej) nie tworząc znaczącego zagrożenia dla środowiska. Nowe technologie, takie jak odsiarczanie, zabudowa zwałowisk odsiarczonych odpadów, wspólne składowanie odpadów przerobczych i skał odpadowych, geotekstynowe rury odwadniające oraz użycie odpadów w produkcji cementu i do budowy dróg – co jest korzystne zarówno dla przemysłu jak i środowiska – są omawiane pod kątem minimalizacji ilości odpadów. Omówione zostały także stosowane obecnie metody i sposoby efektywnego unieszkodliwiania i składowania odpadów.

ADVANCES IN REDUCING LARGE VOLUMES OF ENVIRONMENTALLY HARMFUL
MINE WASTE ROCKS AND TAILINGS

Key words

Tailings, waste rocks, waste minimization, environmental hazards, emerging methods

Abstract

A large amount of solid and liquid wastes produced by mines and mills each year needs to be managed and minimized by alternative disposal methods like paste and dry stack. Increasingly strict environmental legislation and cost competitiveness also dictate the utilization of technically suitable, economically viable, environmentally acceptable, and socially responsible techniques. This paper reviews some of these techniques that could potentially reduce large volumes of mine wastes (with a focus on mine tailings and waste rocks) without causing significant environmental hazards. The new emerging techniques such as environmental desulphurization, covers built with sulphide-free tailings, co-disposal of tailings and waste rocks, geotextile tube dewatering, and use of tailings in the cement production and road construction for both industrial and environmental purposes are discussed in terms of waste minimization. The existing methods and approaches for efficient waste treatment and disposal are also discussed in this review paper.