Decommissioning of the old pyritic tailings facility previously used in a talc operation, eastern Finland

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Abstract

The Luikonlahti tailings facility was originally constructed for tailings from an old copper mine operation and was later used for tailings from talc processing. Geochemical partitioning showed that the pyritic tailings were only partially oxidized in dried layers under the magnesite tailings at the edges of the impoundment, whereas water saturated layers below these edges and the tailings in the centre and south were unoxidised. Groundwater contamination under the facility is unlikely due to the compressed basement. The waterproof basement has allowed seepage to the surface, through the lower parts of dams, and into moraine hills which dam the tailings (mainly in the west). Effluents were strongly acidic and rich in heavy metals.

Decommissioning of the facility includes reshaping of the tailings to keep the water table high enough (water/wet cover) and to prevent oxidation and acid generation. The impoundment will be divided into two ponds, both engineered into a basin shape to collect melt and rain water for the late summer dry season. The depression will be covered with peat and the edges planted with wetland vegetation. The edges of the impoundment will have a double-layer dry cover (magnesite tailings and glacial till). Seepage waters will be managed in a wetland complex (mixture of aerobic and anaerobic) constructed in the Suursuo bog. Anaerobic limestone drains will be designed to collect seepage water. Construction materials will include peat, hay bales, limestone and dolomite rocks.

1 Introduction

Rehabilitation of an acid generating tailings impoundment for final closure requires relevant data about the structure and composition of the tailings material and underlying glacial and postglacial sediments. Information about the water table and its temporal and spatial variation inside the impoundment is also needed. In Finland, iron sulphide bearing till and host rock materials from open pits have been used in dam construction. Therefore, it is important to detect chemical changes in facility's dams that may markedly influence seepage mechanisms and the quality of effluents. Since oxygen concentration in the dam is greater than in tailings inside the dam, oxidation of leachate may not occur until it infiltrates through the dam, resulting in the release of elements from weatherable, sulphide containing dike materials (Räisänen et al. 2003).

Underwater disposal, water covers and flooding are commonly preferred prevention techniques for sulphide bearing tailings (Elander et al. 1998, Tremblay and Hogan 2001). The use of an elevated water table by itself does not, however, entirely prevent acid generation, as there may be zones of near-surface or near-edge exposure and drained tailings that remain available for oxidation. Water cover or flooding technology is applicable for the impoundment that maintains a water cover over the long-term. In an earlier study, Räisänen (2003a) suggested that tailings of poor permeability and a waterproof basement are required for a self-sustained water table.

In addition to reshaping the tailings surface, the treatment of leachate (seepage waters) necessitates site-specific resolution. Passive treatment methods employ natural processes to prevent or control acid drainage at a lower cost and with less maintenance than chemical treatment. These passive treatment techniques include anoxic limestone drains, aerobic and/or anaerobic wetland treatment systems and biosorbents (Tremblay and Hogan 2001). Anoxic limestone drains consist of limestone rock filters designed and constructed to gradually release alkalinity through the dissolution of limestone as acidic water flows through the drain by gravity. Aerobic wetlands act as sedimentation basins by various plant-mediated filtering mechanisms. In an anaerobic wetland, metals removal and acid neutralization is achieved by the activity of sulphate reducing bacteria. In most cases, constructed wetlands consist of mixtures of the above techniques (Tremblay and Hogan 2001).

In Finland, tailings of several metal sulphide mines have been engineered in bog basins or depressions of small lakes. In both cases, the substrata are organic rich sediments underlying glaciolacustrine silt sediments that are compressed under load. The Luikonlahti tailings facility in this case study has been engineered in a small lake surrounded by a peatland in a valley. The facility was originally constructed for tailings from an old copper mine operation and was later used for tailings from talc processing. This paper overviews the main impacts of the tailings on surrounding soils, surface waters and groundwater, along with keys to decommissioning the facility. The choice of rehabilitation techniques (flooding, wetland) is based on geological, hydrogeological and topographical investigations with special emphasis on the geochemistry of Quaternary deposits under the impoundment and its surroundings, tailing materials, seepage and surface waters, and groundwater.

2 Site Characterization

The Luikonlahti tailings facility is located in the Kaavi municipality, eastern Finland. The study site is about 70 km east of Kuopio and 500 km northeast of Helsinki, the capital of Finland. From 1968–1983, the Luikonlahti Copper Mine of Myllykoski Oy worked the area. During 15 years of operation, a total of 10 million tons of ore were mined. The copper ore contained Cu 1.1 % (in chalcopyrite), Zn 0.6 % (iron sphalerite), Co 0.1 % (in Co-pentlandite and in the lattice of pyrite and pyrrhotite) and S 18 % (mainly in pyrrhotite, Eskelinen et al. 1983). In addition to the copper concentrate, the Luikonlahti mine produced cobalt-nickel concentrate and zinc concentrate. The talc mining and production started in 1979 and was continued after 1984 by Finnminerals Oy. In 1991, Mondo Minerals Oy purchased the talc production facilities and ore reserves. After the mine closed, talc ore was transported from the Polvijärvi talc mines, and now from the Horsmanaho talc mine of Mondo Minerals Oy. The plant is also processing minor amounts of nickel concentrates from Horsmanaho.

The Luikonlahti tailings facility is about 27 hectares in size. The facility consists of two types of tailings: pyritic tailings (potentially ARD generating) from previous operations and overlying magnesite rich tailings (alkaline nature) from the talc processing. The amount of pyritic tailings is about 6 million tons along with 2.1 million tons of magnesite tailings.

The tailings are dumped in the old Petkellampi Lake. Due to the topography, steep outcrops and moraine hummocks with crystalline bedrock cores naturally dam the tailings. Dams have been constructed from glacial till and waste rock materials in a narrow valley to the west (20 m high main dam), and to the north and south (dikes less than 10 m high). In contrast to the small dikes, the upper part of the main dam has been constructed from tailings and later covered by a thin till layer to prevent a dust problem. The dam is between two moraine hills edging onto the Suursuo bog at the depression. Originally, waters from the lake discharged via a creek into the Suursuo peatland and, at present, the bog basin forms the main seepage area of the facility.

At present, the tailings water is chemically purified in the settling pond, which is dammed in the southern part of the facility. Tailings water contains some As and Ni, which are precipitated by adding ferrisulphate for the oxidation of As and lime for Ni. The water from the settling pond drains into the canal and further into the Heinälampi Lake. In the lake, the final purification of waters is attributed to natural biogeochemical processes in the uppermost sediment.

3 Materials and Methods

The study consists of field observations and collection of sediment, tailings and water samples from the tailings impoundment and its surroundings, and their chemical analyses. The basement and layer structure of the tailings facility, and its hydrogeological conditions, were studied by drilling with a non-rotating percussion drill at 5 sites (Räisänen 2003b). Profile samples from Quaternary sediments and overlying tailings materials were continuously taken with a special soil core sampler during the drilling. In addition, sediment sample profiles (peat, silt and till) were taken from the main seepage areas at the west side of the facility. Altogether, 56 layer samples from the profiles were selected for chemical analysis.

For groundwater monitoring, two observation holes were installed in the moraine hummocks at the west side of the facility (main seepage area), and two observation holes at less contaminated sites (background). The groundwater quality was also monitored from spring water at two uncontaminated sites. Altogether 50 samples were taken from groundwater, pure seepage waters and contaminated surface waters, as well as uncontaminated surface waters and groundwater. In addition, iron precipitate samples were collected at seven sites in the western seepage area of the facility.

3.1 Chemical analysis of tailings and sediment samples

Tailings, peat and mineral sediment samples were freeze-dried and then sieved to <2.0 mm fraction. Four different single extractions were performed to determine element concentrations in the physically and chemically adsorbed fractions, fractions of secondary crystalline precipitates, micas and well crystalline clay minerals. Dilute (0.01 M) barium chloride solution was used to extract physically adsorbed elements (water soluble/easily leachable), ammonium acetate (1M) solution buffered to pH 4.5 for chemically adsorbed elements (exchangeable, surface complexes), ammonium oxalate (0.2 M) buffered to pH 3.0 for Fe and Al oxyhydroxides and hot (90^o) *aqua regia* for mica and clay mineral fraction (Niskavaara 1995, Räisänen and Tauriainen 2001, Räisänen and Carlson 2003, Schultz et al. 2004). In contrast to mineral sediment samples, the nitric acid leach assisted by microwave (EPA 3051) was used for peat samples to determine the immobile fraction (Niskavaara 1995). The ICP-AES technique was used for measurements of element concentrations in all the above extracts.

The total sulphur concentration was determined using the Leco-S technique and the total concentration of carbon and nitrogen with a CN-analyzer. In addition, the X-ray fluorescence (XRF) method was used to measure total element concentrations from tailings samples. The extractions and ICP-AES, S, C and N determinations were made in the FINAS accredited Geolaboratory of the Geological Survey of Finland (GSF) at Kuopio and XRF analysis at Espoo.

3.2 Physical and chemical analysis of water samples

The pH of water samples was determined both in the field immediately during sampling and in the laboratory. In the laboratory, water samples were left for 1.5-2 days in a fridge to stabilize dissolution and precipitation of Fe, S and Al. With this pretreatment, conditions are assumed to simulate precipitation in stagnant water (i.e. in a wetland environment). After settling, the pH, electrical conductivity, oxygen concentration and oxygen saturation rate were measured before filtering with <0.45 µm filters. It is assumed that elements in settled and filtered waters mainly represent their ionic forms. To prevent further precipitation, 0.5 ml suprapure nitric acid was added in the filtrates. Concentrations of 30 elements were measured with ICP-AES and MS-ICP techniques in the FINAS accredited Geolaboratory of Geological Survey of Finland in Espoo.

4 Results

4.1 Chemical composition and weathering of tailings

The tailings from the talc processing contain mainly magnesite, talc, chlorite, micas and a minor amount of iron, nickel and arsenic sulphides. These are characterised by high Mg and C concentrations, moderate Ni, and low S and Fe concentrations (Table 1). Also noteworthy is the abundance of As. On the basis of the geochemical partitioning, the chemical transformation of the tailings was weak. The pH of the weakly oxidized tailings varied from 6.7-7.5. This reflects the low content of acid generating minerals (Fe sulphides) and high content of buffering carbonate minerals (magnesite). Magnesite tailings did, however, contain some mobile Ni and As that was released from the broken crystal surfaces of the sulphides during the flotation.

Major minerals of the pyritic tailings are quartz and iron sulphides. In addition, there are variable amounts of talc, chlorite, calcite, diopside, graphite, sphalerite, chalcopyrite and pentlandite. Originally, lime was added to the tailings before they were pumped into the facility. The pH varied from 3.5-4.5 in the highly oxidized tailings to 6.5-8.7 in the water saturated, unoxidized tailings. Compared to the magnesite tailings, the pyritic tailings have markedly higher concentrations of S, Fe, Zn, Cu and Co, and less Ni and As (Table 1). As Table 1 shows, concentrations of S and heavy metals are higher in the uppermost oxidized layer than in the unoxidized lower layer. This indicates that part of the metals and sulphur are precipitating *in situ* during the oxidation of Fe sulphides and the subsequent weathering and precipitation process (Table 2). Moreover, the geochemical partitioning showed that the chemical transformation of the tailings, and therefore the mobility of heavy metals, was more enhanced in the upper layers than in the lower unoxidized layers. According to the chemical data, acid generating rather than buffering ability characterizes the old, pyritic tailings.

The chemical transformation of the magnesite and underlying pyritic tailings depends on the water saturation rate. The free water table varies by seasons and the location of the pipe where tailings are discharged. According to drilling data, the water table was about 3-4 m deeper at the edges in the west and north than elsewhere, with the water table approaching the surface in the centre and east and rising above it in the south. This, combined with geochemical partitioning data, results in intensive oxidation of the pyritic tailings being mainly limited to the west and north. However, the tailings displayed minor changes in the uppermost layers and were unoxidized in the middle and lower layers in the centre and eastern parts of the facility. Obviously, tailings that are beneath the water table in the south are still unoxidized (not drilled).

Table 1. Total element concentrations of magnesite and pyritic tailings samples in the Luikonlahti tailings facility. Key: < concentration under the detection limit, - no measurement.

		Magnesite tailings (upper layer)	Pyritic tailings, unoxidized	Pyritic tailings, oxidized
Fe	g/kg	52	109	145
S	g/kg	10	70	97
As	mg/kg	83	<20	<20 (max 35)
Cd	mg/kg	0.8	4.0	4.4
Co	mg/kg	57	369	497
Cr	mg/kg	196	82	36
Cu	mg/kg	37	836	1228
Mn	mg/kg	954	481	345
Ni	mg/kg	960	392	610
Zn	mg/kg	117	3211	3764
C	g/kg	87	-	-
Si	g/kg	98	318	-
Al	g/kg	4.9	16	-
Mg	g/kg	224	45	-
Ca	g/kg	20	50	-
Na	g/kg	<0.5	4.7	-
K	g/kg	0.1	4.7	-
Ti	g/kg	0.5	0.8	-

Table 2. The geochemical fractions of Fe and S, Luikonlahti tailings facility (see the text).

Geochemical fractions	pH	Fe mmol/kg	S mmol/kg
	Magnesite tailings, oxidized (N = 8)		
Physical adsorption	7.0	<0.04	0.5
Chemical adsorption		12	4.0
Well crystalline precipitate		43	0.5
Sulphides (+ silicates)		889	314
	Pyritic tailings, oxidized (N =12)		
Physical adsorption	4.9	18	26
Chemical adsorption		23	61
Well crystalline precipitate		117	9.3
Sulphides		2157	2254
	Pyritic tailings, unoxidized (N=12)		
Physical adsorption	5.4	<0.04	2.2
Chemical adsorption		14	33
Well crystalline precipitate		84	0.9
Sulphides		2033	2320

4.2 Nature of contamination in surroundings of the facility

The total thickness of the tailings is 21-22 m in the central area of the old Petkellampi Lake. The thickness decreases to the west (18 m), the south (16 m) and east (12 m). The shallowest site is at the northern part of the facility where the tailings have been partially dumped onto the outcrop. The thickness of the overlying magnesite tailings varied from one meter (in the west and north) to 5-7 meter (in the centre, east and south).

Based on drilling data, peat and organic rich lake sediments have been compressed under the mass of tailings, forming a waterproof basement. Thus, the impact of the tailings water on the groundwater under the facility is minimal. The compressed organic sediment acts as a filter, accumulating metals and sulphur released from the above tailings layers (Sipilä and Salminen 1995, Räisänen 2003a). This leads to seepage through the edges of the facility in places where the dams are constructed and where tailings rest on the water permeable moraine hill slope.

The base topography of the facility forms a shallow, NW-SE elongated basin. The basin declines towards the west and, therefore, seepage waters are mainly discharged to the west, the Suursuo bog area and bordering moraine hills, and to a lesser extent towards the north and south.

Table 3. The composition of contaminated and uncontaminated groundwaters, Luikonlahti study area (see text).

		Contami-nated	Uncontaminated
Valid Value Count		2	3
pH (in field)		4.3	6.2
pH (in lab)		4.1	6.1
Electric conductivity	mS/m	175	11
Oxygen	mg/l	3.5	6.1
Oxygen saturation	%	34	56
Acid generating elements			
Fe	mg/l	13	0.1
S	mg/l	604	3.7
Al	µg/l	34100	61
Mn	µg/l	10875	12
Silicon, earth alkaline and alkaline elements			
Si	mg/l	37	5.1
Ca	mg/l	214	2.4
Mg	mg/l	232	4.3
K	mg/l	10	1.3
Na	mg/l	12	1.8
Heavy metals			
As	µg/l	0.9	0.2
Cd	µg/l	8.4	0.04
Co	µg/l	2050	1.3
Cr	µg/l	5.4	0.4
Cu	µg/l	313	2.2
Ni	µg/l	2940	21
Zn	µg/l	13845	55

Table 4. The composition of waters taken from the tailings pond, seepage sites and ditches in the Suursuo bog area, Luikonlahti study area.

		Pond water		Seepage water		Suursuo, ditch water	
		Mean	Range	Mean	Range	Mean	Range
Valid Value Count		2		10		6	
pH(in field)		6.5	no	3.6	2.7-5.3	3.9	3.3-5.6
pH (in lab)		6.6	6.5-6.7	3.6	2.7-5.3	3.8	3.3-5.0
Electric conductivity	mS/m	28	14-43	198	112-486	144	71-199
Oxygen	mg/l	7.1	6.9-7.3	4.9	1.4-7.3	6.6	6.0-7.3
Oxygen saturation	%	69	65-72	46	12-69	63	58-67
Acid generating elements							
Fe	mg/l	0.3	0.07-0.5	228	4.7-1730	21	4.2-45
S	mg/l	55	22-87	580	254-1900	387	168-564
Al	mg/l	0	0.03-0.2	10	0.3-30	4	0.8-5.9
Mn	mg/l	1	0.4-2.1	20	14-49	15	13-19
Silicon, earth alkaline and alkaline elements							
Si	mg/l	4.0	3.0-5.0	19	9.7-48	13	11-16
Ca	mg/l	35	14-56	333	153-511	313	108-499
Mg	mg/l	22	12-33	102	54-265	73	47-92
K	mg/l	2.5	0.9-4.1	7.3	5.2-9.2	8.0	5.2-11
Na	mg/l	5.3	2.4-8.2	10	3.4-12	15	8.0-27
Heavy metals							
As	µg/l	25	2.7-48	0.6	<0.2	0.7	max 2.4
Cd	µg/l	<0.02	max 0.1	2.7	0.3-6.0	1.9	0.2-3.6
Co	µg/l	20	14-25	348	61-1860	166	128-202
Cr	µg/l	0.3	max 0.4	49	0.4-438	3.2	0.6-6.9
Cu	µg/l	2.9	2.2-3.7	513	6.2-3730	74	16-124
Ni	µg/l	573	505-641	822	371-1940	548	339-693
Zn	µg/l	18	16-20	4135	142-21200	1795	502-3260

In the Suursuo basin area, the contamination of Quaternary sediments, surface waters and groundwater is characterized by elevated concentrations of acid generating elements (Fe, S, Mn, Al) and heavy metals such as Zn, Ni, Cu and Co (Tables 3 and 4). In addition, elements indicating silicate and carbonate mineral weathering were elevated in the waters of some sampling sites. As Table 4 shows, the composition of the free water in the impoundment differs markedly from the composition of the seepage waters. Therefore, the elements are mainly released from the weatherable dike materials, pyritic tailings oxidized at the edges of the upper part of the dam and sulphide bearing rock in the lower and middle parts of the engineered dam. Moreover, the uppermost sediments (iron precipitates and peat) in the bog showed raised element patterns similar to the surface waters and groundwater.

Seepage waters from the northern dike were less acidic and had lower concentrations of heavy metals. These waters are mainly settled in a wetland that has been naturally formed outside the northern dike. Seepage waters from the southern constructed dam were slightly acidic. Concentrations of acid generating elements and heavy metals were, however, markedly lower there than in the waters of the Suursuo bog area. These observations support the interpretation that the main seepage area is towards the west in the Suursuo bog area.

5 Rehabilitation options

Results lead to the following conceptual model of the facility:

- The basement of the facility is essentially waterproof, so that there is little contamination of the underlying groundwater.
- The bottom topography of the facility slopes westward and rises steeply to the north and east, but more gently to the south. The main water gradient inside the facility is, therefore, towards the Suursuo bog basin located in the western section of the facility.
- The water table is pretty close to the surface in most of the facility (centre and east sites). Moreover, the southern part of the facility is under water. The water table lies deeper near the northern and western edges.
- The oxidation of the old pyritic tailings is limited to the upper layers of the facility along the western and northern edges, while most of tailings in the centre, east and especially in the south showed minor chemical transformations. Noteworthy is the *in situ* precipitation of weathering products along the dried edges, which potentially decreases the metal release into the outflow.

Partially dry cover (edges) and partial water or wet cover (centre) is recommended to mitigate acid generating and metal release from the old pyritic tailings. Due to the present topography, the division of the impoundment into two shallow basins is needed to flood and keep the water table above or close to the surface during most of the year. Furthermore, the western main dam should be sealed from the top part with glacial till. Reshaping can be achieved with the magnesite tailings, till and peat. The thickness of the magnesite tailings will increase in the western and northern parts of the impoundment during the final operation of the plant. The size and depth of the depressions in the impoundment will be planned according to annual precipitation (melt and rain water) estimates and annual seepage. The edges and possibly the bottom of the basins will be covered with peat to promote the growth of the wetland vegetation.

The basin shape topography of the facility enables the accumulation of melt and rain waters for the dry season in late summer (Räisänen 2003a). The moderately low permeability (10^{-6} – 10^{-7} m/s) of both the tailings materials can result in slow downward filtering and outward seepage (Saarelainen 1999, Räisänen 2003a). Obviously, the submergence of the tailings in most parts of the impoundment will markedly retard oxidation, acid generation and the potential for metal release. Moreover, the oxygen consumed in the basin's wetland will prevent acid generation.

The flooding of the oxidized tailings along the edges may increase the metal content in seepage waters, especially during the first years (Elander et al. 1998). Therefore, the edges of the facility should be covered with dry till and vegetated with leaf trees, grass and other meadow vegetation. The main goal will be to keep the water table approximately at the present level.

The best approach for seepage water purification is passive treatment. Limestone drains are suitable for seepage water collection and a mixture of anaerobic and aerobic wetlands for the settling of solids and prevention of heavy metals and sulphur. The constructed wetland will be engineered in the Suursuo bog area and will consist of 3-4 pools. The first or second pool into which the seepage waters are diverted will work as a mixed aerobic-anaerobic sedimentation basin for Fe precipitates. The main processes are oxidation in the uppermost layer and sulphate reduction in the lower layers of sediments (Räisänen et al 2001). The second or third pool will be shallow and aerobic for Mn oxidation and precipitation. The last pool will be engineered for removal of solids during flooding seasons. Carbonate rocks (limestone or dolomite) will be used as construction materials in the bottom of the pools and will be covered with a peat layer. To promote Mn precipitation, dolomite cascade and/or hay bales can be used in the shallow pool.

At the beginning of the decommissioning, waters from the wetland will be pumped back into the depressions of the facility and, if necessary, chemically purified in the present settling pool. This will continue until the wetland functions according to the water quality guidelines. Overall, the follow-up project will investigate and monitor the capacity and workability of the proposed remedial constructions.

6 Conclusions

Geochemical partitioning has shown that the old pyritic tailings at the Luikonlahti facility are only partially oxidized in dried layers under the magnesite tailings at the edges of the impoundment, whereas water saturated layers below and the tailings in the centre and south are unoxidised. Groundwater contamination under the facility is unlikely due to the compressed basement. Seepage has occurred above this to the surface, through the lower parts of dams and the moraine hills, which dam the tailings. According to the geomorphology of the basement, seepage waters are mostly discharging into the Suursuo bog, located on the west side of the facility. Effluents are strongly acidic and rich in heavy metals.

Decommissioning of the facility includes reshaping of the tailings to keep the water table high enough (water/wet cover) to prevent oxidation and acid generation. The impoundment will be divided into two ponds that are both engineered into a basin shape to collect melt and rain water for the late summer dry season. The depression will be covered with peat and the edges planted with wetland vegetation. The edges of the impoundment will have a double-layer dry cover (magnesite tailings and glacial till). Seepage waters will be managed in a wetland complex (mixture of aerobic and anaerobic) constructed in the Suursuo bog. Anaerobic limestone drains will be designed to collect seepage water. Construction materials will include peat, hay bales, limestone and dolomite rocks.

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