The KaiHaMe project – increasing raw material value of exploited ores

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Abstract Mining generates large amounts of waste materials, since only a small part of excavated ores is usually utilized. Waste disposal requires large areas, is costly and may mean squander of natural resources, if only the most obvious commodities are utilized. The objective of the KaiHaMe project is to assess ways to increase raw material value of ores from gold deposits and to decrease the amount of disposed hazardous wastes. Based on the preliminary results, removal of harmful contaminants and minerals, in particular arsenic, from tailings through mineral processing seems to be a potential technique to achieve these goals.

Key words Mining waste, tailings, valorization, mineral processing, lysimeter tests

Introduction

Management of mining wastes is one of the primary challenges of sustainable mining due to their large amounts and potential long-term generation of low quality mine drainage. Only a small part of excavated ores can usually be utilized and the rest of the material is disposed as a waste, i.e. as waste rocks or tailings. This is especially true for the gold and base metal ore deposits, in which the ratio between generated wastes to the extracted valuable metals is particularly high. In these cases, the waste materials typically contain notable amounts of acid producing sulphide minerals and hazardous metals, and are prone to generate drainage waters with elevated metals and sulphate. Long-term management of these wastes in an environmentally and geotechnically acceptable manner is costly and requires large areas. Disposal of wastes may often also mean squander of natural resources, if only the most obvious commodities are utilized from the ore. Thus, new methods and approaches to promote eco-efficient use of mineral resources are needed.

Consequently, various solutions have been developed during the last decades to increase valorization of mining wastes to decrease their environmental impacts. In addition, the objective of the valorization has been to respond to the shortage of raw materials, growing costs to explore and mine new ore deposits, and a necessity to manage natural resources in accordance with the sustainable development principles. The new solutions include, for instance, desulphurization of tailings (*e.g.* Benzaazoua & Kongolo 2003), production of glass-ceramics from tailings (*e.g.* Marabini et al. 1998), and recovery of precious metals from tailings using bioleaching (Liu et al. 2008) or chemical treatment (Lv et al. 2014).

The project "Mining waste management methods", KaiHaMe, aims at increasing raw material value of excavated gold and base metal ore deposits and decreasing the amount of disposed hazardous wastes. This is done by modifying gold ore tailings with mineral processing techniques and by seeking new options for the use of waste rocks from base metal mining. The objective of the mineral processing is to generate tailings with lower levels of hazardous elements and minerals, especially As and sulphide minerals. The influence of the improved tailings composition on their leaching behaviour is further studied using mineralogical and geochemical characterization together with filled-in lysimeters measuring longer term behaviour together with drainage quality in field conditions. The project started in 2015 and will continue until the beginning of 2018.

This paper focuses on the preliminary results from the beneficiation tests targeting at reducing As and sulphide mineral content in gold ore tailings from the Kopsa ore deposit, and the filled-in tailings lysimeter tests to evaluate longer term performance of the modified tailings in field conditions. Initial results from waste rock studies are presented in a separate paper by Karlsson et al. (2017; these proceedings).

Study area and methods

Sample material for the beneficiation tests and filled-in lysimeters originated from the Kopsa gold ore deposit, located in Western Finland (fig. 1). The Kopsa ore deposit is a porhyric Au-Cu mineralization, which is hosted by tonalite and mica schist. The major ore minerals in the deposit are arsenopyrite, chalcopyrite and pyrrhotite with accessory löllingite, marcasite, pyrite, sphalerite, gold, cubanite, bornite, stannite, bismuth and Bi-bearing sulphosalts (Gaál & Isohanni 1979). The estimated ore reserves are 13.6 Mt with 0.81 g/t Au, 0.15% Cu and 2.15 g/t Ag (SRK 2013). Elevated As contents are very typical for the mineralization, the As content varying between 0.1-1.2% in the deposit (Gaál & Isohanni 1979, Nurmi *et al.* 1991). Exploration has been carried out since the 1940s around the Kopsa deposit and the latest holder of the exploration claims, Belvedere Mining Oy, planned to open a mine but went bankrupt in 2015. Therefore, no tailings exist at the site yet, providing possibility for tailings optimization.

Beneficiation tests were carried out on the Kopsa ore to evaluate realistic ways to decrease As and sulphide mineral content in the tailings in order to decrease the amount of hazardous waste and to generate tailings that could be used as a cover material for mining waste facilities. In the flotation tests, influence of the grind size, flotation time, and flotation chemicals and their dosage was studied. Prior to the beneficiation tests, thorough mineralogical analyses were carried out on the ore samples using a Mineral Liberation Analyser (MLA; MLA FEI Quanta 600) equipped with a scanning electron microscope, two energy dispersive spectrometers and the MLA software. The mineralogical phases, and liberation, association, and grain size distribution of the As bearing minerals were determined with the MLA. Electron probe microanalyser (Cameca SX100) was applied for more detailed identification of the key mineral phases. The total chemical composition of the ore samples was measured using XRF, Au and Ag content by fire assay with FAAS, and total sulphur content using combustion technique (Eltra). Similar mineralogical and chemical characterizations were made on the beneficiation test products (i.e. concentrate and tailings) as for the ore sample to help to modify the process.

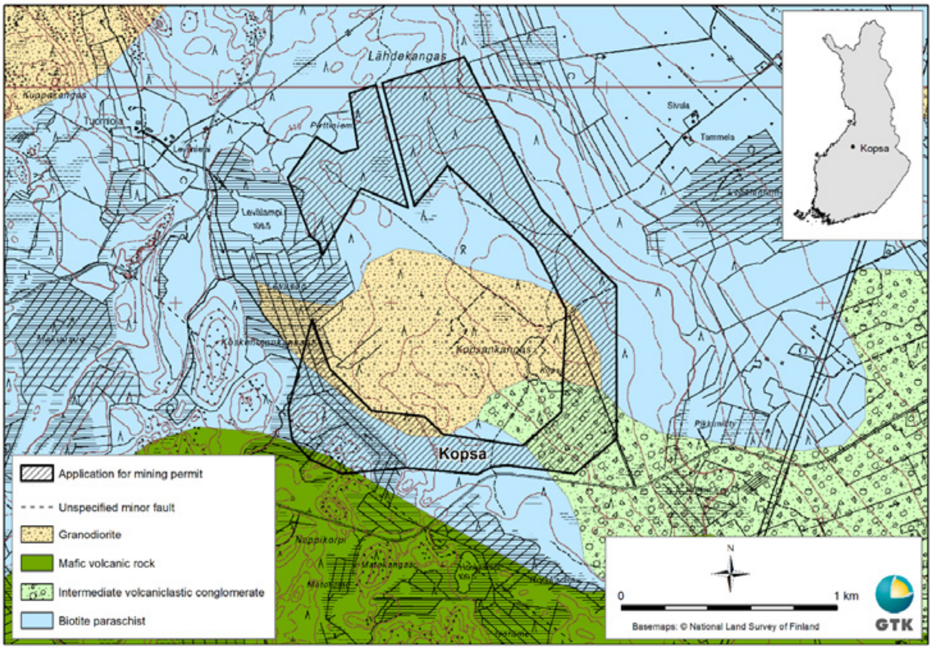

Figure 1 *Location and geology of the Kopsa Au deposit (GTK 2017). Basemaps © National Land Survey of Finland.*

Tailings samples and water samples were collected from unmodified (i.e. following the original process flow sheet planned by the Belvedere Mining Oy) and modified beneficiation tests to study the impact of the process changes on their environmental properties and the occurrence of As in particular. Water samples were separated from the tailings slurry using vacuum filters. pH, T, EC, O_2 (mg/l), O_2 (%) and redox potential were measured using a portable multi-parameter instrument (YSI Professional Plus). Alkalinity was also titrated during the sampling with a HACH digital titrator with 1.6N H_2SO_4 to an end point of pH 4.5. Chemical analyses of the water samples included total and dissolved elements (ICP-OES/MS), anions (ion chromatography), ferrous iron, and dissolved and total organic carbon (pyrolytical method based on standard SFS-EN 1484). Characterization of tailings included both chemical and mineralogical measurements. The total chemical composition of the tailings was analysed using XRF, and total sulphur and carbon concentrations (total C, carbonate-C) were measured pyrolytically with sulphur and carbon analysers. Maximum concentrations of mobile elements were measured using *aqua regia* digestion and ICP-OES/MS analysis. NAG (AMIRA 2002) and ABA tests (CEN EN-15875) were applied to determine the tailings' potential to produce acid mine drainage. NAG leachates were further analysed to evaluate contaminant leaching from the tailings. Mineralogical analyses of the tailings followed the same methods applied for the ore samples (described above).

Filled-in lysimeters were additionally applied to compare leaching behaviour and drainage quality of the unmodified (As rich) tailings with the modified (As poor) tailings in field conditions to evaluate suitability of the modified tailings as a cover material for other mining wastes. The lysimeter tests were carried out in Kuopio, Eastern Finland. Two plastic lysimeters were filled with approximately 200 kg of tailings material (As rich and As poor tailings) collected from the beneficiation tests in July 2016. An empty lysimeter was used as a background for water analysis and to monitor potential contamination of the lysimeter containers. Water quality was analysed periodically from the lysimeters and the analyses included the same measurements as were made for the tailings water after the beneficiation tests.

Results and discussion

Modification of As content and environmental properties of tailings with beneficiation tests

Prior to the beneficiation tests, the sources and content of As in the ore feed were determined using mineralogical methods and XRF. The results showed that the main hosts for arsenic were arsenopyrite (1.7 Wt%), Fe arsenate mineral (0.04 Wt%) and löllingite (0.01 Wt%) (tab. 1). Otherwise the ore was composed mainly of quartz (23.5 Wt%), plagioclase (23.2 Wt%), potassium feldspar (22.0 Wt%), and biotite (10.7 Wt%) with small amounts of other sulphides than As sulphides (1.0 Wt%; pyrrhotite, chalcopyrite, pyrite) and with minor carbonates (calcite 0.26 Wt%). The As bearing minerals occurred mainly as free grains in the ore feed (80% < 44 µ) i.e. as well liberated grains, even though in the coarsest fraction they were also associated with silicate minerals. The As content of the ore feed was 0.7% (tab. 1).

Table 1 *As content (XRF) and amounts of primary As hosts in the Kopsa ore feed and tailings from the beneficiation tests based on MLA. (n.d. = not detected)*

Parameter	Ore feed	Unmodified, As rich tailings	Modified, As poor tailings
As (%)	0.7	0.03	0.02
Arsenopyrite (Wt%)	1.71	0.02	0.01
Fe arsenate (Wt%)	0.04	0.02	0.02
Löllingite (Wt%)	0.01	n.d.	n.d.
Other sulphides	1.01	0.09	0.04
Calcite	0.26	0.31	0.31

Beneficiation tests were started by following the original process flow sheet planned by the Belvedere Mining Oy. It consisted of crushing, grinding with a ball mill, Cu flotation, and sulphide flotation (tab. 2). The reagents used in the Cu flotation included $Ca(OH)_2$ for pH adjustment, Aero 5100 as a selective copper sulphide collector, and methyl isobutyl carbinol (MIBC) as a frother. In the sulphide flotation H_2SO_4 was applied to adjust pH, $CuSO_4$ as an activator for sulphides and gold, potassium amyl xanthate (PAX) as a sulphide collector, Aero 7249 as a promoter for gold, and MIBC as a frother (tab. 3). This beneficiation process yielded tailings with As content of 310 mg/kg (referred to later as "As-rich tailings"; tab. 4) and with 0.04 Wt% of As sulphides and Fe arsenates (tab. 1), which occurred mainly as fresh mineral grains in the finest fraction (< 20 µm) of the tailings. In the beneficiation, the highest portion of As was reported to the sulphide concentrate.

Table 2 *Methods and parameters used in the beneficiation tests.*

Beneficiation test	Crushing	Grinding	Cu flotation time	Sulphide flotation time
Original process	100% −1 mm	80% −52 µm	6 min	14 min
Modified process	100% −1 mm	80% −35 µm	6 min	84 min

After this, several modifications were made on the process flow sheet to decrease the As and sulphide mineral contents of the tailings and the overall amount of hazardous tailings. The grinding time was increased to further improve liberation of As bearing minerals. Reagent dosages and flotation time of the sulphide flotation were amplified to enhance reporting of As sulphides and other sulphides to the concentrate and to decrease the amount of As containing tailings (tab. 3). As a result, tailings As concentration was reduced to 200 mg/kg (tab. 4), the amount of As containing minerals from 0.04% to 0.03% (tab. 1), and the quantity of tailings from 90.1 Wt% to 77.8 Wt% ("As poor tailings"). The number of other sulphides in the tailings was also decreased (from 0.09% to 0.04%, tab. 1) reducing the amount of sulphur in the tailings and increasing its neutralization potential ratio (NPR; tab. 4) as the carbonate content remained the same (tab. 1). Based on the results from the NAG leachate, the reduction of total As in the tailings resulted also in the decrease of the leachable As (tab. 4).

Table 3 *pH and reagent dosages in the beneficiation tests.*

Beneficiation test	Cu flotation chemicals (g/t)			Sulphide flotation chemicals (g/t)				
	$Ca(OH)_2$	Aero 5100	MIBC	H_2SO_4	$CuSO_4$	PAX	Aero 7249	MIBC
Original process	pH 11.5	20	10	pH 10.5	200	200	200	20
Modified process	pH 11.5	20	10	pH 10.5	275	310	200	30

Table 4 *Key chemical characteristics of the As rich (unmodified) and As poor (modified) tailings. (AR = aqua regia, NAG leach. = NAG leachate, NPR = neutralization potential ratio)*

Tailings	pH	NPR	As (mg/kg)			S (%)	S (mg/kg)	
			Total	AR	NAG leach.	Total	AR	NAG leach.
As rich	8.1	3.4	310	292	51	0.09	876	799
As poor	8.3	7.6	200	206	37	0.04	473	433

As a result of the tailings modification, the quality of the tailings water also improved. This was especially observed as a decreased EC and contents of As, Mo, and SO_4 in the tailings water of the As poor tailings compared with those of the As rich tailings (tab. 5). Both waters were alkaline, as the beneficiation process was carried out at alkaline pH (tab. 3) and the tailings were fresh and unoxidized. The tailings water of the As poor tailings was less alkaline (pH 8.7) than the water from the As rich tailings (pH 10.1, tab. 5). This is probably because the modified enrichment process lasted longer than the original process leaving more time for the slurry pH to balance.

Table 5 *Tailings water quality of the As rich (unmodified) and As poor (modified) tailings.*

Tailings	pH	EC (mS/m)	SO_4 (mg/l)	As (µg/l)	Cu (µg/l)	Mo (µg/l)
As rich	10.1	76	310	775	<0.5	55
As poor	8.7	57	220	174	<0.5	21

The results of the beneficiation tests and the subsequent characterization of tailings and tailings water suggest that it is possible to improve tailings environmental properties and contribute to the water quality in the enrichment process with reasonable adaptations of the beneficiation process. However, the feasibility of these adaptations with respect to the acquired benefits in the waste management requires further evaluation.

Evaluation of the performance of the modified tailings in field conditions using filled-in lysimeter

Lysimeter tests were started in July 2016 to study the performance of the modified As poor tailings generated in the beneficiation test as a cover material for other mining wastes in field conditions. Sampling from the lysimeters was made once in the autumn 2016 and it will continue once the lysimeters unfreeze after the winter period in Eastern Finland. Summaries of the mineralogy and key chemical characteristics of the tailings used in the lysimeters are presented in tables 1 and 4.

Based on the preliminary results of the lysimeters, the seepage waters from both As rich and As poor tailings were alkaline (tab. 6) as expected based on the NPR. The main contaminants in the seepages were As and Mo with minor Cu. Sulphate concentrations were also elevated suggesting minor sulphide oxidation, but as the sulphide content of the tailings was overall quite small and the sulphide mineral grains were unoxidized, most of the SO_4 presumably originates from the H_2SO_4 and $CuSO_4$ used in the ore processing.

Based on the results, the modification of the tailings has decreased leaching of metals from the tailings. Especially EC and concentrations of As, Cu, and Mn were smaller in the lysimeter seepages of the modified As poor tailings than in the original As rich tailings (tab. 6). However, as the monitoring represents only one sampling event after the installation of the lysimeters, it is not expected that mineral weathering reactions have yet started. Instead, the current metal loading most likely results from the element leaching from the mineral edges broken during mineral processing. To observe the longer term changes in the water quality and to further evaluate the suitability of the As poor tailings for a cover material, the monitoring of the lysimeters will be continued and extended even after the end of the KaiHaMe project.

Table 6 *Monitoring results of the lysimeters. (Blank = empty lysimeter to control background concentrations of rainwater and possible contamination from the containers.)*

Lysimeter	Sampling time	pH	EC (mS/m)	SO_4 (mg/l)	As (µg/l)	Cu (µg/l)	Mn (µg/l)	Mo (µg/l)
Blank	Sept. 2016	6.4	6.7	1.2	4.2	2.5	1.4	0.1
As rich	Sept. 2016	7.9	127	740	235	13.5	176	62
As poor	Sept. 2016	8.0	57	190	186	0.1	37	37

Conclusions

To find solutions to reduce the amount of hazardous waste and to increase the usage potential of tailings, modifications of the ore enrichment process were studied with a particular aim to assess ways to decrease As and sulphide mineral content of the Kopsa gold mine tailings. The results showed that the amounts of As and sulphide minerals in the tailings can be reduced *e.g.* by adjusting grind size, flotation reagent dosages and flotation time. Based on the preliminary results of the filled-in lysimeters, the improved quality of the Kopsa tailings decreases leaching of As and other contaminants from the tailings in field conditions.

During the KaiHaMe project, the beneficiation tests will be continued to test additional techniques to further decrease As content in the Kopsa tailings and the studies will also be extended to other gold deposits. Monitoring of lysimeters will be still continued to evaluate the suitability of the As poor tailings as a cover material for other mining wastes. In addition, the field tests will be complemented with laboratory leaching tests to study leaching of As and other contaminants from the As poor and As rich tailings. Economic aspects of the modifications, such as increased costs for energy, reagents and materials, will be further evaluated with respect to the acquired benefits in the waste management.

One of the key conclusions from these preliminary results is that if more focus and efforts were put on the waste properties already during the ore processing, it would be possible to improve the environmental quality of the waste materials and their drainage, to create smaller amounts of hazardous waste, produce new products, and to enhance the eco-efficiency of raw materials.

Acknowledgements

The authors thank Belvedere Mining Oy for providing sample material for the study. ERDF funding programme, Boliden Kevitsa Mining Oy, FQM Kevitsa Mining Oy, Kemira Oyj, and Endomines Oy are acknowledged for co-funding the project.

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