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Improving the environmental properties, utilisation potential and long-term prediction of mining wastes

Päivi M. Kauppila and Timo Tarvainen (eds)

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**Improving the environmental properties, utilisation potential and
long-term prediction of mining wastes**

by

Päivi M. Kauppila and Timo Tarvainen (eds)

Unless otherwise indicated, the figures have been prepared by the authors of the article.



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One of the key issues in modern mining is the sustainable management of extractive wastes. The key challenges related to the disposal of these wastes include their large amounts and the hazardous components they may contain, which can cause long-term environmental impacts if left unmanaged. Reducing the amounts of wastes, especially those with hazardous properties, and improving their environmental performance require new insights to increase the raw material value of the wastes, for example, by removing hazardous substances from them to reduce their management costs.

This publication summarises the results from the Mining Waste Management Project (KaiHaMe), which developed tools for the management of mining wastes to facilitate the prediction of their long-term stability, to reduce the environmental impacts of waste disposal and to increase the eco-efficient use of raw materials. To meet the first objective, various acid generation and metal release prediction tests (e.g. partial extractions, ABA calculations) were evaluated by comparing their results with the drainage quality measured from waste facilities at Finnish mine sites. In addition, the use of reactive transport modelling was developed to support predictions of the long-term behaviour of wastes. Filled-in lysimeters were applied to assess the usage options for waste rocks containing hazardous substances, for example, as a cover material in mine closure. Moreover, different mineral processing methods were tested to improve the raw material value and environmental performance of arsenic-containing sulphide mine tailings, and the effects of these modifications were further evaluated with thorough environmental characterisation and field tests. Lastly, an iterative operational model was developed to optimise the environmental properties of tailings as part of the extraction of the main valuables in mineral processing. The project especially focused on the extractive waste from gold and base metal ore exploitation.

Keywords: extractive waste, mining, base metals, arsenic, tailings, waste rock, optimisation, prediction, waste management, mineral processing, characterisation, reactive transport modelling

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PREFACE

*Päivi M. Kauppila, Teemu Karlsson, Antti Taskinen,
Muhammad Muniruzzaman & Marja Lehtonen*

Mineral processing generates large amounts of mining waste, which may be hazardous to the environment. This is especially true for gold and base metal ore deposits, in which the ratio of the generated wastes to the extracted valuable metals is particularly high (e.g. BRGM 2001) and the wastes contain harmful compounds. The management of these wastes requires large areas and costly structures to control the environmental impacts, which are largely caused by the sulphide minerals in the wastes (e.g. Blowes & Jambor 1990, Jambor et al. 2003, Price 2003, INAP 2009, Kauppila et al. 2011). In ore processing, sulphide minerals are the hosts for valuable substances, but in the waste they become the sources of primary contaminants and the cause of low quality mine drainage (e.g. Blowes & Jambor 1990, Nordstrom & Alpers 1999, Jambor et al. 2003). At the same time, the disposal of wastes may mean the squandering of marked amounts of natural resources, since part of the disposed wastes have potential for utilisation. Therefore, new methods and approaches are needed to increase the value of wastes and to promote the eco-efficient use of mineral resources.

Because the main mechanism resulting in the adverse environmental impacts from mine wastes is sulphide oxidation and the subsequent release of hazardous compounds, the primary solution to control these impacts is the prevention of oxidation. Several techniques have been developed to limit this oxidation of the disposed waste (MEND 2001, INAP 2009, Sahoo et al. 2013). These include physical barriers such as covers (MEND 1994, Eriksson et al. 2001, MEND 2001, MEND 2004, INAP 2009, cf. also Kauppila & Räsänen 2015a, 2015b), bacterial inhibition (e.g. Lalvani et al. 1990, Kleinmann 1990), chemical passivation (Evangelou 2001, Eger & Mitchell 2007, cf. also Kauppila 2015) and desulphurisation (e.g. Benzaazoua et al. 2000, Benzaazoua & Kongolo 2003, cf. also Punkkinen et al. 2015). Most of these techniques focus on preventing the oxidation on site, once the waste has been disposed of. However, desulphurisation, for example, tackles the problem before the waste is generated. Namely, in desulphurisation, the acid-forming sulphide minerals are partly or fully removed from the tailings during mineral processing using froth flotation (Kongolo et al. 2004, Kauppila et al. 2011). This approach results in a smaller volume of sulphide-rich waste and a higher volume of waste with a low sulphur content, making waste management easier and providing opportunities for enhanced utilisation of wastes (Benzaazoua et al. 2000, Benzaazoua & Kongolo 2003, Bois et al. 2004, Hesketh et al. 2010). Similar approaches to improve the environmental properties or the recovery of valuable metals from the tailings with mineral processing have been applied, for example, by Liu et al. (2008), Choi et al. (2013) and Lv et al. (2014). However, none of these examples has considered optimisation of the environmental performance of the eventual waste streams generated in ore processing, alongside the optimised recovery of valuables with the aim of producing new products. This approach would facilitate the more efficient use of raw materials with reduced volumes of wastes and their environmental impacts.

Another challenge in waste management is the prediction of drainage water quality from the mine wastes. The first predictions of the potential drainage quality should already be made prior to the start of mining activities, in a phase when no mining waste yet exists. Such prediction requires detailed knowledge of the long-term behaviour of wastes, and is typically based on various laboratory tests, such as chemical assays, static and kinetic tests, field tests and predictive modelling (Price et al. 1997, White et al. 1999, Hansen et al. 2002, Lapakko 2002, Räsänen et al. 2010, Nordstrom & Nicholson 2017, Muniruzzaman et al. 2018). Despite the wide range of predictive tests, some uncertainty remains in their predictive capabilities (e.g. Parbhakar-Fox & Lottermoser 2015, Dold 2017). Therefore, more data are needed on their performance in comparison with the realised values at the mine sites. In particular, the ability of static tests to measure the acid generation potential has

been widely discussed (e.g. Jambor et al. 2002, Jambor 2003, Parbhakar-Fox & Lottermoser 2015, Dold 2017), and mineralogical methods have been proposed to supplement them (e.g. Lawrence & Scheske 1997, Heikkinen & Räsänen 2008, Dold 2017, Karlsson et al. 2018). This is to take the role of specific minerals more accurately into account in assessments of the acid production and neutralisation capacity (Lawrence & Scheske 1997, Dold 2017, Karlsson et al. 2018). Furthermore, even though laboratory tests are usually good screening tools, the conditions in the tests do not correspond to the natural conditions at field sites (e.g. Kempton 2012, Kirchner & Matsson 2015, Pearce et al. 2015). Therefore, different field tests have been developed to complement these tests (e.g. Hansen et al. 2000, Lapakko 2002). However, there is little experience of using small-scale filled-in lysimeters, and there has been only a few studies that comprehensively addressed these tests. Aside from laboratory and field tests, numerical modelling has been widely used in predicting and evaluating the quality of drainage from mine wastes (e.g. Johnson et al. 2000, Mayer et al. 2003, Steefel et al. 2005, Blowes et al. 2014). The majority of predictive modelling investigations have focused on modelling the geochemical processes in an existing waste pile (e.g. Johnson et al. 2000, Mayer et al. 2003, Blowes et al. 2014), while published studies on the predictive modelling of a proposed waste facility, in an early phase of the mine life-cycle, are scarce (e.g. Charles et al. 2016).

To address these challenges, the project Management of Mining Wastes (i.e. the KaiHaMe project) was established with funding from the European Regional Development Funding (ERDF) programme. The overall aim of the project was to develop tools for the management of mining wastes to reduce the environmental impacts of waste disposal, facilitate the prediction of their long-term stability, and to increase the eco-efficient use of raw materials. This was firstly done by evaluating the performance of typically used prediction tests with respect to measured drainage quality, and by testing and developing the use of reactive transport modelling in the prediction. The performance of mineralogy-based ABA calculations was of particular interest. In addition, field tests were applied to seek new options for the use of waste rocks. In the tests, the influence of grain size on metal leaching was assessed, and the potential use of serpentinite waste rocks as a cover material for acid-producing waste rocks was studied. Improvement of the raw material value and environmental properties of tailings was sought by testing the performance of various mineral processing methods in modifying tailings. Filled-in lysimeter tests were further applied to test the success of the modifications on the longer-term behaviour of the tailings under field conditions. Lastly, an iterative operational model was developed for the optimisation of mining wastes. The project concentrated in particular on the mining wastes from gold and base metal ore exploitation. In the following, conclusions based on the main results of each case study of the project are provided. More detailed descriptions of the case studies are presented as separate papers in this volume.

The comparison of prediction methods emphasised that different chemical methods and static tests vary in their ability to predict drainage quality from mining wastes. Relatively good correspondence was observed between the elevated concentrations in the drainage water and the aqua regia and ammonium citrate extractions, and also the NAG leachate. However, the latter only applied when the pH of the NAG solution was less than ~4. The two-stage shake flask test was nevertheless mainly successful in evaluating element leaching from clearly weathered waste rocks. In addition, the ABA calculation based on mineralogy reflected more accurately the observed drainage pH than the static tests and thus complemented these tests well. The better accuracy of the mineralogy-based calculation arises from the fact that it takes more comprehensively into account the different ability of sulphide minerals to produce acidity and various minerals to neutralise it (cf. also Karlsson et al. 2018). The filled-in lysimeters appeared well suited in assessing the utilisation potential of waste rocks. Their results suggested that Hitura serpentinite could be a potential cover material for other waste rocks at the site. Furthermore, as the grain-size distribution was seen to notably affect the solubility of harmful substances, the utilisation of waste rocks with hazardous elements as aggregates at mine sites could be promoted by using as large a grain size as possible.

The reactive transport model was capable of simulating the drainage quality of potential future mining waste sites under different environmental and closure conditions. It thus provides a valuable tool for quantifying the occurrence of acid mine drainage and can be used in robust risk assessment of waste facilities. However, the simulations underlined the importance of sufficient, good quality data to improve the accuracy of the predictions. The extent of the collected data should be adequate at least to identify the key processes and mechanisms of each site. More importantly, the conceptual model behind the reactive trans-

port model should be updated over time as more detailed data become available from the site. The Kopsa case study emphasised that it is possible to use mineral processing methods to improve the environmental performance of tailings and process water without jeopardising the recovery of valuables from the ore. In the Kopsa case, the removal of As and sulphides from the tailings, as well as the reduction in the amount of tailings, was significant with the modified process applying enhanced grinding and flotation combined with high-gradient magnetic separation. These improvements also notably reduced the leaching of As from the tailings and positively affected the process water quality. The results suggested that the modified tailings would be suitable, for example, to form a cover structure for other tailings. However, the modified process should still be tested on a pilot scale and the longer-term environmental performance of the final tailings investigated with kinetic or field tests. In addition, evaluation of the additional investment costs in mineral processing versus the savings in waste management should be further carried out.

In the Kuikka case, the removal of As from the tailings was not successful when using a polyacrylamide-based chemical (Grinding aid 2). This was presumably because Grinding aid 2 depressed As in the flotation, increasing the As content in the modified tailings. Overall, further testing is needed to better understand the influence of Grinding aid 2 on As behaviour in the flotation.

In general, the results of the presented case studies underlined the importance of mineralogical investigations in both the prediction of the long-term behaviour of mine wastes and the optimisation of tailings properties in mineral processing.

In the operational model, GTK's expertise in mineral processing and mining environmental studies will be combined to create a new "one-door service" for clients. As a part of the service, the characterisation of mining wastes will be provided together with mineral processing tests to facilitate the planning of waste management in an early phase of mining. The key to the operational model is that it provides an opportunity to optimise the environmental performance of the eventual waste streams alongside the optimised recovery of valuables with the aim of producing new products. This approach facilitates the more efficient use of raw materials with reduced volumes of wastes and their environmental impacts, promoting the sustainability and prospects of future mining. However, an overall change in the way of thinking in the mineral sector is required to fully benefit from the model.

This volume summarises the results of the KaiHaMe project. The first part of the volume focuses on the prediction methods for the drainage quality and long-term behaviour of mine wastes. In Chapter 1, the laboratory methods applied in the mine waste characterisation are evaluated against the actual seepage water quality observed at the sites. Chapter 2 presents the results of the predictive modelling of drainage water quality with simulations from three mine sites in Finland, and Chapter 3 addresses the use of filled-in lysimeters in assessing the beneficiation potential of waste rocks containing hazardous trace metals. The second part of the volume emphasises the use of mineral processing in the optimisation of wastes. Chapters 4 and 5 present the case studies carried out on the Kopsa and Kuikka gold ores to modify the environmental properties of tailings by mineral processing techniques, with a special focus on the removal of arsenic and sulphide minerals. Finally, the operational model developed for the optimisation of wastes is presented in Chapter 6.

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REFERENCES

- Benzaazoua, M. & Kongolo, M. 2003.** Physico-chemical properties of tailing slurries during environmental desulphurization by froth flotation. *International Journal of Mineral Processing* 69, 221–234.
- Benzaazoua, M., Bussière, B., Kongolo, M., McLaughlin, J. & Marion, P. 2000.** Environmental desulphurization of four Canadian mine tailings using froth flotation. *International journal of mineral processing* 60, 57–74.
- Blowes, D. W. & Jambor, J. L. 1990.** The pore-water geochemistry and the mineralogy of the vadose zone of sulfide tailings, Waite Amulet, Quebec, Canada. *Applied Geochemistry* 5, 327–346.
- Blowes, D. W., Ptacek, C. J., Jambor, J. L., Weisener, C. G., Paktunc, D., Gould, W. D. & Johnson, D. B. 2014.** The Geochemistry of Acid Mine Drainage. In: Holland, H. D. & Turekian, K. K. (eds) *Treatise on Geochemistry* (Second Edition), Volume 11. Oxford: Elsevier, 131–190. Available at: <https://doi.org/10.1016/B978-0-08-095975-7.00905-0>
- Bois, D., Poirier, P., Benzaazoua, M., Bussière, B. & Kongolo, M. 2004.** A Feasibility Study on the Use of Desulphurized Tailings to Control Acid Mine Drainage. *Proceedings 2004 – 36th Annual Meeting of the Canadian Mineral Processors*, January 20–22, 2004. Ottawa (Ontario), 361–380.
- BRGM 2001.** Management of mining, quarrying and ore-processing waste in the European Union. 79 p.
- Charles, J., Barnes, A., Declercq, J., Warrender, R., Brough, C. & Bowell, R. 2015.** Difficulties of Interpretation of NAG Test Results on Net Neutralizing Mine Wastes: Initial Observations of Elevated pH Conditions and Theory of CO₂ Disequilibrium. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. *Proceedings of the 10th International Conference on Acid Rock Drainage & IMWA Annual Conference*, April 21–24 (Santiago, Chile). *Gecamin*, 575–584.
- Choi, J., Park, K., Hong, J., Park, J. & Kim, H. 2013.** Arsenic removal from mine tailings for recycling via flotation. *Materials Transactions* 54, 2291–2296.
- Dold, B. 2017.** Acid rock drainage prediction: A critical review. *Journal of Geochemical Exploration* 172, 120–132.
- Eger, P. & Mitchell, P. 2007.** The use of microencapsulation to prevent acid rock drainage; presented at Mining and the Environment IV Conference, Sudbury, Ontario, Canada, October 19–27. Available at: <http://pdf.library.laurentian.ca/medb/conf/Sudbury07/Eger.pdf>. Accessed 3rd December 2014.
- Eriksson, N., Lindvall, M. & Sandberg, M. 2001.** A quantitative evaluation of effectiveness of the water cover at the Stekenjokk tailings pond in northern Sweden: Eight years of follow-up. Securing the Future, *International Conference on Mining and the Environment*, Skellefteå June 25 – July 1, 2001. *Proceedings*, Volume 1, 216–227.
- Evangelou, V. P. 2001.** Pyrite microencapsulation technologies: Principles and potential field application. *Ecological Engineering* 17, 165–178.
- Hansen, J. B., Holm, P. E., Hansen, E. A. & Hjelm, O. 2000.** Use of lysimeters for characterization of leaching from soil and mainly inorganic waste materials. *Nordtest Technical Report* 473. 51 p.
- Heikkinen, P. M. & Räisänen, M. L. 2008.** Mineralogical and geochemical alteration of Hitura sulphide mine tailings with emphasis on nickel mobility and retention. *Journal of Geochemical Exploration* 97, 1–20.
- Hesketh, A. H., Broadhurst, J. L. & Harrison, S. T. L. 2010.** Mitigating the generation of acid mine drainage from copper sulfide tailings impoundments in perpetuity: A case study for an integrated management strategy. *Minerals Engineering* 23, 225–229.
- INAP 2009.** The GARD Guide. The Global Acid Rock Drainage Guide (GARD Guide). The International Network for Acid Prevention (INAP). Available at: <http://www.gardguide.com/>
- Jambor, J. L. 2003.** Mine-waste mineralogy and mineralogical perspectives of acid-base accounting. In: Jambor, J. L., Blowes, D. W. & Ritchie, A. I. M. (eds) *Environmental aspects of mine wastes*. Mineralogical Association of Canada, Short Course Series 31, 117–145.
- Jambor, J. L., Blowes, D. W. & Ritchie, A. I. M. (eds) 2003.** *Environmental aspects of mine wastes*. Mineralogical Association of Canada, Short Course Series, Vol. 31. 430 p.
- Jambor, J. L., Dutrizac, J. E., Groat, L. A. & Raudsepp, M. 2002.** Static tests of neutralization potentials of silicate and aluminosilicate minerals. *Environmental Geology* 43, 1–17.
- Johnson, R. H., Blowes, D. W., Robertson, W. D. & Jambor, J. L. 2000.** The hydrogeochemistry of the Nickel Rim mine tailings impoundment, Sudbury, Ontario. *Journal of Contaminant Hydrology* 41, 49–80.

- Karlsson, T., Räisänen, M. L., Lehtonen, M. & Alakangas, L. 2018.** Comparison of static and mineralogical ARD prediction methods in the Nordic environment. *Environmental Monitoring and Assessment* 190:719. Available at: <https://doi.org/10.1007/s10661-018-7096-2>
- Kauppila, P. M. 2015.** Chemical passivation using microencapsulation. Mine Closure Wiki pages, Closedure, Geological Survey of Finland. Available at: <http://wiki.gtk.fi/web/mine-closedure/wiki/-/wiki/Wiki/Chemical+passivation+using+microencapsulation>
- Kauppila, P. M. & Räisänen, M. L. 2015a.** Dry cover. Mine Closure Wiki pages, Closedure, Geological Survey of Finland. Retrieved April 20, 2018. Available at: <http://wiki.gtk.fi/web/mine-closedure/wiki/-/wiki/Wiki/Dry+Cover>
- Kauppila, P. M. & Räisänen, M. L. 2015b.** Water cover. Mine Closure Wiki pages, Closedure, Geological Survey of Finland. Retrieved April 20, 2018. Available at: <http://wiki.gtk.fi/web/mine-closedure/wiki/-/wiki/Wiki/Water+cover>
- Kauppila, P., Räisänen, M. L. & Myllyoja, S. (eds) 2011.** Best Environmental Practices in Metal Ore Mining. *The Finnish Environment* 29en/2011. Helsinki: Finnish Environment Institute. 219 p.
- Kempton, H. 2012.** A Review of scale factors for estimating waste rock weathering from laboratory tests. In: Price, W. A., Hogan, C. & Tremblay, G. 9th International Conference on Acid Rock Drainage (ICARD 2012), Ottawa, Ontario, Canada, 20–26 May 2012. Volume 1 of 2, 1026–1038.
- Kirchner, T. & Mattson, B. 2015.** Scaling geochemical loads in mine drainage chemistry modeling: An empirical derivation of bulk scaling factors. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) Proceedings of 10th ICARD & IMWA 2015 conference, Santiago, Chile, 21–24 April 2015, 1495–1503.
- Kleinmann, R. L. P. 1990.** At-source of acid mine drainage. *Mine Water and the Environment* 9, 85–96.
- Kongolo, M., Benzaazoua, M., de Donato, P., Drouet, B. & Barrès, O. 2004.** The comparison between amine thioacetate and amyl xanthate collector performances for pyrite flotation and its application to tailings desulphurization. *Minerals Engineering* 17, 505–515.
- Lalvani, S. B., Deneve, B. A. & Weston, A. 1990.** Passivation of pyrite due to surface treatment. *Fuel* 69, 1567–1569
- Lapakko, K. 2002.** Metal Mine Rock and Waste Characterization Tools: An Overview. Minnesota Department of Natural Resources, US. April 2002 No. 67. 30 p.
- Lawrence, R. W. & Scheske, M. 1997.** A method to calculate the neutralization potential of mining wastes. *Environmental Geology*, 32, 100–106.
- Liu, Y.-G., Zhou, M., Zeng, G.-M., Wang, X., Li, X., Fan, T. & Xu, W.-H. 2008.** Bioleaching of heavy metals from mine tailings by indigenous sulfur-oxidizing bacteria: Effects of substrate concentration. *Bioresource Technology* 99, 4124–4129.
- Lv, C. C., Ding, J., Qian, P., Li, Q. C., Ye, S. F. & Chen, Y. F. 2015.** Comprehensive recovery of metals from cyanidation tailing. *Minerals Engineering* 70, 141–147.
- Maest, A. S., Kuipers, J. R., Travers, C. L., & Atkins, D. A. 2005.** Predicting Water Quality at Hardrock Mines: Methods and Models, Uncertainties, and State-of-the-Art. Kuipers & Associates and Buka Environmental. 77 p. Available at: http://www.ceaa-acee.gc.ca/050/documents_staticpost/cearef_3394/hearings/SM09.pdf
- Mayer, K. U., Blowes, D. W. & Frind, E. O. 2003.** Advances in reactive-transport modelling of contaminant release and attenuation from mine-waste deposits. In: Jambor, J. L., Blowes, D. W. & Ritchie, A. I. M. (eds) Environmental aspects of mine wastes. Mineralogical Association of Canada, Short Course Series 31, 283–302.
- MEND 1994.** Evaluation of alternate dry covers for the inhibition of acid mine drainage from tailings. Prepared by: SENES Consultants Limited. March 1994. Mine Environment Neutral Drainage Program (MEND). MEND Project 2.20.1. 155 p.
- MEND 2001.** MEND Manual. Volume 4. Prevention and Control. February 2001. Editors: Tremblay, G. A. & Hogan, C. M. Mine Environment Neutral Drainage Program (MEND). MEND Report 5.4.2d. 352 p.
- MEND 2004.** Design, Construction and Performance Monitoring of Cover Systems for Waste Rocks and Tailings. Volume 5. Case Studies. Edited by: O’Kane Consultants, Inc. OKC Report No. 702-01. July 2004. Mine Environment Neutral Drainage Program (MEND). MEND Report 2.21.4. 86 p.
- Muniruzzaman, M., Kauppila, P. M. & Karlsson, T. 2018.** Water quality prediction of mining waste facilities based on predictive models. Geological Survey of Finland, Open File Research Report 16/2018. 65 p. Available at: http://tupa.gtk.fi/raportti/arkisto/16_2018.pdf
- Nordstrom, D. K. & Alpers, C. N. 1999.** Geochemistry of acid mine waters. In: Plumlee, G. S. & Logsdon, M. J. (eds) The environmental geochemistry of mineral deposits. Part A: Processes, Techniques, and Health Issues. Reviews in Economic Geology, Vol. 6A, 133–160.
- Nordstrom, D. K. & Nicholson A. (eds) 2017.** Geochemical Modeling for Mine Site Characterization and Remediation. Colorado: Society for Mining, Metallurgy & Exploration. 181 p.
- Parbhakar-Fox, A. & Lottermoser, B. G. 2015.** A critical review of acid rock drainage prediction methods and practices. *Minerals Engineering* 82, 197–124.
- Pearce, S., Scott, P. & Weber, P. 2015.** Waste rock dump geochemical evolution: matching lab data, models and predictions with reality. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) Proceedings of 10th ICARD &

- IMWA 2015 conference – Agreeing on solutions for more sustainable mine water management, Santiago, Chile, 21–24 April 2015, 1469–1479.
- Price, W. A. 2003.** Challenges posed by metal leaching and acid rock drainage, and approaches used to address them. In: Jambor, J. L., Blowes, D. W. & Ritchie, A. I. M. (eds) Environmental aspects of mine wastes. Mineralogical Association of Canada, Short Course Series, Vol. 31, 15–30.
- Price, W. A., Morin, K. & Hutt, N. 1997.** Guidelines for prediction of acid rock drainage and metal leaching for mines in British Columbia: Part II. Recommended procedures for static and kinetic tests. Fourth International Conference on Acid Rock Drainage. Vancouver, B.C. Canada, May 31 – June 6, 1997. Proceedings, vol. I, 15–30.
- Punkkinen, H., Juvankoski, M., Kaartinen, T., Laine-Ylijoki, J., Merta, E., Mroueh, U.-M., Mäkinen, J., Niemeläinen, E. & Wahlström, M. 2015.** Desulphurisation. Mine Closure Wiki pages, Closedure, Geological Survey of Finland. Available at: <http://wiki.gtk.fi/web/mine-closedure/wiki/-/wiki/Wiki/Desulphurisation>
- Räisänen, M. L., Kauppila, P. M. & Myöhänen, T. 2010.** Suitability of static test for acid rock drainage assessment of mine waste rock. Bulletin of the Geological Society of Finland 82, 101–111. Available at: http://www.geologinenseura.fi/bulletin/Volume82/Raisanen_2010.pdf
- Sahoo, P. K., Kim, K., Equeenuddin, S. M. & Powell, M. A. 2013.** Current Approaches for Mitigating Acid Mine Drainage. In: Whitacre, D. M. (ed.) Reviews of Environmental Contamination and Toxicology, vol. 226, 1–32.
- Steeffel, C. I., DePaolo, D. J. & Lichtner, P. C. 2005.** Reactive transport modeling: An essential tool and a new research approach for the Earth sciences. Earth and Planetary Science Letters 240(3–4), 539–558. Available at: <https://doi.org/10.1016/j.epsl.2005.09.017>
- White, W. W. III, Lapakko, K. A. & Cox, R. L. 1999.** Static-test methods most commonly used to predict acid mine drainage: Practical guidelines for use and interpretation. In: Plumlee, G. S. & Logsdon, M. (eds) The Environmental Geochemistry of Mineral Deposits, Part A: Theory and background. Society of Economic Geologists Reviews in Economic Geology, vol. 7A, 325–328.

PREDICTION OF THE LONG-TERM BEHAVIOUR OF EXTRACTIVE WASTES BASED ON ENVIRONMENTAL CHARACTERISATION: CORRESPONDENCE OF LABO- RATORY PREDICTION TESTS WITH FIELD DATA

by

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The characterisation of extractive waste is already essential in the early phases of a mining project. The short- and long-term behaviour of extractive waste should be assessed to design appropriate extractive waste facilities and water management, and to evaluate the possibilities for waste material utilisation. The objective of this study was to obtain further information concerning the long-term behaviour of extractive wastes and the various analytical methods used in the preliminary screening of their environmental properties, as well as the mobility of potentially harmful elements. In addition, the utilization potential of selected extractive waste materials was assessed. According to the results, the investigated extractive waste materials were not generally suitable for earthwork purposes, but some could be utilised in less vulnerable areas. The element concentrations of leachates from aqua regia and H₂O₂-citrate extraction tests corresponded well with the elevated element concentrations in the drainage waters of extractive wastes. Furthermore, leachate concentrations in the net acid generation (NAG) test were consistent with the corresponding aqua regia extraction and drainage water analysis results, but only when the pH of the NAG test leachate was sufficiently low, i.e. below or around 4. In general, ARD predictions based on the ABA test (EN 15875) and NAG test were similar to the corresponding drainage water pH. In some cases, it could be observed that ARD prediction based on static tests does not sufficiently consider the mineralogical properties of the investigated rock material. Therefore, the suitability of mineralogy-based ARD prediction methods for the Finnish climate and extractive waste types should be further investigated.

Keywords: Extractive waste characterisation, utilisation, drainage quality, ARD, static test

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1 INTRODUCTION AND OBJECTIVES

The characterisation of extractive waste is already needed before the start of actual mining activities to assess the behaviour of waste material in the short and long term, as well as to design appropriate extractive waste facilities and drainage water management. The characterisation of extractive wastes is also required to evaluate the utilisation potential of the wastes, e.g. to identify materials suitable for earthworks or to estimate the potential recoverable commodities (Dino et al. 2018), and to assess the risks related to extractive waste reuse (Mehta et al. 2018).

The long-term evolution and quality of drainage can be assessed by multiple methods, including geochemical laboratory tests, longer term kinetic tests, geochemical modelling and by utilising available analogies from similar older extractive waste sites (Price et al. 1997, White et al. 1999, Lapakko 2002, Kauppila & Räsänen 2015, Nordstrom & Nicholson 2017, Karlsson et al. 2018c, Muniruzzaman et al. 2018). The potential of extractive waste to produce acid rock drainage (ARD) is usually determined based on different acid–base accounting (ABA) tests (Sobek et al. 1978, Price 2009), of which the standardised method SFS-EN 15875 is widely used in Europe. Another commonly used method is the net acid generation (NAG) test (AMIRA 2002). However, these static laboratory tests have some limitations related to the mineralogical properties of the samples. For example, they do not consider the differences between diverse sulphide minerals and often underestimate the neutralisation potential of silicate minerals (Jambor et al. 2002, Jambor 2003, Parbhakar-Fox & Lottermoser 2015, Dold 2017).

The mobility of potentially harmful substances from extractive wastes can be assessed using different selective extraction and leaching methods. Aqua regia extraction (Doležal et al. 1968, Niskavaara 1995) is the most commonly used partial extraction method in Finland, since it is intended to dissolve elements bound to sulphide phases, which are the main sources of harmful elements in extractive wastes. Based on previous studies, aqua regia

extractable concentrations of waste materials indicate which elements are most likely to be of concern in extractive waste drainage (Price et al. 1997, Fosso-Kankeu et al. 2015, Karlsson & Kauppila 2016). Aqua regia extraction is also the preferred method to evaluate whether mining waste is inert (Government Decree 2013) and to assess soil contamination in Finland (Government Decree 2007, Reinikainen 2007). The leaching of elements from extractive wastes is usually evaluated based on a two-stage batch test, according to the standard SFS-EN 12457-3, which is one of the methods recommended in the mining waste characterisation standard (CEN/TR 16376:2012). Less commonly used methods include analysis of the NAG test leachate (Räsänen et al. 2010, Karlsson & Kauppila 2016) and Ni-sulphide-specific hydrogen peroxide (H_2O_2)-citrate extraction (Katsnelson & Osipova 1960).

The objective of this study was to obtain further information concerning the long-term behaviour of extractive wastes and different analytical methods used in the preliminary screening of their environmental properties. Particular emphasis was placed on the assessment of sulphide-specific methods: aqua regia extraction, the so-called sulphide leach using a mixture of $KClO_3$, 12 M HCl and 4 M HNO_3 , and H_2O_2 -citrate extraction. In addition, the usability of the two-stage batch test and the NAG test leachate was investigated, as well as the performance of the ABA (EN 15875) and NAG tests. Samples for this study were collected from seven Finnish mine sites. The results from different acid production and element mobility prediction methods were compared with actual drainage water qualities from the target mine sites. The information produced in this study could be utilised in geochemical modelling and extractive waste characterisation. This paper summarises the main observations concerning the performance of different prediction methods and the general environmental properties of the selected extractive waste materials. A more detailed description of the results is presented in Finnish in GTK Open File Work Report by Karlsson et al. (2018c).

2 RESEARCH MATERIALS

2.1 Investigated materials

Extractive waste and drainage water samples were collected from seven active or closed mine sites around Finland, representing different types of deposits and disposal periods (Table 1, Fig. 1). Extractive waste samples, which included samples of waste rocks and tailings, were mainly collected above the drainage points, i.e. the seepage points.

In this study, a relatively simple technique was used to obtain composite samples from the waste pile surface. Comprehensive sampling of a waste rock pile is complicated due to the large scale and heterogeneity of the material. As the main objective of this study was to assess different laboratory-scale prediction methods rather than perform a detailed investigation of the geochemistry of extractive waste facilities, the simplified sampling approach was considered adequate.

The waste rock samples consisted of 15–20 kg composite samples, with individual fist-sized subsamples collected from an approximately 10 x 10 m area, mainly above the drainage point, but in some cases additionally from elsewhere around the waste rock pile. The waste rock subsamples were

randomly picked by hand utilising a rock hammer. No screening of waste rock material was performed. Tailings samples consisted of 5–10 kg composite samples collected from the surface parts (0–60 cm depth) of the tailings impoundment using a white plastic spoon. The subsamples of the composite tailings samples were taken from 4 to 5 pits from an approximately 10 x 10 m area. At the Kevitsa and Laiva mine sites, the tailings were unweathered and no oxidization layer could be observed. At the Pyhäsalmi mine site, the oxidized upper (0–40 cm) and unoxidized lower parts (from 40 cm downwards) of the tailings were sampled separately.

Drainage water samples were collected at the same time as the extractive waste samples, from the seepage points at the base of the extractive waste facility. Water samples for dissolved cation analysis were filtered in the field through 0.45- μm filters into polyethylene bottles and were acidified with concentrated HNO_3 . For anion analysis, unfiltered and unacidified water samples were taken. The sample bottles were rinsed twice with the sampled water before sampling.

Table 1. The investigated mine sites and extractive waste samples collected from them (WR = waste rock, T = tailings).

Mine site	Commodity	Deposit type and related waste rock types and sulphides	Target waste site(s) active	Waste samples	Reference
Hitura	Ni, Co	Paleoproterozoic (1.9 Ga) magmatic ultramafic intrusion-hosted nickel deposit, consisting of closely spaced serpentinite massifs surrounded by migmatized mica gneiss. Mica gneiss and amphibole rocks in one pile, serpentinite in another pile. Pyrrhotite, pentlandite, chalcopyrite, vallerite, mackinawite and cubanite.	1970–1993	WR_Hitura_1 (serpentinite pile), WR_Hitura_2-4 (mica schist pile)	Meriläinen et al. 2008, Eilu et al. 2012
Hällinmäki (Virtasalmi)	Cu	Paleoproterozoic (1.9 Ga) mafic basinal hydrothermal SedEx (sedimentary exhalative) deposit, the ore appearing as brecciated and disseminated in amphibole host rock. Mica and diopside gneisses, amphibolites, skarn and calcite stone. Chalcopyrite, cubanite and pyrrhotite, with lesser amounts of pyrite, sphalerite, pentlandite, mackinawite, molybdenite, bornite and other Fe- and Cu-containing sulphides.	1966–1984	WR_Hällinmäki_1-3	Hyvärinen 1969, Pappunen 1986, Lawrie 1992, GTK 2017
Särkiniemi	Ni	Paleoproterozoic (1.9 Ga) metamorphosed magmatic deposit, the main ore sulphides occurring disseminated in the eastern, gabbro-hosted ore body and disseminated, net-textured and massive in the western, peridotite-hosted ore body. Mica gneiss, peridotite, gabbro and hornfels. Pyrrhotite, pentlandite and chalcopyrite.	2007–2008	WR_Särkiniemi_1-3	Kontoniemi & Forss 1997, Makkonen & Halkoaho 2007
Kylylahti	Cu, Co, Zn, Ni, Au	Paleoproterozoic (1.9 Ga) mafic–ultramafic mixed hydrothermal, volcanogenic massive sulphide (VMS), disseminated sulphide ore hosted by quartz rock and metacarbonate rock. Mica schist, black schist, serpentinite, talc-carbonate rock, carbonate-skarn rock and quartz rock. Pyrite, pyrrhotite, chalcopyrite and sphalerite.	2012–	WR_Kylylahti_1	Kontinen et al. 2006
Kevitsa	Ni, Cu, PGE	Paleoproterozoic (2.1 Ga) mafic–ultramafic magmatic deposit hosted within a composite ultramafic layered intrusion, ore appearing in olivine pyroxenite as disseminated sulphides. Olivine-pyroxenite, olivine-websterite, gabbro and dunite. Pyrrhotite, pentlandite and chalcopyrite.	2012–	WR_Kevitsa_1, T_Kevitsa_1	Santaguida et al. 2015
Laiva (Laivakangas)	Au	Paleoproterozoic (1.9 Ga) orogenic metamorphic hydrothermal deposit hosted by silicified shear zones and quartz veins within quartz diorite and intermediate to mafic metavolcanic rocks, cut by post-mineralisation granite. Quartz diorite, mafic volcanic rock, quartz vein and granite. Arsenopyrite.	2011–2013	WR_Laiva_1, T_Laiva_1	Eilu et al. 2012
Pyhäsalmi	Cu, Zn	Paleoproterozoic (1.9 Ga) VMS deposit, hosted in a metamorphosed volcanic sequence composed of lapilli tuffs, coherent lava flows and sill-shaped intrusions, ore appearing as massive sulphides. Pyrite, pyrrhotite, chalcopyrite, sphalerite, arsenopyrite.	1962–	T_Pyhäsalmi_1 (unoxidized material from 40-60 cm), T_Pyhäsalmi_2 (oxidized material from 0-40 cm)	Mäki et al. 2015

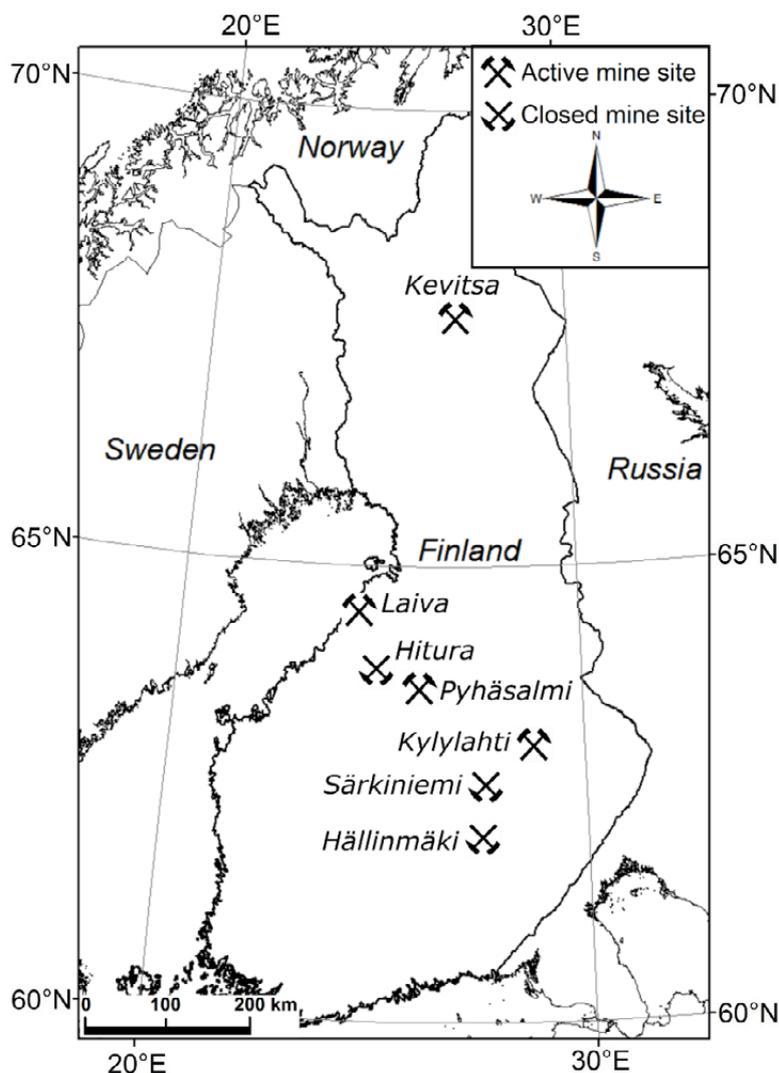


Fig. 1. The investigated mine sites. Basemap © National Land Survey of Finland and HALTIK 2013.

2.2 Characterisation methods

The chemical composition of the extractive waste and drainage water samples were analysed in an accredited laboratory by Labtium Oy. Drainage water analyses included the determination of dissolved element concentrations by ICP-OES and ICP-MS and the determination of anions with ion chromatography. The electrical conductivity and pH of the drainage waters were measured on-site using a portable multi-parameter YSI sonde (YSI Professional Plus).

For geochemical analyses, the waste rock samples were dried at below 40 °C, crushed with a Mn jaw crusher and ground in a hardened steel bowl. The tailings samples were freeze-dried and sieved to <2 mm grain size for the selective extraction methods. The extractive waste samples treated for geochemical analyses were divided into two, with one half of the samples being sent to the mineralogical labora-

tory of the Geological Survey of Finland (GTK) for mineralogical investigations.

From the extractive waste samples, the element mobilities were investigated using aqua regia extraction, which leaches sulphides and some silicates, including biotite, chlorite and clay minerals (Doležal et al. 1968, Heikkinen & Räsänen 2009), and also using H₂O₂-citrate extraction, which was proposed to be a Ni-selective leaching method by Katsnelson and Osipova (1960). In addition, the leaching of elements was determined from the extractive wastes using a two-stage batch test according to the standard SFS-EN 12457-3. The sulphide-bound fraction of elements was additionally analysed from the tailings using a mixture of KClO₃, 12 M HCl and 4 M HNO₃ (Hall et al. 1996, Heikkinen & Räsänen 2008, 2009). Element concentrations were measured from the solutions with ICP-OES

and ICP-MS.

The potential of the extractive wastes to produce ARD was determined using the ABA test according to the standard SFS-EN 15875 and also based on the NAG test (AMIRA 2002). In the ABA test, the neutralisation potential (NP) is determined by titration and the acid production potential (AP) is calculated from the total sulphur concentration. The total sulphur content was measured with the Leco furnace method according to the standard ISO 15178. Based on NP and AP, the neutralisation potential ratio (NPR) was calculated ($NPR = NP/AP$). It is commonly assumed that extractive waste is potentially acid producing if $NPR < 1$, in the uncertainty zone if NPR is 1–3 and non-acid producing if $NPR > 3$ (Sobek et al. 1978, White et al. 1999, Price 2009). Based on the NAG test, a sample is classified as potentially acid generating if the NAG test leachate pH is < 4.5 and the net acid production potential (NAPP) is > 0 , and non-acid generating if $NAGpH > 4.5$ and $NAPP < 0$ (AMIRA 2002). The NAG test leachates were also analysed for element

concentrations with ICP-OES/MS to investigate the usability of the method in the assessment of element mobility.

The quality of the drainage water samples was checked by taking double and blank (laboratory distilled water) samples during the field campaign, after approximately every ten samples. The quality of the water and geochemical analysis was ensured by the accredited laboratory by analysing control samples and providing the quality control analysis results along with the actual sample results.

Mineralogical investigations of the extractive waste samples were conducted in the mineralogical laboratory of GTK using a field emission scanning electron microscope (FE-SEM; JEOL JSM 7100F Schottky) with an automated energy dispersive spectrometer (EDS; Oxford Instruments EDS X-Max 80 mm²). Identification of the minerals was based on a comparison of the element composition determined from EDS spectra with the mineralogical database of the Geological Survey of Finland (GTK).

3 SUMMARY OF THE RESULTS

3.1 Utilisation potential of the investigated extractive waste materials

A comparison of the aqua regia extractable concentrations, sulphur content and acid production potential of the extractive waste samples with the reference values mentioned in the Government Decree on Extractive Waste (Government Decree 2013) is presented in Table 2. The Hitura serpentinite waste rock sample (WR_Hitura_1) contained elevated concentrations of Ni, Cu, Cr, Co and As. According to the ABA test, the serpentinite material was not potentially acid producing. The Hitura mica schist waste rocks (WR_Hitura_2–4) contained elevated concentrations of Ni, Cu, Zn, V and Co. According to the ABA test, the mica schist pile material was acid producing.

The Hällinmäki waste rock samples contained elevated concentrations of Cu. The sulphur contents were relatively low (0.3–0.5%), but the ABA test suggested the samples WR_Hällinmäki_1 and WR_Hällinmäki_3 to be potentially acid producing and the acid production potential of the sample WR_Hällinmäki_2 to be in the uncertainty zone.

Both the waste rock and tailings samples from Kevitsa contained elevated concentrations of Ni, Cu, Cr and Co, but were not classified as potentially acid

producing by the ABA test.

The Kylylahti waste rock sample contained elevated concentrations of Cu, Co, Ni, Zn, As, Cr, Cd and Sb. The sulphur content was high (10%) and the material was classified as acid producing by the ABA test.

The Laiva waste rock sample contained elevated concentrations of Cu and As, and the Laiva tailings sample contained elevated concentrations of As. The sulphur content of both Laiva samples was low (0.1%), and they were classified as non-acid producing by the ABA test.

The Pyhäsalmi tailings samples contained elevated concentrations of Zn, Cu, As, Pb, Cd and Sb. Their sulphur contents were also high (30–39%) and they were classified as acid producing by the ABA test.

The Särkiniemi waste rock samples contained elevated concentrations of Ni, Cu, Cr, V, Co and As. According to the ABA test, they were classified as acid producing.

In addition to exceeding the PIMA reference values, the drainage from the extractive waste facili-

ties at Kylylahti, Pyhäsalmi, Särkiniemi and Hitura mine sites was acidic, with high contents of metals (Fig. 2). The drainage pH was around neutral and the metal contents were lower at Laiva, Kevitsa and

Hällinmäki mine sites. In addition to the metal concentrations considered in the Ficklin diagram (Fig. 2), the drainage from the Laiva tailings facility was enriched in As (120 µg/L).

Table 2. The aqua regia extractable concentrations of the potentially harmful elements mentioned in the PIMA decree (Government Decree 2007) and their comparison with the PIMA reference values, sulphur content, and the neutralization potential ratio according to the ABA test. Extractive waste is classified as potentially acid producing if NPR < 1, in the uncertainty zone if NPR is 1–3 and non-acid producing if NPR > 3 (Sobek et al. 1978, White et al. 1999, Price 2009). According to the Government Decree on Extractive Waste (2013), the concentrations of potentially harmful elements in mining waste should be compared with the PIMA threshold values or the local soil baseline concentrations.

	Sb	As	Cd	Co	Cr	Cu	Pb	Ni	Zn	V	S	NPR
	mg/ kg	%										
Aqua regia extraction												
PIMA threshold value	2	5	1	20	100	100	60	50	200	100		
PIMA lower guideline value	10	50	10	100	200	150	200	100	250	150		
PIMA upper guideline value	50	100	20	250	300	200	750	150	400	250		
WR_Hitura_1	0.4	32	0.2	162	214	888	3.0	3020	25	7.0	0.6	9.4
WR_Hitura_2	<0.2	1.9	1.0	47	47	1655	8.0	2115	279	69	5.3	0.02
WR_Hitura_3	<0.2	1.0	0.8	20	84	430	10	332	231	107	2.5	0.1
WR_Hitura_4	<0.2	0.9	0.3	19	90	82	6.0	715	110	75	1.4	0.1
WR_Hällinmäki_1	<0.2	0.4	0.7	14	12	3130	1.0	36	36	27	0.5	0.5
WR_Hällinmäki_2	<0.2	0.8	0.8	12	45	2140	1.0	30	34	71	0.3	2.6
WR_Hällinmäki_3	<0.2	0.7	0.5	13	21	2100	1.0	32	26	27	0.4	0.8
WR_Kevitsa_1	<0.2	2.8	<0.04	67	474	460	3.0	718	19	34	0.3	6.0
T_Kevitsa_1	<0.2	1.6	0.1	41	350	455	2.2	632	16	26	0.3	4.0
WR_Kylylahti	3.5	711	4.3	1985	443	8900	14	1195	1130	64	10	0.02
WR_Laiva_1	<0.2	220	0.2	15	69	262	4.0	17	32	64	0.1	3.1
T_Laiva_1	<0.2	95	0.1	7.3	54	83	4.9	11	36	48	0.1	5.5
T_Pyhäsalmi_1	4.9	408	7.2	100	29	2435	187	18	2710	18	30	0.1
T_Pyhäsalmi_2	2.5	365	5.4	76	17	649	60	16	2010	8.5	39	0.01
WR_Särkiniemi_1	<0.2	6.6	0.1	75	166	198	6.0	818	108	139	1.7	0.2
WR_Särkiniemi_2	<0.2	6.4	0.2	68	238	471	8.0	648	114	147	1.9	0.3
WR_Särkiniemi_3	<0.2	8.8	0.2	80	266	217	5.0	760	100	111	1.7	0.4

The risk of ARD and the mobility of harmful elements for the selected extractive wastes, together with their utilisation possibilities, are summarised in Table 3. In general, the investigated extractive wastes were not well suited to earthwork purposes, as they contained elevated amounts of harmful substances that exceeded the PIMA threshold values for contaminated soils (Government Decree 2007, Reinikainen 2007). They were thus classified as non-inert mining waste according to the decree on extractive waste (Government Decree 2013).

The waste rocks from Hällinmäki, Kevitsa and Laiva, the Hitura serpentine and the Kevitsa tailings were non-acid producing. Moreover, the drainage concentrations of the potentially harmful elements were relatively low. Thus, they could potentially be used for earthworks in less vulnerable areas, mainly

at mine sites, even though they contained elevated concentrations of potentially harmful elements. However, possible utilisation options should be individually assessed according to the utilisation purpose. Based on Karlsson et al. (2018b), it is nevertheless recommended that waste rocks are used in as large grain sizes as possible to minimise the content of fine-grained fractions and the mobility of harmful elements (cf. Karlsson et al. 2018a in this GTK Bulletin publication). In addition, it is important to remove boulders with a high sulphide content from the waste rock materials to improve their utilisation possibilities. The Laiva tailings were also non-acid producing, but the As concentration of the drainage water was high, reducing the utilization potential.

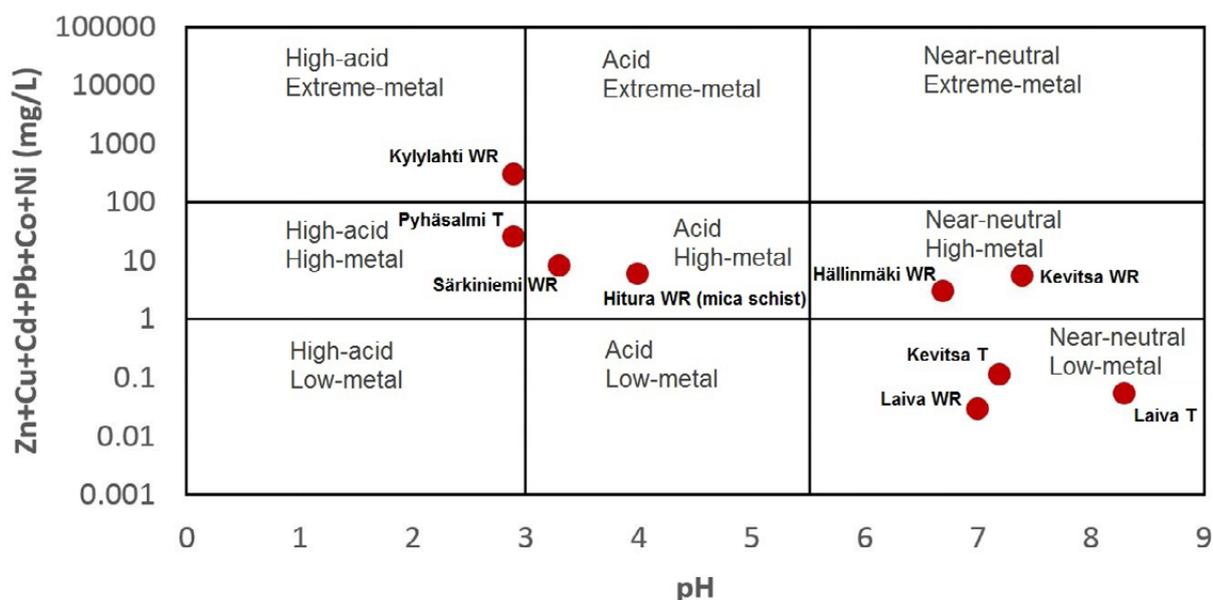


Fig. 2. Ficklin diagram (Plumlee et al. 1999) showing the drainage qualities at the seven target mine sites and at the nine investigated extractive waste facilities. The heavy metals Zn, Cu, Cd, Pb, Co and Ni are typical for acid generating environments. (WR = waste rock, T = tailings)

Table 3. Mineralogy, risk of ARD and mobility of harmful elements, as well as the utilisation possibilities of the investigated extractive waste materials based on their environmental properties.

Waste site	Main minerals, sulphides and carbonates	High risk of ARD	The potentially most harmful substances	Utilisation possibilities
Hitura mica schist pile	Quartz, plagioclase, biotite, muscovite, pyrrhotite (2.5%), pyrite (0.2%), pentlandite (0.1%), chalcopyrite (0.1%)	Yes	Co, Cu, Ni, Zn	Poor
Hitura serpentinite pile	Serpentine, olivine, pyrrhotite (0.15%), pentlandite (0.05%), chalcopyrite (0.03%), calcite (0.01%)	No	Co, Cu, Ni	Possibly in earth constructions at the mine site
Hällinmäki waste rock	Plagioclase, augite, hornblende, biotite, quartz, chalcopyrite (0.2%), pyrrhotite (0.1%), pyrite (0.01%), calcite (0.1%)	No	Co, Cu, Ni	Possibly in earth constructions; boulders with high amounts of Co and Ni should be removed
Kevitsa waste rock	Diopside, tremolite, serpentine, pyrrhotite (0.2%), pentlandite (0.05%), chalcopyrite (0.03%), calcite (0.04%)	No	Co, Ni	Possibly in earth constructions; boulders with high amounts of sulphides should be removed
Kevitsa tailings	Diopside, tremolite, serpentine, pyrrhotite (0.1%), chalcopyrite (0.1%), calcite (0.6%), dolomite (0.1%)	No	Ni	Possibly in earth constructions at the mine site
Kylylahti waste rock	Plagioclase, quartz, biotite, phlogopite, pyrite (8.79%), pyrrhotite (0.61%), sphalerite (0.08%), pentlandite (0.05%), calcite (1.89%), dolomite (0.02%)	Yes	As, Co, Cu, Ni, Zn	Poor
Laiva waste rock	Plagioclase, quartz, K-feldspar, biotite, actinolite, hornblende, pyrrhotite (0.1%)	No	As, Cu	Possibly in earth constructions at the mine site; boulders with high amounts of arsenopyrite should be removed
Laiva tailings	Plagioclase, quartz, K-feldspar, biotite, actinolite, hornblende, chalcopyrite (0.04%), pyrite (0.03%), arsenopyrite (0.03%), calcite (0.06%)	No	As	Poor
Pyhäsalmi tailings	Pyrite (58.1%), pyrrhotite (2.5%), plagioclase, quartz, calcite (0.8 %), dolomite (0.8%)	Yes	Co, Cu, Ni, Zn	Poor
Särkiniemi waste rock	Biotite, plagioclase, quartz, hornblende, chlorite, pyrrhotite (1.2%), pyrite (0.4%), chalcopyrite (0.01%), pentlandite (0.01%), dolomite (0.03%)	Yes	Co, Cu, Ni, Zn	Poor

3.2 Geochemical laboratory tests in drainage quality assessment

Aqua regia leachable concentrations and concentrations from the H₂O₂-citrate extraction and the NAG test leachate were compared with the actual drainage water qualities to evaluate the differences between these methods. The results of this comparison are presented in Figure 3, which illustrates that the results from aqua regia and H₂O₂-citrate

extractions corresponded well with the elevated element concentrations detected in drainage waters. Instead, the leachate pH appeared to have a strong influence on the performance of the NAG test. The NAG test leachate served as a good indicator in many cases. However, in the case of the Kevitsa waste rock sample (WR_Kevitsa_1), for instance,

the NAG test leachate concentrations were notably lower than the concentrations in the actual drainage water. Based on further investigation of the results, the NAG test leachate concentrations appear to be consistent with the corresponding aqua regia extraction results when the pH of the NAG test leachate is below around 4. When the leachate pH increases, the element concentrations in the leachate decrease significantly compared to the aqua regia results. This is most likely due to the precipitation of secondary minerals during the NAG test at a higher pH, which particularly removes cationic elements from the solution (Räisänen et al. 2010, Charles et al. 2015, Karlsson & Kauppila 2016).

Besides aqua regia extraction, the sulphide-bound fraction of elements in the tailings samples was also analysed using so-called sulphide extrac-

tion (Hall et al. 1996). When comparing the results of these methods, it was noticed that the trace metal concentrations dissolved with sulphide extraction were distinctly lower than those leached with aqua regia (Fig. 4). This difference could be explained by the fact that aside from sulphides, aqua regia also partly leaches some silicates, e.g. biotite and chlorite (Doležal et al. 1968), which might include harmful substances in their crystal structure. On the other hand, the results suggest that sulphide extraction did not totally leach all the sulphide minerals, such as Cu-containing sulphides. Nevertheless, as with aqua regia extraction, sulphide extraction also indicates which elements might have elevated concentrations in the drainage waters of an extractive waste facility.

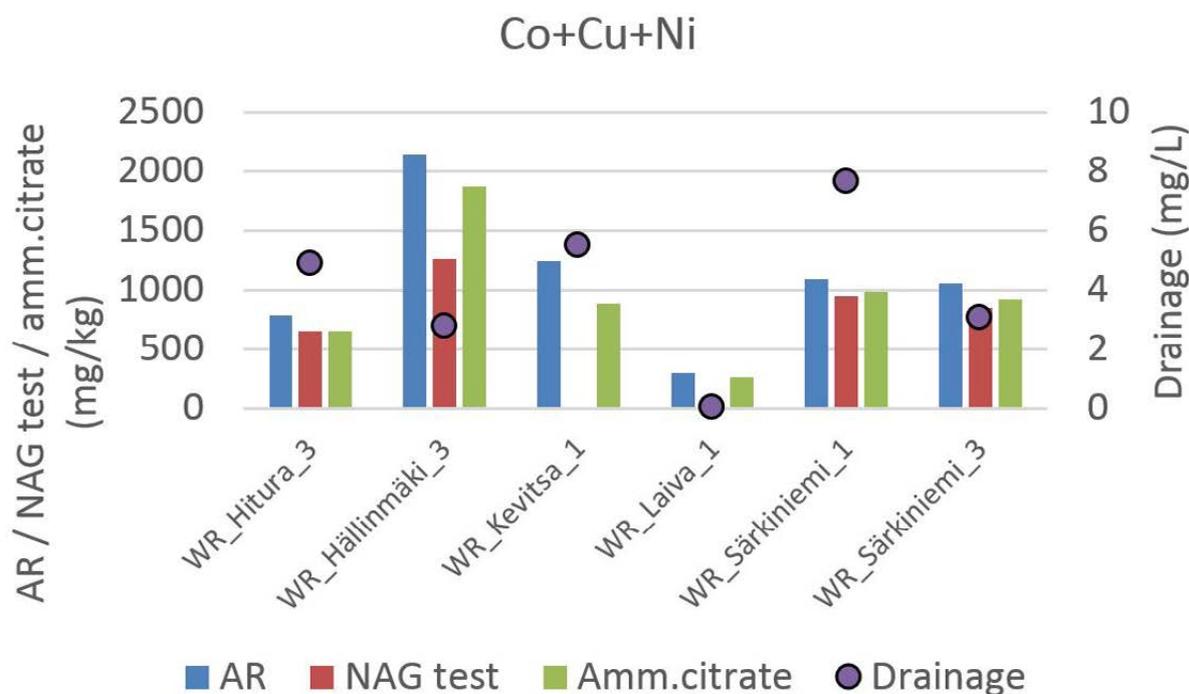


Fig. 3. Comparison of the sum of Co, Cu and Ni concentrations based on aqua regia extraction (AR), NAG test leachate analysis and H₂O₂-citrate extraction and the corresponding drainage water concentrations. For the samples WR_Kevitsa_1 and WR_Laiva_1, the NAG test leachate concentrations are so low that the bar is not visible. (WR = waste rock)

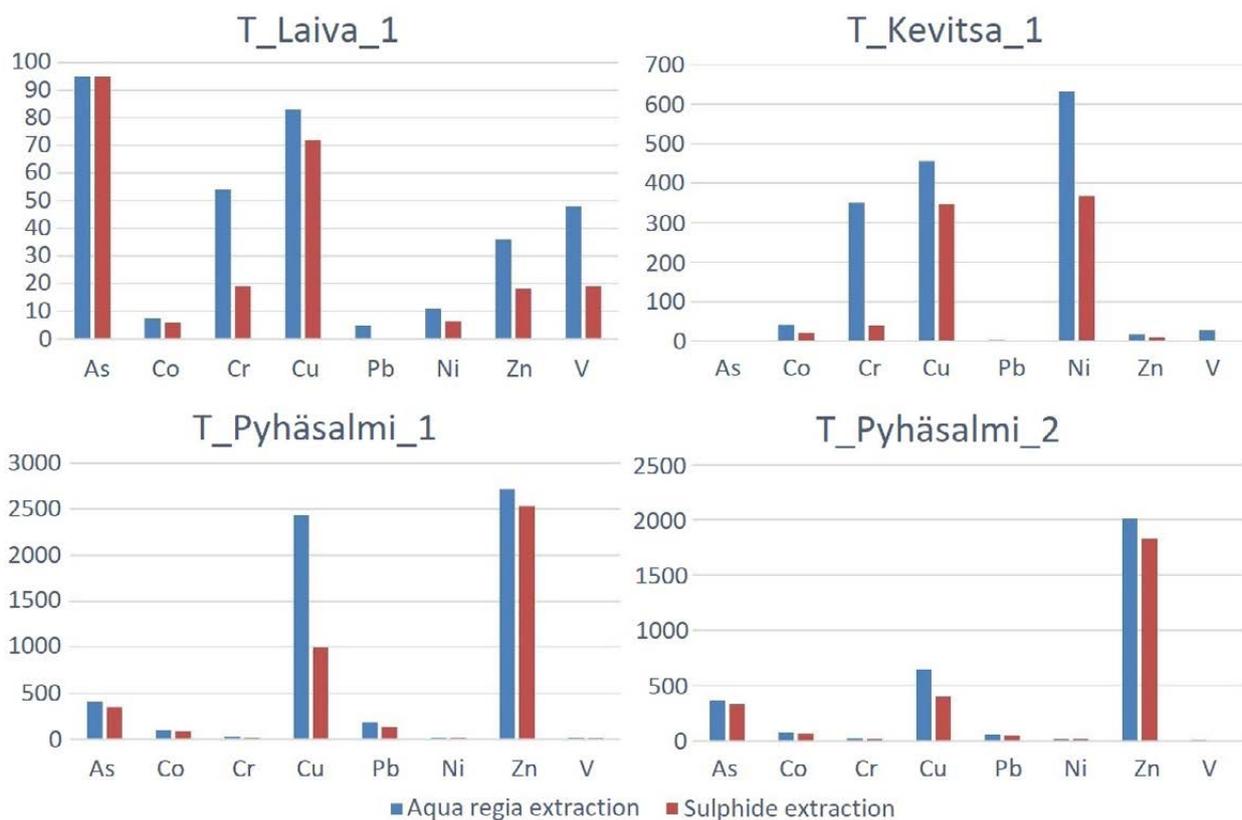


Fig. 4. Comparison of the aqua regia extraction and sulphide extraction results. Concentrations as mg/kg.

The two-stage batch test SFS-EN 12457-3 is used to investigate which harmful substances leach with water. The element concentrations of the batch test in this study were usually below the detection limit, even though the actual drainage waters contained high amounts of metals. This is consistent with previous studies (Räisänen et al. 2002, Karlsson & Kauppila 2016), which have suggested that water is too weak a solvent and the test time in the batch test

is too short to leach elements from fresh unweathered extractive waste material. One of the exceptions was the weathered mica schist sample from the Hitura mine site, for which the leachate concentrations of Cu, Co and Ni in the batch test exceeded those in the drainage water. According to Hageman et al. (2015), weak water extractions are actually most suitable for investigating already weathered extractive waste materials.

3.3 Prediction methods for ARD assessment

The static ABA and NAG tests were applied to assess the potential of the extractive wastes to produce acid rock drainage. The results of the static tests were compared with the actual drainage pH. According to the results presented in Table 4, the ARD predictions mainly yield similar results compared with the drainage water pH, but some exceptions could be observed. These were the predictions for the Hällinmäki and one of the Hitura waste rocks. In the case of the samples WR_Hällinmäki_1 and WR_Hällinmäki_3, the ABA and NAG tests assessed the rock material as potentially acid producing. At the waste rock site, the surface waters were neu-

tral, even 30 years after mine closure. However, the NAGpH values of the Hällinmäki waste rocks were 3.9, 4.1 and 5.4, which were close to the NAGpH of 4.5, which is usually considered as a limit value for the acid generation potential (cf. AMIRA 2002). If the NAGpH values suggested by Oh et al. (2017) for the uncertainty zone (from 3.21 to 4.52) were taken into account, the Hällinmäki waste rocks would nevertheless be classified as uncertain, which would be closer to what was observed in the field.

In the case of the Hitura mica schist (WR_Hitura_2), the rock material was classified as acid generating by all three methods, but the pond

Table 4. Assessments of ARD potential by the ABA test and NAG test, and the corresponding drainage pH. Extractive waste is classified as potentially acid producing if NPR < 1 or NAGpH < 4.5 (orange colour), in the uncertainty zone if NPR is 1–3 (blue colour) and non-acid producing if NPR > 3 or NAGpH > 4.5 (green colour, Sobek et al. 1978, White et al. 1999, AMIRA 2002, Price 2009). (WR = waste rock, T = tailings)

Sample	NPR	NAGpH (pH)	Drainage (pH)
WR_Hitura_1	9.4	8.2	
WR_Hitura_2	0.02	2.8	7.0
WR_Hitura_3	0.1	2.6	4.0
WR_Hitura_4	0.1	2.7	
WR_Hällinmäki_1	0.5	3.9	
WR_Hällinmäki_2	2.6	5.4	
WR_Hällinmäki_3	0.8	4.1	6.7
WR_Kevitsa_1	6.0	9.1	7.4
T_Kevitsa_1	4.0	9.2	7.2
WR_Kylylahti	0.02	2.6	2.9
WR_Laiva_1	3.1	7.5	7.0
T_Laiva_1	5.5	7.5	8.3
T_Pyhäsalmi_1	0.1	2.1	2.9
T_Pyhäsalmi_2	0.01	1.9	2.9
WR_Särkiniemi_1	0.2	2.7	3.3
WR_Särkiniemi_2	0.3	2.9	
WR_Särkiniemi_3	0.4	2.9	3.6

water next to the rock sampling point was neutral. However, the waste rock pile is not the only source of drainage into this rather large pond, and serpentinite material, for example, could also be influencing the water quality.

In the case of Hällinmäki, ARD prediction based on the ABA and NAG tests does not sufficiently consider the mineralogical properties of the investigated rock material. The relative weathering rate of sulphides is (from the fastest to the slowest) pyrrhotite > sphalerite/galena > pyrite/arsenopyrite > chalcopyrite > magnetite (Jambor 1994). At Hällinmäki, the most abundant sulphide mineral is relatively slowly weathering chalcopyrite. In addition, in the ABA test, AP is calculated based on the sulphur content of the sample and it is assumed that all the sulphur is pyritic and produces four protons per one mole of pyrite oxidation (Colmer & Hinkle 1947, Singer & Stumm 1970, Nordstrom 2000,

Dold 2014). However, this approach might result in rather pessimistic AP values compared with reality if the sample also contains other sulphides than pyrite. This is because the oxidation of these other sulphides, such as pyrrhotite, chalcopyrite, pentlandite, sphalerite and arsenopyrite, produces fewer protons than pyrite oxidation (Dold 2017).

To conclude, the mineralogy of the sample material should be better considered when making ARD predictions. Mineralogy-based calculation methods have been proposed by Lawrence and Scheske (1997) and Dold (2017), among others. The suitability of these mineralogical methods for the Finnish climate and extractive waste types have been further investigated by Karlsson et al. (2018d). The results indicate that SEM mineralogical calculation based ARD predictions can be at least as accurate as the commonly used static laboratory methods (Karlsson et al. 2018d).

4 CONCLUSIONS

In general, the investigated extractive waste materials were not suitable for earthwork purposes, as they contained high amounts of potentially harmful substances and were classified as non-inert mining waste. Non-acid-generating waste rocks can potentially be used in less vulnerable areas, mainly at mine sites. It is recommended that waste rocks are used in as large grain sizes as possible, as fine-grained fractions are more reactive. The utilisation possibilities of waste rock materials could be improved if boulders with a high sulphide content were removed.

Various geochemical laboratory tests can be applied to determine the mineral fractions to which harmful substances are bound, and therefore the potential for element mobility in different environments. Based on the results, the element concentrations yielded by aqua regia and H_2O_2 -citrate extractions of wastes correspond well with the elevated element concentrations in the drainage waters from the waste areas. The NAG test leachate concentrations are consistent with the corresponding aqua regia extraction results, but only when the NAG test leachate pH is below around 4. Above pH 4, the element concentrations in the NAG test leachate decrease significantly compared with the aqua regia results, which is most likely due to the precipitation of secondary minerals during the test and coprecipitation of, for example, trace elements with the secondary precipitates.

Besides aqua regia extraction, a similar sulphide-specific method is sulphide extraction with a mixture of $KClO_3$, 12 M HCl and 4 M HNO_3 . The concentrations dissolved with sulphide extraction were distinctly lower than those leached with aqua regia. This difference could be explained by the fact that aqua regia not only leaches sulphides but also some silicates, e.g. biotite and chlorite, while sulphide extraction does not appear to completely leach all the sulphide species. Nevertheless, as with aqua regia extraction, sulphide extraction also indicates which elements might have elevated concentrations in the drainage waters of extractive waste facilities.

The two-stage batch test SFS-EN 12457-3 was applied to investigate which harmful substances are leached with water from extractive waste material. The results of the test indicated that water is too weak a solvent and the test time is too short to leach elements from fresh unweathered extractive waste material. Therefore, the method is not suitable for the long-term predictions based on fresh extractive waste.

The ARD predictions based on the ABA test (EN 15875) and NAG test yielded similar results compared with the corresponding drainage water pH, with some exceptions. In the case of Hällinmäki, it could be observed that ARD prediction based on static tests does not sufficiently consider the mineralogical properties of the investigated rock material.

REFERENCES

- AMIRA 2002.** ARD Test Handbook. Project P387A, Prediction & Kinetic Control of Acid Mine Drainage. AMIRA international May 2002. 42 p.
- Charles, J., Barnes, A., Declercq, J., Warrender, R., Brough, C. & Bowell, R. 2015.** Difficulties of Interpretation of NAG Test Results on Net Neutralizing Mine Wastes: Initial Observations of Elevated pH Conditions and Theory of CO_2 Disequilibrium. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O'Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. Proceedings of the 10th International Conference on Acid Rock Drainage & IMWA Annual Conference, April 21–24 (Santiago, Chile). Gecamin, 575–584.
- Colmer, A. R. & Hinkle, M. E. 1947.** The role of microorganisms in acid mine drainage. *Science* 106, 253–256.
- Dino, G. A., Rossetti, P., Perotti, P., Alberto, W., Sarkka, H., Coulon, F., Wagland, S., Griffiths, Z. & Rodeghiero, F. 2018.** Landfill mining from extractive waste facilities: The importance of a correct site characterisation and evaluation of the potentialities. A case study from Italy. *Resources Policy*. 12 p. (in press)
- Dold, B. 2014.** Evolution of Acid Mine Drainage Formation in Sulphidic Mine Tailings. *Minerals* 2014, 621–641.
- Dold, B. 2017.** Acid rock drainage prediction: A critical review. *Journal of Geochemical Exploration* 172, 120–132.
- Doležal, J., Provondra, P. & Šulcek, Z. 1968.** Decomposition techniques in inorganic analysis. London: Iliffe Books Ltd. 224 p.
- Eilu, P., Ahtola, T., Äikäs, O., Halkoaho, T., Heikura, P., Hulkki, H., Iljina, M., Juopperi, H., Karinen, T., Kärkkäinen, N., Konnunaho, J., Kontinen, A., Kontoniemi, O., Korkiakoski, E., Korsakova, M., Kuivasaari, T., Kylläkoski, M., Makkonen, H., Niiranen, T., Nikander, J., Nykänen, V., Perdahl, J.-A., Pohjolainen, E., Räsänen, J., Sorjonen-Ward, P., Tiainen, M., Tontti, M., Torppa, A. & Västi, K. 2012.** Metallogenic areas in Finland. In: Eilu, P. (ed.) *Mineral deposits and metallogeny of*

- Fennoscandia. Geological Survey of Finland, Special Paper 53, 207–342. Available at: http://tupa.gtk.fi/ju-lkaisu/specialpaper/sp_053_pages_207_342.pdf
- Fosso-Kankeu, E., Waanders, F., Mulaba-Bafubandi, A. & Sidu, S. 2015.** Leachability of Suspended Particles in Mine Water and Risk of Water Contamination. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) 10th ICARD & IMWA 2015 Conference – Agreeing on solutions for more sustainable mine water management”, Santiago, Chile 2015. Available at: https://www.imwa.info/docs/imwa_2015/IMWA2015_Fosso-Kankeu_286.pdf
- GTK 2017.** Mineral Deposit Report 103: Virtasalmi. Geological Survey of Finland, Mineral deposits-report database. Available at: http://tupa.gtk.fi/karttasovellus/mdae/raportti/103_Virtasalmi.pdf
- Government Decree 2007.** Government Decree on the Assessment of Soil Contamination and Remediation Needs 214/2007. Adopted in Helsinki on 1 March 2007. Available at: <https://www.finlex.fi/fi/laki/kaannokset/2007/en20070214.pdf>
- Government Decree 2013.** Government Decree on Extractive Waste 190/2013. Adopted in Helsinki on 14 March 2013. Available at: https://www.finlex.fi/fi/laki/kaannokset/2013/en20130190_20150102.pdf
- Hageman, P. L., Seal, R. R., Diehl, S. F., Piatak, N. M. & Lowers, H. A. 2015.** Evaluation of selected static methods used to estimate element mobility, acid-generating and acid-neutralizing potentials associated with geologically diverse mining wastes. *Applied Geochemistry*, 57, 125–139.
- Hall, G. E. M., Vaive, J. E., Beer R. & Hoashi, M. 1996.** Selective leaches revisited, with emphasis on the amorphous Fe oxyhydroxide phase extraction. *Journal of Geochemical Exploration* 56, 59–78.
- Heikkinen, P. M. & Räsänen, M. L. 2008.** Mineralogical and geochemical alteration of Hitura sulphide mine tailings with emphasis on nickel mobility and retention. *Journal of Geochemical Exploration* 97, 1–20.
- Heikkinen, P. M. & Räsänen, M. L. 2009.** Trace metal and As solid-phase speciation in sulphide mine tailings – Indicators of spatial distribution of sulphide oxidation in active tailings impoundments. *Applied Geochemistry* 24, 1224–1237.
- Hyvärinen, L. 1969.** On the geology of the copper ore field in the Virtasalmi area, eastern Finland. *Bulletin de la Commission Géologique de Finlande* 240, 82 p.
- Jambor, J. L. 1994.** Mineralogy of Sulfide-rich Tailings and Their Oxidation Products. In: Blowes, D. W. & Jambor, J. L. (eds) *Environmental Geochemistry of Sulfide Mine-wastes*. Mineralogical Association of Canada, Short Course Vol. 22, 59–102.
- Jambor, J. L. 2003.** Mine-waste mineralogy and mineralogical perspectives of acid-base accounting. In: Jambor, J. L., Blowes, D. W. & Ritchie, A. I. M. (eds) *Environmental aspects of mine wastes*. Mineralogical Association of Canada, Short Course Series 31, 117–145.
- Jambor, J. L., Dutrizac, J. E., Groat, L. A. & Raudsepp, M. 2002.** Static tests of neutralization potentials of silicate and aluminosilicate minerals. *Environmental Geology* 43, 1–17.
- Karlsson, T. & Kauppila, P. M. 2016.** Waste Rock Characterization versus the Actual Seepage Water Quality. In: Drebenstedt, C. & Paul, M. (eds) *IMWA 2016 – Mining Meets Water – Conflicts and Solutions*. Freiberg: TU Bergakademie, 402–406.
- Karlsson, T., Kauppila, P. M. & Lehtonen M. 2018a.** Potential for beneficial reuse of waste rocks from Kevitsa and Hitura mines: indicative data from lysimeter test. In: Kauppila, P. M. & Tarvainen, T. (eds) *Improving the environmental properties, utilisation potential and long-term prediction of mining wastes*. Geological Survey of Finland, Bulletin 408. (this volume). Available at: <https://doi.org/10.30440/bt408.3>
- Karlsson, T., Kauppila, P. M., Lehtonen, M., Tiljander, M., Forsman, P. & Lahtinen, T. 2018b.** Hituran ja Kevitsan kaivosten sivukivien hyötykäyttö maarakentämisessä. Geological Survey of Finland, Open File Work Report 11/2018. (in Finnish). Available at: http://tupa.gtk.fi/raportti/arkisto/11_2018.pdf
- Karlsson, T., Kauppila, P. M., Lehtonen, M., Tiljander, M., Forsman, P. & Lahtinen, T. 2018c.** Laboratorio-analyysit kaivannaisjätteiden käyttäytymisen ennustamisessa. Geological Survey of Finland, Open File Work Report 13/2018. (in Finnish)
- Karlsson, T., Räsänen, M. L., Lehtonen, M. & Alakangas, L. 2018d.** Comparison of static and mineralogical ARD prediction methods in the Nordic environment. *Environmental Monitoring and Assessment* 190, p. 719.
- Katsnelson, E. M. & Osipova, J. J. 1960.** Usoversenstvovannyi metod opredelenija sul’-fidnogo nikelja. *Obogastsenie rud*, n:o 4, 2426.
- Kauppila P. M. & Räsänen M. L. 2015.** Effluent chemistry of closed sulfide mine tailings – influence of ore type. In: Brown, A., Bucknam, C., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) 10th International Conference on Acid Rock Drainage & IMWA Annual Conference, 264–273.
- Kontinen, A., Peltonen, P. & Huhma, H. 2006.** Description and genetic modelling of the Outokumpu-type rock assemblage and associated sulphide deposits. Geological Survey of Finland, archive report M10.4/2006/1. Available at: http://tupa.gtk.fi/raportti/arkisto/m10_4_2006_1.pdf
- Kontoniemi, O. & Forss, H. 1997.** Tutkimustyöselostus Leppävirran kunnassa valtausalueilla Särki 1 (kaiv. rek. nro 5422/1) ja Särki 2 (kaiv. rek. nro 5422/2) suoritetuista nikkelimalmitutkimuksista vuosina 1993–1996. 14 p. Geological Survey of Finland, archive report M06/3241/-97/2/10. (in Finnish). Available at: http://tupa.gtk.fi/raportti/valtaus/m06_3241_97_2_10.pdf
- Lapakko, K. 2002.** Metal Mine Rock and Waste Characterization Tools: An Overview. Minnesota Department of Natural Resources, US. April 2002 No. 67. 30 p.
- Lawrence, R. W. & Scheske, M. 1997.** A method to calculate the neutralization potential of mining wastes. *Environmental Geology*, 32, 100–106.
- Lawrie, K. C. 1992.** Geochemical characterisation of a polyphase deformed, altered and high grade metamorphosed volcanic terrane: implications for the tectonic setting of the Svecofennides, south-central Finland. *Precambrian Research* 59, 171–205.
- Mäki, T., Imaña, J., Kousa, J. & Luukas, J. 2015.** Chapter 7 – The Vihanti-Pyhäsalmi VMS Belt. In: Maier, W., Lahtinen, R. & O’Brien, H. (eds) *Mineral Deposits of Finland*. Elsevier, 507–530.
- Makkonen, H. & Halkoaho, T. 2007.** Whole rock analytical data (XRF, REE, PGE) for several Svecofennian (1.9 Ga) and Archean (2.8 Ga) nickel deposits in eastern Finland 49p. Geological Survey of Finland, archive report M19/3241/2007/32. Available at: http://tupa.gtk.fi/raportti/arkisto/m19_3241_2007_32.pdf
- Mehta, N., Dino, G. A., Ajmone Marsan, F., Lasagna, M., Romè, C. & De Luca, D. A. 2018.** Extractive waste management: A risk analysis approach. *Science of the Total Environment* 622–623, 900–912.
- Meriläinen, M., Ekberg, M., Lovén, P., Koivistoinen, P., Hakola, J. & Strauss, T. 2008.** Updated Reserve and

- Resource Estimate of the Hitura Nickel Mine in Central Finland. Belvedere Resources, National Instrument 43-101 Technical Report. 65 p.
- Muniruzzaman, M., Kauppila, P. M. & Karlsson, T. 2018.** Water quality prediction of mining waste facilities based on predictive models. Geological Survey of Finland, Open File Research Report 16/2018. 65 p. Available at: http://tupa.gtk.fi/raportti/arkisto/16_2018.pdf
- Niskavaara, H. 1995.** A comprehensive scheme of analysis for soils, sediments, humus and plant samples using inductively coupled plasma atomic emission spectrometry (ICP-AES). In: Autio, S. (ed.) Geological Survey of Finland, Current Research 1993-1994. Geological Survey of Finland, Special Paper 20, 167-175. Available at: http://tupa.gtk.fi/julkaisu/specialpaper/sp_020_pages_167_175.pdf
- Nordstrom, D. K. 2000.** Advances in the Hydrogeochemistry and Microbiology of Acid Mine Waters. *International Geology Review*, 42(6), 499-515.
- Nordstrom, D. K. & Nicholson, A. (eds) 2017.** Geochemical Modeling for Mine Site Characterization and Remediation. Colorado: Society for Mining, Metallurgy & Exploration. 181 p.
- Oh, C., Ji, S., Yim, G. & Cheong, Y. 2017.** Evaluation of net acid generation pH as a single indicator for acid forming potential of rocks using geochemical properties. *Environmental Monitoring and Assessment* 189:165-174 p.
- Papunen, H. 1986.** Suomen metalliset malmiesiintymät. In: H. Papunen, I. Haapala & Rouhunkoski, P. (eds) Suomen malmigeologia. Metalliset malmiesiintymät. Suomen geologinen seura ry. Mänttä: Mäntä Kirjapaino Oy, 133-214. (in Finnish)
- Parbhakar-Fox, A. & Lottermoser, B. G. 2015.** A critical review of acid rock drainage prediction methods and practices. *Minerals Engineering* 82, 197-224.
- Plumlee, G. S., Smith, K. S., Mountour, M. R., Ficklin, W. H. & Mosier, E. L. 1999.** Geologic Controls on the Composition of Natural Waters and Mine Waters Draining Diverse Mineral-Deposit Types. In: Filipek, L. H. & Plumlee, G. S. (eds) *The Environmental Geochemistry of Mineral Deposits, Part B: Case Studies and Research Topics*. Review in *Economic Geology*, Vol. 6B, 373-432.
- Price, W. A. 2009.** Prediction Manual for Drainage Chemistry from Sulfidic Geologic Materials. Natural Resources Canada. MEND Report 1.20.1. 579 p.
- Price, W. A., Morin, K. & Hutt, N. 1997.** Guidelines for prediction of acid rock drainage and metal leaching for mines in British Columbia: Part II. Recommended procedures for static and kinetic tests. Fourth International Conference on Acid Rock Drainage. Vancouver, B.C. Canada, May 31-June 6, 1997. Proceedings, vol. I, 15-30.
- Räisänen, M. L., Kauppila, P. M. & Myöhänen, T. 2010.** Suitability of static test for acid rock drainage assessment of mine waste rock. *Bulletin of the Geological Society of Finland* 82, 101-111. Available at: www.geologinenseura.fi/bulletin/Volume82/Raisanen_2010.pdf
- Räisänen, M. L., Nikkarinen, M., Lehto, O. & Aatos, S. 2002.** Liukoisuustesti- ja heikkouuttomenetelmät kaivannaisteollisuuden ympäristö- ja kaatopaikkakelpoisuuden määrittämisessä. Geological Survey of Finland, archive report S44/0000/1/2002, 21 p. (in Finnish). Available at: http://tupa.gtk.fi/raportti/arkisto/s44_0000_1_2002.pdf
- Reinikainen, J. 2007.** Maaperän kynnys- ja ohjearvojen määrittäysperusteet. Suomen ympäristö 23/2007. Helsinki: Suomen ympäristökeskus. 168 p. (in Finnish)
- Santaguida, F., Luolavirta, K., Lappalainen, M., Ylinen, J., Voipio, T. & Jones, S. 2015.** The Kevitsa Ni-Cu-PGE deposit in the central Lapland greenstone belt in Finland. In: Maier, W., Lahtinen, R. & O'Brien, H. (eds) *Mineral Deposits of Finland*. Elsevier, 195-210.
- Singer, P. C. & Stumm, W. 1970.** Acid mine drainage: the rate-determining step. *Science* 167, 1121-1123.
- Sobek, A., Schuller, W., Freeman, J. & Smith, R. 1978.** Field and Laboratory Methods Applicable to Overburdens and Minesoils. Cincinnati: Industrial Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.
- White, W. W. III, Lapakko, K. A. & Cox, R. L. 1999.** Static-test methods most commonly used to predict acid mine drainage: Practical guidelines for use and interpretation. In: Plumlee, G. S. & Logsdon, M. (eds) *The Environmental Geochemistry of Mineral Deposits, Part A: Theory and background*. Society of Economic Geologists Reviews in *Economic Geology*, vol. 7A, 325-328.

Standards referred to in the text

- CEN/TR 16376:2012.** Characterization of waste – Overall guidance document for characterization of waste from the extractive industries. Committee B/508/3. 140 p.
- ISO 15178.** Soil quality -- Determination of total sulfur by dry combustion. ISO 15178:2000.
- SFS-EN 12457-3.** Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with a high solid content and with a particle size below 4 mm (without or with size reduction).
- SFS-EN 15875.** Characterization of waste. Static test for determination of acid potential and neutralization potential of sulfidic waste.

MODELLING TOOLS FOR THE PREDICTION OF DRAINAGE QUALITY FROM MINE WASTES

by

Muhammad Muniruzzaman, Teemu Karlsson and Päivi M. Kauppila

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The weathering of mine wastes often leads to low quality drainage typically characterised by acidic pH and elevated concentrations of dissolved metals/metalloids. Therefore, prior knowledge and quantitative predictions of drainage quality is crucial during mine planning in order to properly assess the environmental impact in the vicinity of mining activity. In recent decades, a great deal of research attention has been paid to accurately predict the mine waste drainage and that has led to the development of a wide variety of predictive models with different levels of sophistication. Despite the availability of a plethora of modelling approaches and well established tools, there is still a lack of attention towards attempting a rigorous predictive modelling at the planning phase (e.g. environmental impact assessment) of a mine. This work presents a relatively simple predictive model that can be used at such early phase of a mine when data is very limited. The model formulation is based on reactive transport approaches that take into account water flow, gas transport and mineral weathering reactions. Furthermore, this paper also includes example case studies (both in waste rock pile and tailings systems) demonstrating the scope and capability of the presented model and how such approaches can be used effectively at potential mine sites.

Keywords: Prediction, mine waste, drainage quality, AMD, predictive model, reactive transport modelling

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1 INTRODUCTION

Management of mine wastes is a prescient issue in mining sectors since uncontrolled waste disposal may result in liability for the operators with the risk of financial consequences as well as reputational damage (e.g. Blowes et al. 2014). Of primary concern is the release of low quality drainage from the waste deposits that leads to adverse effects on the environment, ecosystem, and human health (e.g. Blowes & Jambor 1990, Blowes et al. 2014, Nordstrom et al. 2015). Such drainages are known to be the results of the weathering processes of sulphide-rich waste deposits under oxic environments and/or under the influence of microbial activities (e.g. Blowes & Ptacek 1994, Tremblay & Hogan 2000, Amos et al. 2015, Nordstrom et al. 2015). Therefore, it is of utmost importance to understand the controlling physicochemical processes leading to toxic drainage in mining environments to sufficiently predict the overall system behaviour in advance (e.g. Dold 2017).

During mine planning, the estimates of the drainage quality are required to properly assess the environmental influences for the environmental impact assessment and for the environmental permit application to facilitate mine planning and to prevent negative impacts on the watersheds. The prediction of effluent quality is, nevertheless, a challenging task. This is mainly because the mineral weathering reactions responsible for the mine drainage are complex and long term (e.g. Blowes & Jambor 1990, Blowes & Ptacek 1994). In addition, they are site-specific and depend on the geology and climatic conditions of each mine site, even though the overall chemical processes are the same (cf. Plumlee 1999).

In recent decades, a wide range of prediction techniques have been developed including experimental methods focusing on laboratory and field scale tests to characterise different properties of waste materials (e.g. Morin & Hutt 1994, Price 2009, Tripathy 2014, Parbhakar-Fox & Lottermoser 2015, Dold 2017), as well as numerical approaches to quantitatively describe and predict the system dynamics by capturing all the key processes (e.g. Mayer et al. 2003, Maest et al. 2005, Amos et al. 2015). Numerical modelling is instrumental in quantifying the overall system behaviour especially where coupling between multi-scale processes leads to non-intuitive system dynamics (e.g. Steefel et al. 2005). Such modelling frameworks rely on pro-

cess based approaches that quantitatively resolve all the relevant physical, geochemical, microbiological, electrochemical, and thermal processes (e.g. Steefel et al. 2015).

Depending on the capabilities, typical predictive models in mining environmental simulations can be categorised as geochemical models that only take into account the geochemical processes occurring in the waste piles (e.g. Parkhurst et al. 1985, Davis & Ritchie 1986, Davis & Ashenberg 1989, Ball et al. 1987, Blowes & Jambor 1990, Allison et al. 1991, Wolery et al. 1992, Alpers & Nordstrom 1999, Tempel et al. 2000, Eary et al. 2003, Ramstedt et al. 2003, Moncur et al. 2005, Gunsinger et al. 2006, Nordstrom & Campbell 2014), and more sophisticated reactive transport models that are capable of simultaneously capturing hydrogeological processes, multicomponent solute and gas transport, thermal processes, microbiological and electrochemical mechanisms in addition to the geochemical processes (e.g. Pruess 1991, Pantelis 1993, Steefel & Lasaga 1994, Wunderly et al. 1996, Bethke 1997, Lefebvre et al. 2001, Mayer et al. 2002, Saaltink et al. 2002, Prommer et al. 2003, Parkhurst et al. 2005, da Silva et al. 2009, Šimunek et al. 2012, Parkhurst & Appelo 2013, Muniruzzaman et al. 2014, Amos et al. 2015, Lichtner et al. 2015, Muniruzzaman & Rolle 2016, Nordstrom & Nicholson 2017, Pedretti et al. 2017, Rolle et al. 2018).

Despite the diversified supply of prediction methods, limited publications exist on how to approach the modelling in a mine planning phase for which data on the mine wastes is still limited. Due to these challenges, one of the aims of the KaiHaMe project (Management of mining wastes) was to provide additional tools for predictive modelling. As a first step, a review of the existing prediction methods, including typical laboratory and field tests, as well as numerical modelling in particular, was carried out within this project (Muniruzzaman et al. 2018b). In addition to the methods, the review covered aspects such as relevant processes resulting and occurring in mine drainage, available codes for numerical modelling, and code and model uncertainties, and limitations and applicability under Nordic climate. Muniruzzaman et al. (2018b) also discussed the potential approaches to enhance the prediction accuracy by using integrated methodologies to properly describe the multifaceted processes occurring in mine wastes.

As a next step, this investigation focuses on the predictive modelling of drainage water quality from mine waste facilities (both waste rock piles and tailings) by means of reactive transport modelling. The study presents examples of predictive simulations at three particular mine sites in Finland illustrating the specific capabilities and scope of predictive modelling. These simulation examples generally demonstrate how reactive transport modelling can be effectively used in predicting the seepage water compositions from mine waste settings under different conditions (e.g. environmental conditions or closure scenarios). Although the presented examples include predictive modelling in existing sites, they can be considered representative of potential future sites where data are very limited. In particu-

lar, the model formulation, quality of the site-specific information, and overall modelling workflow were treated from the perspective of predictions in future waste facilities. The ultimate intent of these simulations is to demonstrate the presented model capabilities and how this tool can be used in the planning phase of a mine. The simulation outcomes suggest that numerical tools in combination with good quality data have a great potential to interpret the timing and occurrence of the future low quality drainages that may be harmful to the surrounding receptors. In the following sections, a brief summary of the results of the predictive modelling is provided and the details of the study are presented in a separate GTK Open File Work Report by Muniruzzaman et al. (2018a).

2 STUDY SITES AND DATA COLLECTION

Mine waste and drainage water samples were collected from three mine sites around Finland for the development of predictive models. Waste rock samples were collected from the Kylylahti Cu-Co-Zn-Ni-Au mine in Polvijärvi (operated since 2012)

and from the Särkiniemi Ni mine in Leppävirta (in operation during 2007–2009), and tailings samples from the Pyhäsalmi Cu-Zn mine in Pyhäjärvi (operated since 1962) (Fig. 1). All the sites were metal sulphide mines.

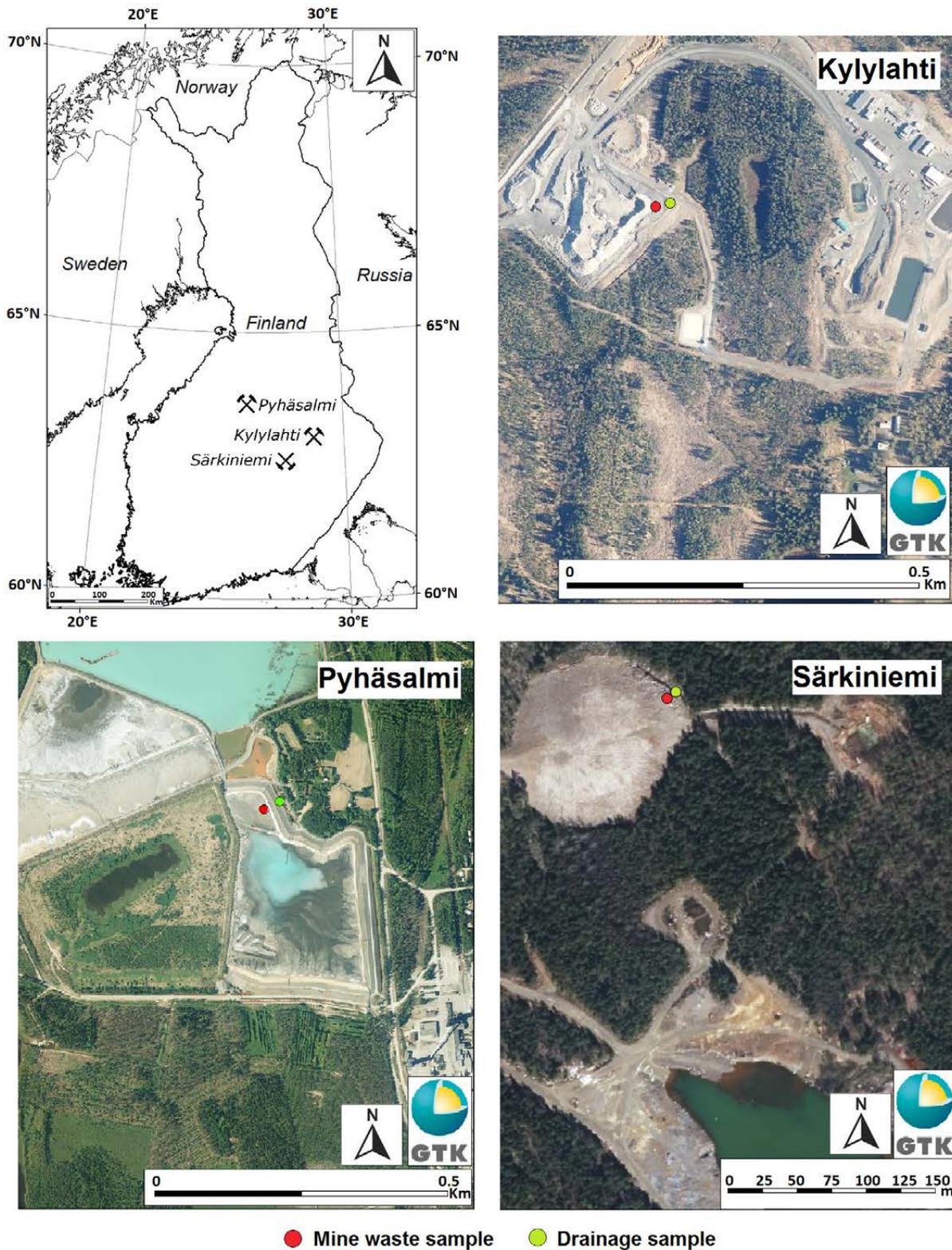


Fig. 1. Location of the study areas and sampling points. The sulphidic waste rock pile of Kylylahti has already been backfilled to the underground mine. The investigated tailings pond at the Pyhäsalmi mine contains 3.0 (situation in 2003) – 7.5 (estimated maximum storage capacity) Mt of highly sulphidic waste material (Pohjois-Suomen ympäristölupavirasto 2007). The sulphidic waste rock pile of Särkiniemi contains around 13 000 t of waste rocks (Tornivaara et al. 2018). Basemaps © National Land Survey of Finland and HALTIK 2013.

3 MODELLING APPROACH

Predictive analyses were performed using the available site-specific information at the three different mine sites. The model formulation incorporates water flow in partially saturated domain, along with multicomponent solute and gas transport, and geochemical reactions. The flow, transport, and reaction problem was solved with finite volume method by employing an operator-splitting approach, in which the reaction problem was solved within PHREEQC (Parkhurst & Appelo 2013). An upwind differentiation scheme was used for the spatial discretisation of the flow and transport equations. For the integration in time the explicit Euler method was used in the computation of advective fluxes, whereas the diffusion/dispersion problem in aqueous/gas phase was solved by using the implicit Euler

time integration method. The resulting system of equations describing the aqueous and gas phase transport was solved with the direct matrix solver UMFPACK (Davis and Duff 1997). Afterwards, the transported concentrations at each location of the discretised domain are updated and passed to reaction step (in PHREEQC) for the calculations of gas-water partitioning and chemical reactions. The solubility of gases in the liquid phase was calculated within PHREEQC, which uses either Henry's law or Peng-Robinson EOS for ideal and non-ideal gases respectively (Parkhurst & Appelo 2013). The entire formulation of the presented modelling approach is implemented in MATLAB®. The fundamental steps of the modelling approach used in this study are briefly explained in Figure 2.

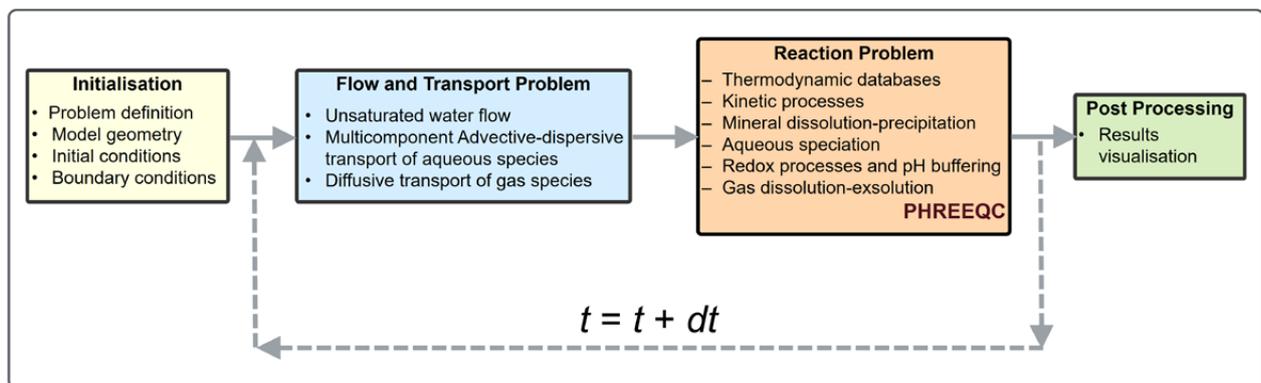


Fig. 2. Schematic diagram of the structure and calculation steps of the modelling approach. $t = t + dt$ (time = time + time step size) refers to the update of temporal steps in a time loop.

4 RESULTS AND DISCUSSION

This section briefly presents different aspects of predictive modelling starting from the conceptualisation of study sites followed by the demonstration of different capabilities of the presented model. In particular, the following sections focus on how such modelling may help in predicting the drainage compositions and mineralogical evolution, estimating long-term behaviour, and analysing different

closure scenarios of waste facilities. The presented examples strictly focus on the demonstration of different features of the model rather than accurately reproducing real conditions in any particular site. The specific model outcomes should also be treated as what kind of insights such predictive modelling can offer, especially in the planning phase of a mine.

4.1 Conceptual model

The predictive simulations were performed along a 1-D vertical simulation domain with homogeneous distributions of hydraulic properties and mineral

assemblages throughout the domain (Fig. 3). The conceptual models were built based on the measurements of mineralogy, drainage water, and from the

insights of laboratory static tests on waste materials. The system was conceptualised as a three phase porous media with water, air, and solid matrix being the main phases. Although in real settings, a variable water saturation is likely to occur and influence of capillary fringe might be important, for simplicity the presented simulation examples considered a constant water saturation along the depth. The kinetics of the mineral dissolution-precipitation reactions were modelled using the literature values.

However, to provide an accurate prediction site-specific kinetic parameters might be required and such parameters can be measured based on laboratory batch experiments (e.g. Williamson & Rimstidt 1994) or humidity cell tests (e.g. Maest & Nordstrom 2017). Geochemical reactions were simulated using a customised database, in which PHREEQC database was extended for additional reactions from WATEQ4F, Ilnl, CrunchFlow, and Sit databases.

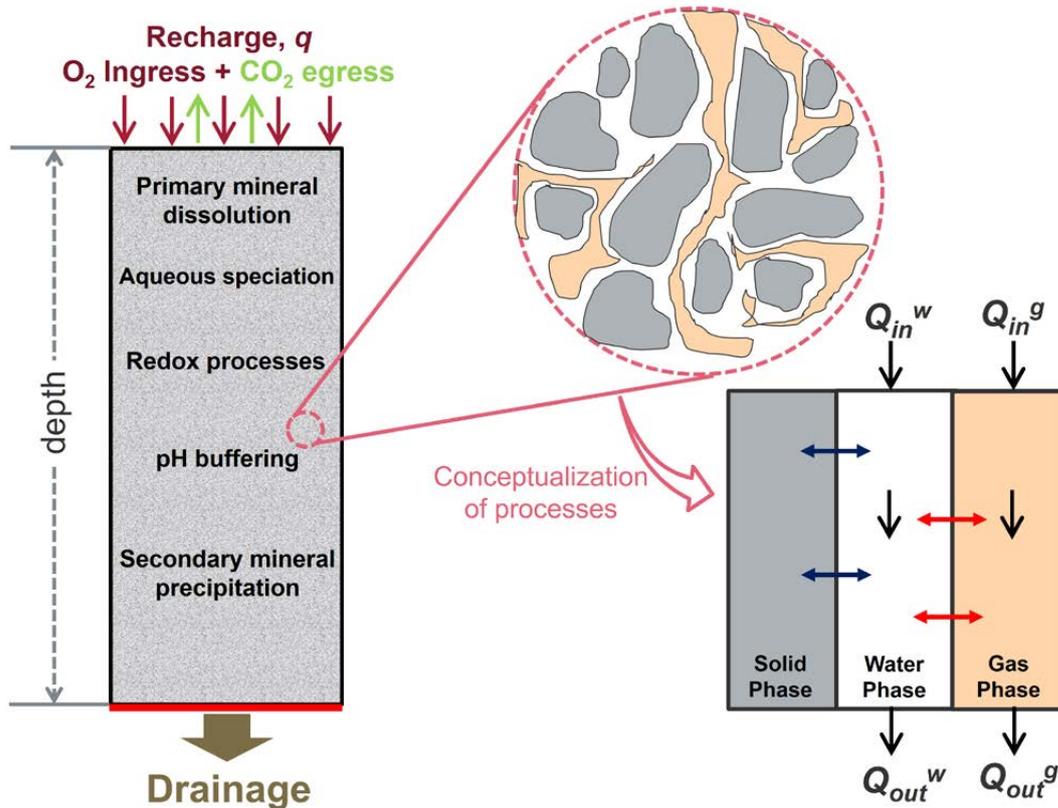


Fig. 3. Conceptual model used in the predictive simulations in the waste piles and the general conceptualisation approaches of physicochemical system at different porous compartment (Q_{in} , Q_{out} represent the general source/sink terms in aqueous and gas phase, and q is the recharge rate).

4.2 Prediction of drainage compositions and evolution of mineralogical assemblages

Figure 4 shows the evolution of the predicted drainage chemistry over time at the outlet of the Särkiniemi waste rock pile. The waste rock pile at this site has approximately a height of 10 m and the waste rocks are composed of biotite, plagioclase, quartz, hornblende, and sulphides (mainly pyrrhotite with minor pyrite, chalcopyrite and pentlandite) (Table 1). Only minor carbonates were present and the waste rock was classified as acid produc-

ing based on the static tests. A constant recharge rate of 300 mm/y, which is ~50% of the mean annual precipitation in that region, was applied at the top boundary of the domain. The recharge water contained a generic rainwater composition (Reimann et al. 1997) and it was also assumed to be in equilibrium with atmospheric O_2 and CO_2 . The gas transport was also simulated applying a constant boundary condition at the top and only

diffusive transport (gas phase diffusion coefficient, $D_g=1.75 \times 10^{-5} \text{ m}^2/\text{s}$) was considered. The drainage from the waste rock was acidic and it contained

elevated concentrations of metals, particularly Ni (cf. also Karlsson et al. 2018).

Table 1. Initial mineral contents, reactive surface areas, and reaction rate coefficients.

Mineral	Mineral Content		Surface Area, A [m ² L _w ⁻¹]	Rate coefficient, k [mol m ⁻² s ⁻¹]	Reference
	[wt%]	[mol L _w ⁻¹] ^a			
Biotite	33.56	2.12	0.65	10 ^{-10.97}	Nagy (1995)
Hornblende	6.07	0.58	0.05	10 ^{-8.10}	Palandri & Kharaka (2004)
Serpentine	3.52	0.33	0.05	10 ^{-9.08}	Declercq & Oelkers (2014)
Albite	1.45	0.15	0.60	10 ^{-10.16}	Palandri & Kharaka (2004)
Chlorite	1.35	0.06	0.50	10 ^{-11.11}	Palandri & Kharaka (2004)
Pyrrhotite	1.52	0.50	0.30 ^b	10 ^{-8.19}	Williamson & Rimstidt (1994)
Anthophyllite	0.45	1.53×10 ⁻²	0.50	10 ^{-11.94}	Palandri & Kharaka (2004)
Pentlandite	0.03	1.03×10 ⁻³	0.70 ^b	10 ^{-8.19}	Williamson & Rimstidt (1994)
Pyrite	0.02	4.42×10 ⁻³	0.30 ^b	10 ^{-8.19}	Williamson & Rimstidt (1994)
SiO ₂ (a) ^c	-	-	-	10 ^{-10.5}	Rimstidt & Barnes (1980)

^a Moles of mineral per L of pore water, calculated from wt% by using a solid density, $\rho_s = 2.65 \text{ [kg L}^{-1}\text{]}$ and an average porosity, $\theta = 0.50$

^b Surface area per moles of minerals per liters of pore water [m²mol⁻¹L_w⁻¹]

^c Both kinetic parameters and equilibrium constant was slightly adjusted to be in the consistent drainage concentration range as the measured values

Besides primary minerals, the model for the Särkiniemi waste rock pile also considered ferrihydrite, gypsum, jarosite, gibbsite, and amorphous silica as secondary minerals. Based on the model, the pH value drops quite fast in the drainage water after the disposal of the waste rock started, due to the oxidation of pyrrhotite, minor fractions of pyrite, and pentlandite and because of the absence of sufficient amount of carbonate minerals to effectively buffer the pH (Fig. 4a). These oxidation processes also lead to elevated concentrations of the dissolved ions in the drainage during the modelled period: SO₄, Mg, Fe, Ni, Al, Si, Ca, K, Na (Fig. 4a-c). This front of the increased concentrations of dissolved species is directly correlated to the drop in pH front (Fig. 4a) as well the increase in electrical conductivity values (Fig. 4d). The simulated concentration of each species also seem to be consistent with the measured drainage water composition represented by the dotted lines with the corresponding

colour for each species in Figure 4. Please note that unlike the simulated profiles, dotted lines represent only a single drainage measurement (not the evolution with time), which was performed approximately after 8 years of the construction of the waste rock pile. Although a few of these species (e.g. Fe, Na) show slight discrepancy between the simulated and measured concentrations, the predicted values are evidently in the similar order of magnitude for all the dissolved species as well the overall conductance of the effluent. This suggests that the model is able to reasonably predict the drainage behaviour even though a simple conceptual model was used for the waste rock pile system. The simulated value of pH at the late time plateau in Figure 4a is also consistent with the NAG (net acid generation) pH (2.7-2.9) value obtained from the NAG test performed with the waste rock samples. The measured data through time can be used for updating such a pre-mine model once the actual waste rock pile is

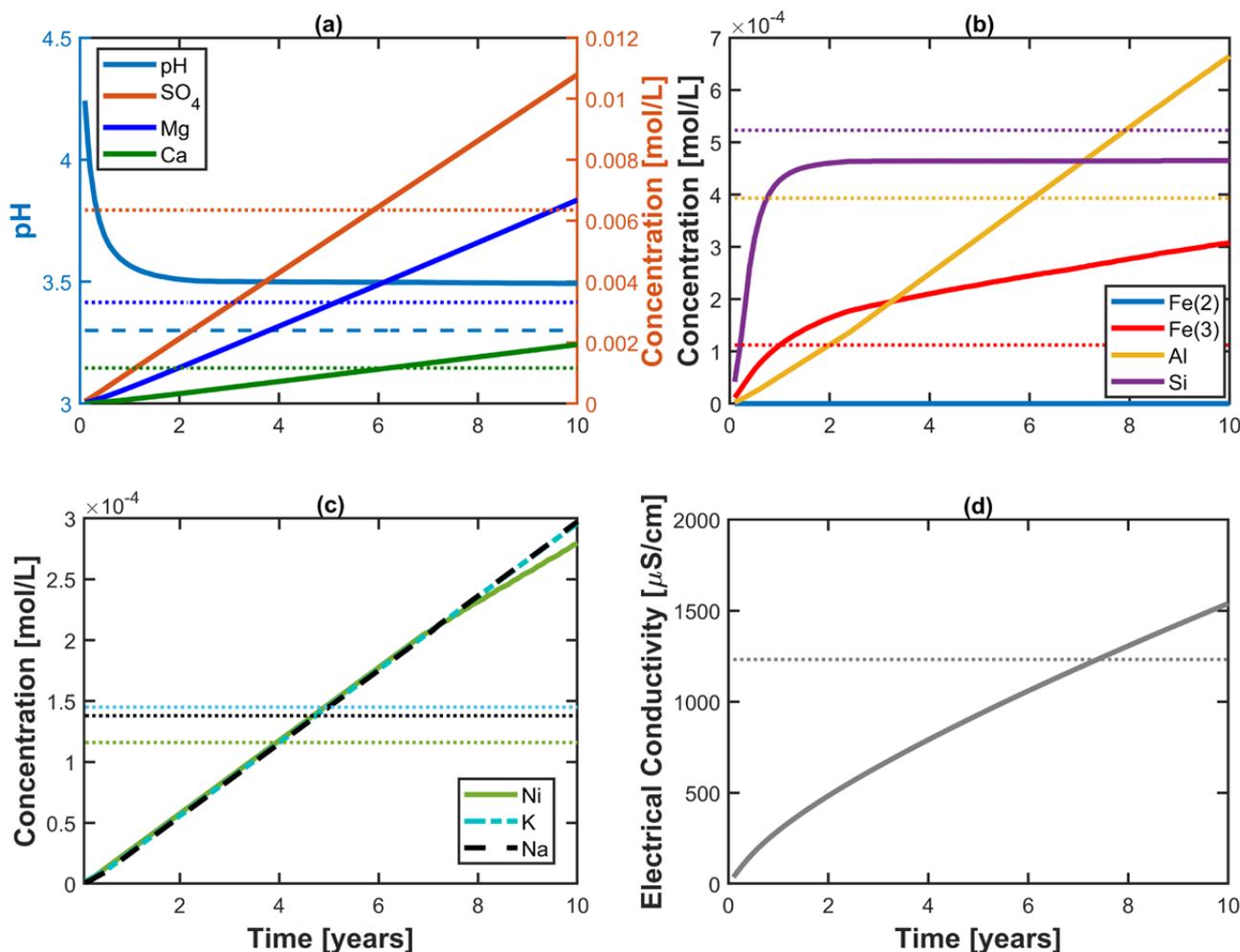


Fig. 4. Simulated (solid lines) and measured (dotted lines) compositions of the drainage water from the Särkiniemi waste rock pile as a function of time: (a) pH (primary y-axis), SO_4 , Mg, Ca (secondary y-axis), (b) Fe, Al, Si, (c) Na, K, Ni, and (d) electrical conductivity of drainage water. Please note that the dotted lines represent only a single measurement point (and not a series of collected data vs. time) that was performed at ~8 years.

constructed. Model refinement at this stage is very likely but the precision of a pre-mine model within an order of magnitude should be good enough for initial mine planning.

Capability of the model to simulate weathering and precipitation of key minerals in the waste rock pile is demonstrated in Figure 5, which illustrates the simulated profiles of the mineral contents in the domain at different times ($t = 0-10$ years) at the 10 m high Särkiniemi waste rock pile. The first column in this figure (Fig. 5a,e,i) shows the dissolution fronts of the different sulphide minerals representing a sequential depletion of these minerals over time. The acidic conditions induced by the sulphide oxidations lead to the potential dissolution of the silicates in the domain (second and third columns, Fig. 5b-c,f-g,j-k).

This mineral dissolution is directly related to the rise in the concentration of other ions (Al, Si, Ca, Mg, Na, and K) as presented in Figure 4. It is apparent from the figure that the silicate minerals (biotite, serpentine, chlorite or hornblende) dissolve much slower compared to typically fast dissolving minerals (such as carbonates) as only a very small fractions of these minerals were removed from the simulation domain after 10 years (Fig. 5, middle rows). The slow dissolution rate of these silicates suggests that these particular minerals may contribute to the acid buffering in the long term (e.g. Jambor et al. 2002). The last column of the figure depicts the precipitation of secondary minerals in the system (Fig. 5d,h,l). The model results reveal that a significant amount of Fe(III) and silica species precipitate as ferrihydrite and SiO_2 (a) phases,

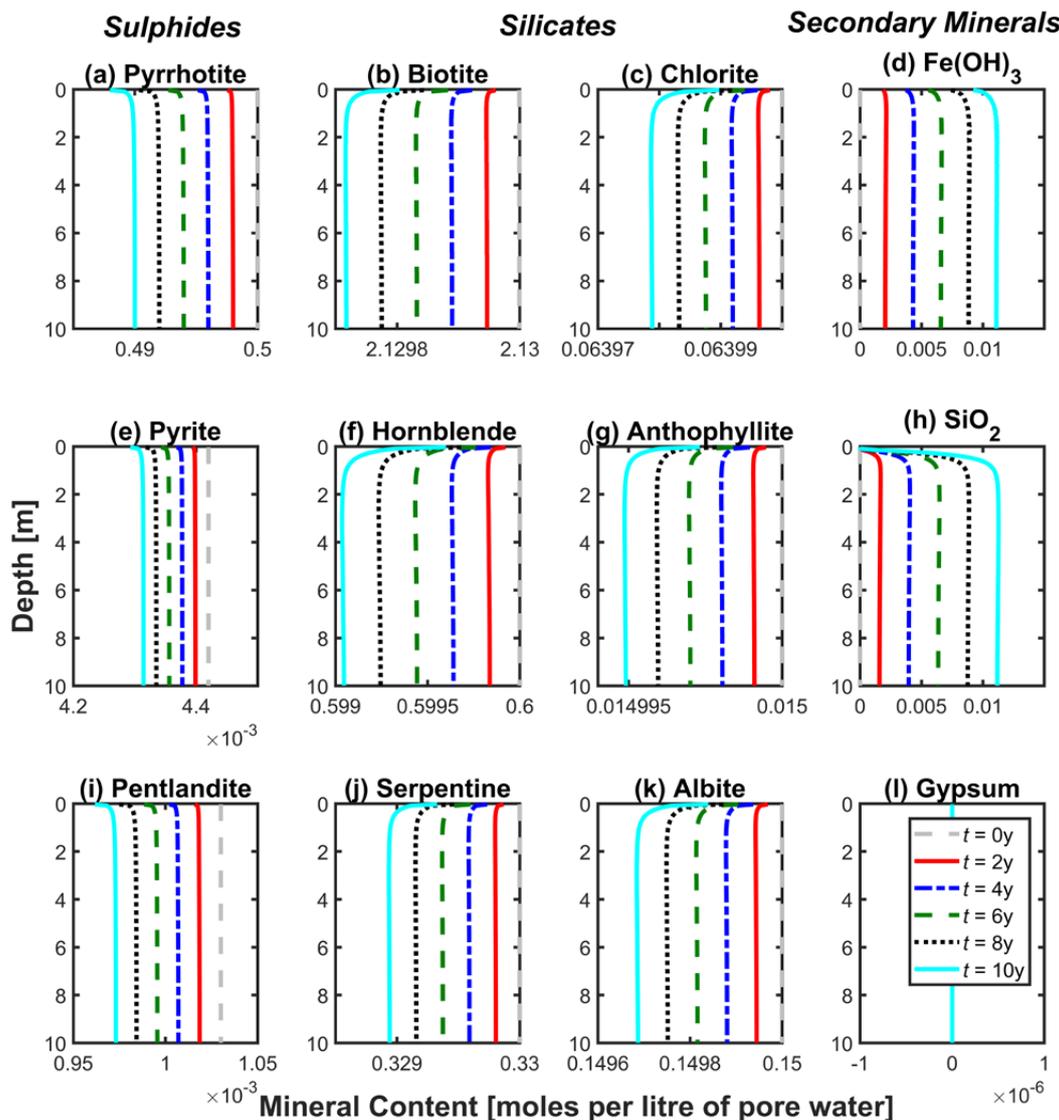


Fig. 5. Mineral contents versus depth and their temporal evolution at the Särkiniemi waste rock pile.

respectively (Fig. 5d,h). The concentrations of protons and Fe are also limited by the precipitation of the ferrihydrite phase. In contrast, the amount of precipitated sulphate phases is negligible (Fig. 5l). The results are in line with the overall field obser-

vations of the evolution of mineral weathering in mine wastes (e.g. Blowes & Jambor 1990, Blowes et al. 1995) and thus indicate that the developed model seems to be able to capture the mineral weathering processes in this waste rock pile.

4.3 Sensitivity of the model input parameters

A sensitivity analysis can be performed by varying different model input parameters and looking at the effect on the model outcome. Figure 6 demonstrates sensitivities of different parameters from the reactive transport simulations. This analysis enhances the system understanding as well as identifying possible improvements in future data collection by focusing on the most sensitive parameters. This approach may help increasing the accuracy of the

predictions. The simulations in Figure 6 are performed by changing the values of input parameters (Table 2) with respect to a “base case” scenario (blue lines). This base case scenario was selected based on the available information at Kylylahti waste rock pile, which is characterised by a rather high sulphide content (>9%), some fractions of carbonates (~2%), and significant amount of silicates (~25%). The waste rock pile has a height of

20 m and a constant recharge rate (~300 mm/y) was applied as the boundary condition. Gas transport was considered to occur only by diffusive mechanisms and a constant concentration boundary, representing atmospheric conditions, was employed at the top of the pile. For more detailed description of all these cases, interested readers are referred to Muniruzzaman et al. (2018a).

Figure 6a1-a2 shows the impact of the sulphide oxidation rate on drainage pH profiles at the Kylylahti waste rock pile. It is evident that a higher

oxidation rate (orange dash-dot line) leads to a significantly earlier breakthrough (and vice versa for lower oxidation rate) of the low pH front compared to the base case. Impact of the oxidation rate is also apparent both at early (a1) and late (a2) times. In contrast, the recharge rate does not show a significant impact on the timing of the acid rock drainage for this scenario (Fig. 6b1). In fact the application of a higher (dash-dot orange line) or lower (dotted yellow line) water flux through the domain does not lead to significantly different arrival times of the

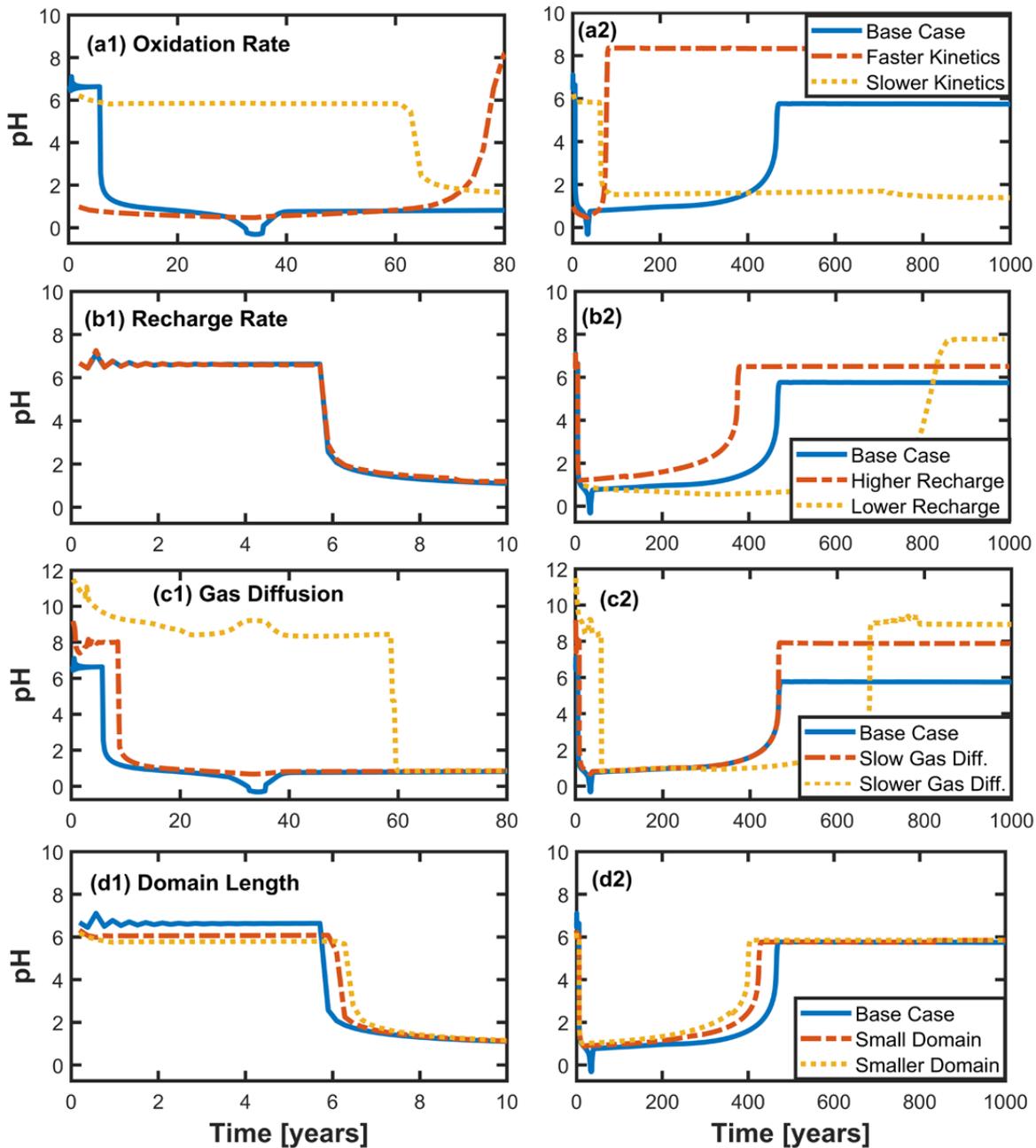


Fig. 6. Impact of the model input parameters on the drainage water quality of the Kylylahti waste rock pile: effects of oxidation rate (a1, a2), recharge rate (b1, b2), gas diffusion (c1, c2), and domain size (d1, d2). The left panel shows smaller time scale behaviour whereas the right panel presents the profiles in longer time scale.

Table 2. Initial parameters used in the sensitivity analysis.

Parameter	Base Case	Additional Case 1	Additional Case 2
Oxidation rate (reactive surface area [m ² /mol/L])	1.43	0.143	14.3
Recharge rate [mm/y]	300	30	3000
Pore gas diffusion coefficient [m ² /s]	5.63×10 ⁻⁶	5.63×10 ⁻⁷	5.63×10 ⁻⁸
Domain length [m]	20	5	10

low pH fronts compared to the base case (blue line). Such phenomena indicates that the early behaviour of the drainage chemistry of this waste rock pile is effectively controlled by the geochemistry rather than the water flow velocity. However, at late times, the impact of the recharge rate is significant (b2).

Figure 6c1–c2 shows the impact of gas transport into the Kylylahti waste rock pile. The model predicts that the gas diffusion influences the timing of the acidic drainage (pH breakthrough) at the end of the waste rock pile. By applying a 10-fold smaller diffusion rate, the temporal pH profiles at the outlet of the domain are very close to the base case with only a slight delay (by only a few years) for the

slow diffusion case (orange lines) compared to the base case (blue lines, Fig. 6c1–c2). The acid mine drainage occurs significantly later (at ~60 years) for the case of 100-fold smaller diffusion coefficient (dotted yellow lines, Fig. 6c1). Similar pattern is also observed at late times, when slower diffusive case leads to a later rise in pH (c2). The bottom row (Fig. 6d1–d2) shows the effects of the domain size on the drainage chemistry. The simulations show that the total height of the 1-D domain is perhaps the least sensitive parameter among these four parameters. Both at early (d1) and late (d2) times, the profiles for all scenarios are quite close.

4.4 Long-term predictive analysis and closure scenarios

Predictive reactive transport simulations are valuable for assessing mine closure scenarios. Figure 7 depicts the predicted drainage quality from the top surface (i.e. top 2 m layer) of tailings impoundment at the Pyhäsalmi mine site for 1000 years (light green lines) with and without a cover on top of the waste facility. These simulation scenarios consider the beginning of waste disposal (i.e. $t = 0$ year) as initial condition. In the simulations, the cover conditions were mimicked by employing a lower (10-fold) recharge rate ($q = 30$ mm/y) as well as gas diffusion coefficient ($D_p = 4.38 \times 10^{-7}$ m²s⁻¹) compared to that of uncovered base case.

The model predicts that it would take around four centuries (as indicated in the low pH conditions and elevated sulphate concentrations) for the sulphide minerals to be completely depleted from this 2 m domain under the “semi-open conditions” as used in the uncovered base case simulation (Fig. 7a).

The model prediction is quite different for a covered tailings facility. This can be seen as a hypothetical scenario that attempts to analyse the effects of a cover on a waste facility compared to the analogous uncovered case. The ultimate objective of

this simulation is merely to demonstrate the model capabilities and how this model can be used upon cover applications. However, accurate reproduction of the current conditions at the Pyhäsalmi mine site is beyond the scope of this simulation.

Due to the reduced penetration rate of the recharge water and lower supply of oxygen in the tailings, the drainage pH stays higher for a longer period ($t = \sim 0$ –80 years) at the beginning of the profile under the cover condition compared to the base case (Fig. 7a and figure inset). Afterwards, the drainage pH stays around 6 for almost another two centuries (dark red line, Fig. 7a) before it drops to acidic conditions (pH < 2). This early time buffering for a couple of 100 years is probably due to a combined effect of the limited supply of the reactants (i.e. water and oxygen) into the system for the sulphide oxidation reactions as well as the equilibrium of the carbonate minerals. The simulations also predict that even though the acidic drainage will not occur before ~400 years under closure conditions, the net duration of the acid mine drainage will be comparatively longer for this condition relative to the base case (Fig. 7a).

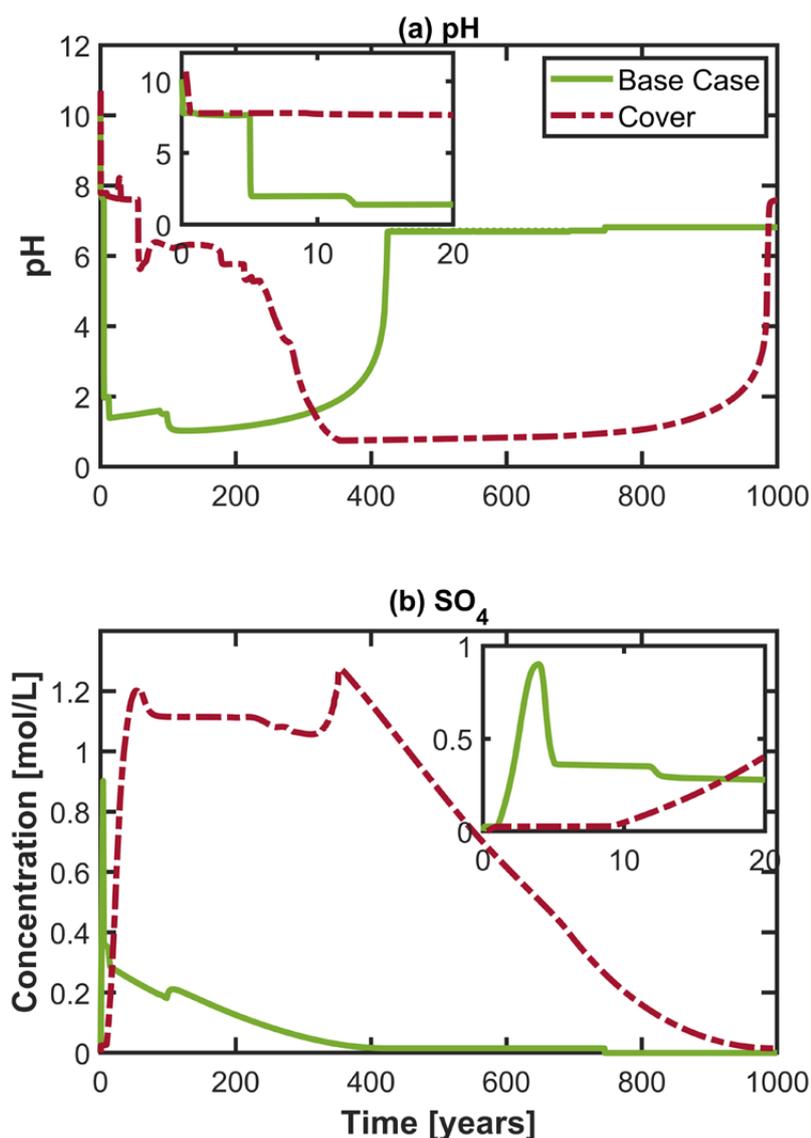


Fig. 7. Prediction of the long-term behaviour of drainage water quality from the tailings impoundment at the Pyhäsalmi site by considering the application of a potential cover on the tailings facility.

4.5 Uncertainties in the predictions

Depending on the unknowns and level of understandings about the key processes, modelling results may be subject to a considerable extent of uncertainties. The major sources of uncertainties in this study can be briefly summarised as:

- Heterogeneity associated with the physical and chemical processes and the related parameters
- Missing data on water saturation and moisture content profiles
- Unknowns related to the presence of preferential flows and fractures
- Kinetic reaction rate coefficients under the investigated settings
- Influence of microbial activities on the overall geochemistry
- Interactions between the pore water species and mineral surfaces due to surface complexation or ion exchange processes
- Insufficient information about the seasonal variations and the key effects on reactive transport processes
- Insufficient information on solute fluxes into multiple dimensions
- Inadequate information regarding the exact distributions of gas contents in the waste systems
- The presented results did not consider heat transport processes which may have some influence on the overall outcome

These sources of uncertainties occur mainly because these models simulate future sites where waste disposal has not been started yet (i.e. planning phase). Rigorous modelling of such future settings can be uncertain due to inadequate site-specific information necessary for a realistic conceptualisation. However, predictive modelling during the mine planning can provide valuable information on potential environmental impacts. Understanding these impacts, even with some uncertainty, can help avoid or reduce environmental impacts by choosing

better closure scenarios. While predictive results can be considered an “order of magnitude” approach, these results still provide information on potential outcomes with various mine planning and closure scenarios. In addition, the sensitivity analyses discussed in section 4.3 allow for an understanding of the most important model parameters. Thus, additional efforts can focus on these specific parameters during the modelling and mine planning process, as needed.

5 CONCLUSIONS

Numerical modelling is an instrumental tool not only for effectively predicting the effluent quality from mine waste dumps but also to perform more robust environmental impact assessment. This work presents a relatively simple reactive transport model that can be used in predictions of drainage quality from potential future waste facilities where site-specific data is scarce. In order to demonstrate the model capabilities, modelling examples were presented at three different study sites based on the available information. Although the exercises were performed at existing sites, they are representative scenarios involving future waste facilities and workflow in modelling was followed from the perception of these representing future sites. Based

on the results of the current study and the literature review (Muniruzzaman et al. 2018b), the key points and limitations of the procedures are briefly summarised as:

- Successful demonstration of the presented modelling approach involving operator-splitting scheme
- Replication of conceptual models
- Simulation results were tested at three different mine sites
- Model can be easily used to test alternative waste designs (e.g. cover, buffer addition)
- Identification of the most sensitive parameters which help managing future data collection

6 RECOMMENDATIONS

Guidelines for the improvement of prediction quality at the planning phase of a mine are briefly summarised as:

Detailed site-specific data should be collected that are representative of the study site to develop a realistic conceptual model. The extent of the collected information should be sufficient to identify at least the key mechanisms for that site.

Kinetic parameters, which are crucial in the overall prediction scheme, should be experimentally measured by means of laboratory or field scale testing (e.g. humidity cell tests, column/flow-through tests).

More efforts, budget, and systematic approaches should be dedicated to detailed data collection (e.g. hydrogeology and geochemistry along with their

spatial variability) and to reasonably characterise the physical and chemical heterogeneity of the waste facility. Model sensitivity can be a useful tool to identify the most important data. Analogues from previous sites could be used for proposed sites where these data are not yet available.

Accurately capturing the scale dependence of reactive transport processes is arguably the most challenging aspect in numerical simulations (e.g. Steefel et al. 2005), since most reactive transport parameters are measured in the laboratory. When using this scaling approach, the scaling factors should be treated as site-specific and they should be experimentally determined applying systematic investigations.

For predictive modelling in a planned waste facility (early stage of a mine), all the detailed data regarding the “proposed” waste pile may not be available at hand. However, in such circumstances, a systematic monitoring scheme should be established allowing more detailed data collection through time in order to continuously update the conceptual model as well as to better constrain the numerical model with more site-specific information.

In addition to the prediction of effluent quality, the predictive simulations incorporating reactive transport models can also be used in the design

and optimisation of the required monitoring/data collection scheme, the waste facility itself or the water treatment requirements to provide a better management of the wastes.

In addition to the information only at the drainage water, spatial profiling of different quantities at the waste pile systems should also be considered in the future data collection scheme.

Besides the characterisation of the geochemistry, emphasis should also be given on the fluid flow and transport processes that are sometimes relatively overlooked in dealing with mine waste management.

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REFERENCES

- Allison, J. D., Brown, D. S. & Novo-Gradac, K. J. 1991. MINTEQA2/PRODEFA2, A Geochemical Assessment Model for Environmental Systems – Version 3.0 User’s Manual. U.S. Environmental Protection Agency Report EPA/600/3-91/021. 106 p.
- Alpers, C. N. & Nordstrom, D. K. 1999. Geochemical modelling of water–rock interactions in mining environments. In: Plumlee, G. S. & Logsdon, M. J. (eds) *The Environmental Geochemistry of Mineral Deposits*, Reviews in Economic Geology, vol. 6A. Littleton, CO: Society of Economic Geologists Inc., 289–323.
- Amos, R. T., Blowes, D. W., Bailey, B. L., Sego, D. C., Leslie, S. & Ritchie, I. A. M. 2015. Waste-rock hydrogeology and geochemistry. *Applied Geochemistry* 57, 140–156.
- Ball, J. W., Nordstrom, D. K. & Zachman, D. W. 1987. WATEQ4F – A Personal Computer FORTRAN Translation of the Geochemical Model WATEQ2 with Revised Data Base. U.S. Geological Survey, Open-File Report 87-50. 108 p.
- Bethke, C. 1997. Modelling transport in reacting geochemical systems. *Comptes Rendus de l’Académie des Sciences* 324, 513–528.
- Blowes, D. W. & Jambor, J. L. 1990. The pore-water geochemistry and the mineralogy of the vadose zone of sulfide tailings, Waite Amulet, Quebec, Canada. *Applied Geochemistry* 5, 327–346.
- Blowes, D. W. & Ptacek, C. J. 1994. Acid-neutralization Mechanisms in Inactive Mine Tailings. In: Jambor, J. L. & Blowes, D. W. (eds) *The Environmental Geochemistry of Sulfide Mine Wastes*. Mineralogical Association of Canada, Short Course Series, Vol. 31, 95–116.
- Blowes, D. W., Al, T., Lortie, L., Gould, W. D. & Jambor, J. L. 1995. Microbiological, Chemical, and Mineralogical Characterization of the Kidd Creek Mine Tailings Impoundment, Timmins Area, Ontario. *Geomicrobiology Journal* 13, 13–31.
- Blowes, D. W., Ptacek, C. J., Jambor, J. L., Weisener, C. G., Paktunc, D., Gould, W. D. & Johnson, D. B. 2014. The Geochemistry of Acid Mine Drainage. In: Holland, H. D. & Turekian, K. K. (eds) *Treatise on Geochemistry* (Second Edition), Volume 11. Oxford: Elsevier, 131–190. Available at: <https://doi.org/10.1016/B978-0-08-095975-7.00905-0>
- da Silva, J. C., Vargas, Jr., E. D. A. & Sracek, O. 2009. Modelling multiphase reactive transport in a waste rock pile with convective oxygen supply. *Vadose Zone Journal* 8, 1038–1050.
- Davis, A. & Ashenberg, D. 1989. The aqueous geochemistry of the Berkeley Pit, Butte, Montana, USA. *Applied Geochemistry* 4, 23–36.
- Davis, G. B. & Ritchie, A. I. M. 1986. A model of oxidation in pyritic mine waste: Part 1 Equations and approximate solution. *Applied Mathematical Modelling* 10, 314–322.
- Davis, T. & Duff, I. 1997. An unsymmetric-pattern multifrontal method for sparse LU factorization. *SIAM Journal on Matrix Analysis and Applications* 18, 140–158. Available at: [doi:10.1137/S0895479894246905](https://doi.org/10.1137/S0895479894246905)
- Declercq, J. & Oelkers, E. H. 2014. CarbFix Report 4 PHREEQC mineral dissolution kinetics database. CarbFix Project no. 281348. Geoscience Environnement Toulouse, Belin, Toulouse. Available at: https://www.or.is/sites/or.is/files/kinetic_database.pdf
- Dold, B. 2017. Acid rock drainage prediction: A critical review. *Journal of Geochemical Exploration* 172, 120–132.
- Eary, L. E., Runnells, D. D. & Esposito, K. J. 2003. Geochemical controls on ground water composition at the Cripple Creek Mining District, Cripple Creek, Colorado. *Applied Geochemistry* 18, 1–24.

- Gunsinger, M. R., Ptacek, C. J., Blowes, D. W., Jambor, J. L. & Moncur, M. C. 2006.** Mechanisms controlling acid neutralization and metal mobility within a Ni-rich tailings impoundment. *Applied Geochemistry* 21, 1301–1321.
- Jambor, J. L., Dutrizac, J. E., Groat, L. A. & Raudsepp, M. 2002.** Static tests of neutralization potentials of silicate and aluminosilicate minerals. *Environmental Geology* 43, 1–17.
- Karlsson, T., Kauppila, P. M., Lehtonen, M., Tiljander, M., Forsman, P. & Lahtinen, T. 2018.** Laboratorionalyysit kaivannaisjätteiden käyttäytymisen ennustamisessa. Geological Survey of Finland, Open File Work Report 13/2018. (in Finnish)
- Lefebvre, R., Hockley, D., Smolensky, J. & Lamontagne, A. 2001.** Multiphase transfer processes in waste rock piles producing acid mine drainage 2: Applications of numerical simulation. *Journal of Contaminant Hydrology* 52, 165–186.
- Lichtner, P. C., Hammond, G. E., Lu, C., Karra, S., Bisht, G., Andre, B., Mills, R. T. & Kumar, J. 2015.** PFLOTRAN User manual: A Massively Parallel Reactive Flow and Transport Model for Describing Surface and Sub-surface Processes. Los Alamos National Laboratory, United States. LA-UR-15-20403. 195 p.
- Maest, A. & Nordstrom, K. 2017.** A geochemical examination of humidity cell tests. *Applied Geochemistry* 81, 109–131.
- Maest, A. S., Kuipers, J. R., Travers, C. L. & Atkins, D. A. 2005.** Predicting Water Quality at Hardrock Mines: Methods and Models, Uncertainties, and State-of-the-Art. Kuipers & Associates and Buka Environmental. 77 p. Available at: http://www.ceaa-acee.gc.ca/050/documents_staticpost/cearref_3394/hearings/SM09.pdf
- Mayer, K. U., Blowes, D. W. & Frind, E. O. 2003.** Advances in reactive-transport modelling of contaminant release and attenuation from mine-waste deposits. In: Jambor, J. L., Blowes, D. W. & Ritchie, A. I. M. (eds) *Environmental aspects of mine wastes*. Ottawa: Mineralogical Association of Canada, Short Course Series 31, 283–302.
- Mayer, K. U., Frind, E. O. & Blowes, D. W. 2002.** Multicomponent reactive transport modelling in variably saturated porous media using a generalized formulation for kinetically controlled reactions. *Water Resources Research* 38, 1174–1195.
- Moncur, M. C., Jambor, J. L., Ptacek, C. J. & Blowes, D. W. 2009.** Mine drainage from the weathering of sulfide minerals and magnetite. *Applied Geochemistry* 24, 2362–2373.
- Moncur, M. C., Ptacek, C. J., Blowes, D. W. & Jambor, J. L. 2005.** Release, transport and attenuation of metals from an old tailings impoundment. *Applied Geochemistry* 20, 639–659.
- Morin, K. A. & Hutt, N. M. 1994.** An empirical technique for predicting the chemistry of water seeping from mine-rock piles. In: *Proceedings, American Society of Mining and Reclamation, 1993*, 12–19. Available at: <http://www.asmr.us/Portals/0/Documents/Conference-Proceedings/1994-Volume-1/0012-Morin.pdf>. (Accessed 4th July 2017)
- Muniruzzaman, M. & Rolle, M. 2016.** Modelling multicomponent ionic transport in groundwater with IPhreeqc coupling: Electrostatic interactions and geochemical reactions in homogeneous and heterogeneous domains. *Advances in Water Resources* 98, 1–15.
- Muniruzzaman, M., Haberer, C. M., Grathwohl, P. & Rolle, M. 2014.** Multicomponent ionic dispersion during transport of electrolytes in heterogeneous porous media: Experiments and model-based interpretation. *Geochimica et Cosmochimica Acta* 141, 656–669.
- Muniruzzaman, M., Karlsson, T. & Kauppila, P. M. 2018a.** Prediction of the Drainage Water Quality from Mine Wastes with Reactive Transport Modelling. Geological Survey of Finland, Open File Work Report 12/2018. Available at: http://tupa.gtk.fi/raportti/arkisto/12_2018.pdf
- Muniruzzaman, M., Kauppila, P. M. & Karlsson, T. 2018b.** Water quality prediction of mining waste facilities based on predictive models. Geological Survey of Finland, Open File Research Report 16/2018. 65 p. Available at: http://tupa.gtk.fi/raportti/arkisto/16_2018.pdf
- Nagy, K. L. 1995.** Dissolution and precipitation kinetics of sheet silicates, in *Chemical Weathering Rates of Silicate Minerals*, *Reviews in Mineralogy* 31, 173–233.
- Nordstrom, D. K. & Campbell, K. M. 2014.** Modelling Low-Temperature Geochemical Processes. In: Holland, H. D. & Turekian, K. K. (eds) *Treatise on Geochemistry*, Second Edition, Vol. 7, 27–68.
- Nordstrom, D. K. & Nicholson, A. (eds) 2017.** *Geochemical Modeling for Mine Site Characterization and Remediation*. Colorado: Society for Mining, Metallurgy & Exploration. 181 p.
- Nordstrom, D. K., Blowes, D. W. & Ptacek, C. J. 2015.** Hydrogeochemistry and microbiology of mine drainage: An update. *Applied Geochemistry* 57, 3–16. Available at: <https://doi.org/10.1016/j.apgeochem.2015.02.008>
- Palandri, J. L. & Kharaka, Y. K. 2004.** A compilation of rate parameters of water-mineral interaction kinetics for application to geochemical modeling: USGS Open File Report 2004-1068, Menlo Park, California, National Energy Technology Laboratory – United States Department of Energy.
- Pantelis, G. 1993.** FIDHELM: Description of Model and Users Guide. Australian Nuclear Science and Technology Organization Report, ANSTO/M123.
- Parbhakar-Fox, A. & Lottermoser, B. G. 2015.** A critical review of acid rock drainage prediction methods and practices. *Minerals Engineering* 82, 197–124.
- Parkhurst, D. L. & Appelo, C. A. J. 2013.** Description of input and examples for PHREEQC version 3 – a computer program for speciation, batch-reaction, one dimensional transport, and inverse geochemical calculations. U.S. Geological Survey, *Techniques and Methods* 6-A43, p. 497. Available at: <http://pubs.usgs.gov/tm/06/a43/>. (Accessed 5th June 2017)
- Parkhurst, D. L., Kipp, K. L., Engesgaard, P. & Charlton, S. R. 2005.** PHAST – A program for simulating ground-water flow, solute transport, and multicomponent geochemical reactions. U.S. Geological Survey, *Techniques and Methods* 6-A35. 235 p.
- Parkhurst, D. L., Thorstenson, D. C. & Plummer, L. N. 1985.** PHREEQE – A computer program for geochemical calculations. U.S. Geological Survey, *Water Resources Investigations Report* 80-96. 195 p.
- Pedretti, D., Mayer, K. U. & Beckie, R. D. 2017.** Stochastic multicomponent reactive transport analysis of low quality drainage release from waste rock piles: Controls of the spatial distribution of acid generating and neutralizing minerals. *Journal of Contaminant Hydrology* 201, 30–38. Available at: <https://doi.org/10.1016/j.jconhyd.2017.04.004>
- Pohjois-Suomen ympäristölupavirasto 2007.** Pyhäsalmen kaivoksen ympäristö- ja vesitalouslupa, Pyhäjärvi. Lupapäätös 85/07/02, Dnro Psy-2004-y-199, 70 p. (in Finnish)
- Plumlee, G. S. 1997.** The Environmental Geology of Mineral Deposits. In: Plumlee, G. S. & Logsdon, M. J. (eds) *The Environmental Geochemistry of Mineral Deposits*:

- Part A: Processes, Techniques, and Health Issues. Reviews in Economic Geology, Vol. 6A, 71–116
- Price, W. A. 2009.** Prediction Manual for Drainage Chemistry from Sulfidic Geologic Materials. Natural Resources Canada. MEND Report 1.20.1. 579 p.
- Prommer, H., Barry, D. A. & Zheng, C. 2003.** MODFLOW/MT3DMS-based reactive multicomponent transport modelling. Ground Water 41, 247–257.
- Pruess, K. 1991.** TOUGH2: A general numerical simulator for multiphase fluid and heat flow. Berkeley: Lawrence Berkeley National Laboratory, Report LBL 29400.
- Ramstedt, M., Carlsson, E. & Lövgren, L. 2003.** Aqueous geochemistry in the Udden pit lake, Northern Sweden. Applied Geochemistry 18, 97–108.
- Rimstidt, J. D. & Barnes, H. L. 1980.** The kinetics of silica-water reactions. Geochimica et Cosmochimica Acta 44(11), 1683–1699. Available at: [https://doi.org/10.1016/0016-7037\(80\)90220-3](https://doi.org/10.1016/0016-7037(80)90220-3)
- Reimann, C., Caritat, P. D., Halleraker, J. H., Volden, T., Åyräs, M., Niskavaara, H., Chekushin, V. A. & Pavlov, V. A. 1997.** Rainwater composition in eight arctic catchments in northern Europe (Finland, Norway and Russia). Atmospheric Environment 31(2), 159–170. Available at: [https://doi.org/10.1016/1352-2310\(96\)00197-5](https://doi.org/10.1016/1352-2310(96)00197-5)
- Rolle, M., Sprocati, R., Masi, M., Jin, B. & Muniruzzaman, M. 2018.** Nernst-Planck based description of transport, Coulombic interactions and geochemical reactions in porous media: Modeling approach and benchmark experiments. Water Resources Research 54. Available at: <https://doi.org/10.1002/2017WR022344>
- Saaltink, M. W., Domenech, C., Ayora, C. & Carrera, J. 2002.** Modelling the oxidation of sulphides in an unsaturated soil. In: Younger, P. L. & Robins, N. S. (eds) Mine water Hydrogeology and Geochemistry. Geological Society of London, Special Publication 198, 187–205.
- Šimuněk, J., Jacques, D., Šejna, M. & Van Genuchten, M. T. 2012.** The HP2 program for HYDRUS (2D/3D): A coupled code for simulating two-dimensional variably-saturated water flow, heat transport, and biogeochemistry in porous media. In: Version 1.0. Prague: PC Progress. 76 p.
- Steeffel, C. I. & Lasaga, A. C. 1994.** A coupled model for transport of multiple chemical species and kinetic precipitation dissolution reactions with application to reactive flow in single-phase hydrothermal systems. American Journal of Science 294, 529–592.
- Steeffel, C. I., Appelo, C. A. J., Arora, B., Jacques, D., Kalbacher, T., Kolditz, O. & Yeh, G. T. 2015.** Reactive transport codes for subsurface environmental simulation. Computational Geosciences 19, 445–78. Available at: doi: [10.1007/s10596-014-9443-x](https://doi.org/10.1007/s10596-014-9443-x)
- Steeffel, C. I., DePaolo, D. J. & Lichtner, P. C. 2005.** Reactive transport modeling: An essential tool and a new research approach for the Earth sciences. Earth and Planetary Science Letters 240(3–4), 539–558. Available at: <https://doi.org/10.1016/j.epsl.2005.09.017>
- Tempel, R. G., Shevenell, L. A., Lechler, P. & Price, J. 2000.** Geochemical modelling approach to predicting arsenic concentrations in a mine pit lake. Applied Geochemistry 15, 475–492.
- Tornivaara, A., Räsänen, M. L., Kovalainen, H. & Kauppi, S. 2018.** Suljettujen ja hylättyjen kaivosten kaivannaisjätealueiden jatkokartoitus (KAJAK II). Suomen ympäristökeskuksen raportteja 12/2018, Helsinki 2018, 157 p. (in Finnish)
- Tripathy, D. P. 2014.** Prevention and Treatment of Acid Mine Drainage: An Overview. In: Sengupta, D. (ed.) Recent Trends in Modelling of Environmental Contaminants. India: Springer, 95–117. Available at: doi: [10.1007/978-81-322-1783-1_4](https://doi.org/10.1007/978-81-322-1783-1_4)
- Tremblay, G. A. & Hogan, C. M. 2000.** MEND Manual, Volume 3 – Prediction. Natural Resources Canada. MEND Report 5.4.2c. 105 p.
- Williamson, M. A. & Rimstidt, J. D. 1994.** The kinetics and electrochemical rate-determining step of aqueous pyrite oxidation. Geochimica et Cosmochimica Acta 58, 5443–5454.
- Wolery, T. J. 1992.** EQ3/6 – A Software Package for Geochemical Modelling of Aqueous Systems. Lawrence Livermore National Laboratory, CA.
- Wunderly, M. D., Blowes, D. W., Frind, E. O. & Ptacek, C. J. 1996.** A multicomponent reactive transport model incorporating kinetically controlled pyrite oxidation. Water Resources Research 32, 3173–3187.

POTENTIAL FOR BENEFICIAL REUSE OF WASTE ROCKS FROM KEVITSA AND HITURA MINES: INDICATIVE DATA FROM LYSIMETER TESTS

by

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Mining generates large amounts of mineral waste materials, the utilisation of which should be increased to meet society's need for raw materials. Detailed knowledge of the properties of extractive wastes is the starting point for their extended utilisation. The long-term behaviour of extractive waste materials can be predicted with kinetic tests. In this study, the performance of two-year lysimeter tests was investigated, as well as the performance of commonly applied laboratory methods in lysimeter drainage quality prediction. The study particularly focused on the assessment of element mobility in waste rocks from the Hitura and Kevitsa mines. The lysimeter test results suggested that disturbing the Hitura mica schist pile, e.g. by shaping, may result in the enhanced mobilisation of harmful substances. On the other hand, disturbing the serpentinite waste rock pile at this site by earthworks does not appear to lead to significant mobilisation of harmful substances. Therefore, the serpentinite material has the potential to be used in earthworks at the Hitura mine site, e.g. in shaping the mica schist pile. The Kevitsa waste rocks containing low amounts of sulphur ($S < 0.3\%$) might also have utilisation potential in earth constructions. According to the lysimeter tests, the particle-size distribution of the aggregates correlates with increased releases of harmful substances. Therefore, it is recommended that only the coarse fraction of the waste rocks containing harmful substances is used. The lysimeter tests indicated that of the methods used to predict chemical element mobility, the two-stage batch test best predicted the elevated metal concentrations in the lysimeter drainages. The lysimeter tests further demonstrated that the water retention capacity of waste rocks may increase as weathering advances, which should be further investigated.

Keywords: Waste rock characterisation, utilisation, drainage quality, ARD, lysimeter test, Kevitsa, Hitura, Finland

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1 INTRODUCTION AND OBJECTIVES

Mining generates large amounts of extractive waste materials, which are currently disposed of at the mine sites and have no value, or even a negative value if the material has harmful effects on the environment. The shortage of suitable natural materials for earth construction at mine sites therefore poses challenges in finding new solutions to improve waste utilisation. However, detailed knowledge of the properties of wastes is the starting point for their extended utilisation (Mehta et al. 2018).

A wide range of laboratory and field methods exist to characterise extractive wastes, of which tests to predict long-term behaviour are essential (cf. e.g. Lawrence & Day 1997, Maest et al. 2005, Price 2009). These tests can be divided into two groups: static and kinetic tests (Price 2009, Kauppila et al. 2018, Muniruzzaman et al. 2018b). Static tests refer to short-term, often standardised laboratory tests, including the acid–base accounting (ABA) test (Price 2009, see also Muniruzzaman et al. 2018a). Kinetic tests are more complex, longer-term tests, which are not standardised (excluding the humidity cell test) and are usually designed case-by-case (Lapakko 2002).

The challenge with laboratory tests is that the test conditions in the laboratory do not normally correspond to the natural conditions at the field site (e.g. Kempton 2012, Kirchner & Mattson 2015, Lapakko & Olson 2015, Pearce et al. 2015). Therefore, various field test methods have been developed to investigate the long-term behaviour of extractive wastes. For example, lysimeter tests are designed

to represent the long-term behaviour of extractive waste more accurately than laboratory tests, as the lysimeters are installed in natural conditions and monitored for longer time periods. Lysimeters can also be used to illustrate the differences between laboratory tests and large-scale field tests (Hansen et al. 2000, Lapakko 2002, Karlsson 2017).

This study concentrated on the utilisation potential and prediction of the long-term behaviour of mine waste rocks. The research materials included low-sulphur ($S < 0.3\%$) waste rock from the Kevitsa Ni–Cu mine and serpentinite and mica schist waste rocks from the Hitura Ni mine. In addition to a general assessment of the waste rock usability, the impact of particle size on element release and the usability of serpentinite as a cover material for a waste rock pile were evaluated.

The utilisation potential was assessed using longer term lysimeter tests and environmental characterisation of the waste rock materials with the ABA test (SFS-EN 15875), selective extraction methods, including aqua regia (ISO 11466), ammonium oxalate and ammonium acetate, and a two-stage batch leaching test (SFS-EN 12457-3). The performance of these laboratory methods in predicting the quality of lysimeter drainage was also assessed.

This article provides a summary of the main results of the study. A more detailed description of the results is presented in a GTK Open File Work Report by Karlsson et al. (2018b) in Finnish. Preliminary results from the Hitura lysimeter tests have also been presented by Karlsson et al. (2017).

2 RESEARCH MATERIALS AND METHODS

In this study, field lysimeters were installed at the GTK premises in Kuopio to investigate the long-term behaviour of waste rocks from the Hitura and

Kevitsa mines. The locations of the mine sites and the lysimeter test site are presented in Figure 1.

2.1 Study sites and waste rock samples

The Hitura Ni mine is located in the municipality of Nivala in the Northern Ostrobothnia region (Fig. 1). The mine was active during 1970–2013, and preparations for the closure commenced at the end of 2015. The ultramafic sulphide ore deposit consists

of serpentine and to a lesser extent of amphibole and mica schists (Papunen 1970). The waste rocks generated by the mining activities during the open pit phase, from 1970–1993, have been disposed of in two separate waste rock piles at the mine site.

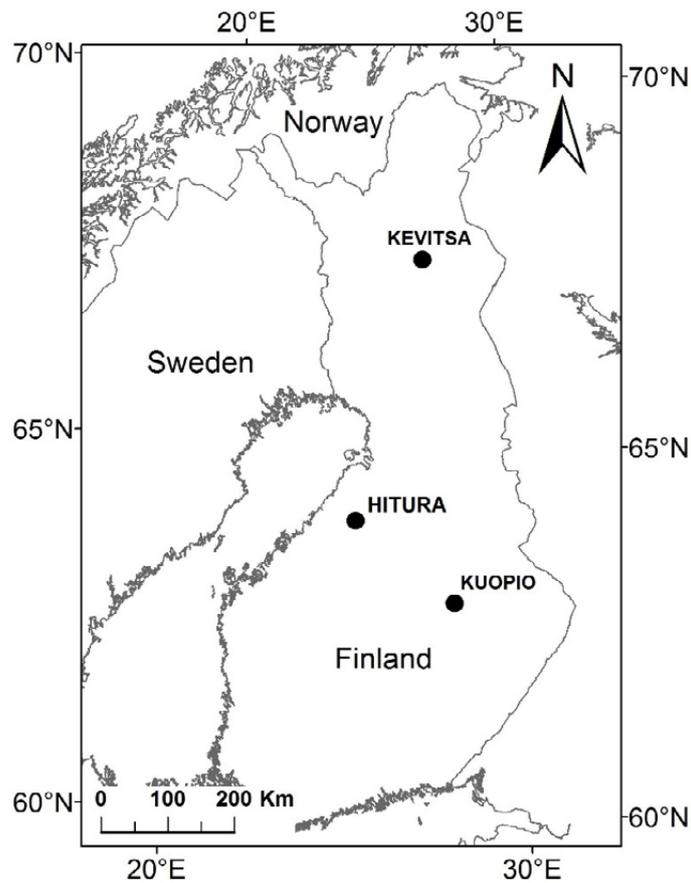


Fig. 1. Locations of the Kevitsa and Hitura mine sites and the installation site of the lysimeters in Kuopio. Basemap © National Land Survey of Finland and HALTIK 2013.

One of them mainly consists of serpentinite and the other of mica schist and miscellaneous material (Ahma Ympäristö Oy 2013).

The Kevitsa Ni-Cu mine, located in the municipality of Sodankylä in Lapland (Fig. 1), started operations in 2012. The ore deposit mainly consists of fine-grained phyllites and black schists surrounded by gabbros and ultramafic cumulates, mostly pyroxenites (Manninen et al. 1996, Lehtonen et al. 1998, Mutanen & Huhma 2001). The waste rocks are primarily composed of olivine pyroxenites, altered olivine pyroxenites, olivine websterite, gabbro and dunite (Pöyry 2011). The waste rocks are divided into three classes based on their sulphur content: $S < 0.3\%$, $S = 0.3\text{--}0.8\%$ and $S > 0.8\%$. If the S content exceeds 0.8%, the rock material is considered as potentially acid producing. With an S content of 0.3–0.8%, the risk of acid generation is lower. With an S content of less than 0.3%, acid

generation is unlikely and the dissolution of harmful substances is expected to be low (Pöyry 2011).

Hitura rock samples for the lysimeter tests were excavated from the surfaces of the serpentinite and mica schist piles with a front loader. The rock materials were clearly weathered: the serpentinite material had been crushed into small pieces and the mica schist material was rusty orange. The particle-size distribution of the Hitura samples was wide, with the largest stones having a diameter of about 10–20 cm. Stones larger than 20 cm were removed from the test material. The Kevitsa mine delivered for the tests two samples of waste rocks with a low sulphur content ($S < 0.3\%$) having two different particle sizes. The first consisted of sorted aggregate of around 2 cm in diameter and the other was composed of assorted aggregate, with the largest particles being around 5 cm in diameter.

2.2 Lysimeter test set-up

Six 1-m³ lysimeters (LY1–LY6) were installed in the grounds of the GTK office in Kuopio (Figs 1 and 2). Installation of the lysimeter tests in natural conditions followed the guidelines described in the MEND report (Price 2009). The test experiments were started on 11 November 2015 by filling lysimeter LY5 with well-sorted, approximately 2 cm diameter waste rock material from Kevitsa with few fine particles, and LY6 with waste rock material of up to 5 cm in diameter and having a wide particle-size distribution. Lysimeter LY4 was left empty for background monitoring of local precipitation and potential contamination from the lysimeter materials. For the Hitura waste rocks, the test started on 3 December 2015, when LY1 was filled with serpentinite, and LY2 and LY3 with mica schist material. One of the mica schist lysimeters (LY2) was later used to investigate the effect of a serpentinite cover on the mobility of harmful substances from the mica gneiss. The serpentinite cover of around 10 cm was deposited on top of LY2 in April 2016.

Rainwater flowing through the lysimeters was collected in plastic canisters, from which drainage was regularly sampled for water analysis. The water samples were composite samples of the drainage collected between the sampling events. Water sampling for laboratory analyses was conducted 15 times in total during the monitoring period of about two years. The first water samples were taken on 16 November 2015 and the last on 14 November 2017. During and between the laboratory sampling, various measurements, including pH and electrical conductivity (EC), were taken from drainage waters at the site using a portable multi-parameter YSI sonde (YSI Professional Plus). The alkalinity of the drainage was determined with a Hach digital titrator using 0.16 N or 1.60 N H₂SO₄ to an end point of pH 4.5. After each sampling and measurement session, the canisters were emptied and the amount of water was recorded.



Fig. 2. Lysimeter test site at GTK Kuopio in summer 2016. Lysimeters: 1) serpentinite (LY1), 2) mica schist with serpentinite cover (LY2), 3) mica schist (LY3), 4) empty lysimeter (LY4), 5) Kevitsa well-sorted aggregate (LY5), and 6) Kevitsa aggregate with a wide particle-size distribution (LY6). (Photo by Teemu Karlsson, GTK)

2.3 Laboratory analyses

The waste rock and lysimeter drainage samples were analysed in an accredited laboratory by Labtium Oy. Drainage water analyses included the determination of dissolved concentrations of elements by ICP-OES and ICP-MS and the determination of anions using ion chromatography. Based on the concentrations, the total masses of dissolved substances were calculated. For sampling occasions without laboratory analysis, the mean of the concentrations from the previous and the following laboratory analyses was used in the calculations.

For geochemical analyses, composite samples of 15–20 kg of waste rocks were collected. The rock samples were dried at below 40 °C, crushed with a Mn jaw crusher and ground in a hardened steel bowl. The total element concentrations were determined using the XRF method (Criss & Birks 1968). Element mobility was investigated using three different extraction methods. The extractions were, from the strongest to the weakest, 1) aqua regia extraction according to the standard ISO 11466, which leaches sulphides and partly also some silicates, such as biotite, chlorite and clay minerals (Doležal et al. 1968, Heikkinen & Räsänen 2009), 2) 0.2 M ammonium oxalate extraction, which leaches fractions attached to Fe precipitates (Dold 2003, Heikkinen & Räsänen 2008), and 3) 1 M ammonium acetate extraction at pH 4.5, which leaches the exchangeable fraction, including chemically bound phases and surface complexes (Dold 2003, Heikkinen & Räsänen 2008). Aqua regia extraction (Doležal et al. 1968, Niskavaara 1995) is the most commonly used partial extraction method in Finland, and it is also the preferred method to evaluate whether mining waste is inert (Government Decree 2007, 2013) and to assess soil contamination in Finland

(Government Decree 2007, Reinikainen 2007). In addition, element mobility was assessed using a two-stage batch test (i.e. shake flask test) according to the standard SFS-EN 12457-3. The sample solutions from the extractions and the batch test were measured by ICP-OES and ICP-MS.

The ability of rock material to produce acid rock drainage (ARD) was determined using the ABA test according to the standard SFS-EN 15875. In the ABA test, the neutralisation potential (NP) is determined by titration. The acid production potential (AP) is calculated from the total sulphur concentration, which was measured with the Leco furnace method according to the standard ISO 15178. Based on NP and AP, the neutralisation potential ratio (NPR) was calculated ($NPR = NP/AP$). It is commonly assumed that extractive waste is potentially acid producing if $NPR < 1$, in the uncertainty zone if NPR is 1–3 and non-acid producing if $NPR > 3$ (Sobek et al. 1978, White et al. 1999, Price 2009).

The mineralogical investigations of the rock samples were conducted in the GTK mineralogical laboratory using a field emission scanning electron microscope (FE-SEM; JEOL JSM 7100F Schottky) with an automated energy dispersive spectrometer (EDS; Oxford Instruments EDS X-Max 80 mm²). The identification of minerals was based on a comparison of the element composition according to the EDS spectra with the mineralogical database of GTK.

The particle-size distributions of the rock materials were determined in the mineral processing laboratory at GTK Mintec by a combination of wet and dry sieving. The densities of rock material dried at room air temperature were determined by weighing 5 litres of sample.

3 RESULTS AND DISCUSSION

3.1 Utilisation potential of the Kevitsa waste rocks: influence of particle size

The aim of the Kevitsa lysimeter tests was to evaluate the utilisation potential of low-sulphur (<0.3%) waste rocks in earth construction and, in particular, how the particle size affects this use and the release of potentially harmful substances.

The Kevitsa waste rocks were mainly composed of pyroxenes, olivine/serpentine and amphiboles. Carbonates (calcite, dolomite, magnesite) were

present as accessory minerals (1.3% in the LY5 sample and 0.5% in the LY6 sample). The detected sulphides included pyrrhotite (0.09% in the LY5 sample and 0.16% in the LY 6 sample), pentlandite (0.02% in the LY5 sample and 0.04% in the LY6 sample), chalcopyrite (0.01% in both samples) and pyrite (0.03% in the LY5 sample).

The total S contents of the Kevitsa rock material samples were 0.29% in LY5 and 0.21% in LY6. Based on the ABA test, the rock materials were not potentially acid generating, the NPR of the LY5 material being 7.4 and the NPR of the LY6 material being 8.6. The primary potentially harmful trace metals included Ni, Cu, Cr and Co (Table 1). Their aqua regia

leachable concentrations exceeded the so-called “PIMA” threshold value (LY5 Co; LY6 Co, Cu) or the higher guideline value (LY5 Cr, Cu, Ni; LY6 Cr, Ni) for contaminated soils (Government Decree 2007). Based on the elevated concentrations of Co, Cu, Cr and Ni, the waste rocks were classified as non-inert mining waste (cf. Government Decree 2013).

Table 1. Chemical analysis results for the Kevitsa lysimeter materials. Aqua regia extractable values are compared with the “PIMA” reference values (Government Decree 2007 and 2013).

	Sb	As	Cd	Co	Cr	Cu	Pb	Ni	Zn	V
	mg/kg									
XRF										
LY5 waste rock material	<100	<20			2570	370	<20	970	50	130
LY6 waste rock material	<100	<20			2680	150	<20	740	50	130
Aqua regia extr.										
PIMA threshold value	2	5	1	20	100	100	60	50	200	100
PIMA lower guideline value	10	50	10	100	200	150	200	100	250	150
PIMA upper guideline value	50	100	20	250	300	200	750	150	400	250
LY5 waste rock material	<0.2	0.7	0.1	69	476	375	1.7	791	16	36
LY6 waste rock material	<0.2	0.4	0	55	511	142	1.4	585	14	39
Amm.oxalate extr.										
LY5 waste rock material	<0.05	0.1	<0.01	5.0	84	9.3	0.1	69	5.0	8.0
LY6 waste rock material	<0.05	0.1	<0.01	5.1	87	4.5	<0.05	43	5.0	8.7
Amm.acetate extr.										
LY5 waste rock material	<2	0.3	0.01	1.8	12	8.5	0.5	26	1.0	0.9
LY6 waste rock material	<2	0.3	0.01	1.9	9.7	4.9	0.4	15	3.0	0.7
2-stage batch test (L/S 10)										
LY5 waste rock material	<0.05	<0.05	<0.04	<0.05	<0.05	<0.05	<0.05	0.08	<0.6	<0.05
LY6 waste rock material	<0.05	<0.05	<0.04	<0.05	<0.05	<0.05	<0.05	<0.05	<0.6	<0.05

Based on the selective extractions (Table 1), the potentially harmful elements, especially Ni and Cu, were mainly bound to the aqua regia extractable fraction, i.e. sulphides, in the Kevitsa waste rocks, most likely to pyrrhotite (Ni), pentlandite (Ni) and chalcopyrite (Cu). The release of these harmful elements is thus related to sulphide oxidation. Cr, V and Zn were mainly bound to the silicate fraction, thus being in a less mobile form.

Based on the Kevitsa lysimeter monitoring results, the harmful substances did not appear to be in a very mobile form. During the observation period, the metal concentrations in the drainage were relatively low, e.g. Ni 9–89 µg/l and Cu 1–137 µg/l, compared with the total concentrations in the rock material. The Ni concentrations, which were

the most significant of the potentially harmful elements during the observation period, are presented in Figure 3. In general, after the initial first flush with elevated substance concentrations, the concentration levels decreased. The drainage was alkaline and the pH varied between 7.6 and 9.2 (Fig. 4). The SO₄ concentrations continued to increase during the summer period, suggesting that sulphide oxidation accelerated during summer (Fig. 4). Despite this, the pH remained high and Ni and Cu concentrations remained low. The main mineral responsible for the generation of sulphate in the drainage is apparently the easily decomposable pyrrhotite, which presumably also contains minor amounts of Ni. However, the alkalinity and high pH of the drainage most likely limits the mobility

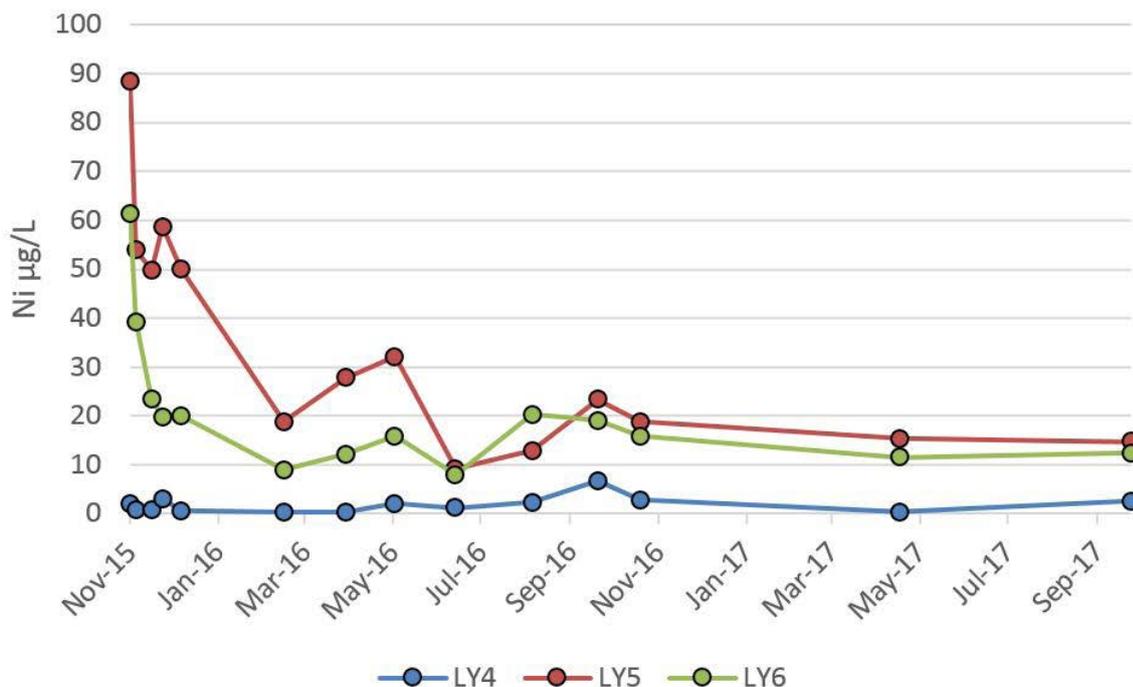


Fig. 3. Soluble Ni concentrations in the drainage of the Kevitsa lysimeters during the monitoring period. (LY4 = empty background lysimeter, LY5 = Kevitsa well-sorted aggregate, LY6 = Kevitsa aggregate with a wide particle-size distribution).

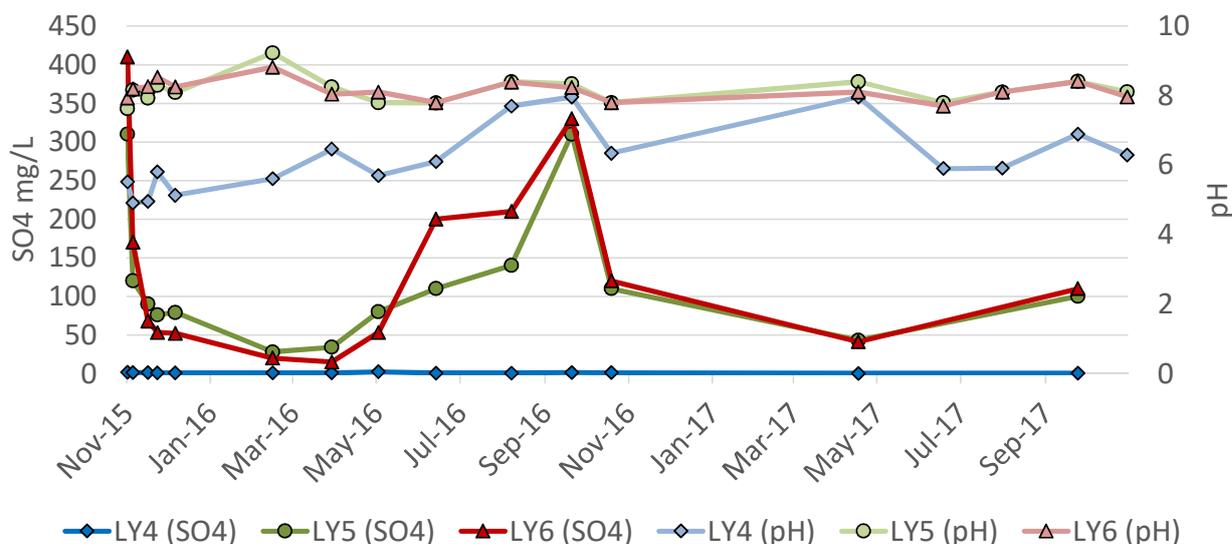


Fig. 4. The SO₄ concentration and pH in the drainage of the Kevitsa lysimeters during the monitoring period. (LY4 = empty background lysimeter, LY5 = Kevitsa well-sorted aggregate, LY6 = Kevitsa aggregate with a wide particle-size distribution).

of Ni. According to Stumm and Morgan (1996), the mobility of Ni typically increases with a decrease in the pH.

Aside from pyrrhotite, the primary hosts for Ni and Cu in the Kevitsa waste rocks are pentlandite and chalcopyrite, respectively. The reactivity of sulphide minerals varies, being from highest to lowest: pyrrhotite > galena > sphalerite > pentlandite >

arsenopyrite > pyrite > chalcopyrite (Jambor 1994, Moncur et al. 2009). Since the oxidation of pentlandite is slower than that of pyrrhotite, the two-year observation period might have been too short to observe the effects of pentlandite weathering. The low concentrations of Ni might have also been due to Ni sorption with iron oxide secondary minerals in an alkaline pH (e.g. Alpers et al. 1994, Heikkinen &

Räisänen 2008). Because the amounts of chalcopyrite were low and it oxidises even more slowly than pentlandite, it is expected that the release of Cu from the waste rocks will be slower and its concentrations will remain lower than those of Ni. Lysimeter monitoring will be continued during the next few years to evaluate the evolution of drainage chemistry in the longer term.

The particle-size distribution of the rock material affected the release of harmful substances (Table 2). The relative total masses of Co and Ni that dissolved from lysimeter LY5, which contained well-sorted material with low amounts of fine particles, were lower than those of LY6, which contained assorted rock material with a higher content of fine particles. The amount of dissolved Cr was low. The amount of dissolved Cu in both Kevitsa lysimeters was lower than that in the background lysimeter. Therefore, most of the Cu originated from the lysimeter structures was bound to the waste rock material in the Kevitsa lysimeters. The drainage collection canisters were occasionally flooded, thus preventing the exact calculation of the total dissolved metal masses. The values presented in Table 2 have been calculated based on the measured water volumes and concen-

trations, and the real masses of the dissolved metals are therefore slightly greater than those in Table 2.

The content of fine particles has a direct effect on the reactive surface area. The greater the surface area a material has, the faster the chemical reactions will be (Stumm & Morgan 1996, Banwart et al. 2002). According to Kempton (2012), the rate of sulphide oxidation also increases with a decrease in the aggregate particle size. Rocks with a diameter of >200 mm have been estimated to have little effect on the quality of drainage, even over a time span of several hundreds of years (Davis & Ritchie 1986). In addition, according to more recent studies, only rock particles with a diameter of less than 20–30 mm are completely rinsed with the water flowing through a waste rock pile, which reduces the weathering rate of larger rocks (Hollings et al. 2001, Stockwell et al. 2003, Kempton 2012). Based on this, the particle size should be as large as possible to decrease mineral liberation and element dissolution. The content of fine particles should also be minimised if rock material containing harmful substances is crushed for utilisation, as brittle sulphides tend to report to the fine fraction in crushing.

3.2 Potential of serpentinite waste rock to be used as a cover material for a mica gneiss waste rock pile: Case study from the Hitura mine site

In the case of the Hitura site, the lysimeter tests were applied to evaluate the utilisation potential of the serpentinite and mica schist, with a special focus on whether the serpentinite could be suitable as a cover material for the mica schist pile.

The Hitura serpentinite waste rock was mainly composed of serpentine, olivine and talc. Carbonates (calcite, magnesite) were present as accessory minerals (1.2%). The content of sulphides was low, and only traces of pyrrhotite (0.01%) and pentlandite

Table 2. The total masses (g) of dissolved Co, Cr, Cu and Ni from the background lysimeter LY4 and the Kevitsa lysimeters LY5 and LY6, compared with the total masses bound to the rock materials. To calculate the masses dissolved from the rock materials, the masses dissolved from the background lysimeter have been deducted from the total dissolved masses from LY5 and LY6. (LY4 = empty background lysimeter, LY5 = Kevitsa well-sorted aggregate, LY6 = Kevitsa aggregate with a wide particle-size distribution).

Lysimeter			Co	Cr	Cu	Ni
LY4	Background	<i>g</i>	0.00006	0.00006	0.0077	0.00088
Rainwater						
LY5	Total amount in rock material	<i>g</i>	104	3855	555	1455
	Total dissolved	<i>g</i>	0.00031	0.00009	0.0046	0.0091
	Total dissolved - background	<i>g</i>	0.00025	0.00003	<0	0.0082
	Dissolved	<i>%</i>	0.000002	8E-07	<0	0.0006
LY6	Total amount in rock material	<i>g</i>	64	3136	176	866
	Total dissolved	<i>g</i>	0.00058	0.00019	0.004	0.0084
	Total dissolved - background	<i>g</i>	0.00052	0.00013	<0	0.0075
	Dissolved	<i>%</i>	0.0008	0.000004	<0	0.0009

(0.01%) were observed. The total S concentration of the serpentine was 0.14%, and the material was classified as potentially non-acid generating by the ABA test, with NPR being 29. The primary potentially harmful trace metals included Ni, Cr, Cu and Co (Table 3). Their aqua regia extractable concentrations exceeded the lower guideline value (Cr, Cu, Co) and the higher guideline value (Ni) for contaminated soils (Government Decree 2007). Based on the elevated contents of Ni, Cr, Cu and Co, the serpentinite waste rock was classified as non-inert mining waste (cf. Government Decree 2013).

The Hitura mica schist waste rock pile was mainly composed of quartz, plagioclase, biotite and muscovite. The content of carbonates (calcite) was low, being below 0.1%. The main sulphides included pyrite (0.7%), pyrrhotite (0.4%), pentlandite (0.2%) and chalcopyrite (0.1%). Traces of secondary minerals (gibbsite, goethite and K-jarosite) were also detected. The total concentration of S was 2.3%, and the material was classified as potentially acid generating by the ABA test, with NPR being 0.2.

The primary potentially harmful substances included Ni, Cu, Cr and Co (Table 3). Their aqua regia extractable concentrations exceeded the threshold value (Co), the lower guideline value (Cr) and higher guideline value (Cu, Ni) for contaminated soils (Government Decree 2007). Based on the acid production potential and the elevated contents of Co, Cu, Cr and Ni, the mica schist waste rock pile material was classified as non-inert mining waste (cf. Government Decree 2013).

According to the laboratory tests (Table 3), the harmful substances in the serpentinite pile material were in a more reactive form than in the Kevitsa waste rocks. Up to about 45–60% of the Co, Ni and Cu were bound to oxalate and acetate leachable fractions, i.e. to the secondary minerals. However, their concentrations in the high pH (>9) solution of the two-stage batch test were low. Although based on the laboratory extraction tests the harmful substances were relatively weakly bound, the metal concentrations in the drainage of the serpentinite lysimeter LY1 were low (cf. Ni in Fig. 5). The drain-

Table 3. Chemical analysis results for the Hitura waste rock materials. Aqua regia extractable values are compared with the “PIMA” reference values (Government Decree 2007 and 2013). (SRP = serpentinite, MS = mica schist pile material).

	Sb	As	Cd	Co	Cr	Cu	Pb	Ni	Zn	V
	mg/ kg									
XRF										
SRP	<100	<20			2660	170	<20	1010	110	40
MS	<100	30			530	770	<20	2290	170	120
Aqua regia extr.										
PIMA threshold value	2	5	1	20	100	100	60	50	200	100
PIMA lower guideline value	10	50	10	100	200	150	200	100	250	150
PIMA upper guideline value	50	100	20	250	300	200	750	150	400	250
SRP	<0.2	3.0	0.2	109	255	166	1.0	869	49	9.4
MS	0.3	23	0.3	90	257	777	16	2260	135	82
Amm.oxalate extr.										
SRP	0.1	2.6	<0.01	63	21	76	0.6	400	45	1.4
MS	0.3	26	0.05	18	20	102	4.0	391	26	6.0
Amm.acetate extr.										
SRP	<2	0.6	0.07	25	7.0	30	0.3	157	20	0.1
MS	<2	2.0	0.05	8.3	4.9	31	2.6	213	7.0	0.4
2-stage batch test (L/S 10)										
SRP	<0.05	<0.05	<0.04	<0.05	<0.05	<0.05	<0.05	0.07	<0.06	<0.05
MS	<0.05	<0.05	<0.04	1.7	<0.05	0.3	<0.05	40	<0.9	<0.05

age pH was around 8 and the SO_4 concentrations remained steady throughout the monitoring period (Fig. 6).

In the Hitura mica schist waste rock material, a proportion of the harmful substances, such as Co, Ni and Cu, were also in a more reactive form than in the Kevitsa waste rocks. According to the laboratory tests (Table 3), the harmful substances were mainly bound to the aqua regia extractable sulphide fraction, but partly also to the oxalate and acetate leachable fractions, which represent phases in poorly crystalline Fe oxyhydroxides, chemically bound phases and in surface complexes (Dold 2003, Heikkinen & Räsänen 2008). The results suggest that these elements have been released in the waste rock pile from their original sources, i.e. the sulphide minerals, as a result of sulphide oxidation, and have been resorbed or coprecipitated with the secondary precipitates, such as goethite, thus being in a more mobile form than originally. Compared with the other waste rock samples, a relatively high percentage of Ni (1.7%) was also leached in the two-stage batch test, mainly corresponding to the water leachable fraction, i.e. the most mobile or readily bioavailable fraction.

Overall, the laboratory leaching test and ABA test suggested that the Hitura mica schist is prone to produce acidic drainage with elevated trace metals. The results from the lysimeter test were in accordance with this observation. The drainage from the mica schist-containing lysimeters LY2 and LY3 was rich in metals (e.g. Ni, Cu, Co, Zn). In particular, the concentrations of Ni were high, ranging from 24 mg/L up to 130 mg/L during the observation period (Fig. 5). The drainage was also acidic (pH of around 4.5) and the sulphate concentrations were high (Fig. 6). The pH of the mica schist drainage remained steadily around 4.5, which increases the mobility of metals such as Ni and Cu. The balanced pH at 4.5 suggests that gibbsite, which was detected in the lysimeter material in the mineralogical analyses, is probably acting as the principal pH buffer mineral (cf. Dold 2017). Based on the results, the mobilisation of Ni and other trace metals from the mica schist material in the lysimeters is most likely due to their release from the secondary precipitates, but also a result of continuing sulphide oxidation.

The total masses of dissolved Co, Cr, Cu and Ni and their comparison with the total masses of these elements in the Hitura waste rock material are

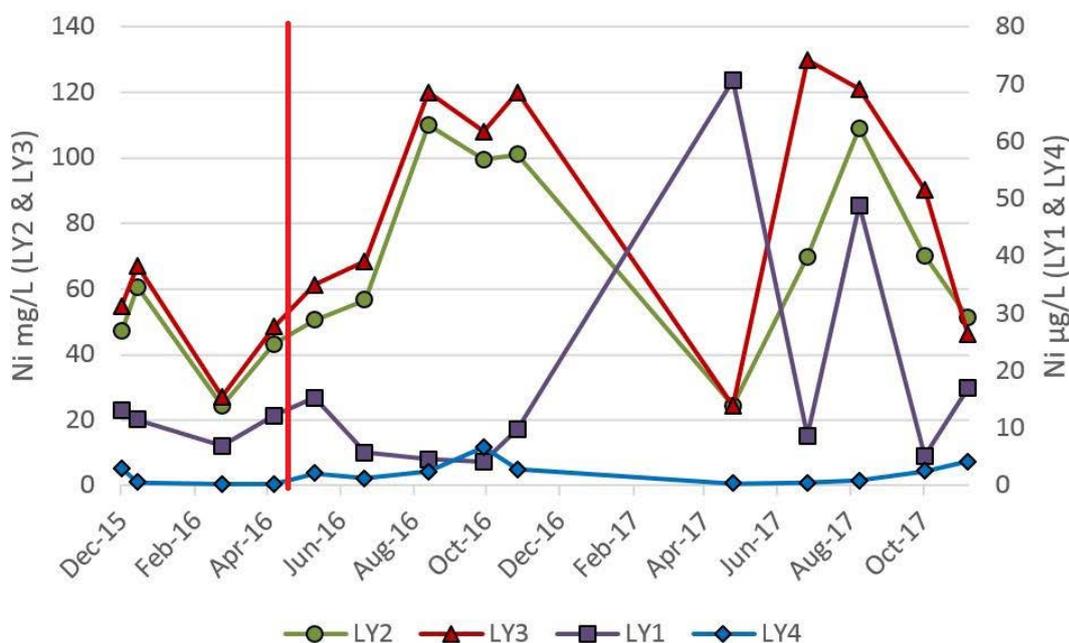


Fig. 5. Ni concentrations in the drainage of the Hitura lysimeters during the monitoring period. Left vertical axis (mg/L) for mica schist material with a serpentinite cover (LY2) and mica schist material (LY3), right vertical axis (µg/L) for serpentinite material (LY1) and the empty background lysimeter (LY4). The red vertical line indicates the time of installing the serpentinite cover layer on top of the mica schist in LY2.

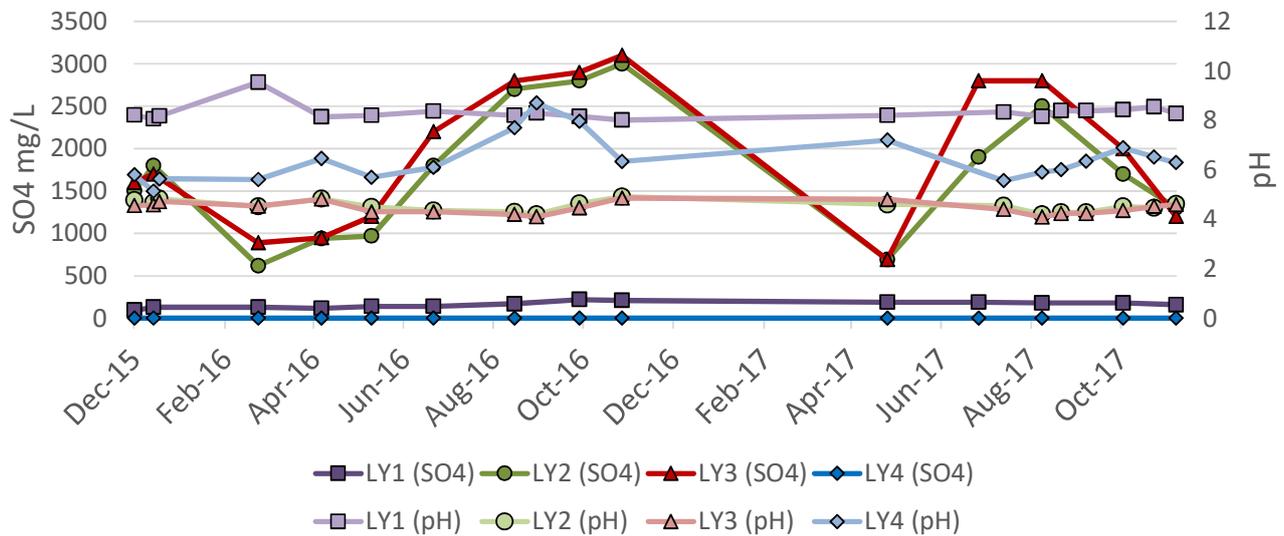


Fig. 6. The SO_4 concentration and pH in the drainage of the Hitura lysimeters during the monitoring period. The red vertical line indicates the time of installing the serpentinite cover layer on top of the mica schist in LY2. (LY1 = serpentinite lysimeter, LY2 = mica schist lysimeter with serpentinite cover, LY3 = mica schist lysimeter, LY4 = empty background lysimeter)

presented in Table 4. As was the case with the Kevitsa lysimeters, the drainage collection canisters of the Hitura lysimeters were also occasionally flooded, preventing the exact calculation of the dissolved metal masses. In general, the amount of drainage from the Hitura lysimeters was lower compared with the Kevitsa and the background lysimeters. The values presented in Table 4 have been calculated based on the measured water volumes and concentrations. Therefore, the real masses of the dissolved metals are slightly larger than those presented in Table 4.

During the two-year monitoring period, the quantity of metals dissolved from the serpentine-containing LY1 was relatively low; around 0.0005% of the total amount of Co and 0.0004% of the total amount of Ni were dissolved. In practice, no Cr or Co was leached from lysimeter LY1. More Cu was leached from the empty background lysimeter LY4 than from LY1, which indicates that the Cu leached from the lysimeter structures was adsorbed to the LY1 serpentine material.

Large amounts of potentially harmful elements were dissolved from lysimeters LY2 and LY3, especially Ni (LY2 0.6% and LY3 0.7% of the total Ni mass), Co (LY2 0.4% and LY3 0.5% of the total Co mass) and Cu (LY2 0.03% and LY3 0.04% of the total Cu mass). Although the amount of dissolved metals from LY2 was slightly smaller than that from LY3, the serpentinite cover on top of LY2 did not have

any significant effect, as the metal concentrations from LY2 were already lower before the installation of the serpentinite cover.

In conjunction with the lysimeter investigations, mapping of the quality of the seepage and surface waters surrounding the Hitura waste rock piles was carried out by Karlsson et al. (2017). Based on their study, the surface waters around the Hitura mica schist pile were acidic and contained elevated metal concentrations. The impact of the mica schist waste rock drainage on the receiving water system was visible, but relatively small. The electrical conductivity and metal concentrations in the ditch flowing next to the mica schist waste rock pile were slightly elevated downstream of the waste rock area. The Ni concentration, which was the highest of the metal concentrations in the ditch, was elevated from the background values of 3–6 $\mu\text{g/L}$ to 94 $\mu\text{g/L}$. The high Ni drainage concentrations in the Hitura mica schist lysimeter tests would have suggested higher Ni concentrations in the ditch. This indicates that some sort of natural attenuation is currently limiting the discharge of metals from the mica schist waste rock pile. It has been observed that the formation of rims of secondary precipitates around the sulphide mineral particles will retard their oxidation (Lottermoser 2010). However, the results of the lysimeter study suggested that disturbance of the mica schist pile and exposure of fresh mineral surfaces, e.g. by shaping (in this case by sampling

Table 4. The total masses (g) of dissolved Co, Cr, Cu and Ni from the background lysimeter LY4 and the Hitura lysimeters LY1 (serpentinite), LY2 (mica schist + serpentinite cover) and LY3 (mica schist), compared with the total masses bound to the rock materials. To calculate the masses dissolved from the rock materials, the masses dissolved from the background lysimeter have been deducted from the total dissolved masses from LY1, LY2 and LY3. (SRP = serpentinite, MS = mica schist pile material).

Lysimeter			Co	Cr	Cu	Ni
LY4	Background	<i>g</i>	0.00006	0.00006	0.0077	0.00088
Rainwater						
LY1	Total amount in rock material	<i>g</i>	107	2607	167	990
<i>SRP</i>	Total dissolved	<i>g</i>	0.00063	0.00006	0.0018	0.0044
	Total dissolved - background	<i>g</i>	0.00057	0	<0	0.00352
	Dissolved	%	0.0005	0	<0	0.0004
LY2	Total amount in rock material	<i>g</i>	108	636	924	2748
<i>MS+SRP</i>	Total dissolved	<i>g</i>	0.439	0.00013	0.269	16.76
	Total dissolved - background	<i>g</i>	0.439	0.00007	0.261	16.76
	Dissolved	%	0.4	0.00001	0.03	0.6
LY3	Total amount in rock material	<i>g</i>	108	636	924	2748
<i>MS</i>	Total dissolved	<i>g</i>	0.517	0.0002	0.377	19.89
	Total dissolved - background	<i>g</i>	0.517	0.00014	0.369	19.89
	Dissolved	%	0.5	0.00002	0.04	0.7

and relocating the material into lysimeters), may cause further mobilisation of harmful substances, especially Ni, Co and Cu, into the surrounding water system for an extended time period (Karlsson et al. 2017). The mica schist waste rock material is not suitable for utilisation in earthworks, even at the mine site, due to its poor environmental characteristics. In addition, reshaping of the pile is recommended to be kept to a minimum during the closure of the pile.

On the other hand, the rock material of the serpentinite pile could be used in earthworks at the mine site, but its geotechnical properties appear to be rather poor, as the weathered serpentinite boulders are easily crushed. Even if the harmful substances did not mobilise in the lysimeter test from the serpentinite, the laboratory tests indicated that the elements might mobilise under suitable conditions, e.g. with increasing acidity. Therefore, the serpentinite material should not, for example, be placed under the influence of acidic drainage of the mica schist material.

The serpentinite cover layer installed on top of the mica schist material in LY2 did not have any significant effect on the drainage quality during the one-and-a-half-year monitoring period (Figs 5 and 6). Although the amount of metals dissolved from lysimeter LY2 was slightly lower than that

from LY3, the difference could not be explained by the serpentinite cover, since the LY2 concentrations were slightly lower even before the cover layer was installed. On the other hand, because no adverse effects were observed, the serpentinite material could be suitable for use in the shaping of the mica schist pile. Moreover, the lysimeter test results suggested that the disturbance of the serpentinite material by sampling does not seem to lead to similar enhanced mobilisation of harmful substances as was observed with the mica schist material. However, the monitoring period of the cover structure was rather short.

Another favourable aspect with respect to the utilisation of the serpentinite is that its drainage has relatively high alkalinity. Alkalinity generally describes the ability of water to neutralise added acid (Langmuir 1997). The utilisation of alkaline waters in the treatment of acidic drainage has been tested, for instance, in Wales, where the results have been promising (Sapsford 2017). For example, according to Sapsford (2017), metals such as Fe and Al could be precipitated from low-quality drainage with seawater. The utilisation of serpentinite drainage in the treatment of the drainage from the mica schist pile (e.g. raising the pH and increasing the precipitation of harmful substances) could be worth further investigation.

3.3 Lysimeter tests in waste rock characterisation

To evaluate the performance and usability of the lysimeter test, its results were compared with laboratory test results.

In general, previous studies have shown that the results of aqua regia extraction performed on waste rock materials provide a good estimate of the harmful substances that will occur as elevated concentrations in the actual drainage (Karlsson & Kauppila 2016, see also Karlsson et al. 2018a in this GTK Bulletin). In this study, the concentrations of trace metals remained low in the lysimeter drainages of the Hitura serpentinite and the Kevitsa waste rocks (LY1, LY5, LY6), even though aqua regia extractable concentrations were elevated, e.g. for Ni, Cu and Co. This might be partly due to a too short period of observation of the lysimeters, during which kinetically more slowly weatherable sulphide minerals, such as pentlandite (Jambor 1994), did not have enough time to oxidise. In addition, the pH strongly influences the mobility of these metals. In all these lysimeters, the drainage was alkaline in pH. In an alkaline or circumneutral pH, the mobility of Ni, Cu and Co is limited/retarded as a result of adsorption and/or coprecipitation processes (e.g. Alpers et al. 1994, Heikkinen & Räisänen 2008).

For the Hitura mica schist, the aqua regia concentrations and the concentrations in the lysimeter drainage corresponded well. In this case, the drainage was acidic. In addition, the results of the two-stage batch test suggested elevated leaching for the Hitura mica schist material, which was

strongly weathered. This observation is in line with the notion that water extractions are better suited for testing weathered extractive waste material than fresh materials (Hageman et al. 2015).

The particle-size distribution of the lysimeter materials was observed to influence the water volumes of the lysimeter discharges. During the observation period, notably lower amounts of drainage seeped through lysimeters LY1–LY3 compared with LY4–LY6. As no clear leaks could be detected in the lysimeter set up, the difference might be due to the water retention capacities of the waste rock materials, which are related, among other factors, to the particle-size distribution of the materials. The Hitura waste rock materials were more weathered and contained higher amounts of fine-grained particles than the Kevitsa lysimeters. The ability of the aggregate to retain water significantly depends on the particle-size distribution; the finer the material is, the better it holds water (Leeper & Uren 1993). Also, the ion contents of the more weathered rock material might affect the water retention capability (Xing et al. 2017). The observed differences in the water retention capacity of the waste rocks may have relevance for (reactive) transport modelling of extractive waste facilities. In the modelling, changes in the water conductivity and water retention capacities of the extractive waste material as it weathers might not have been sufficiently taken into account.

4 CONCLUSIONS

Lysimeter tests and environmental characterisation of the Kevitsa and Hitura waste rocks containing harmful substances were carried out to evaluate their utilisation potential for earth construction at the mine sites and the influence of particle size on element mobility. The use of Hitura serpentinite as a cover material for the Hitura mica schist was assessed. In addition, the correspondence of commonly applied selective extractions with lysimeter drainage quality was assessed.

Based on the tests, harmful substances bound to the weathered Hitura mica schist waste rock, such as Co, Ni and Cu, appeared partly in a relatively soluble form in secondary precipitates formed as

a result of sulphide oxidation. The lysimeter tests suggested that disturbance of the pile, e.g. by shaping, may result in enhanced mobilisation and leaching of these metals to the surrounding water system. The mica schist waste rock material is not suitable for earthworks, even at the mine site, due to high concentrations of potentially harmful substances and the acid production potential.

Harmful substances bound to the Hitura serpentinite waste rock partly appeared in a relatively soluble form. The lysimeter drainage was nevertheless alkaline and low in metal concentrations. Based on the lysimeter test, disturbance of the serpentinite waste rock pile by earthworks does not appear to

lead to significant mobilisation of harmful substances, especially when compared with the mica schist waste rock pile. Based on its environmental properties, the serpentinite material has the potential to be used in earthworks at the mine site, but its geotechnical properties most likely limit its utilisation, as the weathered serpentinite boulders are easily crushed. In addition, acidic solutions may mobilise harmful substances from the serpentinite material, so it is not recommended to be placed under the influence of acidic drainage from the mica schist pile.

The serpentinite cover layer on top of the mica schist waste rock was observed to have no significant effects on the drainage quality during the one-and-a-half-year monitoring period. Despite this, the serpentinite could be a suitable material, for instance, for shaping the mica schist pile.

In the Kevitsa waste rocks, the harmful substances, especially Ni and Cu, were mainly bound to sulphides, and thus the mobilisation of these elements depends on sulphide oxidation. Based on the lysimeter test, the drainage was alkaline and the leaching of harmful substances was limited during the two-year monitoring period. Therefore, the Kevitsa low-sulphur ($S < 0.3\%$) waste rocks might have utilisation potential in earth constructions.

However, monitoring of pentlandite oxidation and Ni concentrations in the drainage should be continued or examined by geochemical modelling, for example.

Based on the Kevitsa lysimeter tests, the particle-size distribution of aggregate material influenced the solubility of harmful substances. Therefore, it is recommended that the waste rocks containing harmful substances are used in as large particle sizes as possible if crushed for utilisation in order to minimise the content of fine particles and mobilisation of harmful substances.

The lysimeter tests demonstrated that the results of the selective extraction methods, e.g. aqua regia extraction, did not correspond with the elements appearing as elevated concentrations in the lysimeter drainage during a one-and-a-half-year observation period. Of the chemical methods used, the two-stage batch test, which is basically a water extraction, best predicted the elevated metal concentrations in lysimeter drainage. The lysimeter tests further showed that the water retention capacity of waste rocks may change as weathering advances, which affects the modelling of water balances and the amount and quality of drainage. This effect of weathering on the water retention capacity should be further investigated.

REFERENCES

- Ahma Ympäristö Oy 2013.** Belvedere mining Oy – Hituran avolouhoksen laajennuksen ympäristövaikutusten arviointiohjelma. Ahma Ympäristö Oy. 72 p. (in Finnish)
- Alpers, C. N., Blowes, D. W., Nordstrom, D. K. & Jambor, J. L. 1994.** Secondary Minerals and Acid Mine-water Chemistry. In: Jambor, J. L. & Blowes, D. W. (eds) The Environmental Geochemistry of Sulfide Mine-wastes. Mineralogical Association of Canada. Short Course Handbook, Vol. 22, 247–270.
- Banwart, S., Evans, K. & Croxford, S. 2002.** Predicting mineral weathering rates at field scale for mine water risk assessment. In: Younger, P. L. & Robins, N. S. (eds) Mine Water Hydrogeology and Geochemistry. London: Geological Society, Special Publications 198, 137–157.
- Criss, J. W. & Birks, L. S. 1968.** Calculation methods for fluorescent x-ray spectrometry. Empirical coefficients versus fundamental parameters. Analytical Chemistry 40, 1080–1086.
- Davis, G. B. & Ritchie, A. I. M. 1986.** A model of oxidation in pyritic mine waste: Part 1 Equations and approximate solution. Applied Mathematical Modelling 10, 314–322.
- Dold, B. 2003.** Speciation of the most soluble phases in a sequential extraction procedure adapted for geochemical studies of copper sulfide mine waste. Journal of Geochemical Exploration 80, 55–68.
- Dold, B. 2017.** Acid rock drainage prediction: A critical review. Journal of Geochemical Exploration 172, 120–132.
- Doležal, J., Provondra, P. & Šulcek, Z. 1968.** Decomposition techniques in inorganic analysis. London: Iliffe Books Ltd. 224 p.
- Government Decree 2007.** Government Decree on the Assessment of Soil Contamination and Remediation Needs 214/2007. Adopted in Helsinki on 1 March 2007. Available at: <https://www.finlex.fi/fi/laki/kaannokset/2007/en20070214.pdf>
- Government Decree 2013.** Government Decree on Extractive Waste 190/2013. Adopted in Helsinki on 14 March 2013. Available at: https://www.finlex.fi/fi/laki/kaannokset/2013/en20130190_20150102.pdf
- Hageman, P. L., Seal, R. R., Diehl, S. F., Piatak, N. M. & Lowers, H. A. 2015.** Evaluation of selected static methods used to estimate element mobility, acid-generating and acid-neutralizing potentials associated with geologically diverse mining wastes. Applied Geochemistry 57, 125–139.
- Hansen, J. B., Holm, P. E., Hansen, E. A. & Hjelmar O. 2000.** Use of lysimeters for characterization of leaching from soil and mainly inorganic waste materials. Nordtest Technical Report 473. 51 p.
- Heikkinen, P. M. & Räsänen, M. L. 2008.** Mineralogical and geochemical alteration of Hitura sulphide mine

- tailings with emphasis on nickel mobility and retention. *Journal of Geochemical Exploration* 97, 1–20.
- Heikkinen, P. M. & Räsänen, M. L. 2009.** Trace metal and As solid-phase speciation in sulphide mine tailings – Indicators of spatial distribution of sulphide oxidation in active tailings impoundments. *Applied Geochemistry* 24, 1224–1237.
- Hollings, P., Hendry, M. J., Nicholson, R. V. & Kirkland, R. A. 2001.** Quantification of oxygen consumption and sulphate release rates for waste rock piles using kinetic cells: Cluff Lake uranium mine, northern Saskatchewan, Canada. *Applied Geochemistry* 16, 1215–1230.
- Jambor, J. L. 1994.** Mineralogy of Sulfide-rich Tailings and Their Oxidation Products. In: Blowes, D. W. & Jambor, J. L. (eds) *Environmental Geochemistry of Sulfide Mine-wastes*, Mineralogical Association of Canada, Short Course Vol. 22, 59–102.
- Karlsson, T. 2017.** Field scale investigations and lysimeters. Mine Closure Wiki, Closedure. Geological Survey of Finland. Retrieved November 7, 2017. Available at: <http://wiki.gtk.fi/web/mine-closure/wiki/-/wiki/Wiki/Field+scale+investigation+and+lysimeters>
- Karlsson, T. & Kauppila, P. M. 2016.** Waste Rock Characterization versus the Actual Seepage Water Quality. In: Drebenstedt, C. & Paul, M. (eds) *IMWA 2016 – Mining Meets Water – Conflicts and Solutions*. Freiberg: TU Bergakademie, 402–406.
- Karlsson, T., Kauppila, P. & Lehtonen, M. 2017.** Assessment of the effects of mine closure activities to waste rock drainage quality at the Hitura Ni-Cu mine, Finland. In: Wolkersdorfer, C., Sartz, L., Sillanpää, M. & Häkkinen, A. (eds) *Proceedings, IMWA 2017, Mine Water and Circular Economy*; Lappeenranta, Finland 2017, 664–671.
- Karlsson, T., Kauppila, P. M. & Lehtonen, M. 2018a.** Prediction of long-term behaviour of extractive wastes based on environmental characterisation: correspondence of laboratory prediction tests with field data. In: Kauppila, P. M. & Tarvainen, T. (eds) *Improving the environmental properties, utilisation potential and long-term prediction of mining wastes*. Geological Survey of Finland, Bulletin 408. (this volume). Available at: <https://doi.org/10.30440/bt408.1>
- Karlsson, T., Kauppila, P. M., Lehtonen, M., Tiljander, M., Forsman, P. & Lahtinen, T. 2018b.** Hituran ja Kevitsan kaivosten sivukivien hyötykäyttö maarakentamisessa. Geological Survey of Finland, Open File Work Report 11/2018. (in Finnish). Available at: http://tupa.gtk.fi/raportti/arkisto/11_2018.pdf
- Kauppila, P. M., Taskinen, A., Korhonen, T., Kurhila, M. & Tiljander, M. 2018.** Environmental properties of arsenic containing flotation tailings from Kuikka 2 gold deposit: Effect of polyacrylamide based chemical. Geological Survey of Finland, Open File Work Report 8/2018. 30 p. Available at: http://tupa.gtk.fi/raportti/arkisto/8_2018.pdf
- Kempton, H. 2012.** A Review of scale factors for estimating waste rock weathering from laboratory tests. In: Price, W. A., Hogan, C. & Tremblay, G. 9th International Conference on Acid Rock Drainage (ICARD 2012), Ottawa, Ontario, Canada, 20–26 May 2012. Volume 1 of 2, 1026–1038.
- Kirchner, T. & Mattson, B. 2015.** Scaling geochemical loads in mine drainage chemistry modelling: An empirical derivation of bulk scaling factors. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) *Proceedings of 10th ICARD & IMWA 2015 conference*, Santiago, Chile, 21–24 April 2015, 1495–1503.
- Langmuir, D. 1997.** *Aqueous Environmental Geochemistry*. New Jersey: Prentice-Hall, Upper Saddle River. 600 p.
- Lapakko, K. 2002.** *Metal Mine Rock and Waste Characterization Tools: An Overview*. Minnesota Department of Natural Resources, US. April 2002 No. 67. 30 p.
- Lapakko, K. & Olson, M. 2015.** Scaling laboratory sulfate release rates to operational waste rock piles. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) *Proceedings of 10th ICARD & IMWA 2015 conference*, Santiago, Chile, 21–24 April 2015, 1480–1494.
- Lawrence, R. W. & Day, S. 1997.** Chemical prediction techniques for ARD. Short course in 4th International conference on acid rock drainage, May 31st, Vancouver, B.C. Available at: <http://mend-nedem.org/wp-content/uploads/IW-02.pdf>
- Leeper, G. W. & Uren, N. C. 1993.** *Soil Science: An Introduction*. 5th edition. Melbourne: Melbourne University Press. 300 p.
- Lehtonen, M., Airo, M.-L., Eilu, P., Hanski, E., Kortelainen, V., Lanne, E., Manninen, T., Rastas, P., Räsänen, J. & Virransalo, P. 1998.** Kittilän vihreäkivialueen geologia: Lapin vulkaniittiprojektin raportti. Geological Survey of Finland, Report of Investigation 140. 144 p. (in Finnish). Available at: http://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_140.pdf
- Lottermoser, B. G. 2010.** *Mine Wastes: Characterization, Treatment and Environmental Impacts*, 3rd ed. Berlin, Heidelberg: Springer-Verlag. 400 p.
- Maest, A. S., Kuipers, J. R., Travers, C. L. & Atkins, D. A. 2005.** Predicting Water Quality at Hardrock Mines: Methods and Models, Uncertainties, and State-of-the-Art. Kuipers & Associates and Buka Environmental. 77 p. Available at: http://www.ceaa-acee.gc.ca/050/documents_staticpost/cearef_3394/hearings/SM09.pdf
- Manninen, T., Hyvönen, E., Johansson, P., Kontio, M., Pänttjä, M. & Väisänen, U. 1996.** Kevitsan alueen geologia. Geological Survey of Finland archive report K/21.42/96/1. 70 p. (in Finnish). Available at: http://tupa.gtk.fi/raportti/arkisto/k21_42_96_1.pdf
- Mehta, N., Dino G. A., Ajmone Marsan F., Lasagna M., Romè C. & De Luca D. A. 2018.** Extractive waste management: A risk analysis approach. *Science of the Total Environment* 622–623, 900–912.
- Moncur, M. C., Jambor, J. L., Ptacek, C. J. & Blowes, D. W. 2009.** Mine drainage from the weathering of sulfide minerals and magnetite. *Applied Geochemistry* 24, 2362–2373.
- Muniruzzaman, M., Karlsson, T. & Kauppila, P. M. 2018a.** Modelling tools for the prediction of drainage quality from mine wastes. In: Kauppila, P. M. & Tarvainen, T. (eds) *Improving the environmental properties, utilisation potential and long-term prediction of mining wastes*. Geological Survey of Finland, Bulletin 408. (this volume). Available at: <https://doi.org/10.30440/bt408.2>
- Muniruzzaman, M., Kauppila, P. M. & Karlsson, T. 2018b.** Water quality prediction of mining waste facilities based on predictive models. Geological Survey of Finland, Open File Research Report 16/2018. 65 p. Available at: http://tupa.gtk.fi/raportti/arkisto/16_2018.pdf
- Mutanen, T. & Huhma, H. 2001.** U–Pb geochronology of the Koitelainen, Akanvaara and Kevitsa layered intrusions and related rocks. In: Vaasjoki, M. Radio-

- metric age determinations from Finnish Lapland and their bearing on the timing of Precambrian volcano-sedimentary sequences. Geological Survey of Finland, Special Paper 33, 229–246. Available at: http://tupa.gtk.fi/julkaisu/specialpaper/sp_033_pages_229_246.pdf
- Niskavaara, H. 1995.** A comprehensive scheme of analysis for soils, sediments, humus and plant samples using inductively coupled plasma atomic emission spectrometry (ICP-AES). In: Autio, S. (ed.) Geological Survey of Finland, Current Research 1993–1994. Geological Survey of Finland, Special Paper 20, 167–175. Available at: http://tupa.gtk.fi/julkaisu/specialpaper/sp_020_pages_167_175.pdf
- Papunen, H. 1970.** Sulfide mineralogy of the Kotalah-ti and Hitura nickel-copper ores, Finland. *Annales Academiæ Scientiarum Fennicæ AIII, Geologica-Geographica* 109. 74 p.
- Pearce, S., Scott, P. & Weber, P. 2015.** Waste rock dump geochemical evolution: matching lab data, models and predictions with reality. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) Proceedings of 10th ICARD & IMWA 2015 conference – Agreeing on solutions for more sustainable mine water management, Santiago, Chile, 21–24 April 2015, 1469–1479.
- Pöyry 2011.** FQM Kevitsa Mining Oy – Ympäristövaikutusten arviointiselostus. Pöyry Oy, 9M209124. 67 p. (in Finnish)
- Price, W. A. 2009.** Prediction Manual for Drainage Chemistry from Sulfidic Geologic Materials. Natural Resources Canada. MEND Report 1.20.1. 579 p.
- Reinikainen, J. 2007.** Maaperän kynnys- ja ohjearvojen määrittämissuhteet. Suomen ympäristö 23/2007. Helsinki: Suomen ympäristökeskus. 168 p. (in Finnish)
- Sapsford, D. 2017.** Mine water treatment and mine waste characterization. Presentation at GTK Kuopio, 10th of September 2017.
- Sobek, A., Schuller, W., Freeman, J. & Smith, R. 1978.** Field and Laboratory Methods Applicable to Overbur-dens and Minesoils. Cincinnati: Industrial Environmental Research Laboratory, Office of Research and Development, U.S. Environmental Protection Agency.
- Stockwell, J., Beckie, R. & Smith, L. 2003.** The hydro-geochemical characterisation of an unsaturated waste rock pile, Key Lake, Saskatchewan, Canada. In: Farrell, T. & Graham, T. F. Sixth International Conference Acid Rock Drainage: proceedings. Cairns, Australia, 12–18 July 2003, 927–938.
- Stumm, W. & Morgan, J. J. 1996.** Aquatic Chemistry. New York: Wiley. 1022 p.
- White, W. W. III, Lapakko, K. A. & Cox, R. L. 1999.** Static-test methods most commonly used to predict acid mine drainage: Practical guidelines for use and interpretation. In: Plumlee, G. S. & Logsdon, M. (eds) The Environmental Geochemistry of Mineral Deposits, Part A: Theory and background. Society of Economic Geologists Reviews in Economic Geology, vol. 7A, 325–328.
- Xing, X., Kang, D. & Ma, X. 2017.** Differences in loam water retention and shrinkage behavior: Effects of various types and concentrations of salt ions. *Soil and Tillage Research*, 167, 61–72.

Standards referred to in the text

- ISO 11466.** Soil quality – Extraction of trace elements soluble in aqua regia. ISO 11466:1995.
- ISO 15178.** Soil quality -- Determination of total sulfur by dry combustion. ISO 15178:2000.
- SFS-EN 12457-3.** Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with a high solid content and with a particle size below 4 mm (without or with size reduction).
- SFS-EN 15875.** Characterization of waste. Static test for determination of acid potential and neutralization potential of sulfidic waste.

IMPROVING THE ENVIRONMENTAL PROPERTIES OF ARSENIC AND SULPHIDE RICH KOPSA AU–CU ORE TAILINGS THROUGH OPTIMISED MINERAL PROCESSING

by

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Taskinen, A., Kauppila, P. M., Tornivaara, A., Heino, N., Kurhila, M., Tiljander, M. & Korhonen, T. 2018. Improving the environmental properties of arsenic and sulphide rich Kopsa Au–Cu ore tailings through optimised mineral processing. *Geological Survey of Finland, Bulletin 408*, 59–82, 19 figures and 4 tables.

Mineral processing methods were applied to improve the environmental properties of Kopsa Au–Cu ore tailings containing arsenic-bearing and sulphide minerals. The effects of modification and optimisation of mineral processing flow sheet in the laboratory scale on tailings properties were studied using mineralogical and geochemical characterisation together with filled-in lysimeters which measured long-term behaviour together with drainage quality in field conditions. Most of the arsenic and sulphide minerals could be removed effectively from the tailings using a combination of fine grinding, froth flotation, high-gradient magnetic separation (HGMS), and sizing. The chemical composition and mineralogy of the tailings together with leaching of contaminants from the tailings changed significantly as a result of process development. E.g. leaching of As decreased from the level of hazardous waste to that of non-hazardous waste. The efforts made to improve the tailings quality also affected positively the process water quality. The filled-in lysimeter test results indicated that leaching of most elements in the drainage water decreased as a function of time during the monitoring period of one and a half years. Moreover, leaching of hazardous elements was generally less pronounced from the more processed tailings. Only the concentration of As in the seepage varied unexpectedly during the monitoring period. Further studies and more sampling is needed to confirm this observation and to predict the long-term behaviour.

Keywords: Mineral processing, tailings, arsenic, sulphide minerals, removal, environmental properties, mineralogy, geochemical characterisation, lysimeter test, seepage water

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1 INTRODUCTION

In gold production, huge amounts of rock need to be mined to yield just an ounce of gold. This is due to very low average gold grades in the ore deposits, usually a few grams per tonne at most. Therefore, large amounts of mining wastes are generated. A global estimate for the ratio of produced gold to the waste is particularly high, 1:950 000 (BRGM 2001). Only a small part of wastes can be used e.g. in mine site construction, most of them requiring long-term disposal.

Gold mining wastes typically contain sulphide minerals and metals hazardous to the environment, which prevents their further utilisation. Sulphide minerals are prone to generate low quality drainage from mine wastes. Acid mine drainage is considered to be one of the most significant environmental concerns associated with extractive industry (e.g. MEND 1991, Price 2003). Another major concern is arsenic (As), which is toxic and causes cancer in humans. Arsenic can be released to air, water, or land through various mining operations of which waste rock and tailings represent by far the largest arsenic fluxes for the gold industry to manage (Asselin & Shaw 2016). For example, in 2013, ca. 65% of total managed arsenic in the United State and 40% in Canada came from gold mining operations, and ca. 11% of total As directly emitted to the environment in Canada and Australia originated from these operations (Asselin & Shaw 2016).

Waste management is clearly a major challenge for the gold industry, and it will become more important and difficult to address as the ore grades decrease. Therefore, efficient waste management methods are needed. By removing As, sulphides and other hazardous metals from the gold mining waste, its utilisation potential and environmental properties could be improved. In addition, the volumes of harmful wastes could be minimized, which would facilitate their management and reduce costs.

Various mineral processing methods have been applied to increase raw material value of tailings and to improve their environmental properties. Liu et al. (2008) studied bioleaching and Lv et al. (2014) froth flotation after chemical pre-treatment to recover valuable metals from tailings. Desulphurisation of tailings by flotation was carried out e.g. by Benzaazoua and Kongolo (2003) and As removal by flotation by Choi et al. (2013). Also gravity concentration and magnetic separation have been applied. For instance, Savas (2016) studied recovery of colemanite from mine tailings using a Knelson concentrator, while Watson and Beharrell (2006) discussed concentration of valuables from mine dumps and tailings by high-gradient magnetic separation (HGMS).

In this work, mineral processing techniques were applied to decrease harmful minerals, especially As-bearing and sulphide minerals, from the tailings of the Kopsa gold-copper ore samples. These techniques included froth flotation, magnetic separation, gravity concentration, and classification. The main objective was to evaluate, whether it would be possible to reduce the amount of hazardous waste and to generate tailings that could be used as a cover material for mining waste facilities. Efforts were also made to increase the recovery of valuables to the concentrates. The influence of modified composition of tailings on their environmental performance was studied using mineralogical and geochemical characterisation together with filled-in lysimeters, which measured long-term behaviour together with drainage quality in field conditions.

This paper summarises the results of the study. More detailed descriptions of the investigations are provided in the GTK Open File Work Reports by Taskinen et al. (2018) and Tornivaara et al. (2018).

2 MATERIALS AND METHODS

2.1 Sampling and analyses

The ore samples for the study originated from the Kopsa Au-Cu deposit, located in Western Finland (Fig. 1). There were two ore samples, so-called sorted and unsorted sample. The sorted sample

had been pre-concentrated by sorting using X-ray transmission technique, while the unsorted sample had not been pre-concentrated by any way.

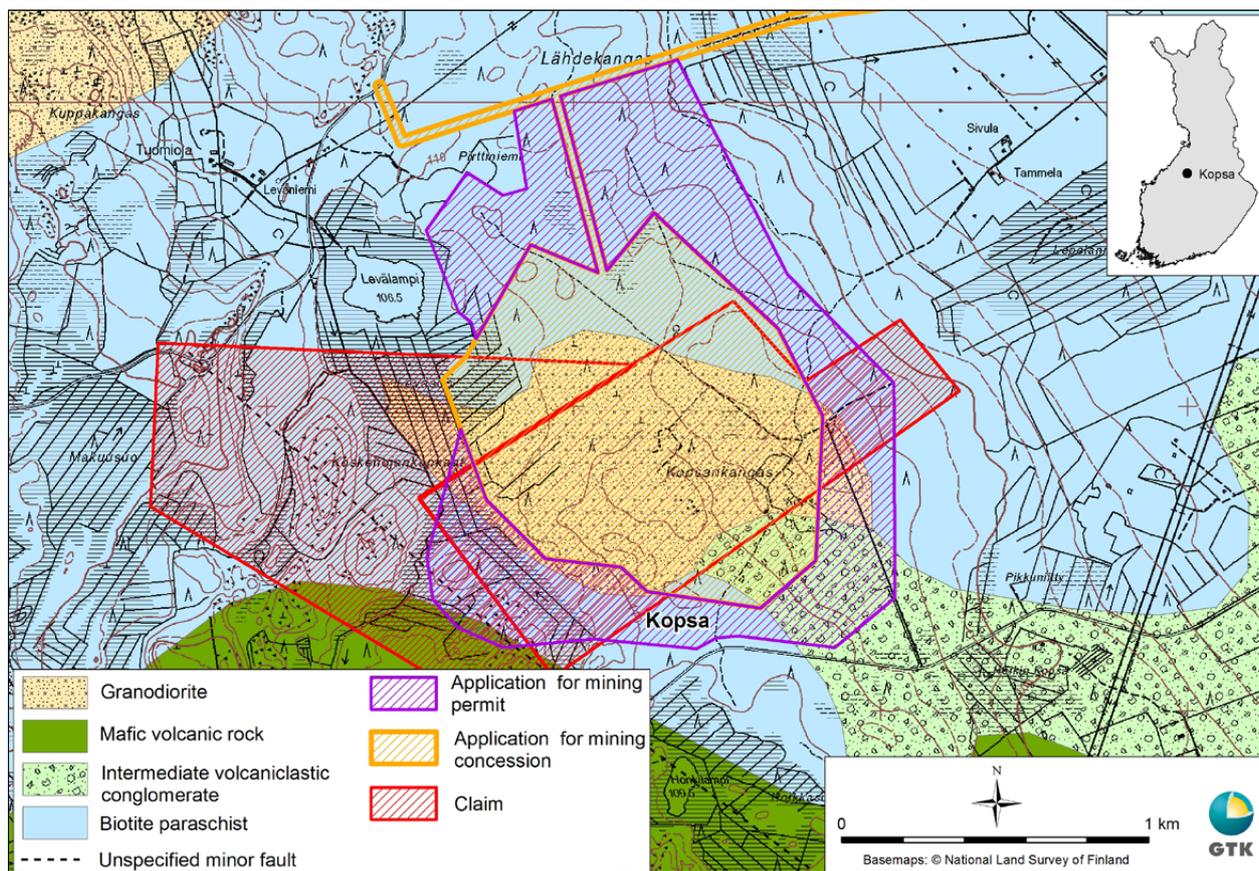


Fig. 1. Location and geology of the Kopsa Au–Cu deposit (Bedrock of Finland – DigiKP; Basemaps © National Land Survey of Finland and HALTIK 2013).

The Kopsa ore deposit is a porphyric Au–Cu mineralisation, 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 grade is very typical for the mineralisation, the As contents varying between 0.1–1.2% in the deposit (Gaál & Isohanni 1979, Nurmi et al. 1991). Exploration has been carried out around the Kopsa deposit since the 1940s. The latest holder of the exploration claims, Belvedere Mining Oy, planned to open a mine, but went bankrupt in 2015. Therefore, no tailings existed at the site yet, providing good possibilities for tailings optimisation.

2.2 Sample preparation and analyses for the beneficiation tests

The ore samples for the beneficiation tests were crushed to <1 mm particle size using a small scale crushing circuit consisting of two jaw crushers in series and a roll crusher in closed circuit with a Sweco screen. The crushed samples were homogenised and divided into subsamples of 5.0 kg and 1.5 kg using Jones riffles and a sample divider (Retsch PT 100). The crushed subsamples were stored in a freezer to minimize oxidation of sulphide minerals.

Ground ore samples and slurry samples from the beneficiation tests were filtered by vacuum filtration and dried thermally at 90 °C. Representative

samples for chemical analyses and mineralogical characterisations were extracted by the sample divider (Retsch PT 100).

Size analyses of the samples were carried out by sieving. First, wet sieving was performed by hand to separate the finest –20 µm fraction. The oversized material was dry-sieved by a Ro-Tap sieve shaker using sieves with various apertures. Some particle size distributions were also determined by laser diffraction technique using Beckman Coulter LS 13320 MW Particle Size Analyser.

The chemical analyses of the ore samples and beneficiation test products were carried out by Labtium Oy. Total element concentrations were determined by XRF, Au and Ag grades by fire assay (FA) completed with flame atomic absorption spectroscopy (FAAS), and sulphur assays using an Eltra carbon/sulphur analyser. Some arsenic assays were also analysed by graphite furnace atomic absorption spectroscopy (GFAAS).

Modal mineralogy, grain size distribution, liberation and association of the ore and tailings samples

were studied using a mineral liberation analyser (MLA). The MLA equipment consisted of a standard modern scanning electron microscope (SEM; FEI Quanta 600) with two energy dispersive detectors (EDAX Genesis) and a special software package. Vertical polished sections were investigated. Electron probe microanalyser (EPMA; Cameca SX100) was applied for more detailed identification of some specific mineral phases and their quantitative composition.

2.3 Sampling and environmental characterisation of tailings

The environmental characterisation of the tailings and process waters from the beneficiation tests included mineralogical and chemical analyses of the tailings and determination of the process water quality. The purpose of the characterisation was to evaluate impacts of the modifications made in the ore processing on the environmental performance of waste materials and to determine the properties of tailings used in the filled-in lysimeter tests. In this paper, the focus is on the characterisation of the tailings and process water from the sorted ore sample. The results for the unsorted ore sample are provided in the report by Taskinen et al. (2018).

Tailings and process water samples were collected from the final slurry of the original and modified beneficiation tests using vacuum filtration (Table 1). Characterisation of tailings was carried out on freeze dried samples, sieved <2 mm for most of the analysis. The sieving was made mainly to break down clods generated during the drying. For total concentration measurements the samples were further ground to <100 µm (90%). The studied environmental properties included mineralogy, chemical composition, potential to produce acid mine drainage, and leaching and fractionation of

harmful elements. Mineralogy of the tailings was studied using MLA and EPMA as described above.

Total concentrations of elements in the tailings were determined by XRF and a mixture of concentrated acids (hydrofluoric acid, perchloric acid, hydrochloric acid and nitric acid) i.e. so-called four acid leach in combination with the ICP-OES/MS technique (method modified after Briggs (2002) and Briggs & Meier (2002)). Concentrations of total sulphur, total carbon, sulphide sulphur and carbonate carbon were measured pyrolytically with IR detection (ISO 15178, ISO 10694, CEN/TR 16376, SFS-EN 13137:en; Räsänen et al. 2010). Potential of the tailings to produce acid mine drainage was evaluated based on the ABA (SFS-EN 15875) and NAG tests (Amira 2002).

Leachability and fractionation of harmful elements from the tailings was studied using series of selective extractions in parallel. The applied extractions included: 1) 0.01 M NH₄-chloride to extract easily dissolving fraction (Heikkinen & Räsänen 2008), 2) 1 M NH₄-acetate at pH 4.5 to dissolve exchangeable and/or carbonate bound phases (e.g. Dold 2003, Heikkinen & Räsänen 2008), 3) 0.2 M NH₄-oxalate at pH 3.0 in darkness to extract phases

Table 1. Tailings and process water samples used in the environmental characterisation.

Beneficiation test	Tailings sample	Process water sample
Original process (cf. Fig. 4)	TAIL 0A "As-rich"; used in filled-in lysimeter test	PWAT 0A
Modified process 1; finer grinding, higher reagent dosage, longer sulphide flotation than in the original (cf. Fig. 5)	TAIL 1A, "As-poor"; used in filled-in lysimeter test	PWAT 1A
Modified process 2; enhanced Cu and sulphide flotation, regrinding and (scavenger) flotation (cf. Fig. 8)	TAIL 2	PWAT 2
Modified process 3; high-gradient magnetic separation on scavenger tailings (cf. Fig. 8)	TAIL 3	PWAT 3

bound to Fe oxyhydroxides or oxides (Räisänen et al. 1992, Dold 2003, Heikkinen & Räisänen 2008), as well as 4) KClO_3 -12 M HCl + 4 M HNO_3 (Hall et al. 1996) and 5) aqua regia (1:3 HNO_3 :HCl) to digest sulphide bound fraction (modified from SFS-ISO 11466:2007, cf. also Doležal et al. 1968, Heikkinen & Räisänen 2009). The aqua regia concentrations are considered to indicate the elements that are most likely of concern in the drainage from waste (Price et al. 1997, Fosso Kankeu et al. 2015). In addition, they are used when evaluating whether mining waste is inert (Government Decree 2013a) by comparing the values with the threshold values of contaminated soils (Government Decree 2007). Element concentrations were measured from all the leachates with the ICP-OES/MS technique and pH of the tailings was determined potentiometrically from the 0.01 M NH_4Cl leach. Leaching of harmful elements from the tailings was further studied using standardized leaching tests (SFS-EN 14405 and/or SFS-EN 12457-3) and by analysing leachate from the NAG test (cf. Räisänen et al. 2010).

Process water samples were analysed for total and dissolved concentrations of elements with ICP-OES/MS techniques (SFS-EN ISO 11885, SFS-EN

ISO 17294-2), in which wet digestion technique was used for the total concentrations (SFS-EN ISO 15587-2). Anions (Br^- , Cl^- , F^- , NO_3^- , SO_4^{2-}) were measured using ion chromatography (SFS-EN ISO 10304-1) and phosphate content with flow injection analysis (FIA; SFS-EN ISO 15681-1). Ferrous iron was measured spectrophotometrically and total and dissolved concentrations of organic carbon (TOC, DOC) pyrolytically using IR detection (SFS-EN 1484). Alkalinity of the process waters was determined with titration (SFS 3005), suspended solids gravimetrically (SFS 872), and pH and EC potentiometrically (SFS 3021, SFS-EN 27888:en). Dissolved elements, ferrous iron and dissolved organic carbon were measured from filtered (0.45 μm) samples, while the rest of the analysis were made from unfiltered samples. Concentrated nitric acid, phosphorous acid and hydrochloric acid were used for the preservation of ICP-OES/MS, organic carbon and Fe^{2+} samples, respectively.

All the chemical analyses were carried out at an accredited laboratory of Labtium Oy and the mineralogical investigations were made at the mineralogical laboratories of GTK in Outokumpu and Espoo.

3 BENEFICIATION TESTS

Laboratory ball mills were used for grinding of the crushed ore samples and regrinding of tailings. Grind size was 80% <35–56 μm in most tests. Grinding was performed wet at room temperature, the pulp density generally being 50–63% solids by weight. Tap water was used. Grinding media was normally mild steel but stainless steel was also tested. Grinding of the crushed ore samples was undertaken immediately prior to flotation to minimize oxidation of sulphide mineral surfaces. In most cases, air was used as the grinding atmosphere but in one flotation test nitrogen was applied.

Flotation tests were performed using an Outotec GTK LabCell batch flotation machine and its older models. The operation principle was the same in all models. The flotation machines were equipped with automatic froth scrapers and a 45 mm rotor. The flotation cell size varied from 1.5 L to 14 L depending on the sample. In general, pulp density in the beginning of flotation was set to about 35%, and air was used as the flotation gas. Flotation chemi-

cals were added to the pulp as aqueous solutions or undiluted liquids and were measured out using pipettes. During flotation tests, pH of the pulp was measured with a calibrated glass electrode connected to a titrator (Metrohm 877 Titrino Plus). Pulp potential was monitored by the Consort C6020 multimeter using a platinum electrode as the sensing electrode and a saturated calomel electrode (SCE) as the reference electrode. Dissolved oxygen was measured using portable meter (Hach Sension+ DO6 or Hach HQ30D). The main variables studied in the flotation tests were flotation reagents and their dosages, flotation time, pulp pH, grind size, pre-oxidation of the pulp, grinding media, grinding atmosphere, and flotation gas.

Knelson gravity concentration tests were carried out using a 3" Knelson batch concentrator (model KC-MD3, Knelson Concentrators, Langley). The size of the feed batch varied between 0.5–1.5 kg. The flow rate of the feed slurry (ca. 10% w/w) introduced to the concentrator was about 1 litre/min. Rotational speed of the concentrate cone was set to 1500 rpm

and the fluidisation water pressure to 0.20 bar. Also 0.10 and 0.15 bar water pressures were applied.

For wet low-intensity magnetic separation (WLIMS), a drum separator ($\text{Ø}200 \times 115$ mm) with a magnetic field strength of 0.07 T was used (Sala WS 201). A corresponding drum separator with higher intensity (0.30 T) was also tested. Concurrent configuration was applied, and pulp density was set to ca. 20% (w/w). For wet high-intensity magnetic separation, a high-gradient magnetic separator (Sala HGMS 10-15-20 SCR) was used and operated in batch mode. The matrix canister type was 3.5 XMGO, and the pulp density was set to 3–5% (w/w). Magnetic field strength in the HGMS tests varied from 0.1 to 2.0 T.

The size classification tests were carried out using elutriation which is a process based on different sedimentation velocities of particles of different size, shape, and density. First, the pulp was placed in a 4 L flotation cell. After that water was introduced into the cell at a controlled velocity. The small/light particles whose terminal sedimentation velocities were lower than the velocity of rising water rose to the top and were carried over in the water stream (overflow). The larger particles settled against the upward current. The terminal velocity could be calculated using Stoke's law.

4 FILLED-IN LYSIMETER TESTS

Filled-in lysimeter tests were conducted in the backyard of GTK Kuopio office in Eastern Finland (Fig. 2) to evaluate differences in long-term behaviour of As-rich (TAIL 0A) and As-poor (TAIL 1A) tailings. The experiment consisted of three plastic filled-in lysimeters of which one lysimeter was empty and filled naturally by rainwater. It was for the background monitoring of the local precipitation and for the potential contamination from the lysimeter materials. The other two lysimeters were each filled with 200 kg of fresh As-rich and As-poor

tailings from the beneficiation tests. Lysimeters were exposed to rainwater and other weather conditions by leaving their top open. Rainwater was allowed to percolate through the tailings and was collected to the plastic canisters from the base of the lysimeters.

Lysimeter tests were started at the beginning of July 2016, and the last water samples were taken at the beginning of November 2017. Sampling was conducted periodically 6 times, when the drainage water was unfrozen. After each sampling



Fig. 2. Plastic lysimeter filled with As-rich tailings and drainage water canister in Kuopio in summer 2016. Photo by A. Tornivaara, GTK

session, the seepage water canisters were emptied. During winter, the plastic canisters were removed and the tailings were allowed to freeze and be covered by snow. During each sampling, pH, T, EC, O₂ (mg/l), O₂ (%), and redox potential were measured by a portable multi-parameter instrument (YSI Professional Plus). The alkalinity (mmol/l) was additionally measured by titration method using a HACH digital titrator with 0.16N or 1.6N H₂SO₄ to an

end point of pH 4.5. Water samples were delivered to Labtium Oy for further analyses which included determination of dissolved solids, pH, alkalinity, dissolved and total element concentrations by ICP-OES/MS methods, anions by ion chromatography, dissolved (DOC) and total organic carbon (TOC) by pyrolytical method (SFS-EN 1484) and content of ferrous iron with spectrophotometer.

5 SUITABILITY OF MINERAL PROCESSING TECHNIQUES TO REMOVE ARSENIC AND SULPHIDE MINERALS

5.1 Mineralogy and chemical composition of the ore samples

The main valuable and harmful elements in the sorted ore sample were Au (1.0 g/t), Ag (2.4 g/t), Cu (0.10%), As (0.74%), and S (0.59%). The sample was composed mainly of various silicates such as quartz (23.5%), plagioclase (23.2%), potassium feldspar (22.0%), biotite (10.7%), actinolite (3.9%), epidote (2.8%), and muscovite (1.8%). The main sulphide minerals were arsenopyrite (1.7%), pyrrhotite (0.48%), chalcopyrite (0.32%), and pyrite (0.20%). Some goethite (0.15%) and iron oxides (0.03%) were found, too. Besides arsenopyrite, löllingite (0.01%) and various arsenate minerals such as pharmacosiderite, arseniosiderite, and scorodite (totally 0.04%) were determined as the hosts for arsenic. Goethite contained some arsenic, too. Gold was found to exist as native gold and electrum.

The unsorted ore sample contained less valuable and harmful elements than the sorted ore sample the ore grades being 0.8 g/t Au, 0.9 g/t Ag, 0.06% Cu, 0.48% As, and 0.38% S. Same minerals were

found as in the sorted ore sample but in different proportions. In general, the unsorted ore contained less sulphides and As-bearing minerals than the sorted ore sample. Interestingly, the unsorted sample contained more plagioclase (35.5%) and biotite (16.0%) than the sorted sample but less K-feldspar (7.2%).

The As-bearing minerals occurred mainly as liberated grains in the sorted ore sample comminuted for the beneficiation test (80% –44 µm). In other words, the degree of liberation was high: 97% of arsenopyrite and 80% of arsenates existed as totally free grains. The locked As mineral grains were mainly associated with silicate minerals. The degree of liberation of chalcopyrite (90%) and pyrrhotite (78%) was high, too, and the locked grains were associated with silicates for the most part. In the unsorted ore sample (80% –52 µm), liberation and association of arsenopyrite, arsenates, chalcopyrite, and pyrrhotite were similar.

5.2 Original process and As-rich tailings

Beneficiation tests were started by following the original process flow sheet planned by Belvedere Mining Oy (Ahma ympäristö Oy 2013). It consisted of crushing, grinding, copper flotation, sulphide flotation, and cyanide leaching (Fig. 3). Cyanide leaching was not investigated in this work. Some cleaner flotation tests were carried out but the main focus was on optimising the process which affected the properties of final tailings (e.g. grinding and rougher flotation in Fig. 3).

The baseline test is illustrated schematically in Figure 4. In short, it was comprised of ball mill grinding to 80% –52 µm, 6 min copper flotation

and 14 min sulphide flotation preceded by reagent addition and conditioning stages. In copper flotation, Ca(OH)₂ was used for pH adjustment, Aero 5100 as a selective copper sulphide collector, and methyl isobutyl carbinol (MIBC) as a frother. In sulphide flotation, H₂SO₄ was used as a pH regulator, CuSO₄ 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.

The Cu rougher concentrate assayed 13.0 g/t Au, 2.7% Cu, 7.7% As, and 8.1% S with recoveries of 28.0% for gold, 63.5% for copper, 27.2% for arsenic and 27.3% for sulphur. Thus, the recovery of

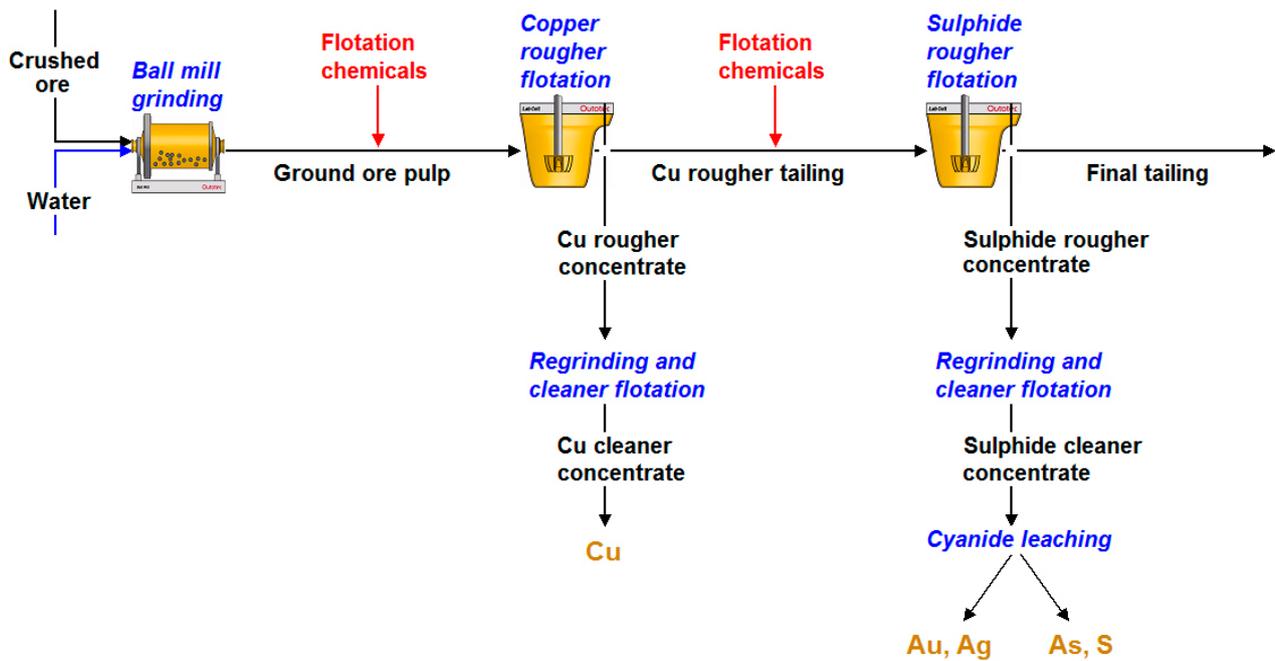


Fig. 3. Process flow sheet for beneficiation of the Kopsa ore by Belvedere Mining Oy.

copper was only moderate, and flotation was not very selective, either. The sulphide flotation gave a concentrate containing 7.1 g/t Au, 0.27% Cu, 5.6% As, and 5.5% S with recoveries of 53.5% for Au, 22.0% for Cu, 69.2% for As, and 64.0% for S. More details on the metallurgical performance and pulp chemistry can be found in the GTK Open File Work Report by Taskinen et al. (2018).

The baseline test yielded tailings called arsenic-rich in this study. The As-rich tailings assayed 0.21

g/t Au, 0.015% Cu, 0.025% As, and 0.064% S (Table 2), and contained 0.015% arsenopyrite, 0.024% arsenates, and 0.094% other sulphides. Thus, the recovery of arsenopyrite to the flotation concentrates was high, but the recovery of arsenates was much lower. The $-20\ \mu\text{m}$ size fraction of the tailings contained most of the As-bearing mineral grains, and their degree of liberation was over 97%. Coarser particles contained more locked grains. Liberation of chalcopyrite was poor in the tailings, only 5%.

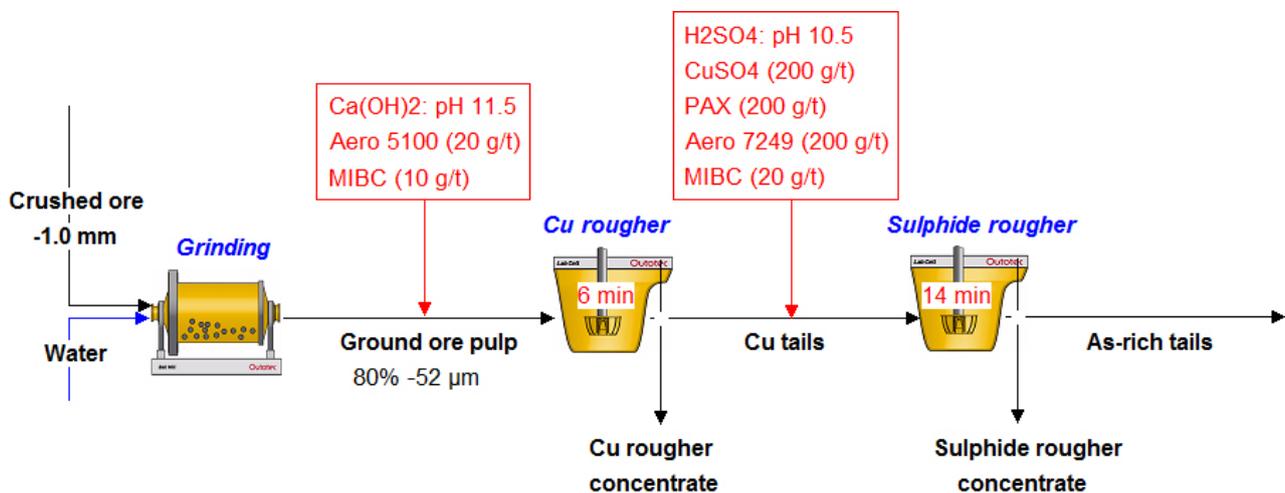


Fig. 4. Original, unmodified flow sheet including selective copper and sulphide rougher flotation stages. Grind size, total flotation times, pH regulators, and other flotation reagents with dosages are shown.

Table 2. Elemental and mineral assays in ore samples and various tailings. (n.d. = not detected)

Ore sample	Process sample	Weight (%)	Elemental assay (%)					Mineral assay (%)			
			Au (g/t)	Ag (g/t)	Cu	As	S	Arsenopyrite	Arsenate	Löllingite	Other sulphides
Sorted	Feed	100.0	0.99	2.4	0.104	0.74	0.59	1.71	0.039	0.012	1.01
	As-rich tails (Fig. 4)	90.1	0.21	—	0.015	0.025	0.064	0.015	0.024	n.d.	0.094
	As-poor tails (Fig. 5)	77.8	0.12	—	0.009	0.017	0.053	0.011	0.021	n.d.	0.042
	Scavenger tails (Fig. 8)	74.1	0.20	1.2	0.011	0.013	0.032	0.014	0.006	0.001	0.029
	HGMS tails (Fig. 8)	45.5	0.18	1.0	0.005	0.008	0.017	0.001	0.001	n.d.	0.005
Unsorted	Feed	100.0	0.82	0.9	0.056	0.48	0.38	1.10	0.010	0.016	0.63
	As-rich tails (Fig. 4)	92.7	0.15	—	0.005	0.017	0.057	0.004	0.003	0.003	0.039
	As-poor tails (Fig. 5)	76.1	0.07	—	0.003	0.010	0.036	0.002	0.006	0.000	0.015

5.3 Process modification and As-poor tailings

To improve recovery and selectivity of copper in Cu flotation and to reduce valuable and harmful element contents in the tailings, various modifications to the original flow sheet (Fig. 4) were studied. Pre-oxidation of the pulp after grinding increased selectivity of copper flotation (i.e. depressed arsenic and gold). However, it also increased As and S contents in the final tailings even though reagent dosages were increased and flotation time was extended by several dozens of minutes. More promising results with respect to tailings properties were obtained when the extended sulphide flotation was followed by regrinding of the rougher tailings to 80% –28 µm and its flotation. This procedure gave final tailings containing 0.010% Cu, 0.010% As, and 0.023% S.

As it would have been very time-consuming to carry out dozens of batch tests including regrinding in order to produce material for lysimeter tests (cf. later), another processing option was sought to improve the environmental properties of tailings. A flow sheet shown in Figure 5 was developed. Compared to the original flow sheet, it consisted of finer grinding (80% –35 µm) to improve liberation of locked copper, arsenic, and sulphide min-

erals, as well as higher reagent dosages and much longer sulphide flotation time to enhance reporting of those minerals to the sulphide concentrate. As a result, so-called arsenic-poor tailings were produced with 0.12 g/t Au, 0.009% Cu, 0.017% As, and 0.053% S (Table 2). Flotation kinetics of various elements in copper and sulphide flotation is illustrated in Figure 6. In Figure 7, tailings assays are presented as a function of flotation time. The assays decreased quickly during the first 20 minutes after which the reduction was significantly slower.

While arsenopyrite and arsenate grades decreased only slightly, the sulphide mineral content was roughly half of that in the As-rich tailings (Table 2). Liberation of chalcopyrite in As-poor tailings was better than in As-rich tailings but still poor, 20%, implying that even finer grinding would be needed to improve its recovery to the concentrates. On the contrary, liberation of As-bearing minerals was excellent in As-poor tailings, about 93%. The locked grains were mainly associated with silicates.

Tailings with reduced arsenic and sulphur could also be generated from the unsorted Kopsa ore sample by applying the modified process (Table 2).

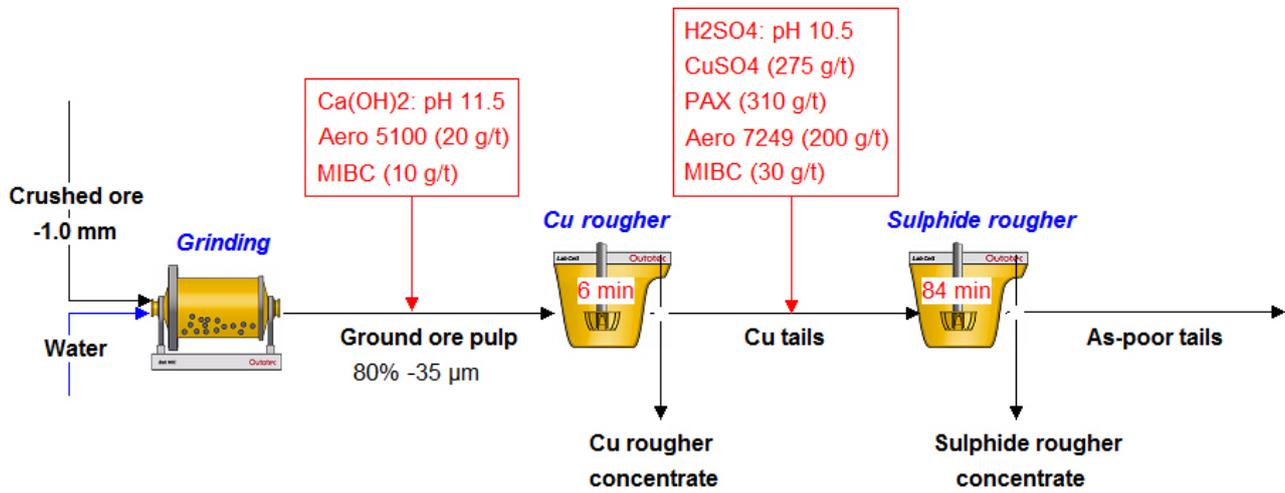


Fig. 5. Modified flow sheet including selective copper and sulphide rougher flotation stages. Grind size, total flotation times, pH regulators, and other flotation reagents with dosages are shown.

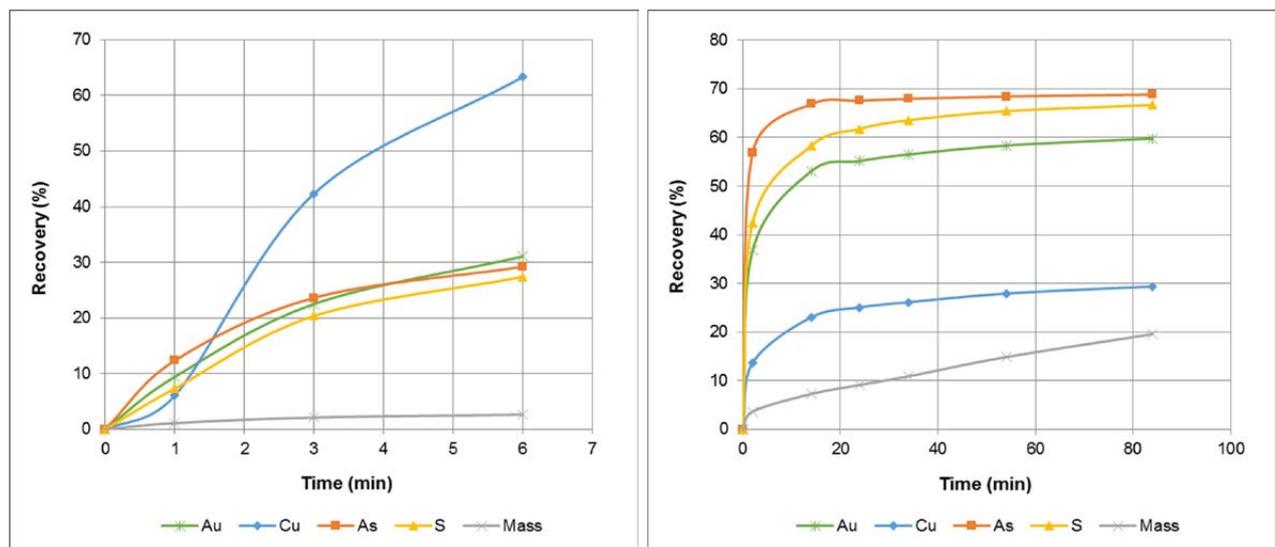


Fig. 6. Flotation kinetics of valuable and harmful elements in copper rougher flotation (left) and sulphide rougher flotation (right) of the modified flow sheet (Fig. 5).

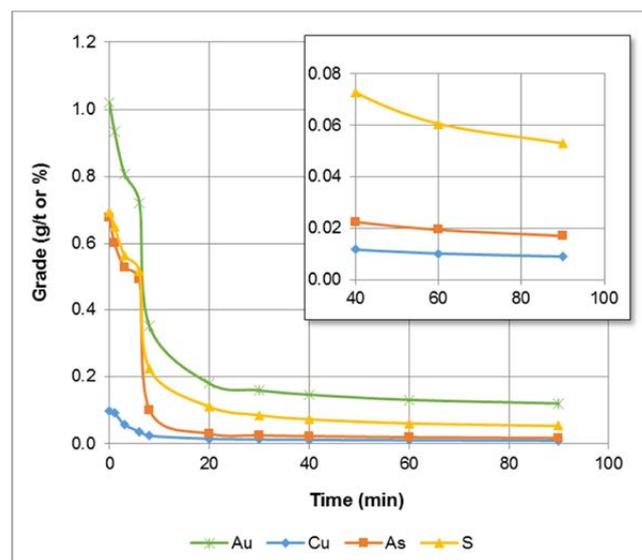


Fig. 7. Development of assays in tailings of the modified process (Fig. 5) as a function of flotation time. The inset plot is a magnification of the assays between 40 and 90 min.

5.4 Further process development and its results

To further reduce valuable and harmful elements in the tailings, several flotation, gravity concentration, magnetic separation, and classification tests were performed. Flotation alone seemed to be unable to reduce arsenic and sulphur concentrations to <0.01% and <0.02%, respectively. It was also found that both gravity concentration using a Knelson centrifugal separator and wet low-intensity magnetic separation were of little help in this endeavour. However, high-gradient magnetic separation using high magnetic fields (at least 1.0 T) appeared to be a feasible way to remove both As and S from flotation tailings. Consequently, the flow sheet optimised in this work consisted of selective copper and sulphide rougher flotation, regrinding of the rougher tailings, (scavenger) flotation, and HGMS on the scavenger tailings (Fig. 8).

Elemental and mineralogical composition of the scavenger tailings and the HGMS tailings (i.e. non-magnetic product in this case) showed that As-bearing minerals and sulphide minerals could be removed quite efficiently (Table 2). The HGMS tailings assayed 0.18 g/t Au, 1.0 g/t Ag, 0.005% Cu, 0.008% As, and 0.015% S. Therefore, the Cu, As, and S concentrations could approximately be halved by HGMS. The HGMS tailings contained only 0.002% of As-bearing minerals (excluding goethite) and only 0.005% of other sulphides. Arsenopyrite and arsenate grains were very small; ca. 80% of arsenopyrite existed as $-4\ \mu\text{m}$ grains and 80% of arsenates as $-9\ \mu\text{m}$ grains. Their degree of liberation was quite good, 70–80%.

As the process mineralogical results implied that As-bearing minerals were concentrated in the finest

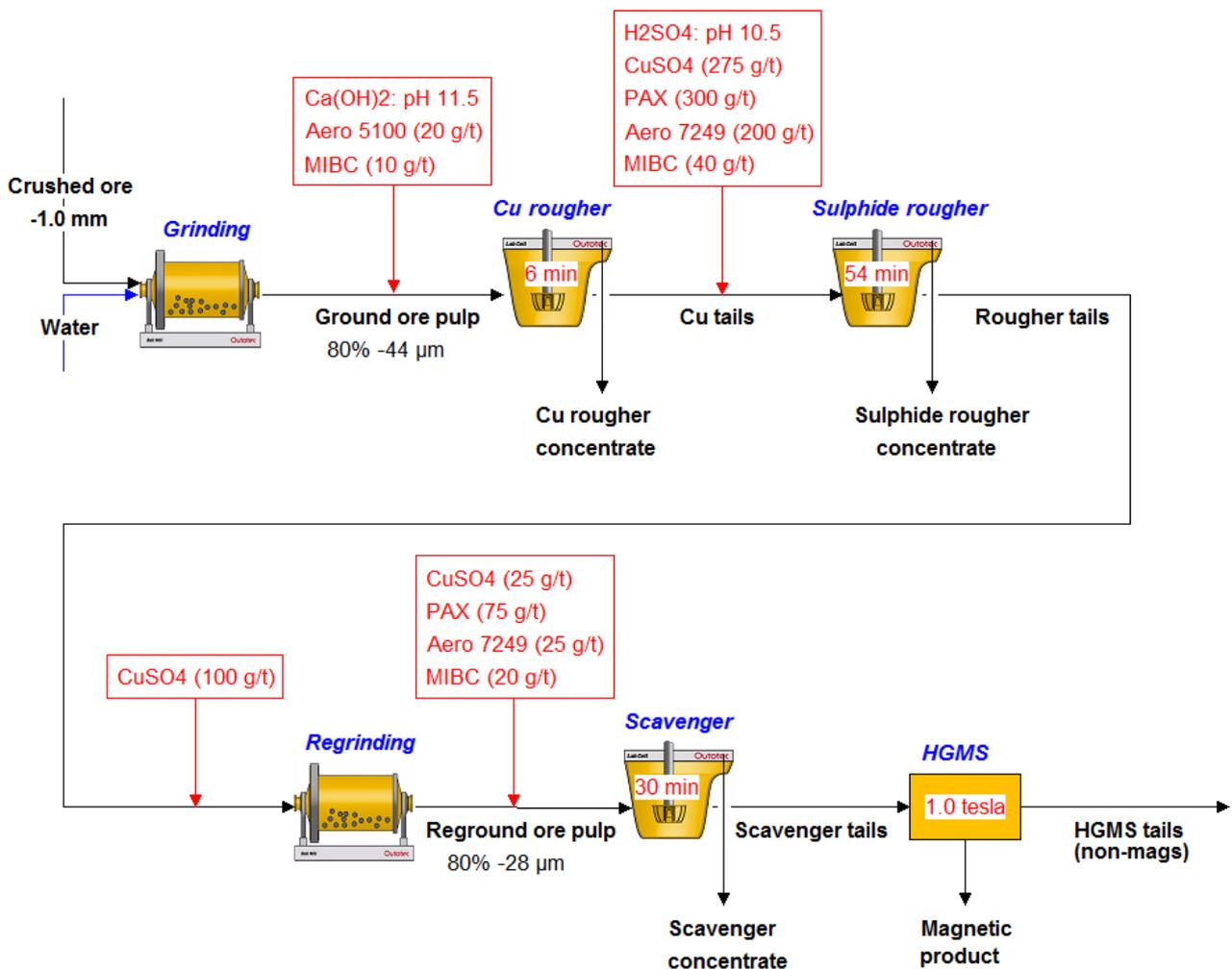


Fig. 8. Optimised flow sheet including selective copper and sulphide rougher flotation, regrinding and scavenger flotation of rougher flotation tailings, and high-gradient magnetic separation (HGMS). Grind size, total flotation times, pH regulators, and other flotation reagents with dosages are shown.

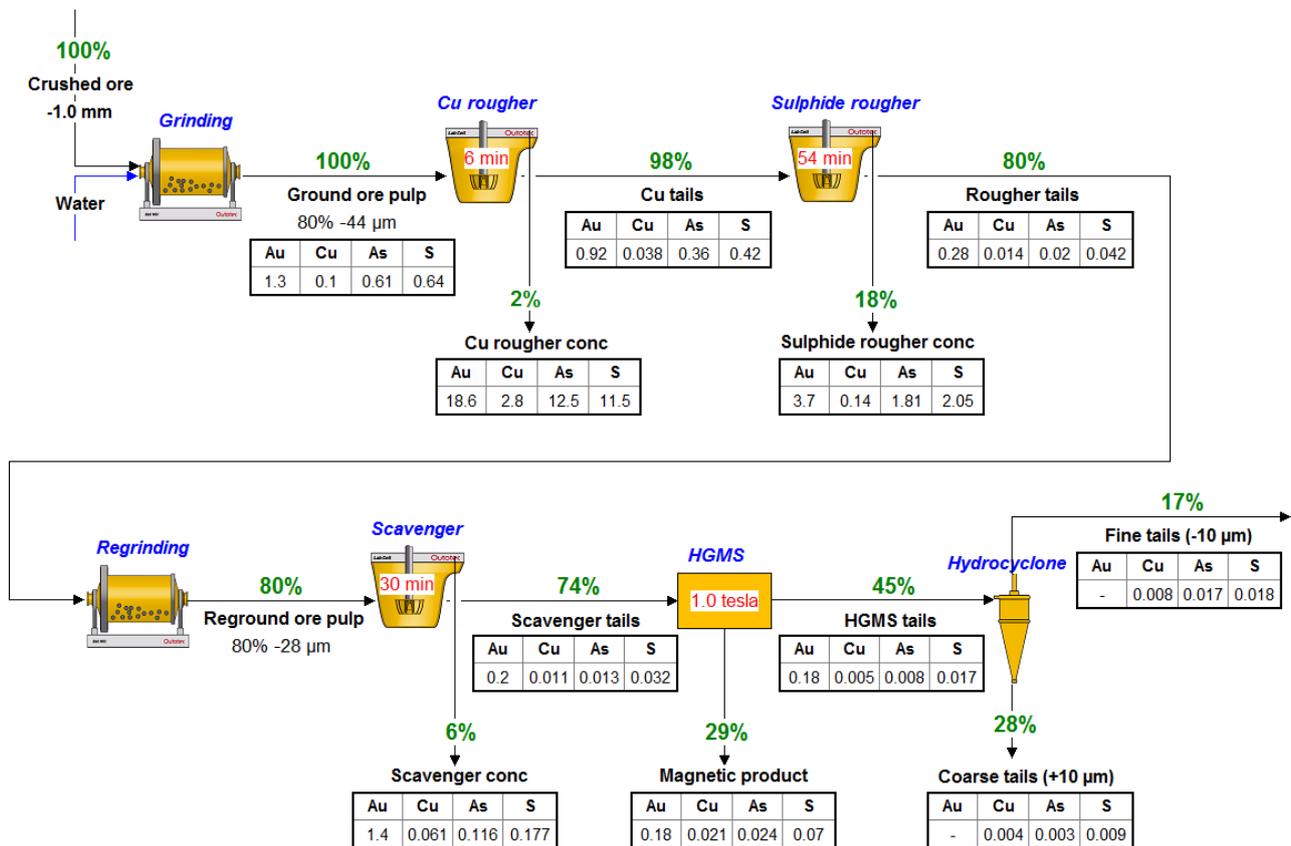


Fig. 9. Final flow sheet including classification of HGMS tailings into coarse and fine fractions by a hydrocyclone. The numbers in green denote mass of solids in each stream compared to the feed stream. Elemental assays in the streams are illustrated in the tables (Au in g/t, others in %).

particles of the HGMS tailings, it was inferred that classification could be utilised to produce a tailings fraction with even lower levels of arsenic. An elutriation process was applied to size the tailings. Arsenic concentration in the -10 μm fraction (36.7 Wt%) was analysed to be 0.014% by XRF (166 ppm by GFAAS), whereas As grade in the +10 μm fraction (63.3 Wt%) was as low as 0.001% by XRF (33 ppm by GFAAS). Thus, the coarse particles contained much less arsenic than the finest particles.

In the final process, it might be reasonable to separate the finest particles of the HGMS tailings by classification to generate waste with even lower levels of arsenic. The final flow sheet could look like the one in Figure 9 where a hydrocyclone is used to classify material into coarse and fine fractions. The mass of the coarse HGMS tailings is about 28% of the feed mass. It might be reasonable to combine the magnetic HGMS product and the fine HGMS tailings into another tailings fraction with mass of 46%, especially since their As concentrations are very similar. In continuous operation, one would probably return the scavenger concentrate to sul-

phide rougher flotation to increase the recovery of valuables into the sulphide rougher concentrate. As a result, three different tailings fractions would be formed during processing: the cyanide leach residue with high As content, combined magnetic HGMS product and fine HGMS tailings with low As content, and the coarse HGMS tailings with the lowest amounts of valuable and harmful elements.

Compared to the original flow sheet in Figure 4, the optimised flow sheet in Figure 9 is more complex and would cause higher costs for a concentrator due to longer sulphide flotation time (more/larger flotation cells), higher reagent consumption, regrinding, scavenger flotation, and a high-gradient magnetic separator. It should also be remembered that the mass percentages and elemental assays of the streams in Figure 9 were derived from open circuit, laboratory scale batch tests. In a continuous, industrial scale process including closed circuits these numbers could be different. A more accurate estimate of the tailings properties could be obtained by conducting a locked cycle test at the laboratory scale or, better, a test work at the pilot plant. The

continuous pilot-scale test run would also give information about energy consumption of various

process options, making it possible to compare the economics of various flow sheets.

6 IMPACTS OF PROCESS MODIFICATIONS ON THE ENVIRONMENTAL CHARACTERISTICS OF THE TAILINGS AND PROCESS WATER

Environmental characterisation of the Kopsa tailings and process waters was carried out to evaluate the influence of process modifications on their environmental properties and performance. The studies focused on the occurrence and long-term behaviour of arsenic, copper and sulphur in the

original versus modified tailings. In the following chapters, the main results of the environmental characterisation are discussed. Additional details of the results are provided in the report by Taskinen et al. (2018).

6.1 Influence on the properties of the Kopsa tailings

6.1.1 Chemical and mineralogical composition of the tailings and the occurrence of As-bearing minerals and sulphides

Based on the XRF results, the primary contaminants in the Kopsa tailings included As (0.01–0.03%), Cu (0.005–0.15%), and S (<0.01–0.09%). Concentrations of other potentially hazardous trace metals were low (<100 mg/kg), except for W. All the tailings were classified as non-inert mining waste, since the aqua regia leachable concentrations of As (106–292 mg/kg) exceeded the threshold value (5 mg/kg) of contaminated soils in the tailings (Government Decree 2007, 2013a). In addition, the Cu content (101–154 mg/kg) was above the threshold value (100 mg/kg) except for the HGMS tailings

(61 mg/kg). The total S content was, nevertheless, below the limit value (0.1%) for inert mining waste (Government Decree 2013a). Even though the trace metal concentrations were overall low, some of the trace metals occurred in elevated concentrations (e.g. Bi 5.7–10.6 mg/kg, Mo 0.2–2.7 mg/kg, W 116–162 mg/kg) compared e.g. with the fine fraction of Finnish tills (Koljonen 1992) or the subsoils in Europe (Salminen et al. 2005).

The highest aqua regia concentrations of As, Cu, and S occurred in the original Kopsa tailings (TAIL 0A), processed following the process by Belvedere Mining Oy, while the lowest were in the HGMS tailings (TAIL 3) (Fig. 10). Overall, the As content in the HGMS tailings was only one third of that in the original tailings, S content ca. 11%, and that

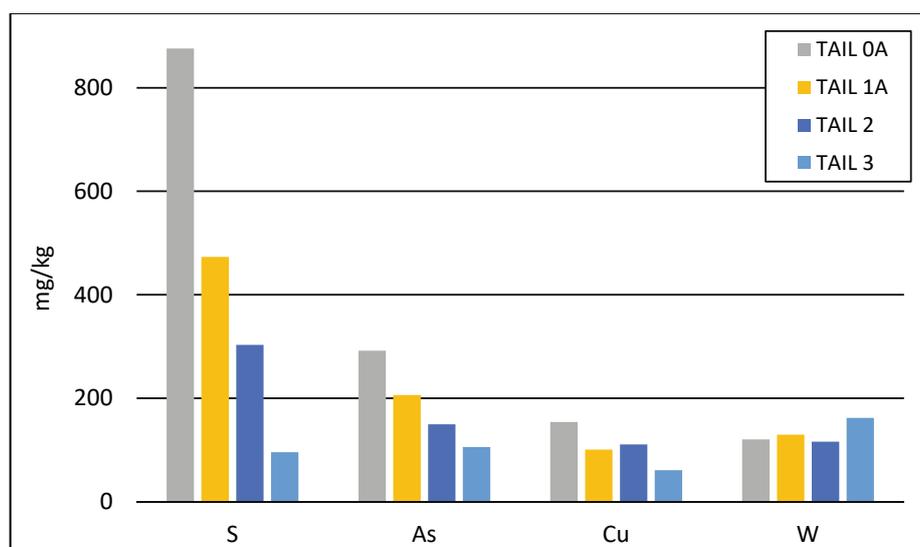


Fig. 10. Aqua regia leachable concentrations of S, As, Cu, and W in the Kopsa tailings. TAIL 0A = As-rich tailings from the original process, TAIL 1A = As-poor tailings from modified flotation, TAIL 2 = tailings from scavenger flotation, TAIL 3 = tailings from HGMS.

of Cu approximately 40%. This indicated that the modification of the process had been successful in reducing As, Cu, and S in the tailings. Interestingly, tungsten content (162 mg/kg) was, nevertheless, highest in the HGMS tailings. Despite the notable reduction of the As content during mineral processing, the HGMS tailings were still classified as non-inert mining waste, since the aqua regia leachable concentration of As was above the threshold limit of the contaminated soils.

The primary sources for As in the tailings included arsenopyrite (FeAsS), löllingite (FeAs₂) and arsenates, such as scorodite/parascorodite (FeAsO₄ · 2H₂O) and pharmacosiderite (KFe₄(AsO₄)₃(OH)₄ · 6H₂O) or arseniosiderite type (Ca₂Fe₃³⁺O₂(As₂O₄)₃) mineral. In addition, based on the microprobe analysis, goethite contained As (As₂O₅ 0.04–5.9%). The

main hosts for S, aside from the As-sulphides, were pyrrhotite, (FeS_{1-x}), chalcopyrite (CuFeS₂), pyrite (FeS₂), sphalerite (ZnS), covellite (CuS) and goethite. Cu originated mainly from chalcopyrite and covellite, and small amounts of Cu occurred also in goethite. The main source for W was scheelite (CaWO₄).

The mineralogical results showed that the reduced contents of As, Cu, and S in the HGMS tailings were a result of efficient removal of As-bearing mineral phases and sulphides with the modified process. Overall, the reduction of these minerals was notable: the amounts of As-bearing mineral phases decreased from 0.04% in the original tailings (TAIL 0A) to 0.002% in the HGMS tailings (TAIL 3), and those of sulphides from 0.09% to 0.005%, respectively (Fig. 11). Specifically, arseno-

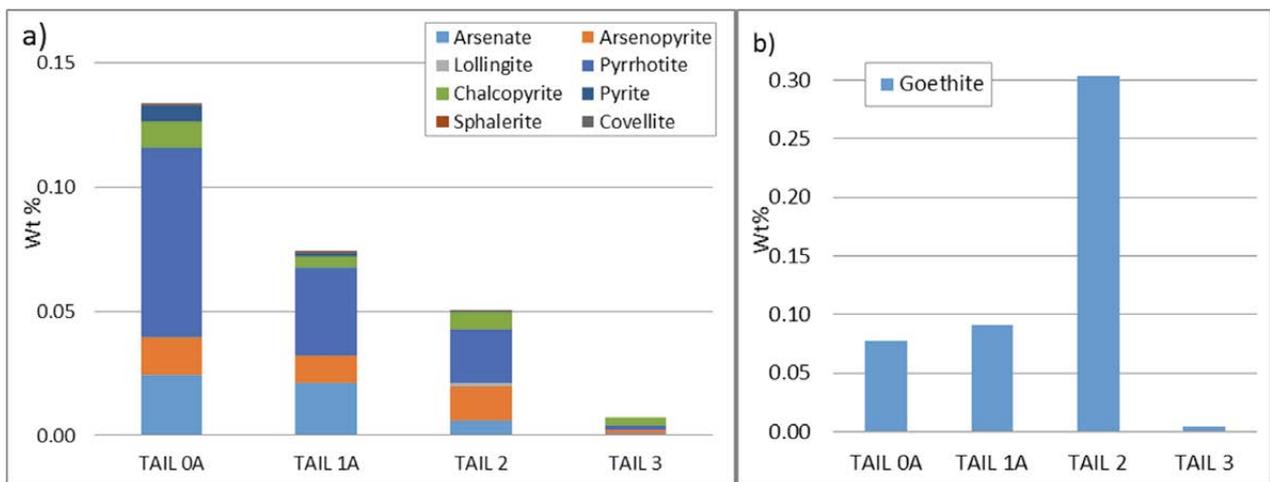


Fig. 11. Amounts of a) As and sulphide minerals and b) goethite in the Kopsa tailings. TAIL 0A = As-rich tailings from the original process, TAIL 1A = As-poor tailings from modified flotation, TAIL 2 = tailings from scavenger flotation, TAIL 3 = tailings from HGMS.

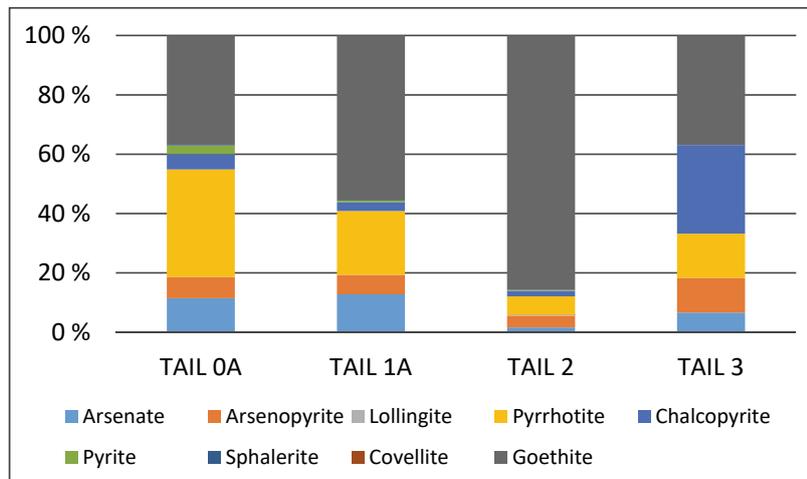


Fig. 12. Proportions of As-bearing minerals and sulphides in the Kopsa tailings. TAIL 0A = As-rich tailings from the original process, TAIL 1A = As-poor tailings from modified flotation, TAIL 2 = tailings from scavenger flotation, TAIL 3 = tailings from HGMS.

pyrite decreased from 0.015% to 0.001%, arsenates from 0.024% to 0.0007%, pyrrhotite from 0.08% to <0.002%, and chalcopyrite from 0.011% to 0.004%. In the HGMS tailings, goethite was the most abundant As-bearing mineral phase and also the most abundant source of Cu and S (Fig. 12).

Despite the successful removal of As and sulphide minerals, the scheelite content was somewhat higher in the HGMS tailings (0.05%) than in the original tailings (0.03%). In addition to As, W is a toxic metal and its aqua regia concentration was clearly elevated in the HGMS tailings (162 mg/kg) e.g. with respect to the concentration in Finnish tills (0.2 mg/kg, Koljonen 1992). The enrichment of W is most likely due to the fact that scheelite is heavy mineral (Koljonen 1992 and references therein), and as such ends up in the waste fraction. Similar concentrations of W have been observed in the tailings of the closed Ylöjärvi Cu–W–As mine (Parviainen et al. 2012).

Degree of liberation, grain size and mineral associations of the As-bearing mineral phases and sulphides were further studied to evaluate impacts of process modifications on their reactivity. Based on the results, these minerals occurred in the tailings mainly as well liberated grains in the finest fraction, but partly also associated with silicate minerals. In the HGMS tailings (TAIL 3), the portion of both As minerals and sulphides associated with silicates was slightly higher than in the original tailings (TAIL 0A), decreasing their liberation and also reactivity.

6.1.2 Leachability of As, Cu, and S from the tailings

Effects of process modifications on the distribution of As, Cu, and S in different mineral phases and their mobility were evaluated based on selective extractions, leaching tests (SFS EN 12457-3, SFS EN 14405) and leachates from NAG test.

The results of the selective extractions showed that both As and Cu were distributed in the tailings quite evenly mainly in three fractions: sulphide, oxalate, and acetate fractions, while S was mainly present in the sulphide fraction (Fig. 13). Small portion of S occurred also in the oxalate and soluble fractions. The sulphide bound As originated from arsenopyrite and löllingite, Cu from chalcopyrite and covellite, and S from sulphides in general. The oxalate and acetate fractions most likely represented As and Cu in goethite and (secondary) arsenates (cf. e.g. Parviainen et al. 2012). The host for S in the oxalate fraction was also goethite, while the soluble fraction of S was presumably largely from H_2SO_4 and $CuSO_4$ used in mineral processing (cf. Heikkinen 2009), but also from the sulphide mineral edges broken during processing (cf. Räisänen et al. 2002).

The distributions of As, Cu, and S clearly changed as a result of process modifications. In the original tailings (TAIL 0A), the sulphide fraction was the primary fraction for all these elements (As 49%, Cu 69%, and S 84%), but in the HGMS tailings (TAIL 3) the proportion of the sulphide fraction was noticeably smaller, particularly for As (As 33%, Cu 58%, S 71%). Instead, higher percentage of As, Cu, and S occurred in the HGMS tailings in the oxalate and acetate fractions (As 66%, Cu 41%, S 16%), i.e. in goethite and arsenates, than in the original tailings (As 49%, Cu 31%, S 8%). This change is in line with the mineralogical results according to which goethite was the most abundant host for these elements in the HGMS tailings (cf. Fig. 12). Unlike sulphide minerals whose dissolution is strongly dependent on oxygen availability, the solubility of goethite and arsenates is pH dependent and also relies on the crystallinity of these mineral phases (Paktunc & Bruggeman 2010). For example, synthetic scorodite has higher solubility at low (<2) and high pH (>6)

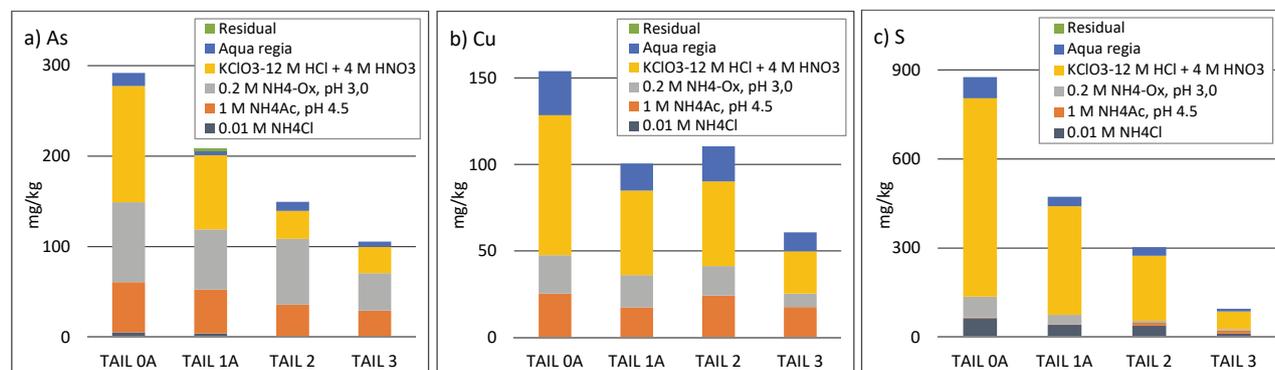


Fig. 13. Distribution of a) As, b) Cu, and c) S in different fractions based on selective extractions.

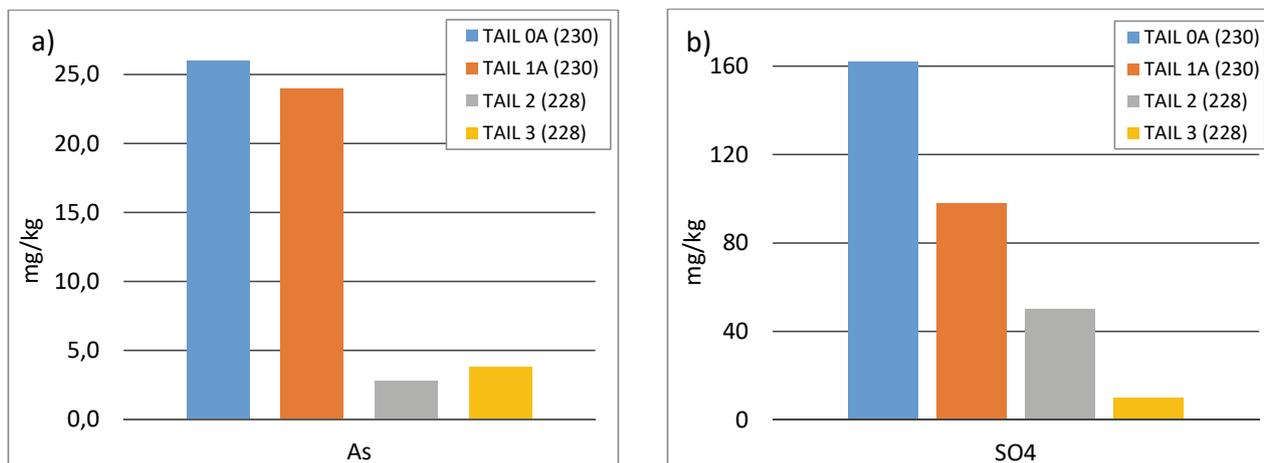


Fig. 14. a) As and b) SO₄ concentrations of the Kopsa tailings based on the leaching tests. TAIL 0A = As-rich tailings from the original process, TAIL 1A = As-poor tailings from modified flotation, TAIL 2 = tailings from scavenger flotation, TAIL 3 = tailings from HGMS. (230 = SFS-EN 14405, 228 = SFS-EN 12457-3).

than at around pH 3–4. The dissolution rate of e.g. Fe arsenates has been found to be slower than that of sulphides (Paktunc & Bruggeman 2010). Therefore, it seems that in the HGMS tailings As, Cu, and S are less mobile with respect to mineral oxidation than in the original tailings, but their leaching is more susceptible to changes in pH than initially.

The leaching tests and analysis of NAG leachate were further applied to evaluate mobility of As, Cu, and S/SO₄ as well as other trace elements from the tailings. Based on the tests, the leaching solutions and the NAGpH of all the tailings were alkaline (leaching tests: pH 9.0–9.3 (only TAIL 2 and TAIL 3); NAG leachate: 7.9–8.7). The tests showed leaching of mainly As and S together with dissolved organic carbon from all the tailings. In the NAG tests also some W was leached. Concentrations of other trace metals were mainly under detection limits, which is in accordance with the alkaline pH. The alkaline pH decreases mobility of most of the trace metals that occur in solution as cations (e.g. Cu, Ni, Zn), but increases that of metals/semimetals that

occur in anionic form, such as As, Mo, and W (e.g. Stumm & Morgan 1996, Bednar et al. 2009). The organic carbon most likely originated from residues of organic process chemicals used in mineral processing and is not discussed here any further. Results of these chemical residues are discussed in more detail in the report by Taskinen et al. (2018).

The process modifications clearly decreased the leaching of As and S from the Kopsa tailings (Fig. 14). Based on the leaching tests, leaching of As had decreased by ca. 85% and that of sulphate by ca. 94% from the original tailings to the HGMS tailings. Despite this, As concentration (3.8 mg/kg) in the leaching test solution (at L/S ratio 10) of the HGMS tailings exceeded e.g. the limit value (2 mg/kg) set by the European Council (2003) for the non-hazardous waste disposed at landfill sites (cf. also Government Decree 2013b). However, this was still a notable improvement, since in the original tailings the limit value for the hazardous waste (25 mg/kg) was exceeded (26 mg/kg).

6.2 Influence on the process water quality

In addition to the tailings solid, the impact of process modifications on the quality of process water was evaluated. Overall, the process waters were alkaline (pH 8.2–10.1) and contained elevated concentrations of As (33–775 µg/l) and SO₄ (37–310) with minor Mo, I, and B. The process modifications had similar effects on the process waters as were observed in the tailings quality and their leaching properties. Namely, the reduction of As and

SO₄ content in the process water from the original process to the HGMS process was notable (Fig. 15), being 96% for As and 89% for SO₄. This indicates that the efforts made to improve the tailings quality also affected positively the process water quality. However, part of the reduction in the concentrations is also due to dilution, since more water was used in the HGMS process than in the original process.

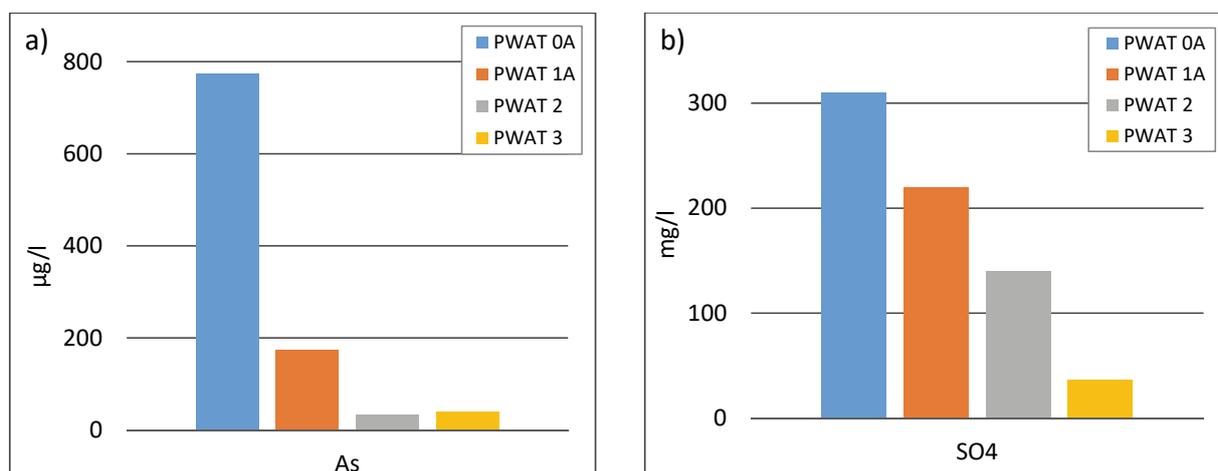


Fig. 15. As and SO₄ concentrations in the process waters from the Kopsa tailings. PWAT 0A = process water of the As-rich tailings from the original process, PWAT 1A = process water of the As-poor tailings from the modified flotation, PWAT 2 = process water of the tailings from scavenger flotation, PWAT 3 = process water of the tailings from HGMS scavenger flotation.

7 FILLED-IN LYSIMETER TESTS TO EVALUATE LONG-TERM BEHAVIOUR OF THE MODIFIED TAILINGS

Filled-in lysimeter test were carried out to study the effects of process modifications on the long-term behaviour of the tailings. In addition, suitability of the modified tailings for a cover material on top of other tailings was assessed.

The tailings used in the filled-in lysimeters included the As-rich tailings (TAIL 0A) from the original process of the sorted ore (Fig. 4) and

As-poor tailings (TAIL 1A) from the modified process (Fig. 5). Both tailings were non-inert, not acid generating mining waste (see above). The As-poor tailings were used in the lysimeter tests instead of the HGMS tailings (Fig. 8) or the coarse fraction of the HGMS tailings (Fig. 9), because they had the lowest As content at the time when the lysimeter test was set up.

7.1 Characteristics of the tailings of the lysimeter tests

Prior to the lysimeter tests, mineralogical and chemical characterisation of the tailings materials was carried out to describe material properties as a background for the interpretation of the test results. In the following, the main results of the characterisation are presented with an emphasis on the marked differences between the two lysimeter materials.

7.1.1 Tailings mineralogy

The differences in the occurrence of the As bearing minerals in the two tailings were rather small. The As-poor sample contained slightly smaller amount of arsenic minerals (arsenopyrite 0.01% and Fe arsenate 0.02%) than the As-rich tailings (both As minerals were 0.02%), but the As-poor tailings contained somewhat more goethite (0.09%) than

the As-rich tailings (0.08%). The sulphide mineral content of the As-rich tailings was higher (0.09%) than that of the As-poor tailings (0.04%). The carbonate content of both tailings was very similar.

The As minerals were in both tailings mainly well liberated and occurred as free grains (liberation degree approximately 90%; except for arsenopyrite 82% in the As-rich tailings). The rest of the As minerals were locked in silicates. The major difference between the two tailings was that in the As-poor tailings arsenate occurred clearly in higher portion as free mineral surfaces (97.5% as free surfaces and only 2% associated with silicates) than in the As-rich tailings (91.4% and 8.3% associated with silicates). In addition, in the As-poor tailings part of the arsenate occurred in association with unliberated mixed particles with Fe-hydroxides, but not in the As-rich tailings.

Furthermore, the As-poor tailings were somewhat finer grained (75% <32 µm) than the As-rich tailings (60% <32 µm), but the grain size of arsenate and arsenopyrite was the opposite way around.

The particle size distribution may affect the leaching of elements from the tailings, since fine grained material can retain more water, thus conducting it slower, which further affects weathering conditions.

7.1.2 Tailings chemistry

Based on the total concentrations and aqua regia leachable concentrations of the lysimeter tailings, the concentrations of As and S and several trace metals were clearly smaller in the As-poor tailings than in the As-rich tailings (Table 3). Particularly, As content had decreased from 300 mg/kg to 200 mg/kg, and S from 900 mg/kg to 500 mg/kg. Also Co, Cr, Cu, Ni, and Mo contents were lower in the As-poor tailings (Table 3).

Based on the selective extractions, most notable difference between the two tailings was in the distributions of As, Co, Cr, Ni, and Mo in different fractions (Fig. 16). For example, higher portion of As occurred in the acetate and oxalate fraction in the As-poor tailings than in the As-rich tailings, in which most of the As was in sulphides. This is in

line with the observations from the mineralogy. The As-poor tailings contained less arsenopyrite, but had same amount of arsenate and higher goethite content than the As-rich tailings. The latter minerals dissolve in oxalate extraction (cf. Dold 2003, Parviainen et al. 2012).

Both tailings showed elevated leaching of As and S in the leaching test (SFS-EN 14405) and the NAG test. However, in the NAG test the content of leachable As and S were clearly smaller in the As-poor tailings (As 37 mg/kg and S 433 mg/kg) than in the As-rich tailings (51 mg/kg and 799 mg/kg, respectively). In the leaching test, the As content in the As-rich tailings (26 mg/kg) exceeded the limit value set by the European Council (2003; also Government decree 2013b) for the hazardous waste (25 mg/kg) to be disposed in landfills, but in the As-poor tailings the content was only slightly lower (24 mg/kg), exceeding the limit value for the non-hazardous waste (2 mg/kg).

Process water quality was further analysed from both tailings samples. Both waters were alkaline in pH (8.7 and 10.1) and showed elevated concentrations of As, SO₄ and Mo (Table 4). Overall, pH, electrical conductivity and concentrations of As, SO₄ and Mo were higher in the As-rich tailings water than in the process water from the As-poor tailings (Table 4).

Table 3. Aqua regia leachable and total concentrations of selected elements in the As-poor and As-rich tailings (mg/kg). * P from the XRF-method has been calculated from P₂O₅ results. Values exceeding the threshold value of contaminated soils (Government Decree 2007) are marked with green shading, those over the lower limit value with yellow, and those exceeding the upper limit value with red shading. (Tail = tailings).

(mg/kg)	As	Cd	Co	Cr	Cu	Mn	Mo	Ni	P	Pb	S	Sb	V	W	Zn
XRF-method (Total)															
As-poor tail	205	n.a.	n.a.	30	102	286	<10	<20	369*	<20	505	<100	71	n.a.	42
As-rich tail	310	n.a.	n.a.	40	149	278	<10	<20	331*	<20	919	<100	72	n.a.	43
Aqua regia 90 °C (AR)															
As-poor tail	206	0.1	1.6	24.6	101	228	1.3	8.3	308	3.6	473	1.3	52	130	26
As-rich tail	292	0.1	2.2	29.8	154	230	2.7	15.8	310	4.2	876	1.6	52	121	28

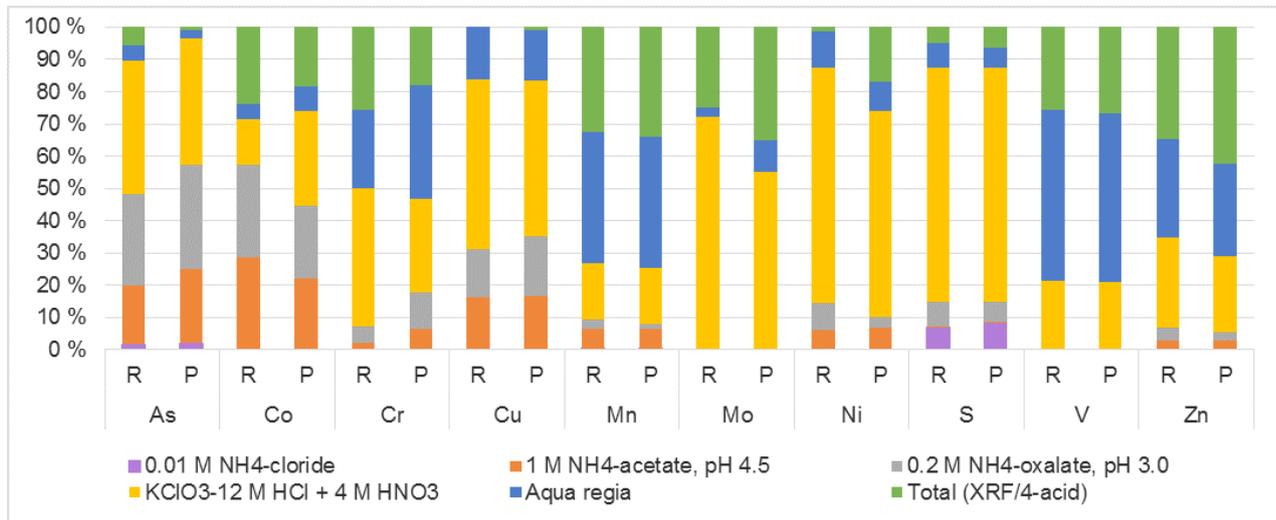


Fig. 16. Relative distribution of selected elements in different fractions based on selective extractions. P = As-poor tailings and R = As-rich tailings.

7.2 Results of the one and a half years of seepage monitoring

The quality of the drainage water from the lysimeters was monitored six times during the observation period of one and a half years. The drainage from both lysimeters was alkaline (7.1–8.0) and their electrical conductivity (EC) indicated elevated content of dissolved ions (Fig. 17). The alkaline pH was expected as the beneficiation process was carried out at alkaline pH, and the tailings materials were unoxidised and contained only minor sulphides. The pH values did not depend much on the lysimeter or the sampling time. The electrical conductivity (EC) suggested higher leaching of ions in the beginning of the monitoring period in the As-rich drainage than in the As-poor drainage, but towards the end

of the monitoring period the EC reached the same level in both drainages (ca. 40 mS/m). Redox potentials of both drainages decreased towards the end of the observation period being negative in the last measurement, thus suggesting a more reducing environment (Fig. 17). The alkalinity and oxygen ratios remained at the same level in both lysimeter drainage waters throughout the monitoring period.

Overall, the drainage waters contained elevated concentrations of As, SO₄, Mn, Mo, and P, while contents of Sb, Cu, and Ni were low (Figs. 18 and 19). This is in line with the tailings chemistry and the fact that alkaline pH of the lysimeter drainages increases the mobility of oxyanions like arsenate,

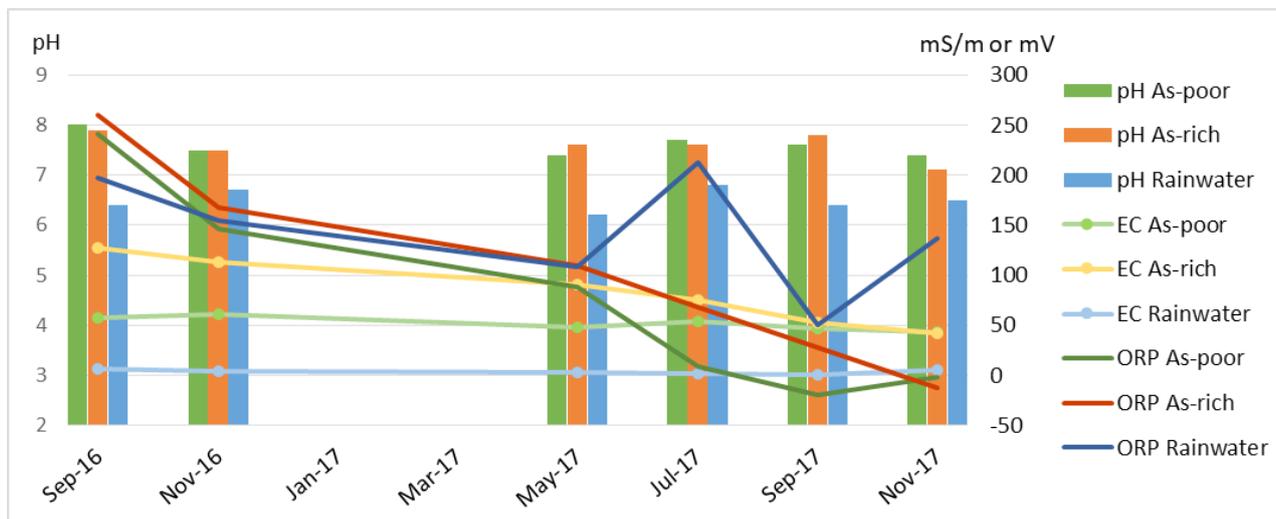


Fig. 17. pH, redox potential (ORP, mV), and electrical conductivity (EC, mS/m) in the As-poor and As-rich seepage waters and in the control lysimeter (rainwater).

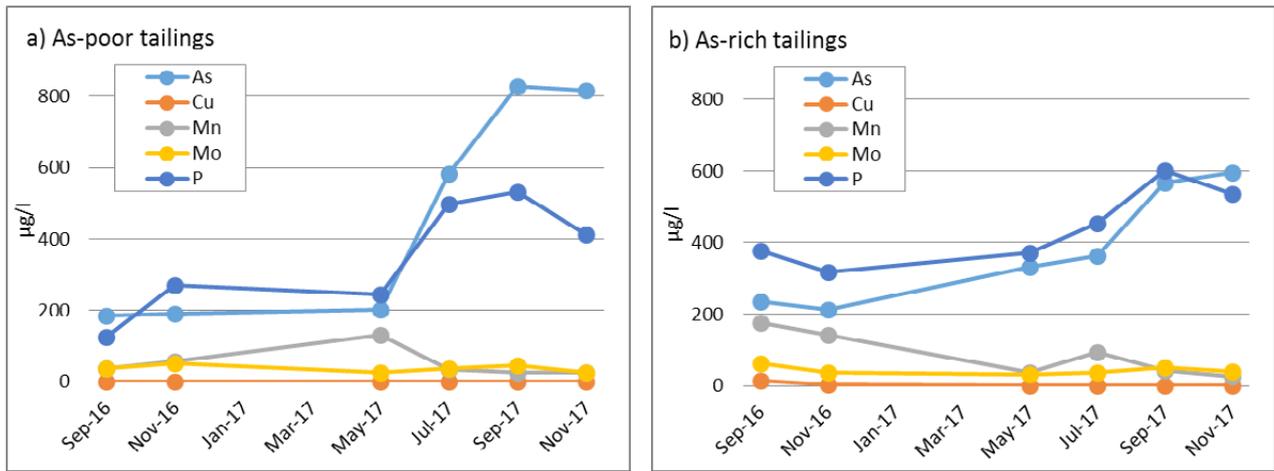


Fig. 18. Concentrations of As, Cu, Mn, Mo, and P in the drainage of the lysimeters of a) As-poor and b) As-rich tailings.

phosphate and molybdenate (cf. Stumm & Morgan 1996). The concentrations of these elevated compounds were clearly higher in the drainage from the As-rich lysimeter than from the As-poor lysimeter at the beginning of the test, which was expected based on the characteristics of the tailings in the lysimeters. Towards the end of the monitoring period, concentrations of SO_4 , Mn and Mo mainly decreased in the drainage from As-rich lysimeter reaching similar levels as the drainage from the As-poor lysimeter at the end. The concentrations of As and P nevertheless steadily increased. However, their concentrations also increased abruptly in the drainage from the As-poor lysimeter, and at the end of the monitoring period the As content (817 µg/l) eventually exceeded that of the drainage from the As-rich lysimeter (596 µg/l) (Fig. 18). During the

whole monitoring period, As concentrations in the drainages were much higher than for example the As threshold 10 µg/l for household consumption water (Decree of Ministry of social affairs and health 2015).

Table 4 emphasises the differences in the drainage quality from the lysimeters between the first three (from 9/2016 to 5/2017) and last three (from 7/2017 to 11/2017) analysis results (average concentrations of soluble concentrations of three measurements) to evaluate a possible first flush effect and longer term behaviour. In addition, the table shows the chemical assays of process waters from both tailings slurries to assess whether the remaining process water had influenced the lysimeter drainage quality. Overall, concentrations of most of the elements were higher in the first measurement period than in the last period suggesting the influence of

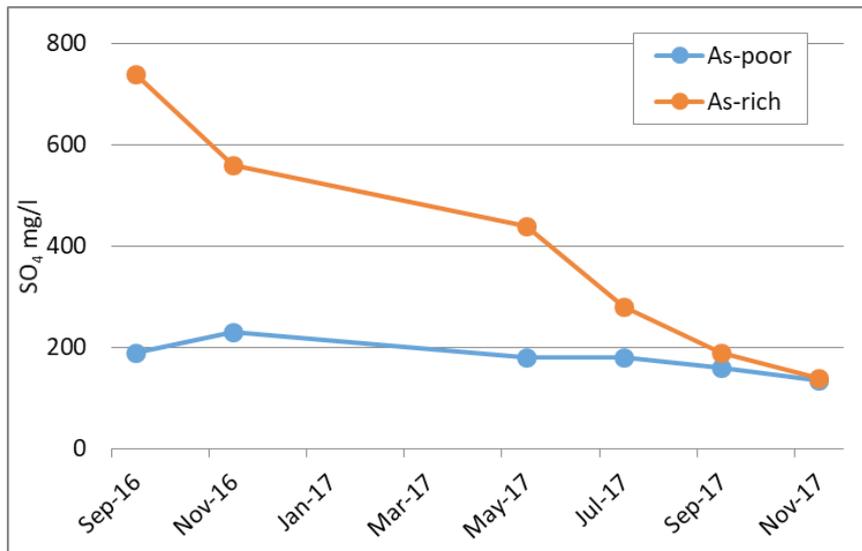


Fig. 19. SO_4 concentrations in the drainage of the lysimeters of As-poor and As-rich tailings.

Table 4. Average concentrations of seepage waters from the lysimeters of As-poor and As-rich tailings of two monitoring periods. Red shadings emphasise the monitoring period (I or II) with higher concentrations, the numbers in bold the lysimeter drainage (As-poor or As-rich) with higher concentrations and the green shadings notably elevated concentrations in the tailings water. (TW = Tailings water, I period = average of 3 seepage samples from 09/2016–05/2017 and II period = average of 3 seepage samples from 07/2017–11/2017.)

µg/l	As	Co	Cr	Cu	Mn	Mo	Ni	P	Sb	U	V	Zn	Al	S	
As-rich	TW	775	0.03	1.8	<0.5	1.4	55	<0.5	4	<2	0.02	4	<1	337	344 000
	I	260	0.2	<0.2	5.8	118	43	1.6	355	11	7.6	0.2	1	18	181 000
	II	508	0	<0.2	0	54	42	0.2	530	6	0.4	0.2	1.8	23	70 000
As-poor	TW	174	0.02	<0.1	<0.5	4	21	0.6	2	<2	0.3	1	<1	77	269 000
	I	193	0.1	<0.2	0.6	74	38	0.4	214	10	2	0.2	4.9	17	71 000
	II	743	0	<0.2	0	28	36	0.1	482	8	0.4	0.1	0.5	23	57 000

first flush. The most notable exception was nevertheless As with the highest content in the last period (Table 4). Influence of the process water seemed to be quite minor, even in the first measurement period (Table 4).

Based on the seepage monitoring results, both tailings are prone to produce neutral drainage with high As concentration. Unexpectedly, the As-poor tailings produced eventually drainage with higher As content during the observation period than the As-rich tailings. Both soluble and total concentrations of all the other elements were low in the seepage.

The higher solubility of As from the As-poor tailings is most likely caused by the differences in the association, liberation and grain size of the As-bearing minerals, or better fracturing due to finer grind size. The grain size distributions of arsenopyrite and arsenates were finer in the As-rich lysimeter, which should have an opposite effect to arsenic weathering and mobility. However, in the As-poor tailings arsenates had more free surface area (ca. 7% more) and were less extensively associated with silicates (2.0%) than in the As-rich tailings (8.3%).

The elevated As concentration in seepage after one year of observation suggests that mineral

weathering reactions had eventually started in the tailings, even though part of the As also originated from the broken edges of As minerals. However, the increased SO₄ concentrations at the beginning of the monitoring period most likely originated mainly from the residues of processing chemicals, such as H₂SO₄ and CuSO₄, and from the mineral edges broken in the processing, instead of sulphide oxidation. This is particularly since the sulphide content of the tailings was quite small and mineral grains were unoxidised at the beginning of the tests. During the tests, alkaline pH favours dissolution of arsenates (cf. Paktunc & Bruggeman 2010). In addition to the reasons mentioned above, the higher solubility of arsenic in the As-poor lysimeter can result from differences in water content, adsorption properties, hydraulic conductivity, pore size and quantity of tailings in the lysimeters. Seasonal variation in seepage concentrations, for instance as a result of an accelerated oxidation and increased element mobility, were not observed in this study. Overall, it is obvious that the As-poor tailings are not suitable for a cover material. Further studies and more sampling is nevertheless needed to confirm these observations and to predict long-term behaviour of the tailings.

8 CONCLUSIONS

Laboratory scale beneficiation tests were carried out to assess the suitability of various mineral processing techniques to improve environmental properties of tailings from the Kopsa Au–Cu ore samples. The influence of process modifications on the tailings was studied using mineralogical and geochemical

characterisation together with filled-in lysimeters which measured long-term behaviour together with drainage quality in field conditions.

The most promising process to reduce arsenic and sulphide minerals from the original, As-rich tailings consisted of froth flotation followed by

high-gradient magnetic separation (HGMS). The results showed that for example very fine grinding, long flotation time, and high magnetic fields were required to liberate and recover most of the harmful and valuable minerals. Sizing the HGMS tailings by classification could be a further option to produce a tailings fraction with even lower levels of arsenic.

Process development had a significant effect on the mineralogy, chemical composition and leaching of contaminants from the tailings. Successful removal of As minerals and sulphides from the tailings had resulted in more than 60% reduction in the content of As and almost 90% of S, and some 40% of Cu. In addition, leaching of As and SO₄ had decreased by ca. 85% and 94%, respectively. This was a major improvement, since even though the HGMS tailings were still classified as non-inert mining waste, the leaching of As had decreased from the level of hazardous waste to that of non-hazardous waste. The efforts made to improve the tailings quality also affected positively the process water quality, even though part of the reduction was due to a higher water amount in the HGMS process.

Filled-in lysimeter tests were performed to evaluate long-term behaviour of the original, As-rich tailings and the so-called As-poor tailings from a modified process. The results indicated that leaching of most elements in the drainage water

decreased as a function of time during the monitoring period of one and a half years. Furthermore, leaching of hazardous elements was generally less pronounced from the As-poor tailings. An interesting exception to this was arsenic. After one year of seepage monitoring, its concentration in the seepage from the As-poor lysimeter increased substantially and stayed higher than the As content of the seepage from the As-rich lysimeter for the rest of the monitoring period. This was most likely due to the changes in As mineral species and their liberations and associations in the tailings. Further studies and more sampling is needed to confirm this observation and to predict the long-term behaviour. Overall, the As-poor tailings proved unsuitable for a cover material. Instead, the environmental properties of HGMS tailings suggested that they could be suitable for a cover.

While the batch tests can provide information on possible ways to reduce harmful minerals from tailings, mini-pilot or pilot scale testing would be needed to provide the optimum conditions for removing the target minerals in a continuous, commercial plant. Economic pros (e.g. benefits in waste management) and cons (e.g. increased costs for energy, process chemicals, and equipment) should also be assessed during the pilot tests.

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REFERENCES

- Ahma ympäristö Oy 2013.** Belvedere Mining Oy. Kopsan kaivos ja Hituran rikastamon toiminnan muutokset – ympäristövaikutusten arviointiohjelma. Ahma ympäristö Oy. 121 p. (in Finnish) Available at: <http://www.ymparisto.fi/download/noname/%7B719ACCCE-FF59-4F7F-A4B2-AB83AE621B23%7D/96521>
- AMIRA 2002.** ARD Test Handbook. Project P387A, Prediction & Kinetic Control of Acid Mine Drainage. AMIRA international May 2002. 42 p.
- Asselin, E. & Shaw, R. 2016.** Developments in arsenic management in the gold industry. In: Adams, M. D. (ed.) Gold ore processing: project development and operations. Amsterdam: Elsevier, 739–751.
- Bednar, A. J., Boyd, R. E., Jones, W. T., McGrath, C. J., Johnson, D. R., Chappel, M. A. & Rinelberg, D. B. 2009.** Chemosphere 75(8), 1049–56. Available at: doi: [10.1016/j.chemosphere.2009.01.039](https://doi.org/10.1016/j.chemosphere.2009.01.039)
- Benzaazoua, M. & Kongolo, M. 2003.** Physico-chemical properties of tailing slurries during environmental desulphurization by froth flotation. International Journal of Mineral Processing 69, 221–234.
- BRGM 2001.** Management of mining, quarrying and ore-processing waste in the European Union. 79 p.
- Briggs, P. H. 2002.** The determination of forty elements in geological and botanical samples by inductively coupled plasma-atomic emission spectrometry. In: Taggart, J. E. (ed.) Analytical methods for chemical analysis of geologic and other materials. U.S. Geological Survey, U.S. Department of the Interior, Open-File Report 02-223, Chapter G. Available at: https://pubs.usgs.gov/of/2002/ofr-02-0223/Go1fortyelementICP-AESsolid_M.pdf
- Briggs, P. H. & Meier, A. L. 2002.** The determination of forty-two elements in geological materials by

- inductively coupled plasma-mass spectrometry. In: Taggart, J. E. (ed.) *Analytical methods for chemical analysis of geologic and other materials*. U.S. Geological Survey.
- Choi, J., Park, K., Hong, J., Park, J. & Kim, H. 2013.** Arsenic removal from mine tailings for recycling via flotation. *Materials Transactions* 54, 2291–2296.
- Decree of Ministry of social affairs and health 2015.** Decree of Ministry of social affairs and health relating to the quality and monitoring of water intended for human consumption. STM 1352/2015. Adopted in Helsinki on 17th November 2015. Appendix 1. (in Finnish)
- Dold, B. 2003.** Speciation of the most soluble phases in a sequential extraction procedure adapted for geochemical studies of copper sulfide mine waste. *Journal of Geochemical Exploration* 80, 55–68.
- Doležal, J., Provondra, P. & Šulcek, Z. 1968.** Decomposition techniques in inorganic analysis. London: Iliffe Books Ltd. 224 p.
- Fosso-Kankeu, E., Waanders, F., Mulaba-Bafubandi, A. & Sidu, S. 2015.** Leachability of Suspended Particles in Mine Water and Risk of Water Contamination. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) 10th ICARD & IMWA 2015 Conference – Agreeing on solutions for more sustainable mine water management”, Santiago, Chile 2015. Available at: https://www.imwa.info/docs/imwa_2015/IMWA2015_Fosso-Kankeu_286.pdf
- Gaál, G. & Isohanni, M. 1979.** Characteristics of Igneous Intrusions and Various Wall Rocks in Some Precambrian Porphyry Copper-Molybdenum Deposits in Pohjanmaa, Finland. *Economic Geology* 74, 1198–1210.
- Government Decree 2007.** Government Decree on the Assessment of Soil Contamination and Remediation Needs 214/2007. Adopted in Helsinki on 1 March 2007. Available at: <https://www.finlex.fi/fi/laki/kaannokset/2007/en20070214.pdf>
- Government Decree 2013a.** Government Decree on Extractive Waste 190/2013. Adopted in Helsinki on 14 March 2013. Available at: https://www.finlex.fi/fi/laki/kaannokset/2013/en20130190_20150102.pdf
- Government Decree 2013b.** Government Decree on Landfills 331/2013. Adopted in Helsinki on 2 May 2013. Available at: https://www.finlex.fi/fi/laki/kaannokset/2013/en20130331_20160960.pdf
- Hall, G. E. M., Vaive, J. E., Beer R. & Hoashi, M. 1996.** Selective leaches revisited, with emphasis on the amorphous Fe oxyhydroxide phase extraction. *Journal of Geochemical Exploration* 56, 59–78.
- Heikkinen, P. M. 2009.** Active sulphide mine tailings impoundments as sources of contaminated drainage: controlling factors, methods of characterization and geochemical constraints for mitigation. Espoo: Geological Survey of Finland. 38 p. Available at: http://tupa.gtk.fi/julkaisu/erikoisjulkaisu/ej_076_synopsis.pdf
- Heikkinen, P. M. & Räsänen, M. L. 2008.** Mineralogical and geochemical alteration of Hitura sulphide mine tailings with emphasis on nickel mobility and retention. *Journal of Geochemical Exploration* 97, 1–20.
- Koljonen, T. (ed.) 1992.** The Geochemical Atlas of Finland. Part 2: Till. Espoo: Geological Survey of Finland. 218 p. Available at: http://tupa.gtk.fi/julkaisu/erikoisjulkaisu/ej_008.pdf
- Liu, Y.-G., Zhou, M., Zeng G.-M., Wang, X., Li, X., Fan, T. & Xu, W.-H. 2008.** Bioleaching of heavy metals from mine tailings by indigenous sulfur-oxidizing bacteria: Effects of substrate concentration. *Bioresource Technology* 99, 4124–4129.
- Lv, C. C., Ding, J., Qian, P., Li, Q. C., Ye, S. F. & Chen, Y. F. 2015.** Comprehensive recovery of metals from cyanidation tailing. *Minerals Engineering* 70, 141–147.
- MEND 1991.** Acid rock drainage prediction manual. Canmet – MSL Division, Department of Energy, Mines and Resources, Canada. MEND project 1.16.1b. 77 p.
- Nurmi, P. 1991.** Geological setting, history of discovery and exploration economics of Precambrian gold occurrences in Finland. *Journal of Geochemical Exploration* 39, 273–287.
- Pactunc, D. & Bruggeman, K. 2010.** Solubility of nanocrystalline scorodite and amorphous ferric arsenate: Implications for stabilization of arsenic in mine wastes. *Applied Geochemistry* 25, 674–683.
- Parviainen, A., Isosaari, P., Loukola-Ruskeeniemi, K., Nieto, J. M. & Gervilla, F. 2012.** Occurrence and mobility of As in the Ylöjärvi Cu–W–As mine tailings. *Journal of Geochemical Exploration* 114, 36–45.
- Price, W. A. 2003.** Challenges posed by metal leaching and acid rock drainage, and approaches used to address them. In: Jambor, J. L., Blowes, D. W. & Ritchie, A. I. M. (eds) *Environmental aspects of mine wastes*. Mineralogical Association of Canada, Short Course Series, Vol. 31, 15–30.
- Price, W. A., Morin, K. & Hutt, N. 1997.** Guidelines for prediction of acid rock drainage and metal leaching for mines in British Columbia: Part II. Recommended procedures for static and kinetic tests. Fourth International Conference on Acid Rock Drainage. Vancouver, B.C. Canada, May 31–June 6, 1997. Proceedings, vol. I, 15–30.
- Räsänen, M. L., Hämäläinen, L. & Westerberg, L. 1992.** Selective extractions and analysis of metals in organic stream sediments. *Analyst* 117, 623–627.
- Räsänen, M. L., Kauppila, P. M. & Myöhänen, T. 2010.** Suitability of static test for acid rock drainage assessment of mine waste rock. *Bulletin of the Geological Society of Finland* 82, 101–111. Available at: www.geologinenseura.fi/bulletin/Volume82/Raisanen_2010.pdf
- Räsänen, M. L., Nikkarinen, M., Lehto, O. & Aatos, S. 2002.** Liukoisuustesti- ja heikkouutmenetelmät kaivannaisteollisuuden sivutuotteiden ympäristö- ja kaatopaikkakelpoisuuden määrittämisessä. Geological Survey of Finland, archive report S44/0000/1/2002. 21 p. Available at: http://tupa.gtk.fi/raportti/arkisto/s44_0000_1_2002.pdf
- Salminen, R. (Chief-editor), Batista, M. J., Bidovec, M., Cemtriades, A., De Vivo B., De Vos, W., Duris, M., Gilucis, A., Gregorauskiene, V., Halamic, J., Heitzmann, P., Lima, A., Jordan, G., Klaver G., Kelin, P., Lis, J., Locutura, J., Marsina, K., Mazreku, A., O’Connor, P. J., Olsson, S. Å., Ottesen, R.-T., Petersell, V., Plant, J.A., Reeder, S., Salpeteru, I., Sandström, H., Seiwerts, U., Steenfelt, A. & Tarvainen, T. 2005.** *Geochemical Atlas of Europe. Part 1 – Background Information, Methodology and Maps*. Espoo: Geological Survey of Finland. 526 p. Available at: http://tupa.gtk.fi/julkaisu/erikoisjulkaisu/ej_048.html
- Savas, M. 2016.** Recovery of colemanite from tailing using a Knelson concentrator. *Physicochemical Problems of Mineral Processing* 52, 1036–1047.
- SRK Consulting 2013.** Preliminary economic assessment for the Kopsa copper-gold deposit, Finland. SRK Consulting (Sweden) AB, October 2013. 168 p.
- Stumm, W. & Morgan, J. J. 1996.** *Aquatic Chemistry*. New York: Wiley. 1022 p.
- Taskinen, A., Kauppila, P. M., Heino, N., Kurhila, M., Tiljander, M., Tornivaara, T. & Korhonen, T. 2018.** Kopsa Au–Cu-malmin arseenipitoisen rikastushiekan muokkaaminen ympäristökelpoisemmaksi rikastus-

teknisin menetelmin. Geological Survey of Finland, Open File Work Report 9/2018. (in Finnish). Available at: http://tupa.gtk.fi/raportti/arkisto/9_2018.pdf

Tornivaara, A., Taskinen, A., Heino, N. & Tiljander, M. 2018. Rikastushiekan muokkaaminen hyötykäyttöpotentiaalin lisäämiseksi ja sen soveltuvuus jätealueen peittoon. Geological Survey of Finland, Open File Work Report 10/2018. (in Finnish)

Watson, J. H. P. & Beharrell, P. A. 2006. Extracting values from mine dumps and tailings. *Minerals Engineering* 19, 1580–1587.

Standards referred to in the text

CEN/TR 16376. Characterization of waste. Overall guidance document for characterization of waste from the extractive industries.

ISO 10694. Soil quality -- Determination of organic and total carbon after dry combustion (elementary analysis) (ISO 10694:1995).

ISO 15178. Soil quality -- Determination of total sulfur by dry combustion. ISO 15178:2000.

SFS 872:en. Water quality. Determination of suspended solids. Method by filtration through glass fibre filters.

SFS 3005. Veden alkaliteetin ja asiditeetin määrittäminen. Potentiometrinen titraus. (in Finnish)

SFS 3021. Veden pH-arvon määrittäminen. (in Finnish)

SFS-EN 1484. Vesianalyysi. Ohjeita orgaanisen hiilen kokonaisuuden (TOC) ja liuenneen orgaanisen hiilen (DOC) määrittämiseen. (in Finnish)

SFS-EN 12457-3. Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with a high solid content and with a particle size below 4 mm (without or with size reduction).

SFS-EN 13137:en. Characterization of waste. Determination of total organic carbon (TOC) in waste, sludges and sediments.

SFS-EN 14405. Characterization of waste. Leaching behaviour test. Up-flow percolation test (under specified conditions).

SFS-EN ISO 15681-1. Water quality. Determination of orthophosphate and total phosphorus contents by flow analysis (FIA and SFA). Part 1. Method by flow injection analysis (FIA) (ISO 15681-1:2003).

SFS-EN 15875. Characterization of waste. Static test for determination of acid potential and neutralization potential of sulfidic waste.

SFS-EN 27888:en. Water quality. Determination of electrical conductivity (ISO 7888:1985).

SFS-EN ISO 10304-1. Water quality. Determination of dissolved anions by liquid chromatography of ions. Part 1: Determination of bromide, chloride, fluoride, nitrate, nitrite, phosphate and sulfate (ISO 10304-1:2007).

SFS-EN ISO 11885. Water quality. Determination of selected elements by inductively coupled plasma optical emission spectrometry (ICP-OES) (ISO 11885:2007).

SFS-EN ISO 15587-2. Water quality. Digestion for the determination of selected elements in water. Part 2: Nitric acid digestion (ISO 15587-2:2002).

SFS-EN ISO 17294-2. Water quality. Application of inductively coupled plasma mass spectrometry (ICP-MS). Part 2: Determination of selected elements including uranium isotopes (ISO 17294-2:2016).

SFS-ISO 11466. Soil quality. Extraction of trace elements soluble in aqua regia. (SFS-ISO 11466:2007).

CASE STUDY: INFLUENCE OF POLYACRYLAMIDE BASED PROCESSING CHEMICAL ON THE ENVIRONMENTAL PROPERTIES OF ARSENIC CONTAINING TAILINGS OF THE KUIKKA 2 GOLD DEPOSIT

by

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Kauppila, P. M., Taskinen, A., Korhonen, T., Kurhila, M. & Tiljander, M. 2018. Case study: influence of polyacrylamide based processing chemical on the environmental properties of arsenic containing tailings of the Kuikka 2 gold deposit. *Geological Survey of Finland, Bulletin 408, 83–96, 8 figures and 3 tables.*

The use of a polyacrylamide based chemical (called Grinding aid 2) was studied in modifying the environmental properties of the flotation tailings from the Kuikka 2 gold deposit. The main focus was to evaluate whether Grinding aid 2 could be used to decrease As and sulphide minerals in the flotation tailings. The results showed that Grinding aid 2 had overall very minor impact on the flotation performance of the Kuikka 2 ore and the environmental properties of the generated tailings. The minor changes observed were, however, mainly opposite to what was expected. Part of the observed dissimilarities might be due to the different mineralogies and occurrence of As in the ore feed. Further investigations are still needed to better understand the impact of Grinding aid 2 on the arsenic mineral behaviour in the flotation.

Keywords: gold deposits, tailings, arsenic, sulphide minerals, removal, modification, environmental performance, mineralogy, grinding aid, mineral processing, process chemicals, Kuikka, Finland

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1 INTRODUCTION

Gold deposits typically contain sulphide minerals and arsenic, large part of which end up in the tailings in mineral processing. This poses challenges for waste management. Removal of arsenic and sulphides from the wastes would improve their environmental management and utilization potential, as well as to ease their management.

In this study, a polyacrylamide based chemical by Kemira Oyj (called Grinding aid 2) was tested to modify environmental properties of As-bearing sulphide mine tailings generated from a gold ore deposit. The investigations focused particularly on reducing the amounts of arsenic and sulphide minerals in the tailings without risking gold recovery. Polyacrylamides are typically used as depressants for silicates and are known to effectively depress flotation of e.g. naturally hydrophobic gangue minerals such as talc (Chiem et al. 2006). The main motivation to study Grinding aid 2 for arsenic management was based on previous mineral processing studies by the Geological Survey of Finland (GTK) (Korhonen 2015, Pasanen et al. 2018). In those studies polyacrylamide based chemicals were shown to affect both gold and arsenic flotation.

Kuikka 2 gold ore deposit located in Northern Finland was chosen as a study area. It contains high grade of arsenic (up to 0.9%) with variable sulphide

minerals (Luukkonen et al. 2002). The estimated gold mineral resources of the whole Kuikkapuro deposit are 54,000 t of mineralized rock with a grade of 14.6 g/t Au (Heino 2000). The exploration permit for the deposit is currently hold by the MEN Finland Ltd.

Flotation tests with and without Grinding aid 2 were carried out to study its effect on the metallurgical performance and particularly the environmental properties of tailings and process water. It should be noted that despite its name, Grinding aid 2 was not applied here to improve grinding efficiency (no effects were found by Korhonen (2015)) but to influence flotation results. Prior to the tests, detailed mineralogical analyses of the ore were carried out to determine As and sulphide minerals in the waste and their mode of occurrence. Flotation test products of both tests were analysed chemically to evaluate the impact on the metallurgical performance, and detailed environmental characterisation of the tailings and process water was performed to assess the influence on their environmental performance.

This paper summarizes the results of the Kuikka 2 study. More detailed description of the investigations is provided in a GTK Open File Work Report by Kauppila et al. (2018).

2 MATERIALS AND METHODS

2.1 Sampling and analyses

The ore samples for the study were provided by MEN Finland Ltd from the Kuikka 2 gold deposit, located in Suomussalmi, Kainuu (Fig. 1). The deposit is part of the Suomussalmi greenstone belt and is composed of basic volcanics (Fig. 1). The mineralisation is hosted by tholeiitic metabasalts, which are composed of quartz, biotite, K-feldspar, epidote, scheelite and calcite. Gold occurs in the mineralisation mainly as coarse grained native gold in quartz veins in folded alteration zone and associated biotitised host rocks. Small amounts of silver occur within the gold grains. Arsenic is present in the deposit as arsenopyrite and the other main sulphide minerals include pyrite and pyrrhotite (Pietikäinen et al. 2000).

The ore sample was crushed to < 1 mm particle size (100%) using two jaw crushers in series and a

roll crusher in closed circuit with a Sweco screen. The crushed sample was homogenised and divided into subsamples of 1.5 kg for the beneficiation tests. Samples were taken from the tests for the chemical characterisation of the flotation test products and tailings using vacuum filtration, and process water samples were collected from the filtered water. During the sampling, pH and redox were measured from the filtered and homogenised tailings with a portable meter (Mettler Toledo) and electrical conductivity (EC), pH, oxygen concentration (O₂ mg/l) and saturation (O₂%), as well redox potential were measured from the process water using a portable YSI multiparameter field meter. Alkalinity of the process water was further titrated with sulphuric acid using Hach digital titrator. All samples were delivered for the chemical analyses to the accredited

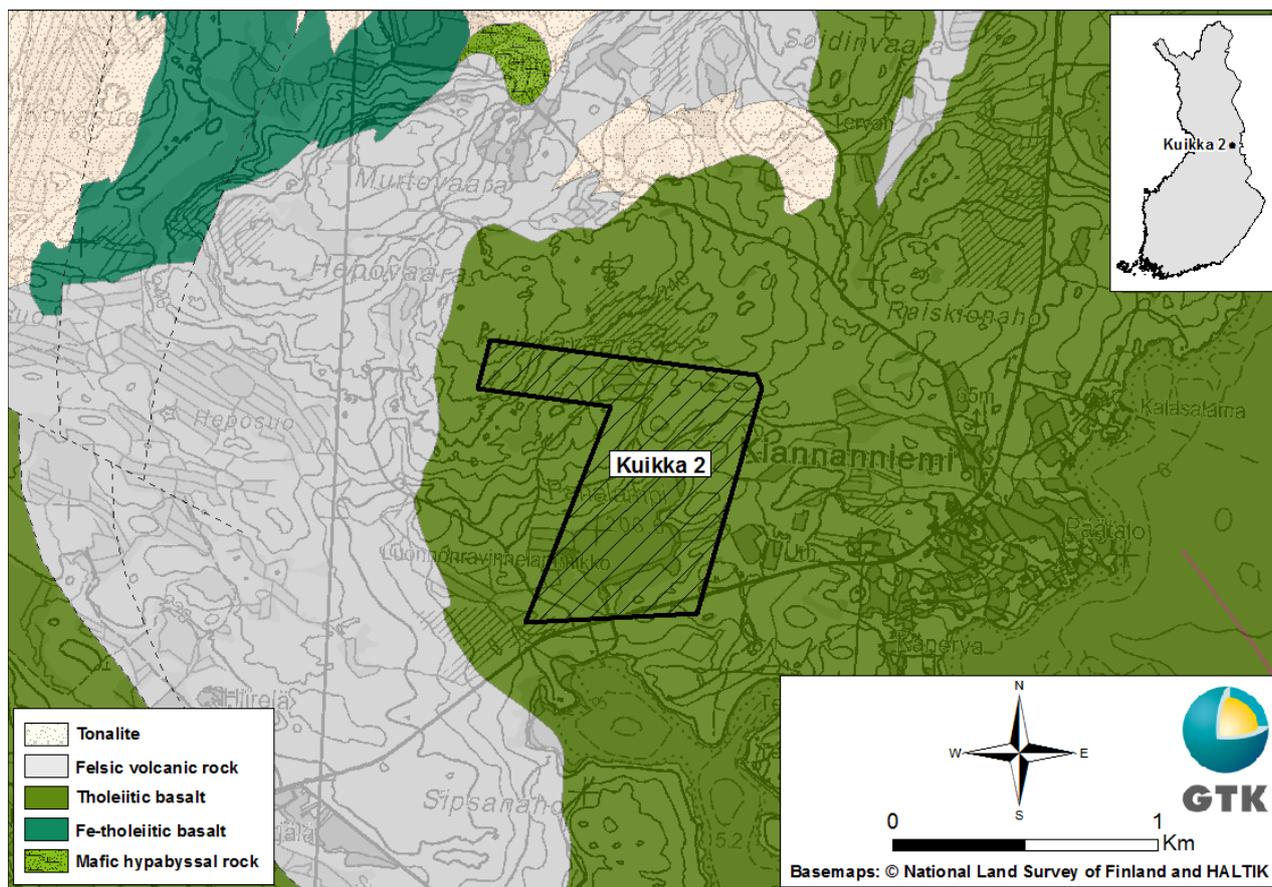


Fig. 1. Location and geological setting of the Kuikka 2 deposit (Bedrock of Finland – DigiKP; Basemaps © National Land Survey of Finland and HALTIK 2013).

laboratory of Labtium Oy, while mineralogical investigations of the tailings and the ore sample were carried out at the mineralogical laboratories of GTK.

The ore sample and the filtered flotation test products were dried thermally at 90 °C for the analyses. The crushed ore sample was further ground (80% –82 µm) and sized (+75 µm, 45–75 µm, 20–45 µm, and –20 µm fractions) for the mineralogical analysis. The chemical analyses of the ore and the flotation products included total element concentrations with XRF, measurements of gold content using fire assay with FAAS or gravimetry, and sulphur analyses with Eltra analyser. Modal mineralogy of the size fractions of the ore was studied from vertical polished sections using SEM-MLA equipment equipped with EDS (FEI Quanta 600) by XMOD_STD and XBSE methods (Saastamoinen 2015).

The environmental characterisation of the tailings was carried out on freeze dried samples, sieved < 2 mm for most of the analysis. For total concentration measurements the samples were further

ground < 100 µm (90%). The studied environmental properties included mineralogy, chemical composition, potential to produce acid mine drainage, and leaching and fractionation of harmful elements. Mineralogy of the tailings was studied similar to the ore sample using SEM-MLA equipment (FEI Quanta 600), but the method used was XBSE-STD method. The analyses included modal mineralogical composition of the tailings and the amounts, liberation state, mineral associations and grain size of As-bearing minerals and sulphide minerals. Microprobe (EPMA, i.e. electron probe microanalyser, Cameca SX100) was additionally used to identify some specific grains and to measure the quantitative composition of selected grains of the modified tailings.

Total concentrations of elements in the tailings were determined with XRF method and a mixture of concentrated acids (hydrofluoric acid, perchloric acid, hydrochloric acid and nitric acid) i.e. so called four acid leach with ICP-OES/MS technique (method modified after Briggs (2002) and Briggs & Meier (2002)). Concentrations of total sulphur, total

carbon, sulphide sulphur and carbonate carbon were measured pyrolytically with IR-detection (ISO 15178, ISO 10694, CEN/TR 16376, SFS-EN 13137:en; Räisänen et al. 2010). Potential of the tailings to produce acid mine drainage was evaluated based on ABA (SFS-EN 15875) and NAG tests (Amira 2002).

Leachability and fractionation of harmful elements from the tailings was studied using series of selective extractions in parallel. The applied extractions included: 1) 0.01 M NH_4 -chloride to extract easily dissolving fraction (Heikkinen & Räisänen 2008), 2) 1 M NH_4 -acetate at pH 4.5 to dissolve exchangeable and/or carbonate bound phases (e.g. Dold 2003, Heikkinen & Räisänen 2008), and 3) aqua regia (1:3 HNO_3 :HCl) to digest sulphide bound fraction (modified from SFS-ISO 11466, cf. also Doležal et al. 1968, Heikkinen & Räisänen 2009). Element concentrations were measured from all the leachates with ICP-OES/MS technique and pH of the tailings was determined potentiometrically from the 0.01 M NH_4Cl leach. Leaching of harmful elements from the tailings was further studied using standardised leaching tests (SFS-EN 14405 and SFS-EN 12457-3) and by analysing leachate from the NAG test (cf. Räisänen et al. 2010, Barnes et al. 2015).

Process water samples were analysed for total and dissolved concentrations of elements with ICP-OES/MS techniques (SFS-EN ISO 11885, SFS-EN ISO 17294-2), in which wet digestion technique was used for the total concentrations (SFS-EN ISO 15587-2). Anions (Br^- , Cl^- , F^- , NO_3^- , SO_4^{2-}) were measured using ion chromatography (SFS-EN ISO 10304-1) and phosphate content with flow injection analysis (FIA; SFS-EN ISO 15681-1). Ferrous iron was measured spectrophotometrically and total and dissolved concentrations of organic carbon (TOC, DOC) pyrolytically using IR-detection (SFS-EN 1484). Alkalinity of the process waters was determined with titration (SFS 3005), suspended solids gravimetrically (SFS 872), and pH and EC potentiometrically (SFS 3021, SFS-EN 27888:en). Dissolved elements, ferrous iron and dissolved organic carbon were measured from filtered (0.45 μm) samples, while the rest of the analysis were made from unfiltered samples. Concentrated nitric acid, phosphorous acid and hydrochloric acid were used for the preservation of ICP-OES/MS, organic carbon and Fe^{2+} samples, respectively.

2.2 Flotation tests

Two bench scale rougher flotation tests were carried out to investigate the effect of a polyacrylamide based chemical, Grinding aid 2 by Kemira Oyj, on flotation results, especially on the recoveries of gold, arsenic and sulphide minerals. The applied mineral processing flowsheet consisted of grinding and a six stage batch flotation (Fig. 2). The grinding of the crushed ore down to $-60 \mu\text{m}$ (80%) prior to the flotation was performed wet in a mild steel ball mill using tap water at room temperature, under normal air pressure. The grinding time was 60 min.

Flotation tests were made in 4 L flotation cells with 45 mm rotor using Outotec GTK LabCell flota-

tion machine equipped with automatic froth scrapers. The solids content in the flotation was 35% (w/w), air flow rate 3 L/min and impeller speed 1800 rpm. pH of the flotation slurries was measured with a glass electrode connected to a titrator (Metrohm 877 Titrino Plus). The flotation was continued for 20 minutes and the rougher concentrates were collected after 3, 6, 9, 12, 15 and 20 min.

The chemicals applied in the flotation included Aerophine 3418A (sodium diisobutyl dithiophosphate) and Dowfroth 250 (polypropylene glycol methyl ether), which were used as a collector and frother, respectively, in the flotation stages 1–5. In

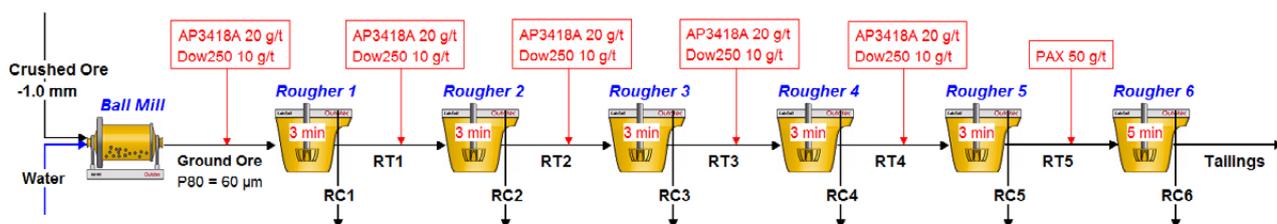


Fig. 2. Flowsheet and test conditions in the flotation test 1 of the Kuikka 2 ore. The conditioning stages that preceded the flotation stages are not illustrated. In test 2, 500 g/t of Grinding aid 2 was added to the pulp before rougher flotation 1 and other process chemicals.

Table 1. Test variables in the flotation tests of the Kuikka 2 ore.

Test	P ₈₀ (µm)	Flotation time (min)	Reagent dosage (g/t)			
			Aerophine 3418A	PAX	Grinding aid 2	Dowfroth 250
1	60	20	100	50	—	50
2	60	20	100	50	500	50

the last flotation stage, potassium amyl xanthate (PAX) was used as a collector to improve recovery of gold and sulphide minerals. The two tests were otherwise similar, but in test 2, 500 g/t of Grinding

aid 2 was added to the pulp after grinding before the 1st rougher flotation stage and other process chemicals. The flotation test variables are presented in Table 1 and the flowsheet is illustrated in Figure 2.

3 RESULTS AND DISCUSSION

3.1 Mineralogical and chemical composition of the Kuikka 2 ore feed

The ore feed of the Kuikka 2 was mainly composed of quartz (45.5%), plagioclase (26.8%; i.e. other plagioclase than albite), albite (7.7%), and biotite (5.5%), and contained chlorite (4.4%), arsenopyrite (2.9%), muscovite (1.6 %), and titanite (1.1%) as primary accessory minerals. The main potential sources for As included arsenopyrite, Fe-arsenate (0.19%), pyrite, goethite (0.90%) and jarosite (0.18%). In addition to arsenopyrite, the ore contained minor Fe sulphides, namely some pyrrhotite (0.34%) and pyrite (0.33%). Gold occurred

in arsenopyrite, silicates and as individual grains (Saastamoinen 2015).

Arsenic content of the ore feed was 1.2% and it contained 0.7% of sulphur. Other potential contaminants/valuable metals present in the ore included cobalt (0.02%), antimony (0.01%), zinc (0.01%), lead (0.01%), rare earth elements (REEs) (e.g. Y, Ce, La) and thorium (0.001%). The gold grade of the sample was about 1.95 g/t and silver content 0.001%.

3.2 Metallurgical performance of mineral processing tests

Influence of Grinding aid 2 on flotation of arsenic and sulphides as well as on recovery of gold were evaluated in the mineral processing tests. Overall, Grinding aid 2 had only a minor effect on metallurgical performance (Table 2). For example, in test 1 (no Grinding aid 2) recoveries of arsenic and sulphur to RC1–6 were 87.9% and 87.4%, respectively, while they were 87.0% and 86.5% in test 2 (500 g/t of Grinding aid 2). As and S grades in RC1–6 were 8.1–8.2% and 5.9–6.1%, respectively. The flotation

kinetics of arsenic and sulphur did not depend much on Grinding aid 2.

Grinding aid 2 had a small impact on the recovery of gold. The recovery of gold to RC1–6 was 83.9% in test 1 and 81.2% in test 2 (Table 2). The gold grade in RC1–6 was around 19 g/t in both tests. Gold grade could be increased by reporting the rougher concentrate to one or several stages of cleaning. However, studying cleaner flotation was outside the scope of this investigation.

Table 2. Metallurgical performance of the flotation tests 1 and 2. (RC = rougher concentrate)

Product	Test	Wt %	Grade (%)					Recovery (%)				
			Au (g/t)	As	S	Fe	SiO ₂	Au	As	S	Fe	SiO ₂
RC1-6 ^a	1	10.6	18.8	8.22	6.11	10.6	54.4	83.9	87.9	87.4	35.3	7.9
	2	11.0	19.3	8.06	5.86	10.2	55.6	81.2	87.0	86.5	34.9	8.4
Tailings	1	89.4	0.43	0.14	0.11	2.31	75.0	16.1	12.1	12.6	64.7	92.1
	2	89.0	0.55	0.15	0.11	2.36	74.8	18.8	13.0	13.5	65.1	91.6
Feed (calc) ^b	1	100.0	2.39	0.99	0.74	3.19	72.8	100.0	100.0	100.0	100.0	100.0
	2	100.0	2.62	1.02	0.75	3.22	72.7	100.0	100.0	100.0	100.0	100.0

^a Combined rougher concentrate.

^b Feed assays calculated from those of concentrates and tailings.

While the flotation kinetics of gold was similar in both tests, the grade–recovery curves were somewhat different (Fig. 3). In the beginning of the test, flotation was more selective with respect to gold when using Grinding aid 2. This observation suggests that Grinding aid 2 depressed gangue minerals. Later on the situation was balanced and the final Au recovery was almost 3% lower in test 2. The depressing effect of Grinding aid 2 might also be responsible for this observation since if gold was partly associated with gangue minerals, e.g. silicates, then a lower Au recovery might result. On the other hand, the bit higher mass pull in test 2 seems not to be in line with this conclusion. However, it should be remembered that the mass pull does not depend only on pulp floatability and selectivity, but also on the froth phase and the influence of Grinding aid 2 on it.

In general, the elemental assays in tailings did not seem to depend on whether Grinding aid 2 was used or not. For example, the S grade was 0.11% in the tailings of both tests. The As grade in tailings was a bit higher in test 2 (0.149%) than in test 1 (0.135%), and this suggests that arsenic was depressed somewhat by Grinding aid 2 during flotation. However, in replicate tests the difference was even smaller (As grade 0.132% and 0.125%, respectively) and may be in the limits of experimental uncertainties. Due to the quite fine grind size, 80% <60 µm, more substantial effects might have been observed, if a larger dosage of Grinding aid 2 had been used.

The arsenic grade in the final tailings was quite high, ca. 0.14%. More gold and arsenic could probably be removed from the tailings by increasing the flotation time, for example. In addition, the

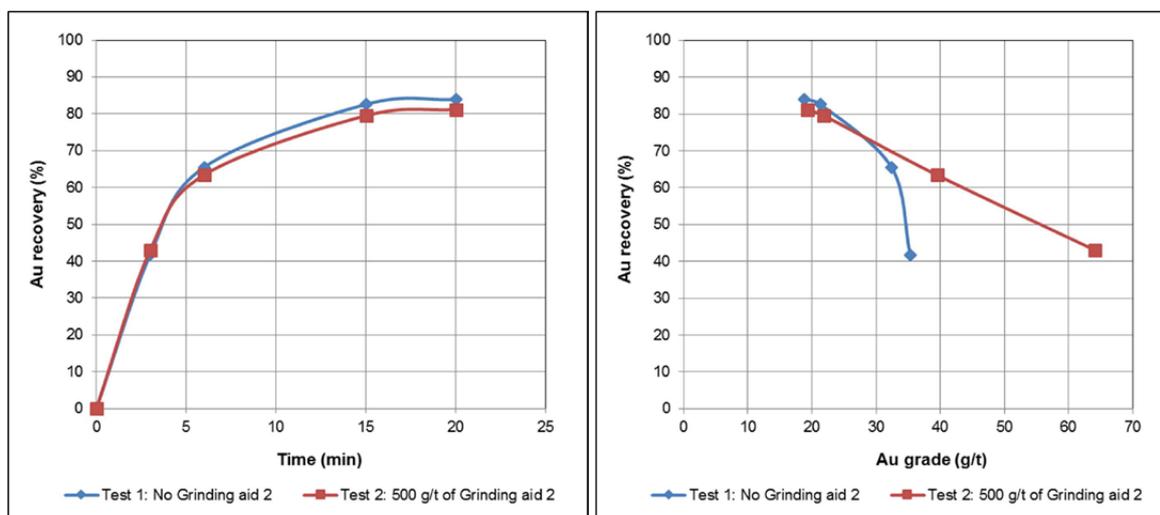


Fig. 3. Cumulative recovery of gold to concentrate as a function of flotation time (left) and cumulative gold grade (right).

combination of flotation, gravity and/or magnetic separation might improve recovery of gold and arsenic to the concentrate and decrease their contents in the final tailings. Extensive mineralogical data on tailings already during the optimisation of the beneficiation tests would help to find the optimal grind size and lead to other metallurgical implications on how to remove valuable elements and contaminants from tailings.

In previous studies the effect of Grinding aid 2 on gold and arsenic flotation was more notable than in this study (Korhonen 2015, Pasanen et al. 2018). This may be explained e.g. by different mineralogies of the ore samples and especially the occurrence of gold and arsenic in those samples. It should

also be noted that in the study by Korhonen (2015), Grinding aid 2 was added to the pulp before grinding and not after grinding as in this work. Further investigations are needed to clarify the effects of Grinding aid 2. If it is confirmed that the chemical depresses arsenic containing minerals in flotation, it should be used in cleaner flotation rather than in rougher flotation. If arsenic minerals are depressed in rougher flotation, they report to final tailings, which is not good from the environmental point of view. However, as arsenic is a potential penalty element, e.g. in gold concentrates (depending on the gold extraction method), it could be beneficial to remove it from the concentrates.

3.3 Impacts of the use of Grinding aid 2 on the environmental properties of tailings and process water

Environmental characterisation of the tailings and process water was carried out to evaluate the influence of Grinding aid 2 on the environmental properties of the tailings and on the quality of the process water. In the following discussion, the tailings and process water from the test without Grinding aid 2 are referred as “unmodified tailings/process water” and those from the test with Grinding aid 2 as “modified tailings/process water”. The focus of the discussion is on the effects of Grinding aid 2 on the contents and mode of occurrence of As and S in the tailings and in the process water.

In general, the Kuikka 2 tailings generated in the flotation tests contained notable As (0.10% and 0.15%) and some S (0.13%) (Table 3). Except for these, total concentrations of other harmful elements (e.g. Cr, Cu, Mo, Th, U, Zn) in the tailings were low, and were < 100 mg/kg. The aqua regia leachable concentrations of trace elements were also low, except for the As content. The aqua regia concentrations indicate the elements that are most likely of concern in the drainage from waste facilities (Price et al. 1997, Fosso Kankeu et al. 2015) and are used when evaluating whether mining waste is inert (Government Decree 2013) by comparing the values with the threshold values of contaminated soils (Government Decree 2007). All the other trace elements were below the threshold values, but As content (1195 mg/kg and 1275 mg/kg) exceeded even the higher guideline value of contaminated soils (100 mg/kg) by more than ten times (Table 3). Based on the aqua regia leachable concentrations of the trace elements and the total S content, the

tailings were classified as non-inert mining waste. The limit value for S is 0.1% for inert mining waste (Government Decree 2013).

The overall chemical composition of both tailings was very similar except that both the total and aqua regia leachable As contents of the modified tailings (0.15% and 1275 mg/kg, respectively) were somewhat higher than in the unmodified tailings (0.10% and 1195 mg/kg, respectively). This suggests that the use of Grinding aid 2 had negligible or even negative impact on the overall As content of the tailings.

The mineralogical investigations were applied to identify the sources of As and S, and to evaluate their mode of occurrence. The results showed that As was hosted by several minerals including goethite (FeO(OH)), arsenopyrite (FeAsS), scorodite (FeAsO₄·2H₂O), chlorite (Fe,Mg,Al)₆(Si,Al)₄O₁₀(OH)₈, parasymphesite (Fe₃(AsO₄)₂·8H₂O), and unidentified, altered Fe and REE-rich phosphate minerals (e.g. REE-As-phosphate). Other sources for S, besides arsenopyrite, included pyrrhotite (FeS_{1-x}), pyrite (FeS₂) and sphalerite (ZnS). In addition, also goethite contained significant amounts of S. There were no acid buffering carbonates in the tailings. The contents of As and S minerals in the unmodified and modified tailings were almost the same: 2.0% As minerals and 0.5% sulphides (others than arsenopyrite) in the unmodified tailings and 2.1% and 0.7%, respectively, in the modified tailings, indicating very minor influence of the use of Grinding aid 2.

Table 3. Total (%) and aqua regia leachable (mg/kg) concentrations of trace elements in the Kuikka 2 tailings. Total concentrations of elements based on XRF, except for Co and Cr based on total leach, and S based on the Leco-measurement. Threshold and guideline values for contaminated soils in Finland (Government Decree 2007) or median concentrations of fine fraction of tills (marked with *) (Koljonen 1992) are presented for comparison.

Tailings	As	Cd	Co	Cr	Cu	Mo*	Ni	Pb
Total (%)								
Unmodified	0.10	<0.0001	<0.001	0.003	0.002	<0.001	<0.002	<0.003
Modified	0.15	<0.0001	<0.001	0.003	0.003	<0.001	<0.002	<0.003
Aqua regia(mg/kg)								
Unmodified	1195	0.16	6.34	19.9	17.8	1.93	13.2	6.60
Modified	1275	0.15	5.99	19.5	16.0	1.78	12.3	5.20
Comparative values (mg/kg)								
Threshold value/ Soil	5	1	20	100	100	0.2*	50	60
Lower guideline value	50	10	100	200	150		100	200
Higher guideline value	100	20	250	300	200		150	750

Tailings	Sb	Th*	U*	V*	W*	Zn	S
Total (%)							
Unmodified	<0.005	<0.003	<0.001	0.008	–	0.005	0.13
Modified	<0.005	<0.003	<0.001	0.008	–	0.006	0.13
Aqua regia(mg/kg)							
Unmodified	0.24	6.56	0.50	57	6.5	47	1255
Modified	0.24	6.65	0.50	57	6.3	45	1270
Threshold value/ Soil	2	5.8*	–	35*	0.2*	200	1000**
Lower guideline value	10					250	
Higher guideline value	50					400	

** Limit for inert mining waste (Government Decree 2013).

In addition to the overall mineralogical composition, degree of liberation, grain size and mineral associations of As-bearing minerals and sulphides were studied to assess whether Grinding aid 2 had affected reactivity of these minerals. As a whole, the differences in these variables were only minor between the unmodified and modified tailings. For example, both tailings were very fine grained (D50 value < 10 µm) and majority of As and sulphide minerals occurred in the tailings as well liberated phases (Fig. 4). However, in the modified tailings, the arsenates (including scorodite), goethite, pyrite and sphalerite were slightly more liberated, i.e. had more free surface, than in the unmodified tailings. This suggests that these minerals would have somewhat increased reactivity in the modi-

fied tailings compared to that in the unmodified tailings. In both tailings samples, arsenopyrite was the most liberated As-bearing mineral phase (about 90% in the liberation class 95% and above) with the highest proportion of free surface, whereas goethite and scorodite were less liberated in both samples and occurred in association especially with silicates (Fig. 4).

Selective extractions were applied alongside the mineralogical investigations to evaluate the impacts of Grinding aid 2 on the distribution of As and S in different mineral phases. Based on the extractions, majority of As and S were dissolved in the aqua regia extraction, which reflects the sulphide bound phases (Fig. 5). In addition, small part of these elements occurred in the exchangeable phase

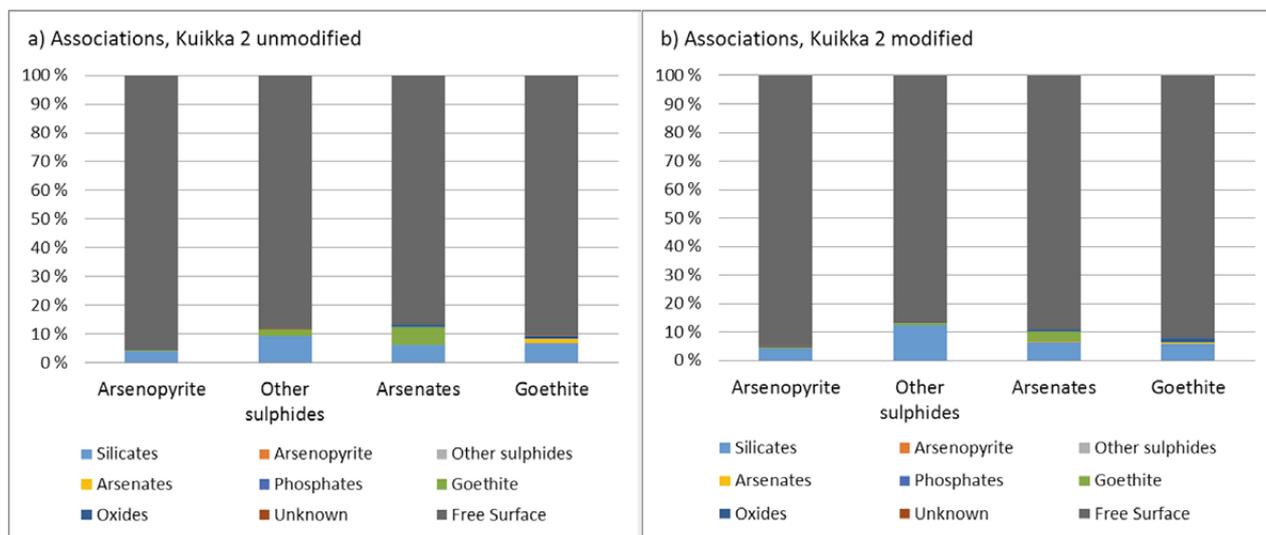


Fig. 4. Mineral associations of the As-bearing minerals and sulphides in the a) unmodified and b) modified Kuikka 2 tailings.

(NH₄-Ac leachable fraction) and S was also present in the easily leachable fraction (NH₄Cl leachable fraction) (Fig. 5). The results are in line with the findings from the mineralogy. Apparently, aside from the sulphides, the aqua regia leach also dissolves most of the identified As minerals. However, the exchangeable fraction presumably represents particularly the As and S present in goethite (e.g. Dold 2003), which adsorbs these elements (e.g. Rietra et al. 1999, Mamindy-Pajany et al. 2009), while the easily leachable fraction of S originates from the sulphide mineral edges broken in the mineral processing (cf. Räisänen et al. 2002). The

distribution of As and S showed no specific changes between the two tailings as a result of the use of Grinding aid 2 (Fig. 5).

Influence on the leachability of As and S by the use of Grinding aid 2 was further studied using leaching tests (SFS-EN 12457-3 and SFS-EN 14405) and by analysing leachates from the NAG test. The pH values of the leaching test solutions and the NAG leachate were acidic in both tailings (SFS-EN 12457-3: pH 4.5-4.6; SFS-EN 14405 4.4-5.1; NAGpH: 4.2), but the release of elements and compounds was only minor, except for As, S/SO₄, Ni and some Co and Zn (Fig. 6). The potential sources of Ni and Co

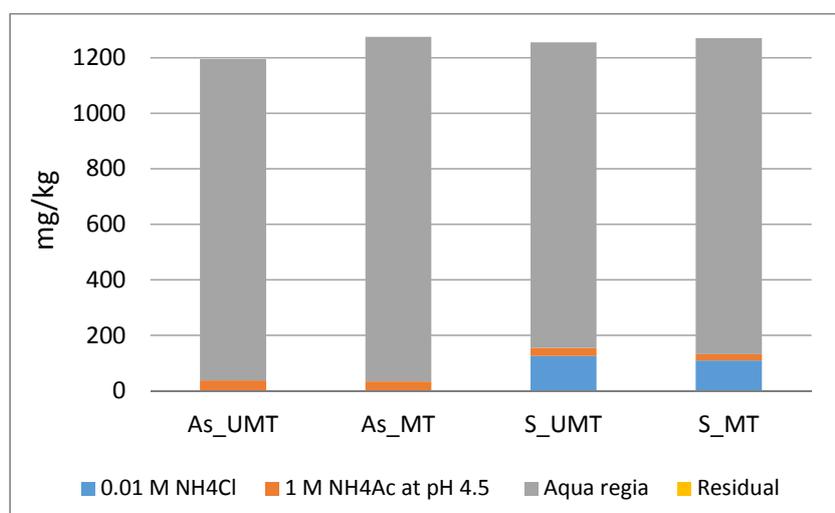


Fig. 5. Distribution of As and S in different fractions in the unmodified (UMT) and modified (MT) tailings based on the selective extractions. Residual fraction is expressed as a difference between total concentrations (HF-HClO₄-HCl-HNO₃-dissolution) and aqua regia extraction.

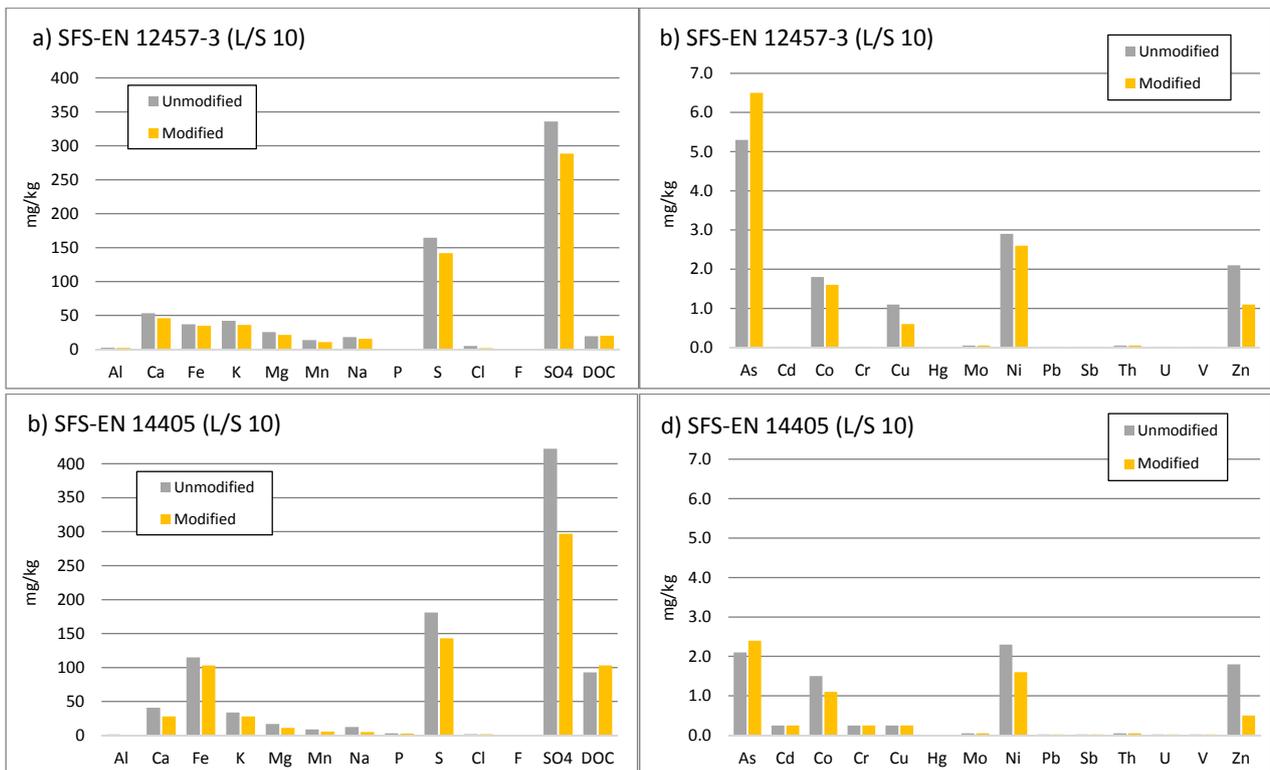


Fig. 6. Release of major compounds and trace metals from the Kuikka 2 unmodified and modified tailings based on a) and b) the shake-flask test (SFS-EN 12457-3) and c) and d) the percolation test (SFS-EN 14405) at L/S 10.

are Fe sulphides (i.e. pyrrhotite and pyrite) and Zn originates from sphalerite. The As content in the leaching test solutions (at liquid solid ratio (L/S) 10) of both tailings exceeded the limit set by the European Council (2003) for the non-hazardous waste at landfills (2 mg/kg) and Ni exceeded the corresponding limit for the inert waste (0.4 mg/kg). Leaching of As was somewhat higher from the modified tailings than from the unmodified tailings in the leaching tests, and that of S/SO₄ vice versa. In the NAG tests, both As and S/SO₄ contents were

higher in the leachates of the modified tailings (Fig. 7). The results of the NAG test were better in line with the results of the mineralogical analysis, which showed slightly higher liberation state of some of the As-bearing mineral phases and sulphides in the modified tailings than in the unmodified tailings. The higher mineral liberation is expected to increase leaching of elements associated with these minerals. However, the differences between the two tailings were in general rather small.

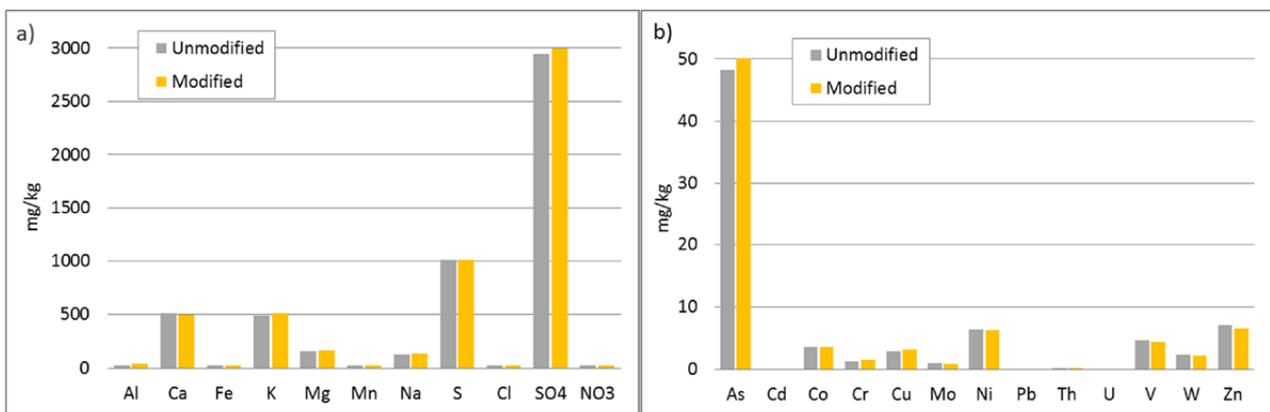


Fig. 7. a) Main cation and anion, and b) trace metal concentrations in the NAG leachate of the unmodified and modified Kuikka 2 tailings.

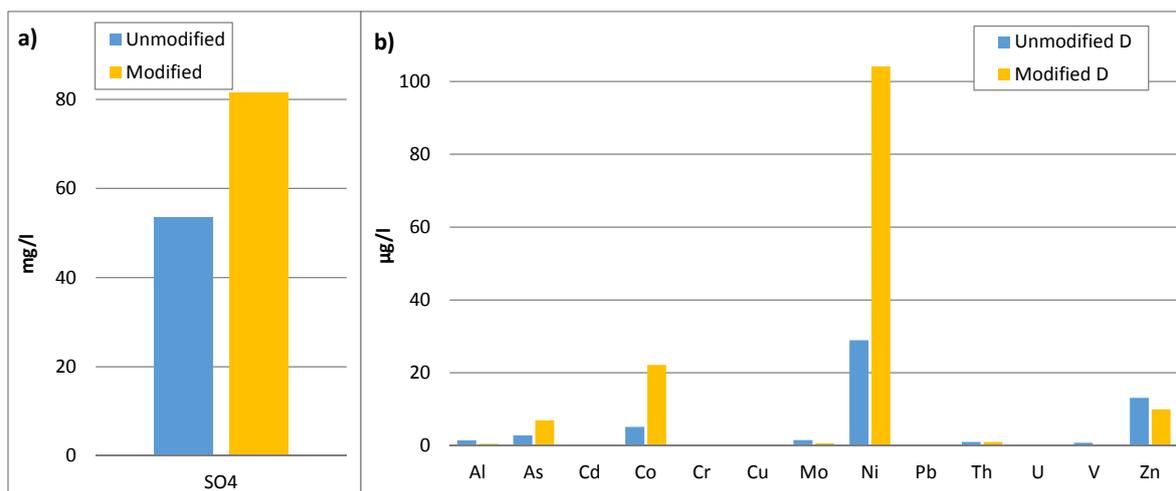


Fig. 8. a) Sulphate concentrations and b) dissolved trace metals in the process waters of the unmodified and modified Kuikka 2 tailings.

One of the key parameters with respect to the environmental performance of the tailings is their acid production potential, which is related to the balance of acid producing (i.e. mainly sulphides) and neutralizing minerals (e.g. carbonates) in the waste, and is determined based on mineralogy and static tests (e.g. ABA and NAG tests) (cf. White et al. 1999). Based on the static test results, both Kuikka 2 tailings were classified as “uncertain” in the ABA test (neutralisation potential ratio, NPR =1.4 in both tailings) and “potentially acid producing” in the NAG test (net acid production potential, NAPP=1.7 in both tailings). The results of the NAG test coincided with the mineralogy of the tailings, which suggested that the tailings might be acid producing, since they contained no acid buffering carbonates, but some acid producing sulphides were present. In the ABA test, the neutralisation potential may be overestimated as a result of dissolution of some silicate minerals, whose weathering rate is in nature so slow that they cannot truly contribute to the buffering of the acidity produced by sulphide minerals (Jambor et al. 2002, Heikkinen 2009). Thus, further kinetic testing would be needed to evaluate more closely the acid production potential of the Kuikka

2 tailings in long-term. However, since the results showed that the use of Grinding aid 2 had no impact on the acid production or neutralising properties of the tailings, it is out of the scope of this study.

The process waters of the Kuikka 2 beneficiation tests showed similar features as the results of the leaching tests and NAG leachates, and contained elevated concentrations of SO₄, As, Ni, Co and Zn (Fig. 8). However, both process waters were close to neutral in pH, even though the pH was slightly more acidic in the modified water (pH 6.1) than in the unmodified water (pH 7.1). The results showed that Grinding aid 2 had principally quite opposite impact on the process water quality than what was aimed for. Namely, the concentrations of dissolved constituents, particularly Ni, Co, As and SO₄, were slightly higher in the water from the process with the Grinding aid 2 than from the process without it. This further supports that the minor differences observed in the liberation state of the As-bearing minerals and sulphides between the unmodified and modified tailings has resulted in an increased mobility of As and SO₄ as well as Ni and Co from the tailings in the mineral processing.

4 CONCLUSIONS

The use of a polyacrylamide based chemical (called Grinding aid 2) by Kemira Oyj had overall very minor impact on the flotation performance of the

Kuikka 2 ore and the environmental properties of the generated tailings. The minor changes observed were mainly opposite to what was aimed for.

The major difference detected in the metallurgical performance of the flotation was that Grinding aid 2 presumably depressed As, increasing As content in the modified tailings. In addition, Grinding aid 2 improved the selectivity of gold with respect to As and gangue minerals in the beginning of the flotation test, but in the end of the test it deteriorated, decreasing the final gold recovery. Other test variables, such as mass pull, and recoveries and grades of As and S in the rougher concentrates, were almost equal in the two tests. In general, the effect of Grinding aid 2 on arsenic flotation was very small.

The tailings generated in the flotation tests contained notable As (0.10% and 0.15%) and S (0.13%), and are most likely classified as hazardous waste as they are potentially acid producing sulphide wastes. Sources of As included several minerals, such as goethite, arsenopyrite, scorodite, chlorite and REE-As-phosphates, which makes the removal of As complex. The sulphides in the tailings included pyrite, pyrrhotite and sphalerite.

Similar to the metallurgical performance, the use of Grinding aid 2 had only minor impact, or even

somewhat negative impact, on the environmental performance of the Kuikka 2 tailings. The modified tailings contained slightly more As and had also higher liberation state of some of the As-bearing minerals and sulphides than the unmodified tailings. This was seen as increased mobilisation of particularly As and SO₄, as well as Ni, Co and Zn, in the leaching tests and also in the higher contents of these substances in the NAG leachate and the process water. Otherwise the total element concentrations, element distributions and acid production potential were practically the same between the unmodified and modified tailings.

Part of the observed dissimilarities might be due to the different mineralogies and occurrence of As in the ore feed. Overall, further investigations are still needed to better understand the impact of Grinding aid 2 on the arsenic mineral behaviour in the flotation. In the future studies, larger dosage of Grinding aid 2 is recommended for fine grained ores. In addition, arsenic content in the tailings could be decreased by increasing flotation time or by using gravity and/or magnetic separation together with flotation.

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REFERENCES

- AMIRA 2002.** ARD Test Handbook. Project P387A, Prediction & Kinetic Control of Acid Mine Drainage. AMIRA international May 2002. 42 p.
- Barnes, A., Bowell, R., Warrander, R., Sapsford, D. Sexsmith, K., Charles, J., Declercq, J., Santonastaso, M. & Dey, B. 2015.** Comparison between Long-Term Humidity Cell Testing and Static Ne Acid Generation (NAG) Tests: Potential for NAG Use in Preliminary Mine Site Water Quality Prediction. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) Proceedings of 10th ICARD & IMWA 2015 conference, Santiago, Chile, 21–24 April 2015.
- Bedrock of Finland - DigiKP.** Digital map database [Electronic resource]. Espoo: Geological Survey of Finland [referred 12.3.2018]. Version 2.1.
- Briggs, P. H. 2002.** The determination of forty elements in geological and botanical samples by inductively coupled plasma-atomic emission spectrometry. In: Taggart, J. E. (ed.) Analytical methods for chemical analysis of geologic and other materials, U.S. Geological Survey, U.S. Department of the Interior, Open-File Report 02-223, Chapter G. Available at: https://pubs.usgs.gov/of/2002/ofr-02-0223/G01fortyelementICP-AESsolid_M.pdf
- Briggs, P. H. & Meier, A. L. 2002.** The determination of forty-two elements in geological materials by inductively coupled plasma-mass spectrometry. In: Taggart, J. E. (ed.) Analytical methods for chemical analysis of geologic and other materials. U.S. Geological Survey.
- Chiem, L. T., Huynh, L., Ralston, J. & Beattie, D. A. 2006.** An in situ ATR-FTIR study of polyacrylamide adsorption at the talc surface. *Journal of Colloid and Interface Science* 297, 54–61.
- Dold, B. 2003.** Speciation of the most soluble phases in a sequential extraction procedure adapted for geochemical studies of copper sulfide mine waste. *Journal of Geochemical Exploration* 80, 55–68.
- Doležal, J., Provondra, P. & Šulcek, Z. 1968.** Decomposition techniques in inorganic analysis. London: Iliffe Books Ltd. 224 p.
- European Council 2003.** Council decision on 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of Annex II to Directive 1999/31/EC (2003/33/EC). Official

- Journal of the European Communities L11/27. Available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:011:0027:0049:EN:PDF>
- Fosso-Kankeu, E., Waanders, F., Mulaba-Bafubandi, A. & Sidu, S. 2015.** Leachability of Suspended Particles in Mine Water and Risk of Water Contamination. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O’Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) 10th ICARD & IMWA 2015 Conference – Agreeing on solutions for more sustainable mine water management”, Santiago, Chile 2015. Available at: https://www.imwa.info/docs/imwa_2015/IMWA2015_Fosso-Kankeu_286.pdf
- Government Decree 2007.** Government Decree on the Assessment of Soil Contamination and Remediation Needs 214/2007. Adopted in Helsinki on 1 March 2007. Available at: <https://www.finlex.fi/fi/laki/kaannokset/2007/en20070214.pdf>
- Government Decree 2013.** Government Decree on Extractive Waste 190/2013. Adopted in Helsinki on 14 March 2013. Available at: https://www.finlex.fi/fi/laki/kaannokset/2013/en20130190_20150102.pdf
- Heikkinen, P. M. 2009.** Active sulphide mine tailings impoundments as sources of contaminated drainage: controlling factors, methods of characterization and geochemical constraints for mitigation. Espoo: Geological Survey of Finland. 38 p. Available at: http://tupa.gtk.fi/julkaisu/erikoisjulkaisu/ej_076_synopsis.pdf
- Heikkinen, P. M. & Räsänen, M. L. 2008.** Mineralogical and geochemical alteration of Hitura sulphide mine tailings with emphasis on nickel mobility and retention. *Journal of Geochemical Exploration* 97, 1–20.
- Heikkinen, P. M. & Räsänen, M. L. 2009.** Trace metal and As solid-phase speciation in sulphide mine tailings – Indicators of spatial distribution of sulphide oxidation in active tailings impoundments. *Applied Geochemistry* 24, 1224–1237.
- Heino, T. 2000.** Mineral Resource Assessment of the Kuikkapuro 1 (mine reg. N:o 6748/1), Kuikkapuro 2 (N:o 6841/1), Kuikkapuro 3 (N:o 6880/1), Kuikkapuro 4 (N:o 6880/2) and Kuikkapuro 5 (N:o 6912/1) gold mineralization. Geological Survey of Finland, archive report CM19/4511/2000/1. 3 p. Available at: http://tupa.gtk.fi/raportti/arkisto/m19_4511_2000_1.pdf
- Jambor, J. L., Dutrizac, J. E., Groat, L. A. & Raudsepp, M. 2002.** Static tests of neutralization potentials of silicate and aluminosilicate minerals. *Environmental Geology* 43, 1–17.
- Kauppila, P. M., Taskinen, A., Korhonen, T., Kurhila, M. & Tiljander, M. 2018.** Environmental properties of arsenic containing flotation tailings from Kuikka 2 gold deposit: Effect of polyacrylamide based chemical. Geological Survey of Finland, Open File Work Report 8/2018. 30 p. Available at: http://tupa.gtk.fi/raportti/arkisto/8_2018.pdf
- Koljonen, T. (ed.) 1992.** The Geochemical Atlas of Finland. Part 2: Till. Espoo: Geological Survey of Finland. 218 p. Available at: http://tupa.gtk.fi/julkaisu/erikoisjulkaisu/ej_008.pdf
- Korhonen, T. 2015.** Grinding and flotation aid tests. Geological Survey of Finland, unpublished work report of the PreGold project. 9 p.
- Luukkonen, E., Halkoaho, T., Hartikainen, A., Heino, T., Niskanen, M., Pietikäinen, K. & Tenhola, M. 2002.** Itä-Suomen arkeiset alueet -hankkeen (12201 ja 210 5000) toiminta vuosina 1992–2001 Suomussalmen, Hyrynsalmen, Kuhmon, Nurmeksen, Rautavaaran, Valtimon, Lieksan, Ilomantsin, Kiihtelysvaaran, Enon, Kontiolahden, Tohmajärven ja Tuupovaaran alueella. Geological Survey of Finland, archive report M19/4513/2002/1. 265 p. Available at: http://tupa.gtk.fi/raportti/arkisto/m19_4513_2002_1.pdf
- Mamindy-Pajany, Y., Hurel, C., Marmier, N. & Roméo, M. 2009.** Arsenic adsorption onto hematite and goethite. *Comptes Rendus Chimie* 12, 876–881.
- Pasanen, A., Lahtinen, T., Turunen, K., Backnäs, S., Lima, A., Fiuza, A., Szlachta, M., Wojtowicz, P., Maftei, R. & Baciu, C. (eds) 2018.** Tools for Sustainable Gold Mining in Europe – Final report of SUSMIN project. Submitted for publication to the report series by the Geological Survey of Finland.
- Pietikäinen, K., Hartikainen, A., Niskanen, M. & Tenhola, M. 2000.** The gold prospects: Kuikka, Syrjälä N, Syrjälä S and Tupakkiloma in Kuikkaniemi, Suomussalmi, Eastern Finland (register numbers of claims 6318/1, 6318/2, 6318/3, 6748/1, 6841/1, 6880/1, 6880/2, 6912/1 and claim reservation 77/2000. Geological Survey of Finland, archive report M06/4511/2000/1. 25 p. Available at: http://tupa.gtk.fi/raportti/valtaus/m06_4511_2000_1.pdf
- Price, W. A., Morin, K. & Hutt, N. 1997.** Guidelines for prediction of acid rock drainage and metal leaching for mines in British Columbia: Part II. Recommended procedures for static and kinetic tests. Fourth International Conference on Acid Rock Drainage. Vancouver, B.C. Canada, May 31–June 6, 1997. Proceedings, vol. I, 15–30.
- Räsänen, M. L., Kauppila, P. M. & Myöhänen, T. 2010.** Suitability of static test for acid rock drainage assessment of mine waste rock. *Bulletin of the Geological Society of Finland* 82, 101–111. Available at: www.geologinenseura.fi/bulletin/Volume82/Raisanen_2010.pdf
- Räsänen, M. L., Nikkarinen, M., Lehto, O. & Aatos, S. 2002.** Liukoisuustesti- ja heikkouuttomenetelmät kaivannaisteollisuuden ympäristö- ja kaatopaikkakelpoisuuden määrittämisessä. Geological Survey of Finland, archive report S44/0000/1/2002. 21 p. Available at: http://tupa.gtk.fi/raportti/arkisto/s44_0000_1_2002.pdf
- Rietra, P. J. J., Hiemstra, T. & van Riemsdijk, W. H. 1999.** Sulfate Adsorption on Goethite. *Journal of Colloid and Interface Science* 218, 511–521.
- Saastamoinen, T. 2015.** Modal mineralogy and occurrence of gold of Kuikka 1 and Kuikka 2. Internal report GTK Mintec, 8.5.2015.
- White, W. W. III, Lapakko, K. A. & Cox, R. L. 1999.** Static-test methods most commonly used to predict acid mine drainage: Practical guidelines for use and interpretation. In: Plumlee, G. S. & Logsdon, M. (eds) *The Environmental Geochemistry of Mineral Deposits, Part A: Theory and background.* Society of Economic Geologists Reviews in Economic Geology, vol. 7A, 325–328.

Standards referred to in the text

- CEN/TR 16376.** Characterization of waste. Overall guidance document for characterization of waste from the extractive industries.
- ISO 10694.** Soil quality -- Determination of organic and total carbon after dry combustion (elementary analysis) (ISO 10694:1995).
- ISO 15178.** Soil quality -- Determination of total sulfur by dry combustion. ISO 15178:2000.
- SFS 872:en.** Water quality. Determination of suspended solids. Method by filtration through glass fibre filters.

- SFS 3005.** Veden alkaliteetin ja asiditeetin määrittäminen. Potentiometrinen titraus. (in Finnish)
- SFS 3021.** Veden pH-arvon määrittäminen. (in Finnish)
- SFS-EN 1484.** Vesianalyysi. Ohjeita orgaanisen hiilen kokonaismäärän (TOC) ja liuenneen orgaanisen hiilen (DOC) määrittämiseen. (in Finnish)
- SFS-EN 12457-3.** Characterisation of waste. Leaching. Compliance test for leaching of granular waste materials and sludges. Two stage batch test at a liquid to solid ratio of 2 l/kg and 8 l/kg for materials with a high solid content and with a particle size below 4 mm (without or with size reduction)
- SFS-EN 13137:en.** Characterization of waste. Determination of total organic carbon (TOC) in waste, sludges and sediments.
- SFS-EN 14405.** Characterization of waste. Leaching behaviour test. Up-flow percolation test (under specified conditions)
- SFS-EN 15875.** Characterization of waste. Static test for determination of acid potential and neutralization potential of sulfidic waste.
- SFS-EN 27888:en.** Water quality. Determination of electrical conductivity (ISO 7888:1985)
- SFS-EN ISO 10304-1.** Water quality. Determination of dissolved anions by liquid chromatography of ions. Part 1: Determination of bromide, chloride, fluoride, nitrate, nitrite, phosphate and sulfate (ISO 10304-1:2007).
- SFS-EN ISO 11885.** Water quality. Determination of selected elements by inductively coupled plasma optical emission spectrometry (ICP-OES) (ISO 11885:2007).
- SFS-EN ISO 15587-2.** Water quality. Digestion for the determination of selected elements in water. Part 2: Nitric acid digestion (ISO 15587-2:2002)
- SFS-EN ISO 15681-1.** Water quality. Determination of orthophosphate and total phosphorus contents by flow analysis (FIA and SFA). Part 1. Method by flow injection analysis (FIA) (ISO 15681-1:2003).
- SFS-EN ISO 17294-2.** Water quality. Application of inductively coupled plasma mass spectrometry (ICP-MS). Part 2: Determination of selected elements including uranium isotopes (ISO 17294-2:2016).
- SFS-ISO 11466.** Soil quality. Extraction of trace elements soluble in aqua regia. (SFS-ISO 11466:2007)

OPTIMISATION OF RAW MATERIAL POTENTIAL AND ENVIRONMENTAL PROPERTIES OF TAILINGS: AN OPERATIONAL MODEL

by

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Constant increase in the amounts of mining wastes and the growing need of raw materials requires activities to improve material eco-efficiency. One option to reach higher utilisation level of mining wastes, in particular tailings, is to modify their environmental properties in mineral processing. Objective of this study was to develop an iterative operational model to optimise both the recovery of valuables and the environmental properties of wastes from mineral processing. In the model, thorough environmental characterisation of tailings and process waters is carried out during mineral processing tests to evaluate their raw material potential and to identify key contaminants and challenges for their management. Based on these properties, the processing methods are tailored accordingly to minimise the amount of hazardous waste and optimise the utilisation of tailings. Mineralogical knowledge and advanced geochemical methods are essential in the optimisation. As a result of the model, a one-door service will be realised at GTK. Overall, the implementation of the operational model will promote the sustainability and prospects of future mining.

Keywords: Mining waste, tailings, optimisation, modification, mineral processing, raw material, value, characterisation, hazardous waste, environmental performance, mineralogy, mineral analytics

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1 INTRODUCTION AND OBJECTIVES

Mineral processing typically focuses on extracting the most obvious valuables from the ore, while the rest of the material is disposed of as tailings at mine sites. Tailings may include both minerals and compounds hazardous to the environment and inert minerals or valuable metals that could have potential for usage. Thus, the disposal of tailings may mean the squandering of natural resources. However, to benefit from the utilisation potential, the environmentally hazardous compounds and minerals has to be separated from the rest of the tailings prior to their disposal. This would also enable the isolated disposal of the most hazardous waste reducing the overall costs and environmental impacts of tailings management. However, successful separation of hazardous compounds requires that tailings are looked as a raw material in ore processing and additional focus is put on modifying their environmental properties already when developing optimised processing of the valuables. This requires thorough mineralogical and chemical characterisation of the tailings during ore processing.

To rise to this challenge, one of the aims in the KaiHaMe project was to create an operational model for GTK to optimise mining wastes. The model was intended in particular to optimise the environ-

mental properties of tailings and process waters from mineral processing without jeopardising the recovery of valuables from the ore feed. The model supports sustainability of mining by increasing the eco-efficient use of raw materials (Fig. 1). GTK has optimal possibilities to develop and take into practise such a model, since GTK can provide a wide range of expert services both for mineral processing and for the environmental characterisation of mining wastes.

As a results of the operational model, “a one door service” will be implemented at GTK, where the mining companies can order environmental characterisation of mining wastes at the same time as the beneficiation tests for their ores (Fig. 1). Aside from increasing the eco-efficient use of raw materials, this approach provides opportunities to modify environmental properties of wastes and new insights for planning their management (Fig. 1). The model will eventually have a positive impact on the operational and employment possibilities of the mining sector as a result of decreased costs of the waste management and increased incomes through new products (Fig. 1).

The environmental characterisation package in the service will include reporting of the estimates



Fig. 1. Main elements and benefits of the operational model to the mining operators.

of utilisation and raw material potential of tailings and assessment of their environmental impacts and long-term behaviour. In addition, quality of process water will be measured to evaluate their treatment needs and recyclability. One of the key aspects in the operational model will be the possibility to modify beneficiation methods of the ore to improve the

environmental performance and usability of tailings. This paper summarises the key aspects and challenges in the development of the operational model and requirements to fulfil its objectives. In addition, the outline for the proposed operational model is presented.

2 DEVELOPMENT OF THE OPERATIONAL MODEL

As a starting point for the development of the operational model, mining operators were interviewed for their expectations regarding GTK's services. Generally, the idea of a combined service model including beneficiation tests and environmental characterisation of the mining wastes was well received. However, the companies acknowledged that the operational model would require from their side new attitude and way of actions to consider the tailoring of environmental properties of wastes simultaneously with the ore processing.

In addition to the needs of the mining operators, GTK's competence and facilities that are needed to provide the "one-door-service" for the customers were assessed. GTK has a wide experience in expert services for both mineral processing and the

environmental characterisation and management of mining wastes. GTK Mintec in Outokumpu offers laboratory and pilot scale beneficiation tests for metallic ores, industrial minerals, synthetic slags and ashes and other secondary raw materials (Figs. 2 and 3), whereas GTK's Industrial Environments and Recycling Unit holds the expertise for the assessment of environmental impacts of mining activities and characterisation of mining wastes.

GTK Mintec facility covers a variety of processing methods, which are combined according to the processed material. The amount of material for pilot scale processing varies typically between 100–400 t. Before the piloting, bench scale studies are usually carried out in the mineral processing laboratory. Chemical analyses are purchased from Labtium Oy



Fig. 2. GTK Mintec Mineral processing facility. The tailings area for the disposal of tailings from the beneficiation tests can be seen behind the buildings. © GTK



Fig. 3. Mineral processing equipment at the GTK Mintec Pilot plant. © GTK

that has an in-house service point in Mintec. The facility also hosts a modern mineralogical laboratory with focal instruments designed for process mineralogy. Additional mineralogical services can be obtained from GTK Research Laboratory in Espoo.

GTK's Industrial Environments and Recycling Unit has carried out mining environmental research and mining waste characterisation for almost 20 years. One of the main interests of the unit has been to develop and evaluate different characterisation methods such as partial extraction methods and tests measuring acid production potential of wastes (e.g. Räsänen et al. 2002, Heikkinen & Räsänen 2008, 2009, Räsänen et al. 2010, Karlsson et al. 2018c). In addition, the unit has provided various guidance for the environmental practises of mining industry (e.g. Heikkinen et al. 2008, Luodes et al. 2011, Kauppila et al. 2011, 2013, Jantunen et al. 2015, Kauppila et al. 2016). Similar to Mintec, chemical analyses for the characterisation are nowadays contracted from Labtium Oy, and the mineralogical analyses are carried out at GTK.

By joining all these GTK resources and knowhow, it will be possible to develop a wider service concept for the clients covering both aspects of mining activities. The challenge of the operational model is to combine different fields of expertise into one service package, when the processing and analytical

facilities and professionals are scattered into different operational units and localities. These and other specific issues that need to be taken into account in the development of the operational model are discussed in more detail in the following chapter (Chapter 3).

As a third step in the model development, the requirements for the environmental characterisation of mine wastes were reviewed. In Europe and in Finland, the environmental classification and characterisation of mining wastes is regulated by the European Union directives (2006/21/EC, EU 2006; 2009/359/EC, EU 2009a; 2009/360/EC, EU 2009b), which have been implemented to Finnish legislation (Government Decree 190/2013, Government Decree 2013a; Government Decree 331/2013, Government Decree 2013b). The required characterisation includes geochemical, mineralogical, geotechnical, and radiological properties of mine wastes. The preferred characterisation methods have been described in the EU's BREF document on management of mining wastes (EU 2009c) and in the standard CEN/TR 16376: "Overall guidance document for characterisation of waste from the extractive industries". The BREF document is currently under revision and the updated version is expected to be published in 2019.

Finally, the methods applied by GTK in the waste characterisation were also reviewed and evaluation was made on the services that should be contracted to complete the operational model. GTK can currently cover many of the required characterisation methods by either in-house analytical facilities, for mineralogy in particular, or by established

sub-contractors, such as Eurofins Labtium Oy for geochemical analyses and Radiation and Nuclear Safety Authority in Finland (STUK) for radiological studies. However, some established partnerships are still needed for a complete set-up. These include for instance the analyses of residues from process chemicals.

3 SPECIFIC ISSUES IN THE MODEL DEVELOPMENT

3.1 Sampling and sample preparation

There are several technical challenges when characterising mining wastes. One of them is the representativeness and pre-treatment of samples, such as drying, classification and preparation (cf. e.g. CEN/TR 16376). Geochemical and mineralogical analyses are performed on very small amounts of sample; usually just few grams are used for preparates and sections (Fig. 4), but their results should reflect the properties and behaviour of huge masses of mining waste. Evidently, proper sampling methods and handling of sample material is crucial to avoid any distortion in representativeness or secondary alteration, gravitational separation or contamination within the sample. For example, drying of tailings samples in high temperature may result in unwanted changes in the mineral-

ogy. Instead, freeze-drying of tailings is recommended (e.g. Jambor 1994). Water sampling is also extremely sensitive for sources of error, and should be carried out only by certified samplers.

At the moment, there are various practices at GTK that are used for recording, pre-treatment and preparation of sample material for analysis. For the operational model of mining waste characterisation, all of these methods need to be unified between the two units and properly documented as working instructions in the GTK's standard operation procedure (SOP). Systematic recording of samples, laboratory treatments and analytical results into an internal electronic database would also be beneficial for the exchange of information.

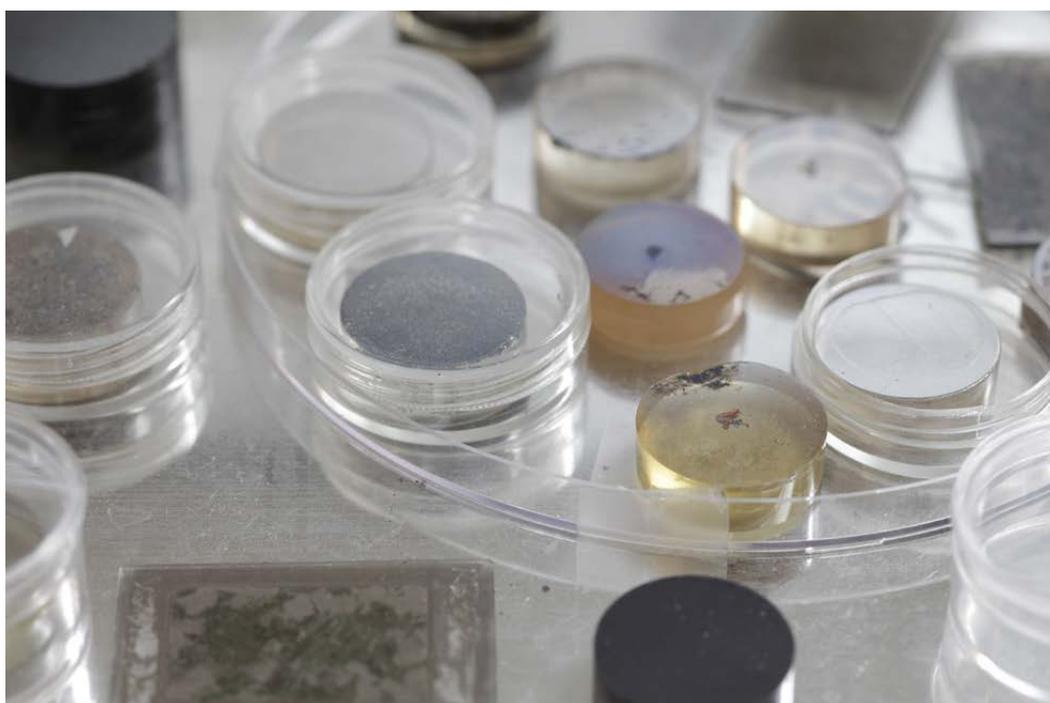


Fig. 4. Sample preparates, thin sections and one-inch polished mounts, for electron optical investigations. © GTK

3.2 Mineralogical methods

One of the special strengths of GTK for the operational model is the high level of expertise and state-of-art equipments (e.g. various scanning electron microscopes, microanalyser and XRDs) for the mineralogical investigations. The role of mineralogical investigations for mining waste characterisation is primarily to solve the carrier mineral phases of elements detected by geochemical analyses. The mineralogical data specifies, whether the hazardous elements, i.e. As, Cd, Co, Cr, Cu, Hg, Mo, Ni, Pb, V, and Zn, are bound to stable or soluble compounds. In addition, they indicate, whether the source minerals occur in the waste as liberated minerals or associated with other minerals. This provides further data on the reactivity and solubility of the key minerals (cf. e.g. Taskinen et al. 2018a and Taskinen et al. 2018b, in this volume). Another important mineralogical aspect is the potential presence of fibrous amphibole or serpentine group minerals, asbestos, in the tailings. If asbestos minerals are discovered during mineralogical investigations, the samples have to be subjected to official determinations of fibre content. These measurements are carried out by the Finnish Institute of Occupational Health and several commercial accredited laboratories. GTK does not have an established practise for subcontracting the asbestos measurements, but it should be defined for the operational model.

GTK has a wide range of modern mineralogical research instruments in the Outokumpu Mintec and Espoo Research Laboratories that can provide detailed information about the content and form of valuables and hazardous substances in the ore feeds and tailings. The key instrument for mineralogical investigations is highly automated SEM-EDS system, such as MLA or QEMSCAN (Fig. 5), that provides versatile and statistically relevant information about the modal mineralogy, elemental deportment, grain size distribution, mineral associations and liberation degree of important minerals. The limitations of the SEM-EDS system include the semiquantitative quality of the data, meaning that mineral phases, which contain OH- or H₂O-groups cannot be always identified by certainty. The electron beam is generated over an area of few microns. Thus the sub-micron scale material is out of the range of reliable analytics, even though the imaging capabilities can optimally reach nanometre scale resolution. Beryllium or lighter elements cannot be analysed, nor different oxidation stages of elements. Electron microprobe, EPMA, is an essential complementary research instrument for SEM-EDS for studying quantitative elemental composition of minerals and trace-element deportment. X-ray diffraction can also provide additional information for mineral phase identification.

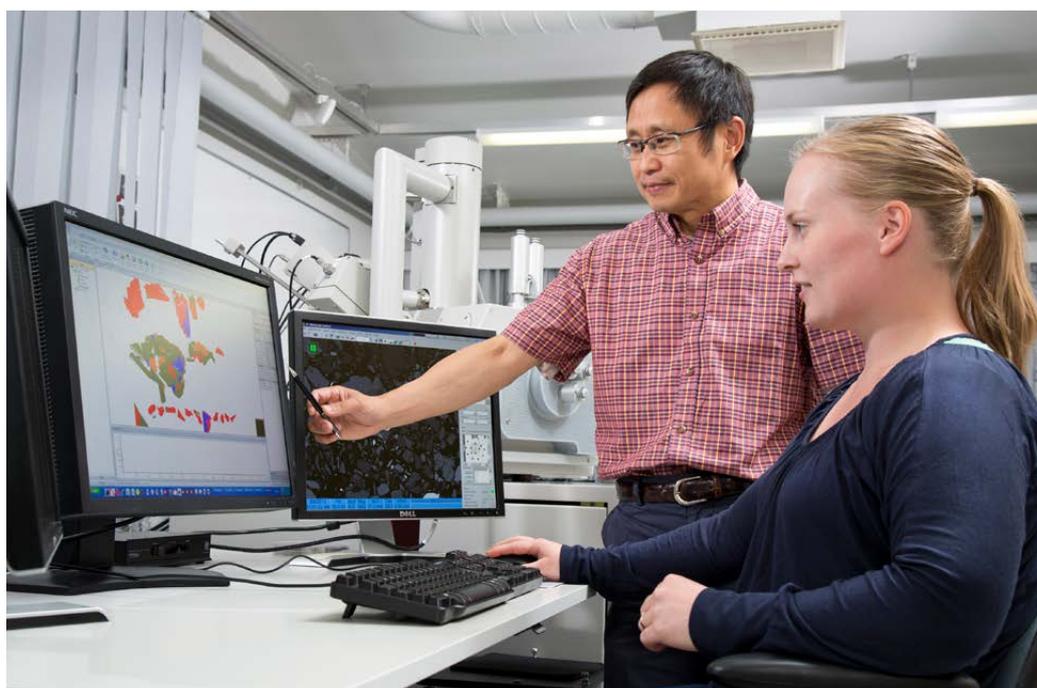


Fig. 5. MLA analyser at GTK Mintec. From left Jason Yang and Neea Heino. © GTK

The Kopsa case study carried out during the KaiHaMe project further underlined the essence of mineralogical data for optimising the mineral processing methods and for evaluating the environmental properties of the mining wastes generated in the processing (cf. Taskinen et al. 2018a and Taskinen et al. 2018b, in this volume). In the study, mineralogical investigations were applied to

identify in detail the sources of As in the tailings and to evaluate their reactivity.

The interpretation of mineralogical data for optimising the tailings processing should be done in close collaboration with mineral processing, environmental characterisation and mineral analytics experts in order to achieve the best possible outcome.

3.3 Geochemical methods

The primary objectives of the geochemical analyses of mining wastes are to measure concentrations, fractionation and leachability of toxic elements, and acid generation and neutralisation potential of the materials (e.g. Lapakko 2002, Price 2009, CEN/TR 16376, Kauppila et al. 2011). If the ore contains uranium or thorium, radiological measurements of the tailings and process water are additionally carried out. These characterisations aim at assessing the long-term behaviour of tailings and at classifying them into different waste classes (inert, non-inert, non-hazardous, hazardous waste; radioactive waste; cf. Government Decree 2012, 2013a, 2013b; STUK 2013a, 2013b, 2016). These together will determine the management methods for tailings. In addition, the geochemical analyses also provide information about the raw material potential of the tailings. Aside from the tailings, the quality of the process water is also analysed to provide information for the process water treatment and recyclability.

For environmental geochemical characterisation, it is essential that the selection of analysed elements covers all potentially toxic and hazardous elements, and that the detection limits meet the criteria for environmental assessment. The geochemical methods include measurements of total concentration, determination of element fractionation using aqua regia and other partial extraction methods, static tests to assess acid generation potential and kinetic tests to evaluate leaching of elements in short- and long-term (e.g. Doležal et al. 1968, Lapakko 2002, Price 2009, CEN/TR 16376, Kauppila et al. 2011, Muniruzzaman et al. 2018). Usually the geochemical methods selected to characterise the ore feed are not that extensive or accurate as they are for the environmental classification of mining wastes. However, to some extent the same analytical methods should be applied to both the ore feed and the tailings in order to fully

understand the effect of the beneficiation process and further the possibility to reduce the amount of hazardous waste.

Determination of acid generation potential of mine wastes is used to evaluate, whether mine wastes are prone to generate acid mine drainage (Price et al. 1997, White et al. 1999). GTK has traditionally used two parallel tests, the ABA and NAG tests (SFS-EN 15875 and AMIRA 2002) in these determinations. However, the ABA and NAG tests do not sufficiently consider the differences in acid generation by various sulphides or the role of other minerals than carbonates in acid neutralisation (e.g. Jambor et al. 2002, Jambor 2003, Dold 2017, Karlsson et al. 2018b, 2018c and also the paper by Karlsson et al. 2018a, in this volume). Therefore, it is recommended to use a calculation that is based on mineralogical composition of waste materials in conjunction with these tests in the operational model (e.g. Lawrence & Scheske 1997, Dold 2017, Karlsson et al. 2018b, 2018c). This approach is presented in a more detail in Karlsson et al. (2018a) in this report (cf. also Karlsson et al. 2018b, 2018c).

The leachability of hazardous substances from mining wastes is mainly due to oxidation of sulphide minerals and related geochemical reactions. For the assessment of long-term behaviour of sulphide-bearing mining wastes, it is recommended to use kinetic tests, for example humidity cell test (Lapakko 2002, ASTM D5744-13) in particular, instead of basic leaching tests to achieve more reliable results (cf. also Räsänen et al. 2002, Barnes et al. 2015). In Finland, kinetic tests are not yet however commercially available. For this reason, GTK should find an international partner or consider carrying out such experiments in-house.

Process water analyses include at the minimum dissolved concentrations of elements (anions and cations), pH, alkalinity and conductivity. For uranium and thorium containing deposits,

also radiological measurements are required. An essential target for the development is the analytics for the remnants of mineral processing reagents. Concentration of organic carbon (TOC, DOC) reflects to some extent the amount of organic chemicals, but based on it, it is not possible to identify the actual reagents or their amounts. More accurate methods, such as NRM, are needed for the purpose. However, GTK does not have an established subcontractor for these analytics.

A measurement requested by the mining opera-

tors to be included in the operational model is the determination of gases. During the beneficiation process, several gases may form (e.g. H₂S, C₂S, SO₂, S₀ and CO₂) that may be toxic or hazardous to the environment, and should thus be monitored (Kauppila et al. 2011). GTK does not have experience of carrying out such measurements, meaning another development target for the operational model.

3.4 Geotechnical measurements

Geotechnical measurements of mining wastes are needed to evaluate their physical stability and hydrological properties (e.g. CEN/TR 16376). GTK has equipment to measure particle size distribution and water content. However, for several other

measurements, such as water conductivity, permeability, compaction, plasticity and specific gravity, there are no established subcontractors. They will need to be established to complete the operational model.

4 PROPOSED OPERATIONAL MODEL

The new operational model means that a mining waste characterisation package and an opportunity to modify mineral processing to optimise tailings will be offered to GTK's clients as a service option in context with laboratory and pilot scale beneficiation tests (Fig. 6). The environmental characterisation will include at the minimum the description of properties of the resulting process waters and tailings (Fig. 6), and certain chemical and mineralogical measurements of the ore feed. The implementation of the operational model requires close internal collaboration within GTK, especially between Mineral Processing and Materials Research (MMA) and Industrial Environments and Recycling (TUK) units. The standard chemical analyses and radiological investigations can be obtained by established subcontractors, such as Eurofins Labtium Oy and STUK.

The environmental characterisation package will include a description of the properties of mining waste stated by the mining waste decree (Government Decree 2013a), including the classification of wastes in accordance with the waste decree (Government Decree 2012, cf. also European Council 2003). In addition, it will include estimation of raw material and utilisation potential of tailings, requirements for their long-term disposal, and possibilities to reduce the amount of hazardous sub-

stances and/or to concentrate them into smaller volumes of wastes. The quality of the resulting process water will also be evaluated to assess water treatment requirements and their recyclability back into the beneficiation process. The mineralogical and total chemical composition of the primary ore will be analysed by using methods that meet the detection limits required for the environmental characterisation.

The environmental characterisation methods for tailings will consist of mineralogical investigations, assessment of their chemical characteristics (total concentration, aqua regia and other partial extraction concentrations if needed), acid generation potential measurements as well as leaching and kinetic tests. All of these characteristics are crucial when evaluating the environmental classification and long-term behaviour of tailings. The characterisation of process waters will include their quality assessment and analyses of the concentrations of residues from mineral processing reagents. If needed, also geotechnical and radiological studies can be covered for the relevant wastes by subcontracting (Fig. 6).

Presently, GTK already has the readiness to offer basic package for mining waste characterisation for the clients by combination of in-house services and established subcontractors. For the complete

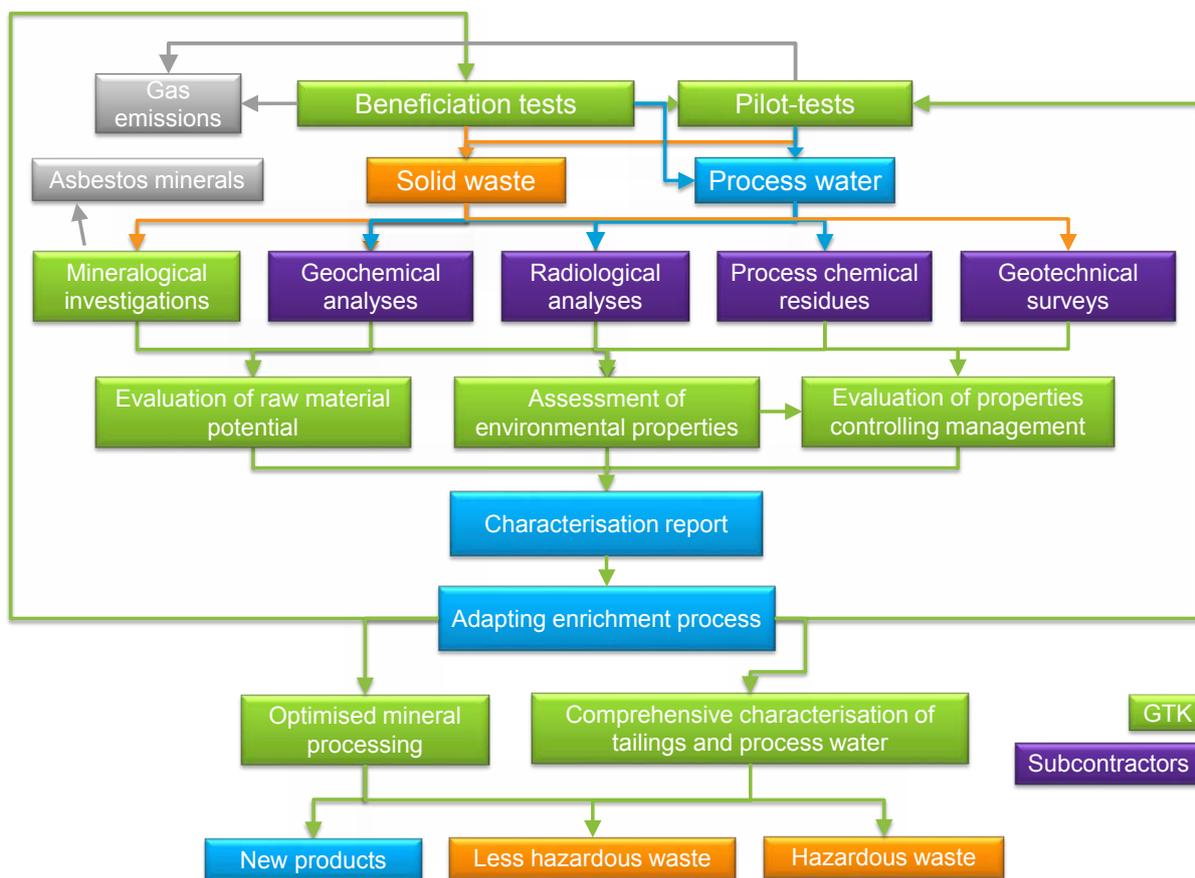


Fig. 6. Schematics of the one-door service package for GTK clients based on the proposed operational model.

package, GTK should still find reliable partners to carry out for instance kinetic tests, process water analyses for reagent remnants, and geotechnical measurements. GTK should also investigate, how the gas formation could be measured during the beneficiation process. Development of an effective data management system for GTK's internal information exchange would be welcome. A real time communication between the mineral processing and environmental characterisation research groups is essential for productivity and success of the operational model.

In an ideal case, the beneficiation process is adjusted after the characterisation of tailings and process water to truly optimise these waste fractions to improve their environmental performance but also to recover higher amounts of valuable substances. Optimally, new raw materials can be produced or waste fractions with variable environmental properties generated with a limited amount of the most hazardous waste (Fig. 6). Once the process is optimised, a comprehensive characterisation of the final tailings and process waters is further carried out (Fig. 6).

Finally, the operational model should be implemented as a working instruction according to GTK's quality system, and as a business model for GTK's service repertoire.

During the KaiHaMe project the operational model was tested in practise for the Kopsa Au-Cu deposit. The aim of the mineral processing was to reduce the amount of arsenic and sulphide minerals in the tailings, and thus to improve their environmental performance. The results of the experiments are described in this publication (paper by Taskinen et al. 2018b) and also in a GTK Open File Work Report by Taskinen et al. (2018a). The results demonstrate that by modifying the beneficiation process, the levels of arsenic and sulphur can be decreased in the tailings. In the Kopsa case, the modifications included increase of the flotation time and the amount of reagents combined with re-grinding, re-flotation and high gradient magnetic separation of the tailings. The Kopsa case study also demonstrates the importance of mineralogical investigations for monitoring and designing the beneficiation processes as well as for characterising the environmental properties of tailings.

Filled-in lysimeter tests were also carried out for the Kopsa tailings to evaluate, in field conditions, the long-term performance of the modified tailings compared to the original tailings (Taskinen et al. 2018b, in this volume, and Tornivaara et al. 2018). Based on the results, the duration of the project was too short to obtain stabilised results from the lysimeters, but useful information was already

obtained on how the modification of the tailings affected their long-term behaviour. For example, the increase of grinding enhanced the leaching of arsenic, which was most likely the result of the higher liberation of some As minerals, such as Fe-arsenates. The mineralogical data proved to be essential when interpreting the lysimeter results.

5 CONCLUSIONS

By combining GTK's expertise for mineral processing and mining environmental studies, it is possible to create a new operational service model for the clients. The key is to characterise the mining wastes that form during the beneficiation process, and tailor the processing methods accordingly to minimise the amount of hazardous waste and optimise the utilisation potential of tailings. Mineralogical knowledge and advanced geochemical methods are essential for optimising the process.

GTK already has a wide set-up of in-house facilities for mining waste characterisation and also established subcontractors for most of the required methods. However, some partnerships are still needed. For example, certain geotechnical studies, analyses of mineral processing reagents in process waters, and kinetic tests for long-term behaviour studies of mining wastes can be identified as targets for development. In addition, GTK needs to evalu-

ate, whether some of the required methods could be adapted to its own repertoire.

To fully benefit from the operational model, an overall change in the way of thinking of the mineral sector is needed to look at the raw material as a whole already at the beginning of the mine planning. Furthermore, the optimised environmental properties of tailings should become as one of the goals for mineral processing aside from the maximised recovery rate of valuables. It should be noted that the investments in the mineral processing for the optimisation most likely result in cost savings in the waste management. As a result of implementing the operational model approach, eco-efficiency of raw materials can be increased, management of mining wastes improved, and cost-efficiency of both mining and the waste management enhanced. These all will promote the sustainability and prospects of future mining.

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REFERENCES

- AMIRA 2002.** ARD Test Handbook. Project P387A, Prediction & Kinetic Control of Acid Mine Drainage. AMIRA international May 2002. 42 p.
- Barnes, A., Bowell, R., Warrander, R., Sapsford, D. Sexsmith, K., Charles, J, Declercq, J., Santonastaso, M. & Dey, B. 2015.** Comparison between Long-Term Humidity Cell Testing and Static Ne Acid Generation (NAG) Tests: Potential for NAG Use in Preliminary Mine Site Water Quality Prediction. In: Brown, A., Bucknam, C., Burgess, J., Carballo, M., Castendyk, D., Figueroa, L., Kirk, L., McLemore, V., McPhee, J., O'Kane, M., Seal, R., Wiertz, J., Williams, D., Wilson, W. & Wolkersdorfer, C. (eds) Proceedings of 10th ICARD & IMWA 2015 conference, Santiago, Chile, 21–24 April 2015.
- Dold, B. 2017.** Acid rock drainage prediction: A critical review. *Journal of Geochemical Exploration* 172, 120–132.
- Doležal, J., Provondra, P. & Šulcek, Z. 1968.** Decomposition techniques in inorganic analysis. London: Iliffe Books Ltd. 224 p.
- EU 2006.** Directive 2006/21/EC of the European Parliament and of the Council of 15 March 2006 on the management of waste from extractive industries

- and amending Directive 2004/35/EC. Official Journal of the European Union L 102/15. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32006L0021>
- EU 2009a.** 2009/359/EY. Commission Decision of 30 April 2009 completing the definition of inert waste in implementation of Article 22(1)(f) of Directive 2006/21/EC of the European Parliament and the Council concerning the management of waste from extractive industries (notified under document number C(2009) 3012). Official Journal of the European Union L 110/46. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1524316524868&uri=CELEX:32009D0359>
- EU 2009b.** 2009/360/EC. Commission decision of 30 April 2009 completing the technical requirements for waste characterisation laid down by Directive 2006/21/EC of the European Parliament and of the Council on the management of waste from extractive industries (notified under document number C(2009) 3013). Official Journal of the European Union L 110/48. Available at: <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX%3A32009D0360>
- EU 2009c.** Reference Document on Best Available Techniques for Management of Tailings and Waste-Rock in Mining Activities. July 2009. European Commission. 511 p. Available at: http://eippcb.jrc.ec.europa.eu/reference/BREF/mmr_adopted_0109.pdf
- European Council 2003.** Council decision on 19 December 2002 establishing criteria and procedures for the acceptance of waste at landfills pursuant to Article 16 of Annex II to Directive 1999/31/EC (2003/33/EC). Official Journal of the European Communities L11/27. Available at: <http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=OJ:L:2003:011:0027:0049:EN:PDF>
- Government Decree 2012.** Government Decree on waste 179/2012. Adopted in 1.5.2012. Available at: <https://www.finlex.fi/fi/laki/kaannokset/2012/en20120179.pdf>
- Government Decree 2013a.** Government Decree on Extractive Waste 190/2013. Adopted in Helsinki on 14 March 2013. Available at: https://www.finlex.fi/fi/laki/kaannokset/2013/en20130190_20150102.pdf
- Government Decree 2013b.** Government Decree on Landfills 331/2013. Adopted in Helsinki on 2 May 2013. Available at: https://www.finlex.fi/fi/laki/kaannokset/2013/en20130331_20160960.pdf
- Heikkinen, P. M. & Räsänen, M. L. 2008.** Mineralogical and geochemical alteration of Hitura sulphide mine tailings with emphasis on nickel mobility and retention. *Journal of Geochemical Exploration* 97, 1–20.
- Heikkinen, P. M. & Räsänen, M. L. 2009.** Trace metal and As solid-phase speciation in sulphide mine tailings – Indicators of spatial distribution of sulphide oxidation in active tailings impoundments. *Applied Geochemistry* 24, 1224–1237.
- Heikkinen, P. M. (ed.), Noras, P. (ed.), Salminen, R. (ed.), Mroueh, U.-M., Vahanne, P., Wahlström, M., Kaartinen, T., Juvankoski, M., Vestola, E., Mäkelä, E., Leino, T., Kosonen, M., Hatakka, T., Jarva, J., Kauppila, T., Leveinen, J., Lintinen, P., Suomela, P., Pöyry, H., Vallius, P., Nevalainen, J., Tolla, P. & Komppa, V. 2008.** Mine closure handbook. Espoo: GTK, VTT, Outo-kumpu Oyj, Finnish Road Enterprise, Soil and Water Ltd. 169 p.
- Jambor, J. L. 1994.** Mineralogy of Sulfide-rich Tailings and Their Oxidation Products. In: Blowes, D. W. & Jambor, J. L. (eds) *Environmental Geochemistry of Sulfide Mine-wastes*. Mineralogical Association of Canada, Short Course Vol. 22, 59–102.
- Jambor, J. L. 2003.** Mine-waste mineralogy and mineralogical perspectives of acid-base accounting. In: Jambor, J. L., Blowes, D. W. & Ritchie, A. I. M. (eds) *Environmental aspects of mine wastes*. Mineralogical Association of Canada, Short Course Series 31, 117–145.
- Jambor, J. L., Dutrizac, J. E., Groat, L. A. & Raudsepp, M. 2002.** Static tests of neutralization potentials of silicate and aluminosilicate minerals. *Environmental Geology* 43, 1–17.
- Jantunen, J. & Kauppila, T. (toim.), Räsänen, M.L., Komulainen, H., Kauppila, P., Kauppinen, T., Törmä, H., Leppänen, M., Tornivaara, A., Pasanen, A., Kempainen, E., Raunio, A., Marttunen, M., Mustajoki, J., Kauppi, S., Ekholm, P., Huttula, T., Makkonen, H. & Loukola-Ruskeeniemi, K. 2015.** Guide: Environmental Impact Assessment Procedure for mining projects in Finland. Ministry of Employment and the Economy. Edita Prima Oy. 102 p.
- Karlsson, T., Kauppila, P. M. & Lehtonen, M. 2018a.** Prediction of long-term behaviour of extractive wastes based on environmental characterisation: correspondence of laboratory prediction tests with field data. In: Kauppila, P. M. & Tarvainen, T. (eds) *Improving the environmental properties, utilisation potential and long-term prediction of mining wastes*. Geological Survey of Finland, Bulletin 408. (this volume). Available at: <https://doi.org/10.30440/bt408.1>
- Karlsson, T., Kauppila, P. M., Lehtonen, M., Tiljander, M., Forsman, P. & Lahtinen, T. 2018b.** Laboratorianalyysit kaivannaisjätteiden käyttäytymisen ennustamisessa. Geological Survey of Finland, Open File Work Report 13/2018. (in Finnish)
- Karlsson, T., Räsänen, M. L., Lehtonen, M. & Alakangas, L. 2018c.** Comparison of static and mineralogical ARD prediction methods in the Nordic environment. *Environmental Monitoring and Assessment* 190:719. Available at: <https://doi.org/10.1007/s10661-018-7096-2>
- Kauppila, P., Räsänen, M. L. & Myllyoja, S. (eds) 2011.** Best Environmental Practices in Metal Ore Mining. *The Finnish Environment* 29en/2011. Helsinki: Finnish Environment Institute. 219 p.
- Kauppila, T. (ed.) 2015.** Hyviä käytäntöjä kaivoshankkeiden ympäristövaikutusten arvioinnissa. Summary: Good Practices in Predictive Assessment of the Environmental Impacts of Mining Projects. Geological Survey of Finland, Report of Investigation 222. 141 p. (in Finnish). Available at: http://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_222.pdf
- Kauppila, T. (ed.), Komulainen, H. (ed.), Makkonen, S. (ed.) & Tuomisto, J. (ed.) 2013.** Metallikaivosalueiden ympäristöriskinarviointiosaamisen kehittäminen: MINERA-hankkeen loppuraportti. Summary: Improving Environmental Risk Assessment for Metal Mines: Final Report of the MINERA Project. Geological Survey of Finland, Report of Investigation 199. 223 p. (in Finnish). Available at: http://tupa.gtk.fi/julkaisu/tutkimusraportti/tr_199.pdf
- Lapakko, K. 2002.** Metal Mine Rock and Waste Characterization Tools: An Overview. Minnesota Department of Natural Resources, US. April 2002 No. 67. 30 p.
- Lawrence, R. W. & Scheske, M. 1997.** A method to calculate the neutralization potential of mining wastes. *Environmental Geology*, 32, 100–106.
- Luodes, H., Kauppila, P. M., Karlsson, T., Nikkarinen, M., Aatos, S., Tornivaara, A., Wahlström, M. & Kaartinen, T. 2011.** Kaivannaisjätteen luokittelu pysyväksi. Louhinnassa muodostuvat sivukivet. (Classification of inert extractive waste. Waste rock from quarrying). Ministry of Environment, Environmental Protection

- Department. The Finnish Environment 21/2011, Environmental protection. 35 p. Available at: https://helda.helsinki.fi/bitstream/handle/10138/37032/SY21_2011_Kaivannaisjätteen_luokittelu_pysyvaksi.pdf?sequence=1 (in Finnish)
- Muniruzzaman, M., Kauppila, P. M. & Karlsson, T. 2018.** Water quality prediction of mining waste facilities based on predictive models. Geological Survey of Finland, Open File Research Report 16/2018. 65 p. Available at: http://tupa.gtk.fi/raportti/arkisto/16_2018.pdf
- Price, W. A. 2009.** Prediction Manual for Drainage Chemistry from Sulfidic Geologic Materials. Natural Resources Canada. MEND Report 1.20.1. 579 p.
- Price, W. A., Morin, K. & Hutt, N. 1997.** Guidelines for prediction of acid rock drainage and metal leaching for mines in British Columbia: Part II. Recommended procedures for static and kinetic tests. Fourth International Conference on Acid Rock Drainage. Vancouver, B.C. Canada, May 31–June 6, 1997. Proceedings, vol. I, 15–30.
- Räisänen, M. L., Kauppila, P. M. & Myöhänen, T. 2010.** Suitability of static test for acid rock drainage assessment of mine waste rock. Bulletin of the Geological Society of Finland 82, 101–111. Available at: www.geologinenseura.fi/bulletin/Volume82/Raisanen_2010.pdf
- Räisänen, M. L., Nikkarinen, M., Lehto, O. & Aatos, S. 2002.** Liukoisuustesti- ja heikkouuttomenetelmät kaivannaisteollisuuden ympäristö- ja kaatopaikkakelpoisuuden määrittämisessä. Geological Survey of Finland, archive report S44/0000/1/2002. 21 p. Available at: http://tupa.gtk.fi/raportti/arkisto/s44_0000_1_2002.pdf
- STUK 2013a.** Matala- ja keskiaktiivisten ydinjätteen käsittely ja ydinlaitoksen käytöstäpoisto. Säteilyturvakeskus ohje YVL D.4/15.11.2013. 21 p. Available at: https://www.finlex.fi/data/normit/41416/YVL_D.4.pdf (in Finnish)
- STUK 2013b.** Päätös radioaktiivisten materiaalien vapauttamisrajoista. Säteilyturvakeskuksen päätös 4/3020/2013. 11.9.2013. 4 p. Available at: <http://www.stuk.fi/documents/12547/476916/paatos-4-3020-2013-radioaktiivisten-materiaalien-vapauttamisrajoista.pdf/d5af7650-453c-4cc5-bd69-e1ae7f-8856ba> (in Finnish)
- STUK 2016.** Categories of radioactive waste and emissions. Available at: <http://www.stuk.fi/web/en/topics/nuclear-waste/categories-of-radioactive-waste-and-emissions>
- Taskinen, A., Kauppila, P. M., Heino, N., Kurhila, M., Tiljander, M., Tornivaara, T. & Korhonen, T. 2018a.** Kopsan Au–Cu–malmin arseenipitoisen rikastushiekan muokkaaminen ympäristökelpoisemmaksi rikastusteknisin menetelmin. Geological Survey of Finland, Open File Work Report 9/2018. 112 p. (in Finnish). Available at: http://tupa.gtk.fi/raportti/arkisto/9_2018.pdf
- Taskinen, A., Kauppila, P., Tornivaara, A., Heino, N., Kurhila, M., Tiljander, M. & Korhonen, T. 2018b.** Improving environmental properties of arsenic and sulphide rich Kopsa Au–Cu ore tailings through optimised mineral processing. In: Kauppila, P. M. & Tervainen, T. (eds) Improving the environmental properties, utilisation potential and long-term prediction of mining wastes. Geological Survey of Finland, Bulletin 408. (this volume). Available at: <https://doi.org/10.30440/bt408.4>
- Tornivaara, A., Taskinen, A., Heino, N. & Tiljander, M. 2018.** Rikastushiekan muokkaaminen hyötykäyttöpotentiaalin lisäämiseksi ja sen soveltuvuus jätealueen peittoon. Geological Survey of Finland, Open File Work Report 10/2018. (in Finnish)
- White, W. W. III, Lapakko, K. A. & Cox, R. L. 1999.** Static-test methods most commonly used to predict acid mine drainage: Practical guidelines for use and interpretation. In: Plumlee, G. S. & Logsdon, M. (eds) The Environmental Geochemistry of Mineral Deposits, Part A: Theory and background. Society of Economic Geologists Reviews in Economic Geology, vol. 7A, 325–328.

Standards referred to in the text

- ASTM D5744-13.** Standard Test Method for Laboratory Weathering of Solid Materials Using a Humidity Cell.
- CEN/TR 16376.** Characterization of waste. Overall guidance document for characterization of waste from the extractive industries.
- SFS-EN 15875.** Characterization of waste. Static test for determination of acid potential and neutralization potential of sulfidic waste.



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Waste management is one of the key challenges in sustainable mining due to the large amounts and long-term environmental impacts involved. The study presented in this publication focused on finding solutions to improve prediction of the long-term behaviour of extractive wastes and to increase their raw material value. The prediction methods applied included laboratory measurements, field tests and reactive transport modelling. One of the key issues in improving material eco-efficiency is the optimisation of wastes in mineral processing. This publication presents an overall model for tailings optimisation and provides examples of the use of mineral processing in improving the environmental performance of arsenic-containing tailings.

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