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Tailings From Mining Activities, Impact on Groundwater, and Remediation

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الفضلات الناتجة عن نشاطات التعدين وتأثيرها على المياه الجوفية، وطرق التخاص منها

خالد الرواحي

خلاصة: تدفق الفضلات من عملياتِ التّعدين وعمليات المعالجة شَملتْ في الغالب الملوثات التّالية: مجموع المواد الصلبة ، القاعدية أو الحمضية ، المواد الصلبة المترسبة، الحديد فى تعدين الفولاذ، والمعادن فى عمليات تعدين اللافلزات ، معادن مُذَوبة في التّعدين اللاحديدي، معلّق المواد الصلبة يتكون من ذرّات صلبة من الملوثات التي تقاوم التجزئة بالوسائل التّقليدية ، ويعتبر عدد من المعادن المُذَوبة ساماً. والملوثات المعدنية الرّئيسية التى توجد فى خام التعدين ومعالجات الفضلات تتضمن الزرنيخ والكادميوم والنحاس والرصاص والزئبق والنيكل والخارصين. برك التخاص تستخدم للتخاص من الفضلات الصلبة ولمعالجة مياه الفضلات ويحتوى الناتج من هذه البرك على معلّق المواد الصلبة وفي بعض الأوقات على بعض الكيماويات المستخدمة فى استخلاص الخام. ويعتبر تسرب المواد من أحواض المعالجة فى عمليات التعدين احد مصادر تلوث المياه الجوفية. وقد يحدث تسرب مياه الفضلات من احواض المعالجة فيما اذا كانت الاحواض رديئة التصميم. وتناقش هذه الورقة التلوث المحتمل للمياه الجوفية الناتج من مخلفات انشطة التعدين والخيارات المحتملة لمعالجة ذلك.

ABSTRACT: Effluent wastes from mining operations and beneficiation processes are comprized mostly of the following pollutants: total suspended solids (TTS), alkalinity or acidity (pH), settleable solids, iron in ferrous mining, and dissolved metals in nonferrous mining. Suspended solids consist of small particles of solid pollutants that resist separation by conventional means. A number of dissolved metals are considered toxic pollutants. The major metal pollutants present in ore mining and beneficiation waste waters include arsenic, cadmium, copper, lead, mercury, nickel, and zinc. Tailings ponds are used for both the disposal of solid waste and the treatment of waste-water streams. The supernatant decanted from these ponds contains suspended solids and, at times, process reagents introduced to the water during ore beneficiation. Leakage of material from tailings pond into groundwater is one possible source of water pollution in the mining industry. Percolation of waste-water from impoundment may occur if tailings ponds are not properly designed. This paper addresses potential groundwater pollution due to effluent from mining activities, and the possible remediation options.

1. Introduction

Metals occur naturally in the ground in a wide range of economic concentrations: from approximately 0.05% for uranium, through 0.5-1.5% for copper, to approximately 60-70% for iron, and invariably occur with a wide range of minor and trace metals. The resulting waste piles, tailings ponds, and slag dumps are unsightly and may impose environmental hazard.

Non-ferrous metal mining activities across the world have produced a variety of environmental problems. Three types of contamination created by large-scale metal extraction have been identified (Moore and Luoma, 1990). Waste rock, tailings, and slag are primary contaminants. Metals are also associated with a wide range of minor and trace elements. Metals or metalloids that may be found at contaminated mine sites include: As, Cd, Cr, Cu, Pb, Hg, Ni, Se, Ag, Zn (McLean and Bledsoe, 1992). Secondary contamination may occur in groundwater, sediments, and soils. There are two primary reasons for concern of trace elements in waters, soils, or mine spoils (Pierzynski, 1994):

1. Elevated human and animal exposure to the metals can occur through food chain transfer, ingestion of wind-blown dust, or direct ingestion of soil.
2. The phytotoxic potential of the metals can limit biomass production (Pierzynski, 1994).

Many non-ferrous metals occur as sulfides such as pyrite, sphalerite, galena and chalcopyrite. Sulfides may not be completely removed during milling process, and may lead to acidic waste as the mineral is comminuted during processing. Effluent from milling and flotation process is normally slurried into tailings ponds. Over time, and due to a number of factors, including weathering (oxidation, and hydrolysis), and biological activity (bacterial action), extreme acidity conditions may result in the tailings. The main consequence of having acid conditions in the tailings environment is the dissolution of heavy metal ions from residual minerals containing them (e.g., Cu, Zn, Ni, Pb, Hg). As a result, tailings, and consequently seepage (if any) to underground water sources, may contain high residual quantities of dissolved heavy metals, thereby impacting the quality and usability of the water, as well as the surrounding environment. This paper discusses the nature of effluent, which results from mining and milling stages of non-ferrous metal ores, impact on groundwater, and remediation options.

2. Mining and Generation of Effluent Waste

Mineral ores are extracted from both surface and underground mining operations. Effluent waste from mining activities is generated from three general sources: waste rock dumps, milling, and tailings.

Waste rock dumps represent the extracted material that has to be transported from a mine to a processing plant in order to concentrate and obtain the mineral. Since natural concentrations of non-ferrous metals in rocks is generally low, large tonnage of material is extracted. Most of this ore remains as waste. The production of a ton of copper can generate five hundred tons of waste, depending on the grade of the ore, and the amount of overburden removed (Tilton, 1994; Ayres, 1992). The extracted material and the associated ore and waste rock greatly increase the surface area of material exposed to the surface and hence affected mainly by water and oxygen. The ore and waste rock undergo oxidation by coming in contact with rainwater, surface water, and oxygen in the air. Where sulfidic deposits (for example, pyrite FeS_2) are being worked, acidic run-off results causing a serious problem. Acid is generated by the following oxidation reactions:

$$2FeS_2 + 2H_2O + 7O_2 \rightarrow 2FeSO_4 + 2H_2SO_4$$

$$2FeSO_4 + 2\,H_2SO_4 + O_2 \rightarrow 2Fe_2(SO_4)_3 + 2H_2O$$

$$Fe_2(SO_4)_3 + 6H_2O \rightarrow 2Fe(OH)_3 + 3H_2SO_4$$

The effect of acid generation can lead to higher concentration of heavy metals and other toxic elements into run-off solutions. When these solutions come in contact with stream or other surface waters contamination may result. This may pose threat to human health and the environment at large.

Since natural concentrations of non-ferrous metals in rocks is generally low, large amount of waste in the form of overburden and tailings results from mining and milling processes. The production of concentrates is schematically shown in Figure 1. Milling is the operation that separates concentrate from gangue. The flotation process is an integral part of milling. The end product of the milling process is the concentrate of the desired metal(s). The slurry, which contains the discarded process water, unwanted gangue, reagents, frothers, collectors and other chemicals added during the flotation stage, passes to the tailings area. Before decanted into the tailings, the slurry may be chemically treated to remove (by oxidation) organic reagents having high oxygen demand, and any cyanides which may be present (Barbour, 1994).

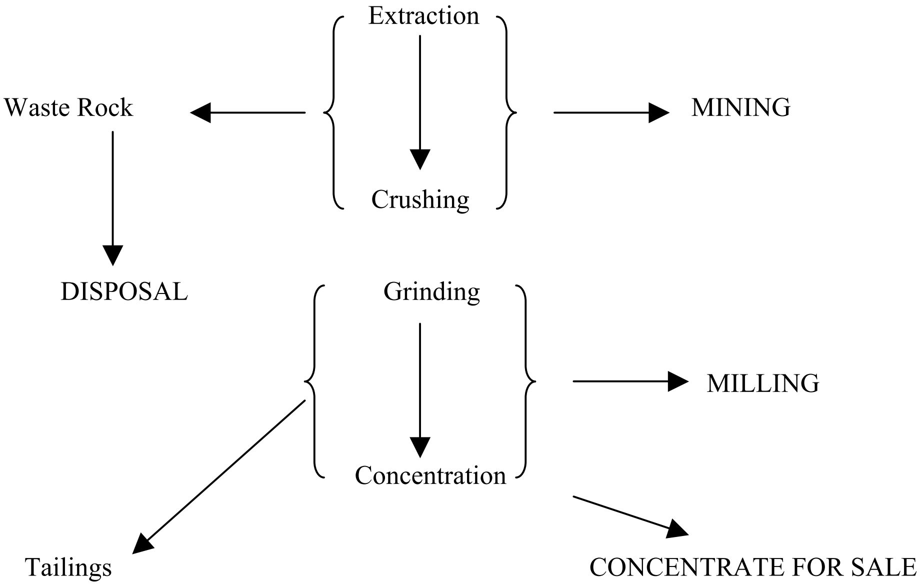

Figure 1. Major stages in the production of non-ferrous concentrates (Barbour, 1994).

3. Tailings: Characteristics, Disposal and Impoundment

Most mineral processing plants produce, in slurry form, fine grained waste material, which result from milling operations. This waste forms the tailings, which must be disposed of in a proper way. The tailings, which contain residual quantities of chemicals and potential contaminants from the processing and milling of ores, are generally confined to a specific area for safety and environmental reasons. Tailings differ in different mining operations. Chemical composition, physical characteristics-including abrasiveness, particle size, specific gravity, pH, all influence the flow, settlement, and toxicity of the tailings. These factors also have major influence on treatment methods in order to minimize environmental damage on receiving streams or other bodies of water. Tailing management is, therefore, of major environmental importance. The long-term effect of contaminant transport via wind, surface drainage and seepage are major concerns for the mining industry. Many tailings problems arise from the low strength of tailings deposit, their ongoing consolidation, erosion by wind and water, spillage and tailings water seepage (Bell, 1997).

Since tailings differ in different mining operations, (the details and mechanics of tailings disposal system are highly site-specific to suit the particular operation in a specific location. Tailings usually are transported as slurries through pipes (by pumping or by action of gravity). Settlement characteristics are important to avoid blockages and breakdown in operations.

The disposal of tailings from milling operations is a major task for mining and mineral processing companies. In most cases, a major fraction of the ore mined eventually ends up as tailings. The material must be disposed of in an environmentally safe way so as to minimize adverse environmental impacts. The classic method to dispose of tailings was to discharge them into a lake, stream, or across nearby land. The two most common practices of tailings disposal have been:

1. To size the tailings, and use the coarse fraction (sand) for construction of a tailings dam, while placing the fine fractions (slimes) in the resulting tailings pond, and
2. To size the tailings, and use the coarse fraction for backfill underground (possibly mixed with cement), while sending the fine fraction to a surface tailings pond.

Factors such as increased in tonnage mined, environmental awareness and increased government regulation, have resulted in changes in techniques of tailings disposal. Impoundment of tailings behind dams is standard industrial practice. The dam structure must be designed and constructed such that it will not fail during use or in later years, (post-mining). This is important, because failure of the dam would necessarily result in the release of vast quantities of slimes from the tailings pond. Pollution of waterways, (lakes, rivers) must also be prevented or minimized.

In contrast to waste rock, slurry transportation of mine tailings provide a wide range of options for disposal (Barbour, 1994):

- Narrow deep valleys versus disposal in shallow valleys or plain land.
- Location to minimize adverse environmental impact on adjacent streams, surface waters, and ground water. Treatment cost required for tailings water disposal into a particular stream need to be compared to those of discharging the untreated tailings into a more distant but environmentally and commercially unimportant stream. Disposal to sea is also a viable option (due to its enormous absorptive capacity).
- Tailings impoundment should be located away from people and human activity as much as possible. Failure of tailings dam can have serious consequences to humans and other activities located nearby.

Impoundment of tailings behind dams is generally applied in most mining operations. The main objective is to isolate the tailings using the best technology available for containment so that the release of potential contaminants can be prevented or minimized. The conventional technique (Sudbury, 1992) utilizes spigotting whereby a tailing slurry pipeline encircles an impoundment area to permit discharge at many points through small pipes or hoses – spigots – inserted through the wall of the main pipe. Surplus slurry discharges from the end of the pipe inside the impoundment area. Coarse sands settles around the periphery providing granular material with which to build up the dam. In addition, the granular tailing material also provides good support for a peripheral access along the top of the dam to service the pipeline, while the high permeability of the coarse sands avoids dam failure due to hydrostatic pressure. Fine slimes flow to the inside of the impoundment area with a clarification pond forming in the center.

This system, however, has serious drawbacks for sulfide-bearing tailings. Acid generation and the resulting metal dissolution may lead to a serious problem especially in areas where the underlying soil is highly permeable; seepage of contaminated effluent into groundwater may adversely impact the quality of the receiving waters. In mountainous terrain local failure of a berm can result in an extensive and uncontrolled spread of waste. In addition, dry elevated tailings may accelerate wind blown heavy- metal contaminated dust.

4. Mining Effluent and Potential Environmental Impacts

Effluent wastes from mining operations and beneficiation processes are comprized mostly of the following pollutants: total suspended solids (TSS), alkalinity or acidity (pH), settleable solids, iron in ferrous mining, and dissolved metals in nonferrous mining. Suspended solids consist of small particles of solid pollutants that resist separation by conventional means. Solids in suspension that will settle in one hour under quiescent conditions are settleable solids.

Acid conditions prevalent in the minerals industry usually result from the oxidation of sulfides in mine waters or discharge from acid leach beneficiation processes. Alkaline leach beneficiation processes also contribute to effluent waste loading. Iron is often present in natural waters and is derived from common iron minerals in the substrata increasing iron levels present in process water and mine drainage. A number of dissolved metals are considered toxic pollutants. The major metal pollutants present in non-ferrous ore mining and beneficiation waste waters include arsenic, asbestos, cadmium, copper, lead, mercury, nickel, and zinc.

Surface water pollutants primarily originate from three major sources: precipitation run-off, mine dewatering, and process waters. The characteristic of the effluent stream is generally determined by the mineralogy of the ore and the beneficiation process. Beneficiation processes include gravity separation, froth flotation utilizing reagents, chemical extraction, and hydrometallurgy. Surface mining can generate large volumes of sediment through precipitation runoff. If the sediments cannot be contained but are allowed to reach adjacent waterways they may become pollutants.

For many mines, mine dewatering may contribute to a significant source of waste water. It is usually low in suspended solids, but may contain dissolved minerals or metals. Water, which accumulates in surface mine, pits or underground mine workings is likely to be heavily loaded with sediment or dissolved salts or both. As a result, mine de-watering can easily result in heavy pollution loads in the receiving waters. Pumping to maintain dry conditions may also lower the water table reducing the yield of nearby wells, springs, and seeps. Mine waters originate from groundwater flows, as well as from rainfall and run-off. Thus mine de-watering can significantly affect receiving waters. Water should be diverted from mine pits or workings if possible, as water pumped out of the mine will most likely require treatment before it can be discharged from the mine area.

Process waters are those used in transportation, classification, washing, concentrating, and separation of ores. As an effluent, it usually contains heavy loading of suspended solids, and in nonferrous metal mining, contains dissolved metals as well. It also contains process reagents. Since mining operations occupy large surface areas, precipitation run-off may contribute a major volume of waste-water and pollutant loading This water typically contains suspended solids, such as minerals, silt, clay, sand, and possibly dissolved toxic metals.

Other possible sources of water pollution include acid mine drainage and tailings pond leakage. The leaching of water through any mine waste or structure containing sufficient pyrites or other sulfides can produce acid drainage.

Tailings ponds are used for both the disposal of solid wastes and the treatment of waste-water streams. The supernatant decanted from these ponds contains suspended solids and, at times, process reagents introduced to the water during ore beneficiation. Percolation of waste-water from impoundment may occur if tailings ponds are not properly designed. The aqueous component of tailings slurry from the mill usually contains some concentration of surface-active frothers and collectors. In addition, where acid conditions are present in flotation circuits, relatively high amounts of cations such as iron, manganese, cadmium, mercury, lead, and zinc may be present in specific circumstances (Barbour, 1994).

Problems in tailings area are exacerbated where sulfidic (example, pyritic) deposits are being worked, due to the presence of acidity by oxidation in presence of water. When the impoundment is in active use, it is usually saturated with water; air access is limited; but when the pond level falls, condition for rapid development of acidity, due to bacterial oxidation with *Thiobacillus ferrooxidans* develops. This can pose serious threat due to acid mine drainage after operations have formally ceased.

If cyanide has been used in the extraction circuit, as in most gold concentrating processes, it may be necessary first to convert it to relatively harmless cyanate by oxidation immediately upon leaving the floatation circuit. Flow characteristics of the effluent as well as uses of the receiving bodies of water is important. Where it is necessary to preserve the existing uses of the receiving body, conventional treatment (precipitate heavy metals by addition of neutralizers, and pH adjustment) is used. Whatever disposal option is selected, adequate monitoring should be practiced to ensure that any significant changes in the quality of the receiving body are quickly detected, assessed, and remedied.

5. Tailing Impoundment and Disposal: Planning and Avoidance of Disaster

Special precautions are required to prevent groundwater contamination. All mining and processing operations require detailed emergency plans designed to mitigate the effects of major accidents on both the operating personnel and near-neighbors. Mine safety is of utmost importance and this should be part of regulatory and professional requirements. Close attention must be given to stability of waste piles and tailing areas, particularly dams and retaining walls for tailings disposal areas. In the location of tailing areas every effort must be made to choose a location with the minimum possible risk to downstream population. Proper management of the tailings in post mining period should be incorporated.

As indicated earlier, the main objective of tailing impoundment is to isolate the tailings so as to minimize adverse environmental impacts, especially on groundwater. The following considerations are significant to achieve the desired objective (Sudbury; 1992, Sengupta, 1993):

- Selection of impoundment site is of critical importance. A detailed geological and geotechnical study of the proposed site is crucial to assess suitability of area for impoundment e.g., permeability, structure in the area-faults, folds, fractures and joints in order to minimize seepage and dam failure. Hydrology of the area as well as type of tailings involved should also be considered.
- Installation of liner in the impoundment area. This is important in order to prevent or to minimize release of contaminants (if any) from the pond area into the underlying groundwater sources or streams and waterways.
- Presence of alkaline mineralogy (such as limestone) in the impoundment locality and high carbonate content in the groundwater are desirable features (see, remediation)
- Where possible, every effort should be made to divert surface waters, local run-off from disposal area. This can be achieved by using stream diversions, peripheral ditches, and underdrain pipes.
- Thickened discharge (60-70% solids) method of tailings disposal avoids steep tailing slopes; discharge on top of tailings in cone shaped hill with maximum slope angles of 3-5°. This results in high deposit stability, low rate of seepage to surrounding area and periodic wetting by the tailings slurry. A low peripheral dam is built with an impermeable clay or synthetic liner to channel effluent water to a single location for treatment. With suitable cover, the cone is to be kept fully saturated with water to prevent acid-generating conditions. Low permeability and low slope of the cone will result in slow rate of migration of contamination that natural processes will be able to assimilate. Thickening should be at disposal site to reduce high energy cost of pumping thickening tailings.

6. Acidity in the Tailings Ponds and Remediation Options

Waste rock dumps and tailings ponds are the most visible end result of the mining process. In mining and processing of sulfide ores, acid generation due to weathering is a more challenging problem facing mining industry. The effect of acid generation can lead to higher concentration of heavy metals and other toxic elements into solutions. Unless the weathering is prevented or the water is treated, acid mine drainage can pose threat to human health and the environment. The main consequence of having acidity (H^+) and Fe^{3+} in the tailings environment is the oxidative dissolution of heavy metal ions from residual minerals containing them. Thus:

$$ZnS + 2Fe^{3+} \rightarrow 2Fe^{2+} + Zn^{2+} + S^0$$

$$CuO + H_2SO_4 \rightarrow Cu^{2+} + SO_4^{2-} + H_2O$$

$$PbS + 2Fe^{3+} \rightarrow 2Fe^{2+} + Pb^{2+} + S^0$$

During the operating life of a mine, the tailings are normally covered by the supernatant mill effluent, leaving only the beaches exposed; this minimizes wind erosion. When mining ends, some sort of tailings and waste rock management is required to minimize serious environmental impact. The drying out period for the tailings area depends on a number of factors, including proportion of slimes, amount of rainfall, and weather conditions. When tailings area have adequately dried, it is common practice to establish vegetation. Control of pH by heavy liming is usually the first step, followed by application of the plant nutrients nitrogen and phosphorus. Where tailings or waste rock is highly pyritic, revegetation is much more difficult due to the generation of acid as indicated earlier.

A number of options for impoundment and remediation techniques have been proposed, and investigated (Sudbury, 1992; Pierzynski et.al., 1993; Sengupta, 1993). Some of these options are listed below:

- ‘Conditioning’ of tailings (i.e., concentrate, remove, or isolate the sulfide minerals from tailings) so that sulfide-oxidation-producing acid will be minimal.
- Promote vigorous healthy biological activity-plant, animal, aquatic life on the surface of the impoundment following closure (revegetation)
- Isolate the uppermost flow of groundwater system by means of a cut-off structure
- Exclusion of water with impermeable barriers such as synthetic membrane covers
- Exclusion of oxygen through placement of cover with extremely low oxygen diffusion characteristics: soil, water, and synthetic materials.
- pH control to inhibit acid generation. If the potential for acid drainage exists through excess acid-producing material (like oxidation of pyrite), addition of neutralizing material, such as carbonate and hydroxide compounds will produce a neutral to alkaline pH in the associated water. The common additives are limestone ($CaCO_3$), lime (CaO or $Ca(OH)_2$), and sodium hydroxide ($NaOH$). Lime and sodium hydroxide provide greater neutralization than limestone per unit weight, but the greater unit cost and the environmentally unacceptable high pH (approaching 10 and above), retracts their use.
- Control bacterial action: when the pH of waste pile drops below 4, the rate of acid generation increases fivefold or more due to the presence of Thiobacillus ferrooxidans. The use of bacterial control compounds such as anionic surfactants (sodium lauryl sulfate), organic acids, and food preservatives can control bacterial action. The purpose of bactericides is to create a toxic environment for bacteria so that the inorganic rate of acid generation cannot be enhanced.
- Covers and seals offer the ability to restrict the access of oxygen and water to reactive wastes. For this to be effective, the cover must have a low permeability to either air or water, it must have no imperfections where entry of outside agents can occur. A variety of materials may be used in this context depending on local availability and site conditions. These include: different types of soils, synthetic membranes, water and a combination of soil and water (which result in saturated soil), and materials such as concrete and asphalt. Example of cover materials and their permeability to water are shown in Table 1.
- Marine disposal: possible option for mines that are situated in close proximity to marine water body. Seawater has a greater absorptive capacity for ‘contaminants’ as well as higher alkalinity than freshwater. The underlying significant factor is to delineate areas where fisheries value is minimal and where waste disposal may be environmentally acceptable. Otherwise, long pipelines or barges may transport the waste far offshore, but the associated costs would be high (Sengupta, 1993).

7. Case Study in Oman

In 1982, Oman Mining Company (OMCO) started copper mining and smelting operations at Lasail area west of Sohar, Northern Oman. Mining and processing activities continued until 1994 (after the mines were depleted). The annual production was about $1.1x10^6$ t. The production of copper ore (mainly from pyrite-chalcopyrite) totaled some 15 million tonnes in the 11-year operation. Before water well development in 1989, seawater was used for milling. During this period, some 11 million tonnes of sulfide-rich tailings and five million cubic meters of seawater have been disposed of behind the unlined Lasail tailings dam, located at the upper stream of the Wadi Suq (Ministry of Water Resources, MWR, 1996).

Mine pollution in the area mainly includes groundwater pollution by salty water seepage from the tailings dam, a slope failure, land subsidence at the mined out area, water pollution of mine water at the mined out area (acid drainage), and air pollution due to soot and dust with high SO_x concentrate from the smelter and refinery plant. Seepage from the tailings dam has effectively impacted the quality of ground water. There have been complaints that groundwater pollution in Wadi Suq has advanced to the extent that 85% of nearby village wells are salinised and undrinkable, while 50% of former agricultural wells in the area are unsuitable for irrigation (MWR, 1996). There is also a potential for toxic metal mobility if the pH of the tailings solution is not effectively monitored and controlled.

Table 1: Alternative cover materials (Source: Sengupta, 1993).

Cover Material	**Permeability to Water (m/sec)**	**Advantages/Disadvantages**
Compacted clay	10^{-9}–10^{-11}	Availability of large quantities problematic in many areas; subject to erosion, cracking, and root penetration; good sealing if protected and maintained
Compacted till	10^{-7}–10^{-9}	As above, but generally more permeable
Compacted topsoil	10^{-5}–10^{-8}	As above, but less robust, more permeable; questionable longevity
Peatland bog	10^{-5}–10^{-6}	Need to maintain in saturated condition; normally impractical for elevated waste dumps and sideslopes
Concrete	10^{-10}–10^{-12}	Subject to cracking, frost, and mechanical damage
Asphalt	10^{-20}	As above
HDPE synthetic	Impermeable	Requires proper bedding and protective cover; highly impermeable; life span unlikely to exceed 100 years; subject to root and mechanical penetration

8. Conclusions

This paper presented a summary of potential environmental damage on groundwater due to tailings impoundments, and the possible remediation options. It is important to note that tailings-related groundwater pollution can be minimized or prevented if a proper tailings management program is in place. In cases where pollution has affected the quality of receiving waters, remediation is neither rapid nor easy.

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