Design of a Co-disposal Facility for Thickened Tailings and Potentially Acid-generating Waste Rock

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Abstract

Environmental and geotechnical risks and impacts from surface disposal of mine waste are increasingly becoming a source of concern for regulators, investors, operators, and communities within the potential area of influence of mining operations. Waste disposal strategies should implement the Best Available Technology and Best Available Practice for waste management, while considering specifics of the local topography, climate, foundation conditions, construction materials, and waste characteristics. The Alacrán Cu-Au-Ag Mine Project (the Project) in northwestern Colombia will need to manage potentially acid-generating waste rock during mining. The steep, rolling terrain limits disposal site options, and water management is challenging, with approximately 3 m of rain annually. Minimizing water in tailings storage facilities and reducing waste rock exposure to atmospheric oxygen and precipitation are common challenges at many mine projects. One emerging technology addressing both issues is co-disposal, which combines tailings and waste rock in a single engineered storage facility.

Co-disposal was selected as the preferred waste management strategy for the Project after multiple investigations. This waste management strategy will create a low-permeability waste deposit, reduce foundation seepage, and centralize the storage of all mining and processing waste. Co-disposal, in places where suitable, may reduce environmental risks and impacts, improve public perception, and lower costs and timelines for mining projects. Multiple lines of investigation are necessary for the effective design of a co-disposal waste management facility.

Introduction

Environmental and geotechnical risks and impacts from surface mine waste disposal are increasingly becoming a source of concern to regulators, investors, operators, and the communities within the potential area of influence of mining operations. Operational, financial, ecological, and reputational risks arise from drainage of mine-impacted water from waste rock storage facilities, reactive surfaces exposed by mining, and tailings storage facilities (TSFs). Recent TSF failures, resulting in the sudden release of large volumes of tailings and solutions, include the Williamson Mine (Tanzania, 12.8 M m^3), Brumadinho (Brazil, 12 M m^3), and the Germano mine (Brazil, 32 M m^3) (WISE, 2024). These challenges have led the mining industry to develop Best Available Practices for waste disposal by minimizing water in tailings storage facilities and reducing the exposure of waste rock to atmospheric oxygen and precipitation. An emerging technology that addresses both issues is co-disposal, which is the placement of tailings and waste rock together in an engineered storage facility. Co-disposal, also known as co-placement, co-deposition, co-mingling, co-layering, or PasteRock®, ranges from heterogeneous co-placement of tailings with waste rock to very homogeneous blends (Figure 1). The proposed co-disposal strategy for this Project involves layered co-mingling as the best balance between effectiveness and feasibility. Due to the space limitations for this publication, only an overview of the details will be provided here. The complete Feasibility Study is available at Cordoba Minerals (Corboba Minerals, 2023).

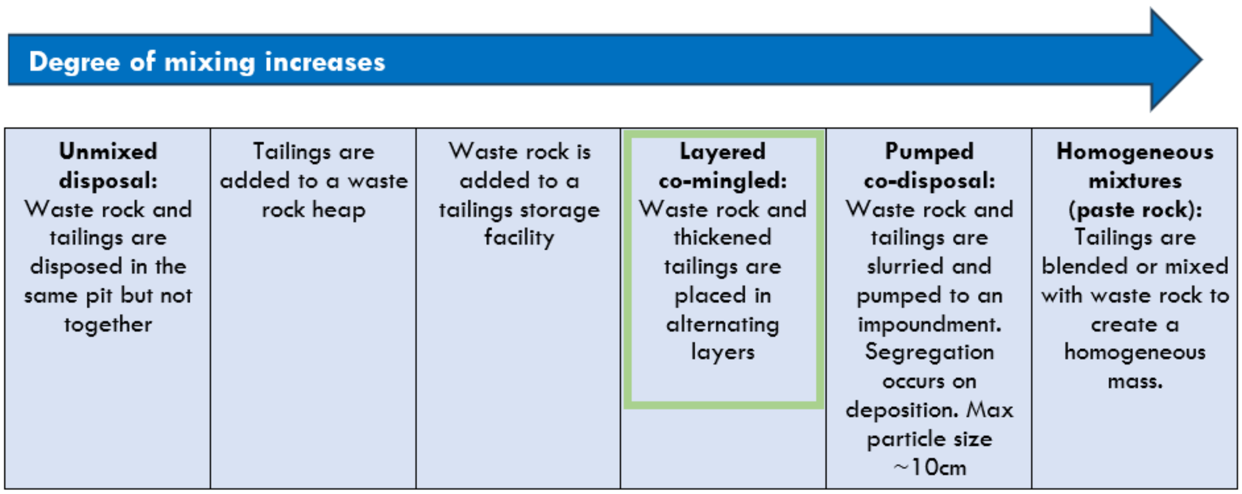

Figure 1: Co-disposal methods (after Pukkinen et al., 2019)

Research and mine site applications have demonstrated that co-disposal has the following benefits (Gowan et al., 2010; Habte and Bocking, 2012; Ulrich and Coffin, 2015; Wickland et al., 2006):

- Reduces oxygen flux and infiltration through mine rock (i.e., to control sulfide oxidation, acidic drainage, and metal leaching).
- Improves stability (static and dynamic) of a disposal facility and decreases probability of liquefaction.
- Reduces the footprint required for the disposal of two waste streams.
- Simplifies water management, monitoring, and closure.
- Accelerates tailings consolidation, improves permitting timeline, and facilitates earlier closure.
- Reduces the erodibility of tailings by either water or wind.

Critical factors for effective co-disposal include the moisture content of the tailings and waste rock placement practices. Oxygen diffusivity in a fine-grained porous media decreases sharply with increasing moisture content. Tailings at approximately 85% saturation form an effective barrier to oxygen diffusion (INAP, 2018), minimizing sulfide oxidation. In a homogeneous blend, the optimal ratio of rock to tailings required to fill the pore space in waste rock is 5:1 or less (Wickland et al., 2006). In co-mingling, the objective is not to fill the waste rock pore space, but to minimize oxygen diffusion and infiltration into the layers of waste rock using contiguous layers of tailings to isolate the waste rock from the atmosphere.

The selection of a specific co-disposal method depends on several factors, including:

- Site topography and ease of construction and operation.
- Climatic conditions (e.g., cold, extremely dry, extremely wet).
- Tailings characteristics (e.g., geochemistry, viscosity, grain size distribution, mineralogy).
- Mine rock characteristics (e.g., geochemistry, grain size distribution, mineralogy).
- The volume ratio of mine rock to tailings.
- Life cycle costs of the co-disposal facility.
- Risk potential (e.g., wind and water erosion, slope stability, liquefaction, closure).

Currently, several mines employ co-disposal, including Marmato (Colombia), Navachab (Namibia), Nunavik (Canada), Greens Creek (USA), Snap Lake (Canada), Caraíba (Brazil), Neves Corvo (Portugal), Mount Thorley (Australia), and Argyle (Australia) (Verburg, 2024; Gowan et al., 2010). All these mines have a daily production of less than 20,000 tonnes per day.

Site background

The Project is in the Department of Cordoba, Colombia, 390 km northwest of Bogotá and 160 km north of Medellín. The mine site lies in the northern foothills of the Western Cordillera of the Andes mountains, with elevations ranging between 100 m and 350 m above sea level.

The Project is in an accreted oceanic terrane of the Western Andean Cordillera. The El Alacrán deposit's mineralization is hosted by a west-dipping Cretaceous succession comprising mafic volcanic rocks overlain by a calcareous volcaniclastic sequence, capped by pre- to syn-mineralization sill-like diorite and felsic sub-volcanic bodies. Cu-Au-Ag mineralization occurs throughout the volcaniclastic package. Research by Manco (2020), in combination with previous work, suggests that the genetic model for the El Alacrán deposit is a hybrid between Iron Oxide Copper-Gold and Carbonate Replacement deposits associated with a porphyry source. The climate in the region is humid and warm, with average monthly temperatures ranging from 24.5°C and 27°C. The Project receives approximately 3,000 mm of rainfall annually, with rain occurring year-round and a wet season between April and November. The evapotranspiration rate is approximately 1,500 mm/year. Due to the high rainfall and warm climate, the igneous and volcaniclastic rocks in the region have undergone extensive weathering, characterized by up to 11 m of saprolite (composed principally of quartz, chlorite and aluminous and lateritic clays), a transition zone (weathered bedrock), and then unaltered bedrock.

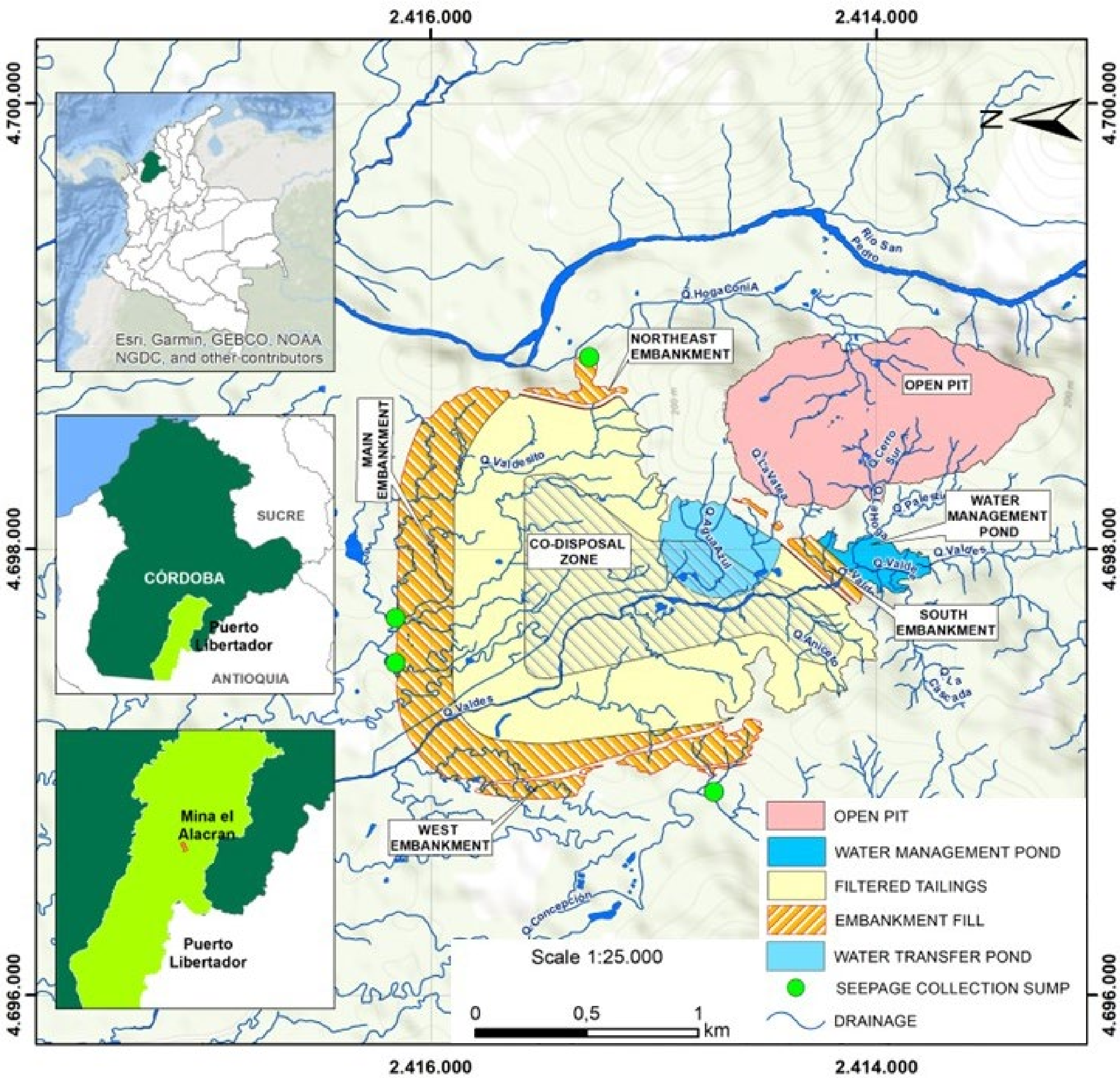

Figure 2: Site location and waste management facility features

Conventional open-pit mining methods will be used to extract ore from the El Alacrán deposit, with an anticipated production period of 14 years. The ore will be processed through crushing and a four-stage flotation circuit, which includes rougher, cleaner scalper, cleaner scavenger, and recleaner stages. Concentrate from the cleaner scalper and recleaner stages will be thickened and filtered to produce the final concentrate. Tailings produced in the rougher and cleaner scavenger stage flotation (after passing through the gravity concentrator) will be sent to the tailings thickener, and subsequently to the waste management facility (WMF) at approximately 55% solids by mass. The mill throughput rate is set at 17,600 tonnes per day. It is anticipated that 34 million tonnes (Mt) of potentially acid-generating (PAG) waste rock and 102 Mt of thickened tailings will be stored in the WMF basin during mining and milling operations over the 14-year mine life.

Investigations

Studies supporting the design and operation of the WMF included foundation assessments, geochemical characterization of waste rock, tailings, and tailings decant within the proposed WMF area (described in more detail below), along with various hydrogeological and water chemistry studies of the valley where the WMF will be located.

Foundation characterization

The foundation characteristics at the WMF reinforce the suitability of co-disposal at the Project. Topsoil covers the entire WMF area, underlain primarily by saprolite, with isolated pockets of fine or coarse alluvium. The fine alluvium has very similar engineering properties to the saprolite. Beneath the soil units, weathered bedrock and bedrock are present. The saprolite will form the basin for tailings deposition and reduce seepage from the WMF. The saprolite typically consists of silt and clay with varying sand content and is classified as CH (inorganic clays of high plasticity) to MH (inorganic silts of high plasticity) according to the United Soil Classification System (ASTM D2487). Five permeability tests indicate that the permeability ranges from 4.2E-10 to 5.6E-08 m/s, which is at the low end of typical values for saprolite, effectively minimizing seepage (Blight, 1997).

Waste geochemical characterization

Geochemical characterization of the waste streams generated by a mine is an essential element of a Feasibility Study. Samples of mine waste to be deposited in the WMF included tailings (n=4), tailings decant (n=1), waste rock (n=80), and saprolite (n=20). These materials were characterized using a standard suite of geochemical static and kinetic analyses, including mineralogy, total elements (52 elements), shake flask extraction and leachate analysis, net acid generation, and acid-base accounting (ABA). Kinetic tests included site barrel (n=10) and humidity cell tests (n=14). A geochemical sampling and analysis program was developed and implemented to inform the Pre-Feasibility and Feasibility studies, as well as the Environmental Impact Assessment required to obtain a Colombian environmental permit. The program was based on a site-specific conceptual geochemical model, considering the range of anticipated waste rock lithotypes (including lithology, alteration, and degree of weathering), expected volumes of each potential waste rock lithotype, and operational factors. Results from this geochemical program were correlated to the much larger exploration data set (n=47,231 for waste rock), which was used to generate a block model for the waste rock.

Results of the program indicate that the range of waste rock lithotypes from the mining operation at the Project are a mixture of PAG, uncertain acid generation, and non-acid-generating (NPAG). Most of the waste rock to be generated by the Project falls into the uncertain range (Figure 3) based on static tests.

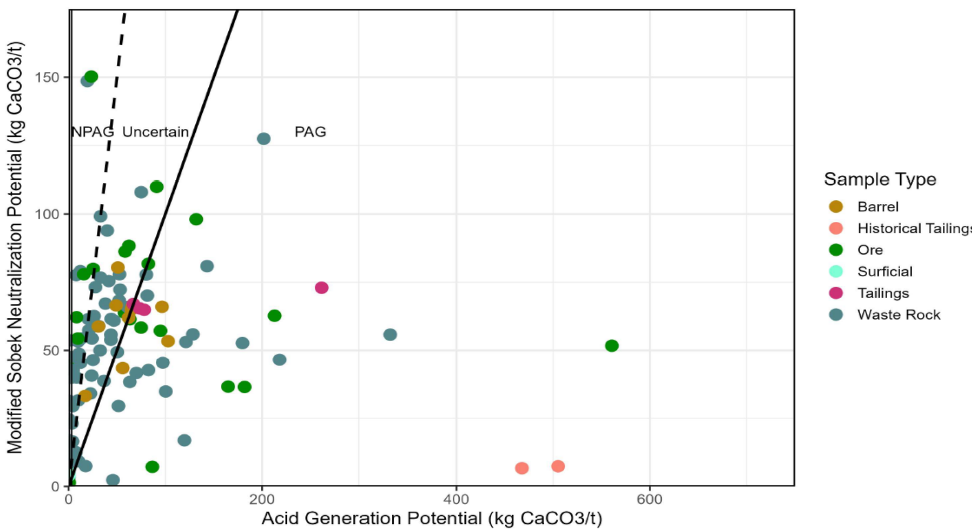

Figure 3: Acid-generation potential vs. acid-neutralization potential for Project waste.

Field barrel test results from 10 waste rock composites after 17 months suggest that mixed waste rock could produce drainage with pH < 6 drainage and elevated metal concentrations, indicating that it could have uncertain acid-generation potential in the long-term. Results for saprolite within the proposed WMF footprint had very low sulfide concentrations and were classified as NPAG. Decant samples were analyzed for the full list of organic compounds, metals, major ions, and potential mining by-products listed in the Resolution 0631 limits for mine discharge (MINAMBIENTE, 2015). The only parameter that exceeded the Resolution 0631 limits was pH at 9.5 (limit is 9). Sulfate concentrations in the decant were 300 mg/L.

Tailings geotechnical characterization

Laboratory physical characterization testing was completed on thickened tailings samples to estimate their Atterberg limits (index test), settling, consolidation, and permeability properties. The index test results suggest that the tailings are non-plastic, consist of 32% sand, 55% silt, and 13% clay, and have a specific gravity of 2.87. The P80 of the tailings is 150 micrometers (i.e., 80% of the particles are finer than 150 micrometers). The tailings are classified as an inorganic silt of slight plasticity.

Undrained, drained, and drained plus air-drying settling tests were completed on tailings slurry samples at 60% and 65% solids content by mass. The results indicate that the estimated settled density ranges from 1.34 to 1.36 t/m^3 under undrained conditions and from 1.45 to 1.50 t/m^3 under drained conditions. Air-dried settling test results at 60% solids content indicate that the solids content increased to 71% (11% increase) in 2 days and were fully dry after approximately 4 weeks.

Consolidation tests were conducted using a Rowe cell, allowing the tailings to settle and consolidate under their own weight. Confining stresses ranging from very low (10 kilopascals [kPa]) to high (800 kPa) were applied in incremental loading stages, while maintaining two-way drainage conditions. The measured Coefficient of Consolidation (Cv) values ranged from 31 m^2/year at low effective stress (10 kPa) to 5 m^2/year at high effective stress (800 kPa). The Cv values are considered to be at the low end of the range of typical values for copper mine tailings (Vick, 1990).

Permeability test results indicate that the hydraulic conductivity of the tailings decreases from 4.9x10^{-9} m/s at 200 kPa to 2.2x10^{-10} m/s at 800 kPa. This suggests that the hydraulic conductivity of the tailings will likely decrease with increased tailings depth and effective stress. Permeability tests on compacted saprolite yielded hydraulic conductivities ranging from 4×10^{-10} to 6×10^{-8} m/s, with a geometric mean of 4×10^{-9} m/s. These values are comparable to the permeability of high plasticity tailings silts and clays (Vick, 1990).

WMF design overview

The WMF will consist of a valley-type impoundment to provide permanent storage for PAG tailings and PAG/uncertain waste rock. A schematic of the proposed WMF is provided in Figure 4.

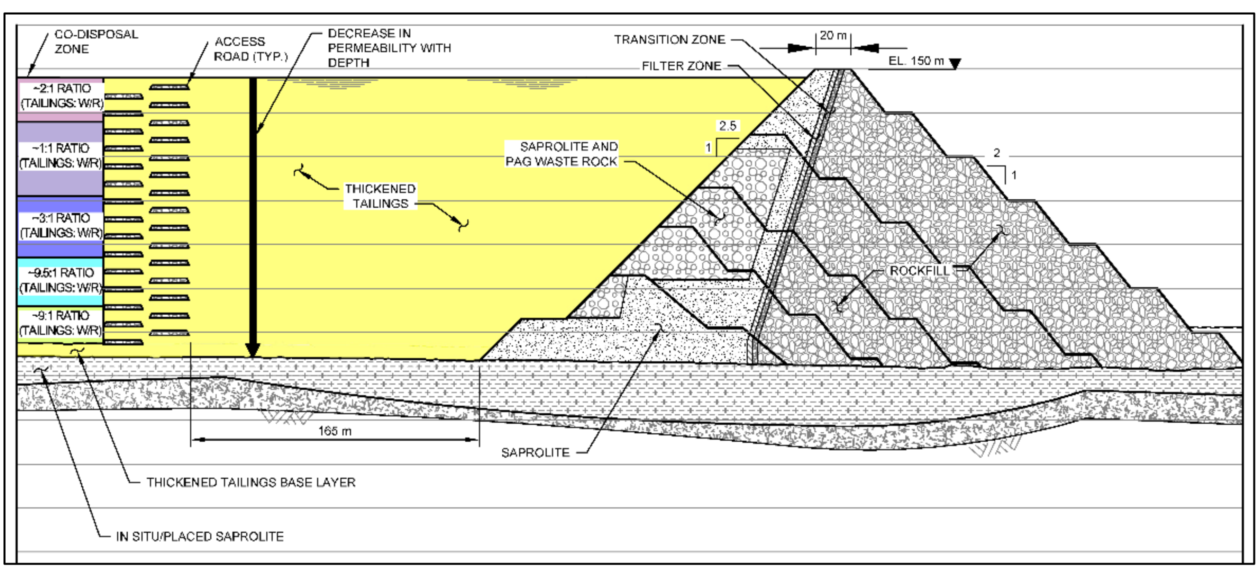

Figure 4: Typical WMF embankment and basin section (Cordoba Minerals, 2023)

Key components of the design of the WMF include perimeter embankments, a basin liner, and drainage.

Perimeter embankments

Perimeter embankments will be constructed using waste saprolite and waste rock from open-pit development to safely store the thickened tailings and PAG/uncertain waste rock. The impoundment will be developed by constructing embankments around the perimeter of the valley (Figure 2). The West, Main, and Northeast Embankments will be raised using the downstream construction method. The South Embankment will be constructed as a full-width divider embankment to establish a water management pond (WMP) in the southern portion of the valley. The embankments will be raised in five stages (Figure 4) to a maximum height of 68 m. The typical embankment cross-section from upstream to downstream includes saprolite to provide a low-permeability zone, filter and transition zones to provide drainage within the embankment fill, and a downstream rockfill shell zone.

Basin liner

The basin liner will consist of at least 3 m of saprolite within the WMF basin to reduce potential seepage from the facility. Saprolite, along with isolated areas of fine to coarse alluvium are present within the WMF basin. The WMF basin will be cleared and grubbed, and topsoil will be removed to expose the saprolite. In most areas, the foundation will consist of in-situ saprolite that is greater than 3 m in thickness, which will be grubbed, compacted and proof rolled. Additional saprolite will be placed and compacted following stripping and grubbing in areas of the WMF footprint with less than 3 m of in-situ saprolite.

Drainage

To manage water and maintain a low phreatic surface within the embankments, the design includes internal filter and transition zones, and a series of finger drains at approximate 200 m intervals in the Main, West, and Northeast Embankment foundations. The finger drains will connect to a conveyance drain along the ultimate downstream toe of the Main and West Embankments (parallel to the embankments) or directly to a collection sump (Figure 2). Multiple collection sumps will be located along the conveyance drain. The finger and conveyance drains will consist of gravel with a slotted CPT pipe wrapped in a filter sock and fully wrapped in non-woven geotextile.

WMF operation

Key aspects of the WMF operation will include water management, tailings deposition, PAG/uncertain waste rock placement, and basin filling.

Water management

The water management strategy for the WMF involves collecting supernatant and runoff for transfer to the WMP and maintaining a small water pond along the southeast side of the WMF basin (Figure 2). This will maximize the WMF basin surface area for drying and consolidation of the tailings and provide a suitable area to haul, place, and spread PAG waste rock.

Tailings deposition

The tailings will be pumped from the thickener at approximately 55% solids by mass to a series of centrifugal pumps and conveyed to the WMF via pressurized HDPE pipelines. Tailings discharge during operation will be rotated around the perimeter of the embankments and basin to achieve a tailings beach slope of approximately 2%. Multiple spigots will be used to maintain a low deposition velocity and the homogeneity and non-segregating properties of the tailings during deposition. Tailings deposition will be managed to route the supernatant liberated from the tailings and runoff towards the Water Transfer Pond located in the southern portion of the basin. This approach will facilitate the efficient transfer of supernatant and runoff to the WMP.

The tailings will consolidate over time due to the weight of overlying layers of tailings and waste rock. The dry density of the tailings will range from 1.3 tonnes per cubic meter (t/m^3) to 1.6 t/m^3, with a corresponding vertical hydraulic conductivity of 8.5×10^{-8} meters per second (m/s) to 1.1×10^{-10} m/s.

Waste rock placement and basin filling

The tailings deposition and waste rock placement strategy are illustrated in Figure 4. Prior to placement of PAG and uncertain waste rock within the WMF basin, tailings will be deposited in layers to develop a low-permeability deposit approximately 3 m thick immediately above the compacted foundation. The initial deposition of tailings will lower the hydraulic conductivity of the foundation and reduce potential seepage from the WMF basin into the underlying material.

Waste rock will be strategically placed at least 165 m from the Main, West, and Northeast Embankments and co-disposed with the thickened tailings. The waste rock will be placed in alternating layers and in such a manner as to avoid the formation of higher-permeability zones through the deposit. The waste rock will be continuously buried by subsequent tailings deposition to encapsulate the waste rock and minimize the potential for the onset of acid-rock drainage (ARD) and/or metal leaching (ML) conditions. The tailings in the co-disposal zone will partially fill the waste rock voids (estimated at 30%) and increase the overall dry density of the stored materials to an estimated dry density of 1.64 t/m^3 by the end of operations.

The ratio of tailings to waste rock placed in the co-disposal zone will vary over the five stages of WMF development. Initially, during Stage 1 operations, the ratio is estimated to be approximately 9:1. This ratio is expected to decrease to approximately 1:1 during Stage 4 operations and to approximately 2:1 during Stage 5 operations. Access roads constructed with waste rock will be incorporated into the WMF impoundment to facilitate waste rock placement. As each road is inundated with thickened tailings, a subsequent access road will be constructed, offset from the previous roads. This approach will prevent the formation of higher permeability zones in the WMF and help maintain the overall 2% tailings beach slope.

Closure

At closure, the WMF will be covered, and a spillway will be constructed to direct runoff from the WMF to the open pit. The WMF closure cover will consist of a 2 m thick, compacted saprolite layer covering the entire WMF basin, graded at 2% towards the closure spillway. Over this saprolite cover, a 0.25 m thick layer of topsoil will be applied and hydroseeded. This will minimize water and air infiltration into the tailings mass and provide controlled drainage from the surface of the WMF. This strategy will also help create a landform that will blend into the local topography, prevent standing water on the closed WMF and eliminate the possibility of uncontrolled embankment overtopping.

The infiltration of meteoric water through the WMF cover, mass of interlayered tailings and waste rock, and into the underlying saturated layer were estimated using a HELP model (USEPA, 2020). The model, developed for the final WMF arrangement, incorporated complex climate and land boundary conditions. The HELP model included parameters such as the saprolite cover layer, six fully saturated layers of tailings and waste rock, a final cover slope of 2%, local climate data, and evapotranspiration estimates, along with characteristics of the saprolite and tailings. The model was simulated for a period of 6 years. The results from the model suggest that the average infiltration rate through the bottom of the thickened tailings will be less than 100 m^3 per year. Based on the modelled flux through the WMF and groundwater flux under the WMF, the pore solution in the WMF will be diluted by a factor of approximately 12,000 by groundwater. Assuming the WMF source term chemistry reflects the pore water chemistry in the WMF that might eventually migrate into the underlying groundwater, mixing with groundwater will have a minimal effect on groundwater quality.

Conclusion

The combination of the compacted saprolite liner, the initial layer of consolidated tailings on the saprolite liner, and the tailings against the embankments will create a low-permeability waste deposit that minimizes oxygen diffusion and water infiltration within the waste. This waste management strategy is designed to reduce the oxidant and transport mechanisms that create ARD conditions. The following key additional conclusions can be made based on the waste co-disposal strategies discussed above.

- The tailings and PAG/uncertain waste rock can be effectively co-disposed in a single facility over the life of the mine, with the waste rock fully encapsulated within the tailings.
- Partial ingress of tailings into the waste rock voids will increase the overall density of the waste deposit over time and reduce the overall height of the perimeter embankments.
- The WMF can become a landform at closure, while minimizing potential seepage to the environment post-closure.

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