Geochemical Monitoring to Use Waste Rock in Mine Component Construction

David Arcos[1], Pablo Quesada[2], Alonso Huamán[3], Emilie Coene[4], Ersan Demirer[5]

[1]*Amphos 21 Consulting S.L. c/ Veneçuela 103, 2ª plta., 08019 Barcelona, Spain, david.arcos@amphos21.com*

[2]*Amphos 21 Consulting Perú S.A.C. Jirón Paseo del Bosque 500 of. 201, Urb. Chacarilla del Estanque – San Borja, 15037 Lima, Peru, pablo.quesada@amphos21.com*

[3]*Amphos 21 Consulting Perú S.A.C. Jirón Paseo del Bosque 500 of. 201, Urb. Chacarilla del Estanque – San Borja, 15037 Lima, Peru, alonso.huaman@amphos21.com*

[4]*Amphos 21 Consulting S.L. c/ Veneçuela 103, 2ª plta., 08019 Barcelona, Spain, emilie.coene@amphos21.com*

[5]*Amphos 21 Consulting S.L. c/ Veneçuela 103, 2ª plta., 08019 Barcelona, Spain, ersan.demirer@amphos21.com*

Abstract

Current mining operations require the use of waste rock for the construction of components, such as the tailings dam. In the case of the mine considered in this study, the possibility of using material defined as PAG (potential acid generation) was also required. To this end, an ambitious testing program was developed for more than 8 years specially focused on the geochemical behaviour of the use of this material. As a result, innovative methodologies were developed in the industry that concluded with the definition of the characteristics of the PAG material that could be used in the construction of the tailings dam.

Keywords: Geochemistry, tailings facilities, mining operations, geochemical monitoring, large-scale tests

Introduction

Mining operations need to construct several components to operate the mine. These components include waste rock dumps, tailings deposition facilities, process plants, water reservoirs, live camps, roads, and many other infrastructures. Many of these infrastructures require large earthworks and the availability of rock material for their construction. Although, in some cases, these rocks can be extracted from quarries inside the mining area, in other cases, the only suitable material is the waste rock excavated from the mine pit. This is the case of the Mine Z in Peru, an open-pit mining operation in a porphyry copper deposit with an associated copper skarn. Mines in this type of deposits usually needs very large tailings facilities. In this case, the dam of the tailings deposit was initially designed using geotechnically acceptable waste rocks of the Non-PAG (Non-Potential Acid Generation) type. However, after several operational modifications, due to increase of mineral reserves, the change in mine planning resulted in a mismatch between tailings dam construction schedule and Non-PAG rocks availability. This led to pushing the limits of non-PAG material and evaluating the use of a material that, while being PAG, could be used during periods of time when non-PAG material was not available for the construction of the tailings dam. For this reason, a geochemical program to test the use of part of the PAG material for the dam construction was initiated. The objective of the program was to evaluate the type of PAG and its encapsulation conditions to prevent or minimize acid mine drainage and metal leaching from the tailings dam. This paper presents the results of this program and demonstrates the usefulness of environmental geochemistry in mining operations.

Methods

The geochemical program was divided in four different stages. Stage 1 consisted in the revision of all the geochemical information from waste rocks recorded by the mine, including lithological and mineralogical descriptions, and geochemical analysis and tests in 250 samples. The main source of analytical data came from ABA, NAG and SPLP tests, as well as humidity cell tests in 35 of the samples. This review allowed to define geoenvironmental units (GEUs), as rock types with equivalent lithologies and mineralogy, and similar geochemical behaviour (Arcos *et al.* 2011).

Stage 2 consisted of field tests in humidity cells. These tests used 1 m3 cells filled with the previously defined GEUs and combinations between them to evaluate the geochemical effect of the encapsulation of the PAG material (Fig. 1). A quartz gravel-filled cell was also constructed to be used as a reference cell. The cells were exposed to the site climatic conditions for over 6 years, during which they were monitored during rainfall events in the wet season. After each rainfall event, drainage water of the cells was collected in buckets, where the volume was measured, and field parameters (pH, electrical conductivity, temperature, total dissolved solids, dissolved oxygen and redox potential) were measured. In addition, a sample was taken for a complete chemical analysis of the drainage water.

In Stage 3, a layer of PAG material was installed in the dam of the tailings facility. This layer was monitored using oxygen and volumetric water content sensors. In addition to these parameters, the sensors also measured electrical conductivity and temperature. The sensors were arranged along four cross sections of the dam in three lines in each section (lower, middle and upper lines). Each line contained three pairs of sensors each one at 15, 25 and 35 m from the outer slope of the dam as shown for one of the sections in Fig. 2. It is important to note that the lower line was located in Non-PAG material and was considered as a reference line. The construction of the system, from the installation of the first line to the upper

Figure 1 *Field humidity cell tests at the mine site.*

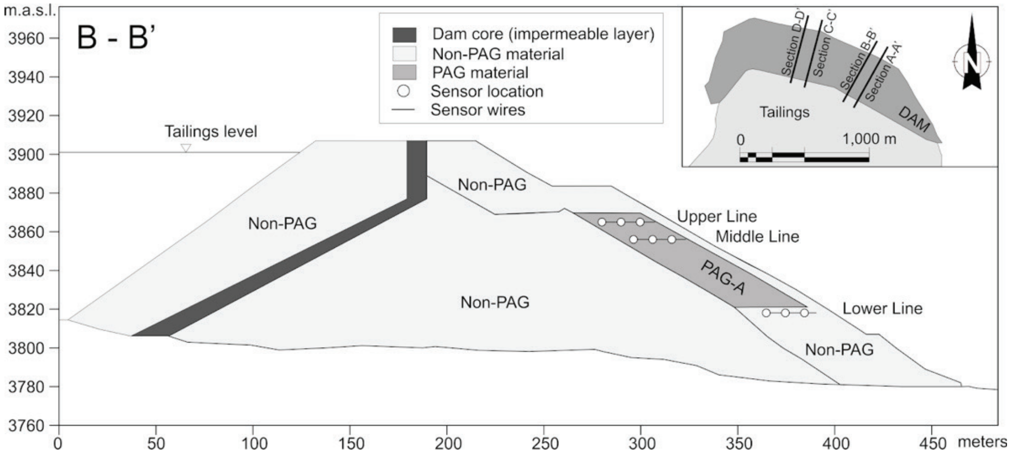

***Figure 2** Profile across the dam of the tailings facility showing the PAG layer and the location of the sensors.*

one, took approximately one year. Sensors have been recording a hourly measurements for a period of more than four years since the installation of the lower line.

Finally, the data collected throughout the previous stages have been used to calibrate a reactive transport model. This model has been implemented in the iCP interface (Nardi *et al*. 2014), which is a coupling between Comsol Multiphysics®, a general-purpose finite element simulation software for modelling coupled physics systems, and the geochemical code PHREEQC (Parkhurst and Appelo 2013). The result of this interface is a tool for solving a wide range of multiphysics and chemical problems, in this case a model of unsteady, variable-temperature reactive transport under unsaturated conditions.

Results and Discussion

Historical geochemical data from the mine reveal that results are highly dependent on lithology and its relationship to the mineralizing event. In terms of acid-generating potential, high carbonate (i.e. calcite) lithologies such as limestones, marbles and skarn alteration have been defined as Non-PAG. Post-mineralization intrusive rocks have also been defined as Non-PAG. In contrast, intrusive rocks associated with or prior to the mineralizing event, as well as some endoskarn samples, are defined as PAG or Non-PAG depending on carbonate and/or sulfide content.

In terms of metal leaching potential, based on leachates from NAG and SPLP tests, the neutralization potential ratio (NPR) has been identified as the main variable. This parameter indirectly includes lithological characteristics, since it usually presents high values for those lithologies with high calcite contents (i.e. limestones) or when the sulfide content is very low (post-mineralization intrusive rocks). The relationship between metal leaching potential and NPR shows that for a NPR > 3 this potential will be very low; while for a NPR < 0.3 the potential almost always exceeds the maximum permissible limit (MPL) defined in the legislation for mining effluents. Between both NPR values, metal concentrations gradually increase, but always below the MPL. This behaviour has been observed for all metals, although not all of them exceed the corresponding MPL value when NPR < 0.3. This allowed the differentiation of GEUs based on the NPR and sulfide content:

- **Non-PAG:** Rocks with an NPR ⩾3.0 and/or $S_{sulfide}$ ⩽0.1
- **PAG-A:** Rocks with an NPR between 0.3 and 3.0 and $S_{sulfide}$ >0.1
- **PAG-B:** Rocks with an NPR <0.3 and $S_{sulfide}$ >0.1

Field humidity cells show a similar behaviour after more than 6 years in operation (Fig. 3). Thus, the most acidic conditions and with higher concentrations of sulfate and metals in the leachates correspond to the

PAG-B material. In contrast, the Non-PAG material presents neutral to slightly alkaline conditions and very low concentrations of metals. While the PAG-A material shows an intermediate behaviour. It is important to highlight the variable behaviour of PAG-A. One of the samples shows a pH ≈ 7 over the 6 years of testing; while the other sample shows a constant decrease from pH = 7 at the beginning of the test, to pH ≈ 3 after 6 years of testing. Similarly, metals evolve to much higher concentrations in the sample with higher acidity, reaching values very similar to those of the PAG-B sample (Fig. 4). The largest difference between the two samples corresponds to the sulfide content (i.e. pyrite), being 0.4 and 0.8 wt.% for the sample kept under neutral conditions and for the sample evolving under acidic conditions, respectively. This could indicate the existence of a threshold value for the sulfide concentration, from which acid generation occurs in PAG-A and, therefore, metal concentrations increase. This is something to consider when using this material in the construction of the tailings dam.

Some of the cells were designed to evaluate the effect of encapsulating PAG material with different configurations and thicknesses of Non-PAG material. Fig. 3 shows the result of two cells in which a 0.5 m thick layer of PAG-A was placed between two 0.25 m thick layers of Non-PAG. The effect of encapsulation, in all encapsulation configurations, was to neutralize the acidity generated in the PAG layer and to reduce the concentration of metals in the drainage water by more than one order of magnitude, to values below the MPL. This behaviour was a clear argument in favour of using PAG-A type material in the construction of the tailings dam.

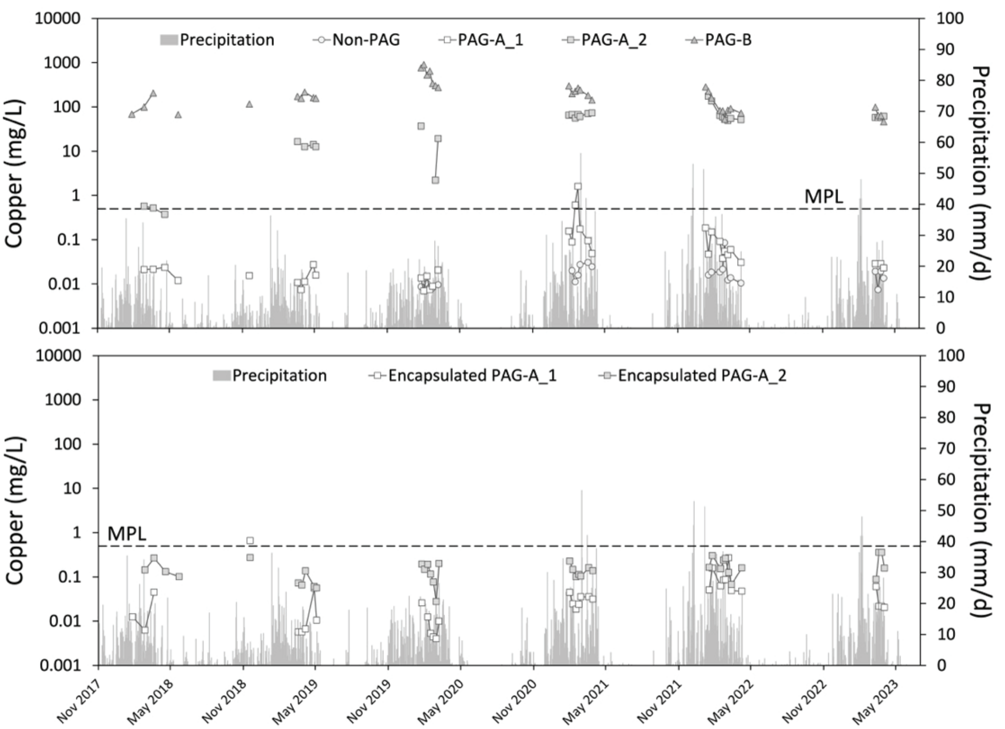

Figure 3 Graphics showing the geochemical evolution of some of the field humidity cells. Upper graphic shows the evolution of cells representative of the three GEUs, whereas bottom graphic shows the evolution of two of the cells where a 0.5 m thick layer of PAG-A material was sandwiched between two 0.25 m thick layers of Non-PAG material. Histogram at the bottom of both graphs represents the daily precipitation MPL: maximum permissible limit.

Installation of the PAG-A layer in the tailings dam began in December 2020. Although the variable behaviour of this material described above had already been identified, there was no possibility to limit this material to lower sulfide contents due to mine planning constraints. It should be noted that the materials used for the construction of the dam are based on the definition of GEUs, which was implemented in the mine block model. Therefore, although each 20 × 20 × 15 m block can be assigned a GEU, there may be some heterogeneity inside.

Since the installation of the lower line, most of the sensors worked perfectly for the first two years, but after two and a half years, failures began to occur in the oxygen sensors installed in the middle lines of all the profiles. As will be seen later, this was attributed to these sensors being more sensitive to the acidic conditions that were being generated in these locations, although this could not be verified for obvious reasons. The water content sensors functioned perfectly throughout the monitoring period.

The results show that the dam materials are unsaturated with respect to water content, but that during the rainy season the saturation increases, without reaching complete saturation. The response time with respect to rain events depends on the depth of the sensor at any given time (it is noting that the dam is under permanent construction according to operational needs) and the distance from the external slope of the dam, but in general it is between two weeks and a month and a half.

Oxygen measurements in the gas phase decreased towards the interior of the dam (Fig. 4). But more importantly, there was a decrease in concentration between the lower and upper lines. Thus, while oxygen contents close to atmospheric levels (21% O2) were recorded in the lower lines (in Non-PAG layers), the values in the middle and upper lines were lower (already in the PAG-A layer). Although this decrease may be due to the oxidation process of pyrite (the predominant sulfide mineral in the waste rock), it is difficult to confirm this relationship.

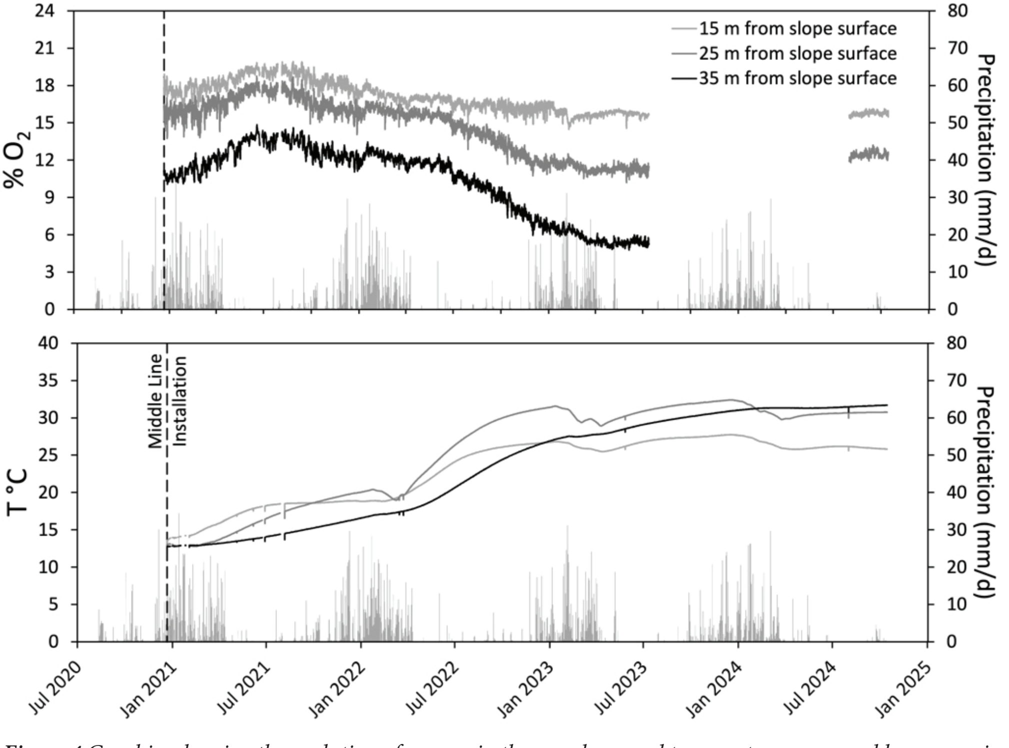

Figure 4 *Graphics showing the evolution of oxygen in the gas phase and temperature measured by sensors in one of the middle lines installed in the tailings dam.*

On the other hand, the evolution of the recorded temperature shows that in the sensors of the lower lines (in non-PAG material) the temperature increases from around 12 °C, just after the installation of the sensors, to 15–19 °C after 4 years. However, this evolution only occurs in the innermost sensors (at 35 m) with respect to the external slope of the dam, while the intermediate sensors show a smaller increase and the outermost ones (at 15 m from the external slope) do not show variation with respect to the beginning. However, the greatest changes are recorded in the sensors installed in PAG-A material. In the middle lines (Fig. 4), an increase was recorded in all the sensors from the initial 12 °C to 26–33 °C in the sensors located 25 and 35 m from the external surface. The sensor located in the outermost part (15 m) also recorded an increase, although smaller (15–26 °C). In the upper lines of sensors, an increase is also recorded up to 16–21 °C, much lower than in the case of the middle lines and more homogeneous for all the sensors in the line. It is worth noting that during the rainy season, the sensors that record higher temperatures show a slight decrease (Fig. 4), which then continues to increase during the dry season.

This temperature evolution inside the dam indicates the existence of an exothermic process and, considering the characteristics of the materials, this process consists of the oxidation of pyrite, so the temperature record is a more effective indicator to identify the existence of acid drainage generation processes. In fact, it not only allows the identification of the pyrite oxidation process but can also be used to quantify and calibrate the process in a reactive transport model.

The information generated from the geochemical tests was included in a reactive transport model for the dam. Only the downstream part of the dam was considered in the model, since the rest is separated by an impermeable layer (Fig. 2). The saturation, water and air flow parameters were calibrated using the information generated from the sensors installed in the tailings facility. The model considered the kinetic dissolution of primary minerals, mainly silicates, sulfides and carbonates, as well as the precipitation-dissolution under equilibrium conditions of secondary minerals. The model also considered the air flow in the system and the consumption of oxygen from the air by dissolution in the aqueous phase and pyrite oxidation. The pyrite oxidation process was calibrated from temperature data from the sensors, since the heat generation of the process from the enthalpy of the reaction was included in the model, so the model was run under non-isothermal conditions. Based on temperature records and to consider the high variability of the sulfide content of the PAG-A material, two subtypes of this material were included in the model, one with 1 wt.% pyrite (PAG-A1) and another with 10 wt.% pyrite (PAG-A2).

The model simulated a three-year period, and the results were compared to data on the quality of the dam drainage water, since the installation of the PAG-A layer, which is analysed monthly. The comparison showed that the model results fit the drainage data reasonably well. As shown in Fig. 5, the temperature results are equivalent to those recorded, and the metal concentrations in the waters inside the dam show that it is the PAG-A2 material that actually generates metal leaching.

It can therefore be concluded that, in this case, the use of PAG-A material with pyrite contents below 1 wt.% is geochemically acceptable for the construction of the dam since it will not generate acidic conditions in the system nor lead to the leaching of metals that may exceed the maximum permissible limits. A long-term model under closure conditions has also been developed, the results of which point in the same direction.

Conclusions

The results of this project show that geochemistry can play a very important role in the mining industry, not only in terms of environmental impact, but also in the mining operation itself, both in the engineering design of the operation and in the management and monitoring of components. In the case of this mine, this translates into a very well-calibrated definition of GEUs that allows defining their uses in the mining operation. It can also

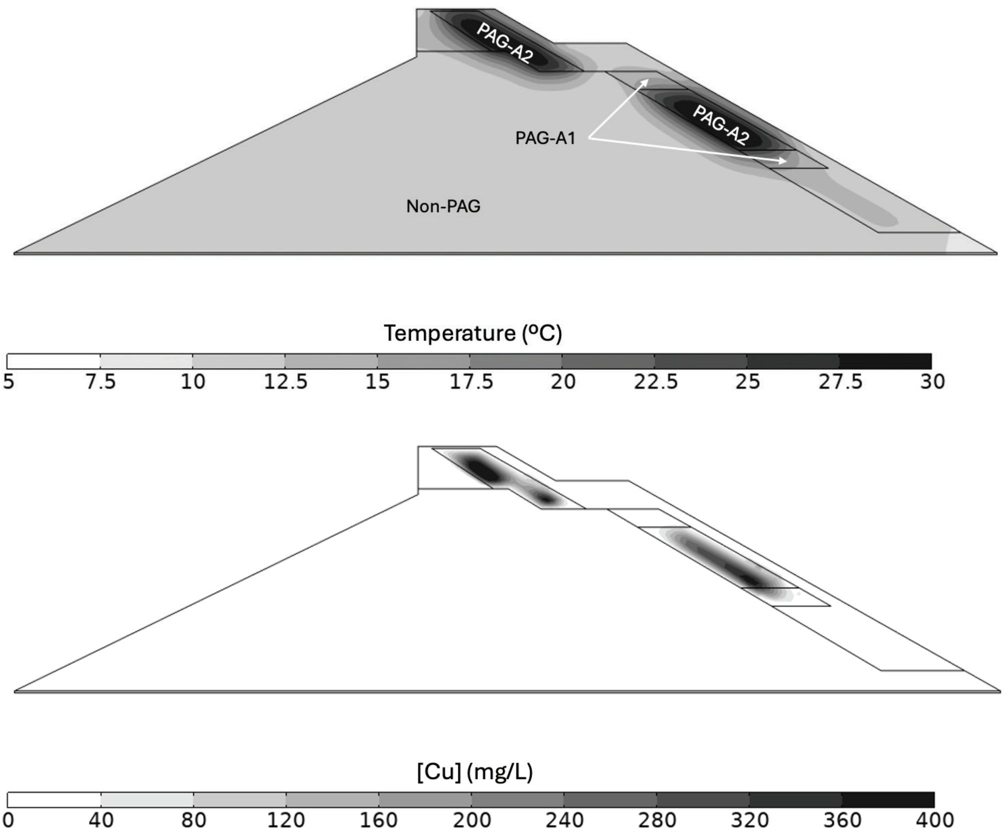

Figure 5 *Calibrated modelling results after 3 years of simulation for temperature (above) and copper concentration in water (below).*

be concluded that one of the key factors in identifying the generation of acid drainage in a mining component is temperature monitoring, which may represent a key factor in the future.

Acknowledgements

The authors thank all the staff of the mine for their support along the project, helping in the design, construction and data acquisition phases, as well as for their useful discussions on the results.

References

Arcos D, von Igel W, Flores LG, Acuña A (2011) Geoenvironmental units (GEUs) in waste dumps from Collahuasi. Proceedings of the 2nd International Seminar on Environmental Issues in the Mining Industry. Santiago, Chile, November 2011.

Nardi A, Idiart A, Trinchero P, de Vries LM, Molinero J (2014) Interface COMSOL-PHREEQC (iCP), an efficient numerical framework for the solution of coupled multiphysics and geochemistry. Computers & Geosciences 69: 10-21

Parkhurst DL, Appelo CAJ (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, book 6, chap. A43, 497 p., available only at http://pubs.usgs.gov/tm/06/a43/.