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Enabling sustainability in mining case study: mine backfill

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Abstract

Mine tailings are the byproduct of the extraction process and they represent a byproduct whose storage is expensive and, in many cases, a reason of environmental concern. As a result, tailings storage must be planned and carefully executed, monitoring changes even after the mine closure.

The rising need in resources worldwide is being accompanied by a progressive decrease in commodity grades per tonne. That means that more material must be extracted and processed to obtain the same amount of commodity (e.g. Au, Cu, Ag etc.). As a consequence, the amount of tailings generated is expected to increase with time, and the correct management of this 'waste' material is a growing concern for the mining business.

Due to the progressive global shift towards underground mining, mine backfill (MBF) practices are becoming a frequent must in flow sheets. MBF reduces the amount of tailings stored on surface by placing them underground together with water and cement, with the aim to fill the voids. This procedure also allows miners to extract material nearby without compromising global stability (avoiding other issues such as subsidence). To achieve this goal, the hardened paste must comply with strict strength requirements which are normally achieved by increasing the amount of cement in the mix.

In the race to net zero many mines have signed strict environmental policies, which compromise the cost balance of any process using cement, including MBF. This compels the businesses to utilise chemicals that reduce the amount of binder, and therefore the carbon footprint, while improving the performance of the mix at all stages.

The Sika® multinational brand provides tailor-made reliable and sustainable chemical solutions to many industries, including the mining business. The application of Sika technologies and know-how supports more sustainable procedures and greener (and more profitable) practices.

Each mine has different mineralogy, which makes every project unique. Finding the right cement and admixture can therefore be a time-consuming task, which directly affects the profitability of the mine, especially during field testing manoeuvres. As such, the development of tools and techniques which shorten the time between testing and decision-making are crucial to resume exploitation fast.

In this work, the authors successfully apply a tailor-made MBF technology to reduce cement (and the associated CO_2 footprint) in an underground gold mining project, and propose a three-dimensional quick-view plot design. In this kind of graph, different field tests analyses are displayed, allowing the viewer to simultaneously compare strength, cement percentages and admixture dosages for a given time (e.g. 3, 7, 28 days). This view enhances the understanding of the system as a whole, allowing for an easy assessment of *the changing properties of the hardened paste when the cement and admixture percentages vary, helping in decision-making.*

Keywords: *cemented paste backfill, mining, cement reduction, time management, data plot*

1 Introduction

Mine backfill (MBF) consists of reintroducing mine tailings combined with cement and water back into the mined voids via gravity or pumping. This practice is performed with the objective to fill the void left by mining to promote global stability to the mine to allow further underground mining activities to take place. Thus, reaching the desired strength after curing is critical to maintain the mining schedule (e.g. Slade 2010).

High proportions of water in the mix design have a negative impact on the strength of the cured paste. Water, however, improves the rheological properties of the paste, enhancing the mixture's fluidity, and lowering the required pressure head to distribute paste into the stopes. The use of Sika® admixtures therefore helps to improve the rheological properties of the paste by decreasing the water input and increasing the strength of the mix without the addition of extra cement.

The ideal Sika solution depends on the mineralogical composition of the tailings, which is unique for each mine. In addition, the admixture behaviour must be flexible, to compensate for the compositional heterogeneity of the tailings, offering the highest performance possible.

Sika solutions are customised in the laboratory for each case, however, industrial tests are key to optimise the cost/benefit balance of the mine.

Sika Ecuatoriana S.A. has conducted numerous laboratory tests on samples of an underground (UG) gold tailings, identifying the best fitting admixture for the current needs of the mine. Ulteriorly, industrial tests have been carried out at the mine, to prepare the paste plant to include this extra component in the flow chart, and to adjust the admixture dosage. Three-dimensional (3D) plots were used as a tool to assess the effectiveness of Sika admixtures in paste with changing cement percentages.

2 Methodology

The two main recipes at the UG gold mine are the 'plug' and the 'body' mix designs, with original cement contents of 12 and 9%, respectively. The objective of the mix design is to reduce the cement content in MBF operations while still achieving strengths of 250 kPa in seven days for the plug mix design, and 400 kPa in 80 days for the body mix design.

Two steps must be differentiated in this study: lab tests and industrial trials.

1. Characterisation and laboratory tests

   A sample of tailings from an underground gold mine was received for characterisation and admixture selection. The equipment utilised was:

   a. X-ray diffraction on powder (XRD): Bruker D8 ADVANCE; angle range: 3–65° 2θ, step size: 0.015°, time/step: 1.0 s (BL), Cu-kα radiation.

   b. Determination of the particle size distribution (PSD) using laser diffraction: Sympatec HELOS, wet dispersion in distilled water (QUIXEL).

   To identify the most suitable admixture, a series of laboratory experiments were conducted using a Abrams truncated cone (scale 1:2,5) and mixing was performed with a Heidolph mixer (RZR 2012) at 1,000 rpm for two minutes. These experiments involved creating paste with a single cement content while assessing various admixture designs and water ratios to evaluate any changes in rheology. The best-performing designs were selected based on these evaluations. The designs showcasing optimal performance were compared against the mine's standard paste formulation. The solid content was adjusted to meet rheology requirements, and strength development.

2. Industrial trials

   Industrial trials were conducted in December 2021. The materials used for the paste backfill include:

   a. Cement (HE type, Cementos Chimborazo, portland and puzzolan mix)
   b. Process water
   c. Filtered tailings with a solids content between 80 and 85%
   d. Slurry with solids content between 50 and 60%
   e. Sika Stabilizer-301 MBF EC admixture (8,000 kg)

   A total of 37 tests were conducted with different percentages of cement, water, and admixture. In each case, cylindrical samples (7.75 × 15.5cm) were casted in duplicate to measure strength. Strength results were obtained at 3, 7, and 28 days, monitoring the elastic modulus of the cylinders under uniaxial compressive stress.

3 Results

3.1 Characterisation and laboratory tests

The mineralogical analysis of the tailings depicted in Table 1 shows that the UG gold mine exhibits a mineralogy common to other epithermal deposits (e.g. Marghany 2022). The sample contains silicium oxide, (mostly chalcedony and crystalline quartz) and various phyllosilicate minerals (22.5% by weight), such as muscovite, chlorite, and the common alteration mineral, kaolinite. Additionally, there is a low amount of potassium feldspar (microcline) and traces of carbonates (calcite, 0.5% by weight). Pyrite occurs as traces (0.8% by weight).

Table 1 X-ray diffraction semiquantitative analysis (%)

Mineral phases	Sample
Quartz	69%
Pyrite	1%
Kaolinite	6%
Muscovite	11%
Smectite	<Detection limit
Chlorite	5%
Microcline/sanidine	8%
Calcite	1%

Figure 1 shows the particle size distribution analyses by laser diffraction of the underground gold mine tailings sample.

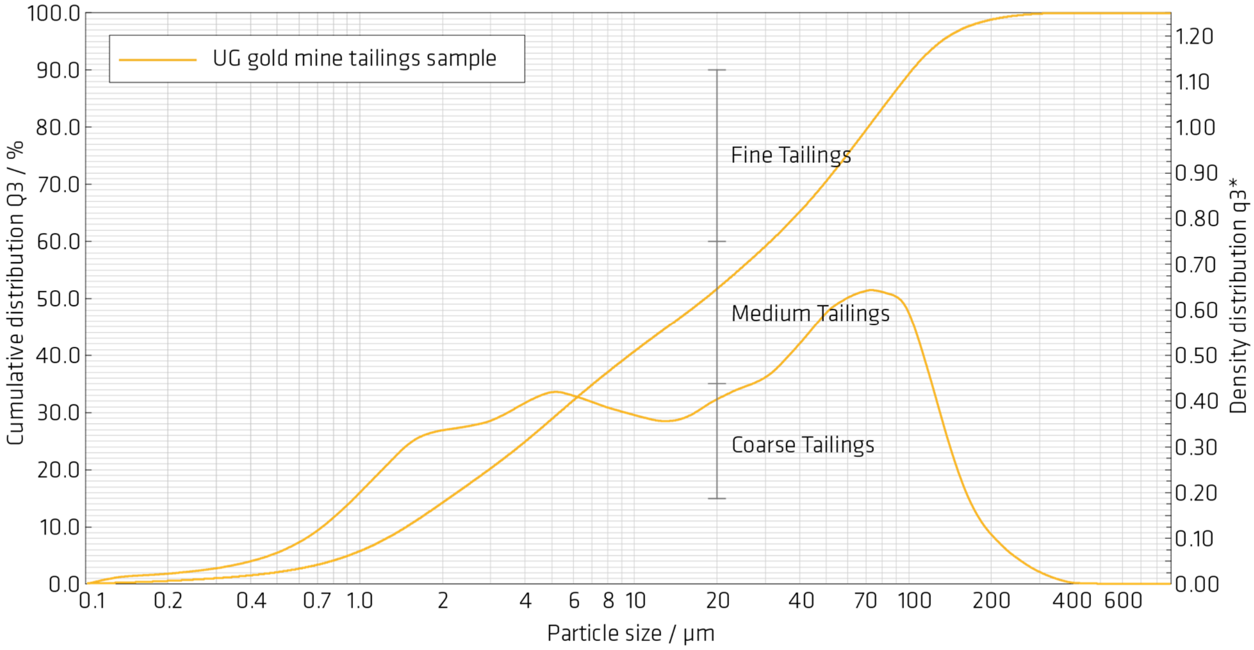

Figure 1 **Particle size distribution analyses by laser diffraction of the underground gold mine tailings sample**

Having characterised the tailings, several mix designs with different Sika admixture designs were tested to evaluate the best-performing admixtures (Figure 2).

The admixture selected must favour dispersion to reduce lumps in the mix, improve flow rate to ease pumping, and reduce water to improve strength at low cement percentages.

The experiments were carried out keeping a constant cement and solid content, with a slump flow above 100 mm (ideally, >140 mm) and with a minimum strength target of 0.25 MPa (limits determined after standard testing with the mine original mix design). As shown in Figure 2, the admixture 3, named Sika Stabilizer - 301 MBF – EC, showed the best results.

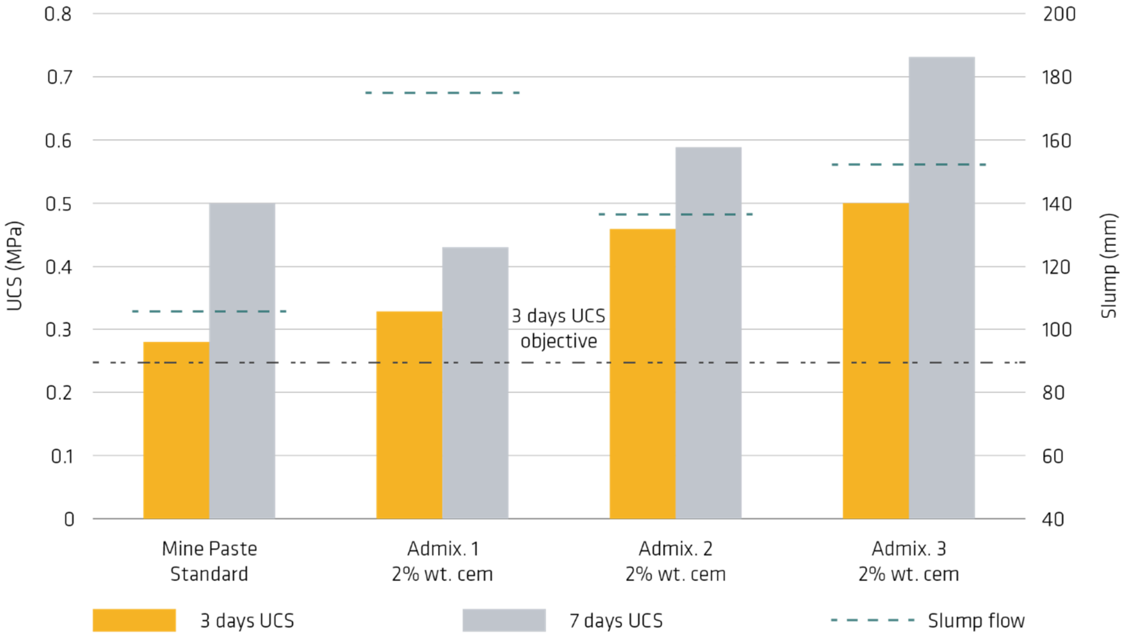

Figure 2 **Strength and slump flow results of paste formulations with different Sika admixture designs. Solid's content and cement content are kept constant**

3.2 Industrial trials

Once the most suitable Sika admixture was selected, full-scale testing and dosage adjustments were to be evaluated through field trials.

These tests had as a goal to optimise the paste designs with different percentages of cement, water, and admixture. In each case, cylindrical samples (7.75 × 15.5cm) were cast to measure the strength after 3, 7 and 28 days, monitoring the elastic modulus of the cylinders when subjected to uniaxial compressive stress. The results of the tests are displayed in the Figures 4 and 5.

As shown in Figure 3, the strength generation after 3, 7 and 28 days with a fixed cement content of 12%, the strength is higher when using Sika® Stabilizer-301 MBF EC, as the trend reaches the desired strength margin after 7 days instead of 28 (sample without admixture). This is a direct consequence of the decrease in water content within the mix, which increases the solids content favouring strength development.

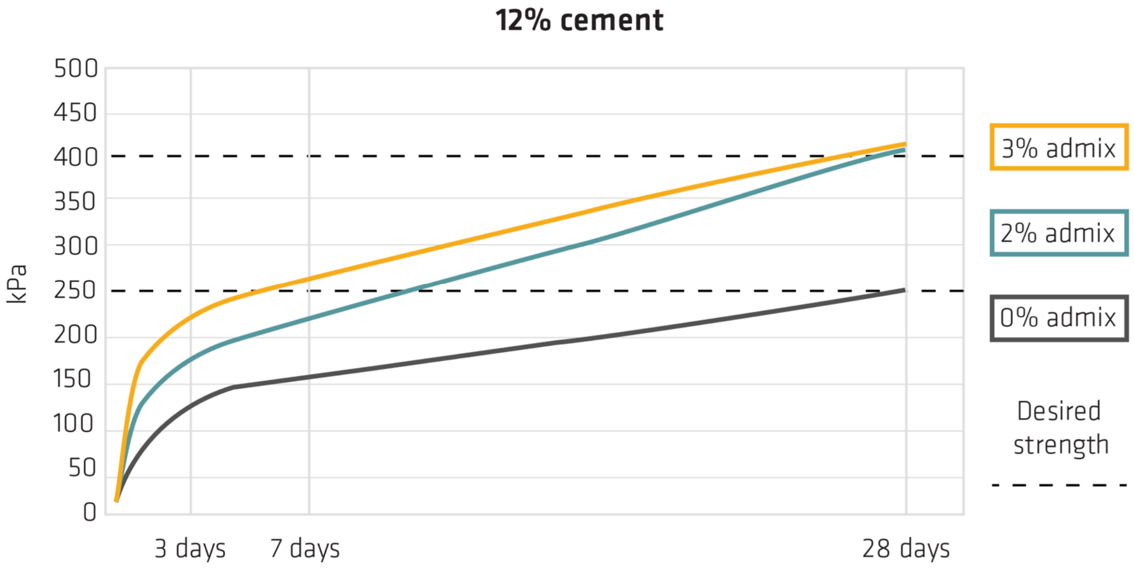

Figure 3 Uniaxial compressive strength comparison with and without admixture in paste mixes with 12% cement. Desired strength (dotted lines): after 7 days, 250 kPa; after 28 days, 400 kPa

The 3, 7 and 28-day plots (Figures 4 and 5) illustrate the strength generation with Sika admixture (yellow line) and without admixture (blue line) using different cement percentages. The figures show a positive increase in the strength tests obtained due to the use of the Sika Stabilizer- 301 MBF EC admixture.

The high number of (automatic and non-controllable) variables present during testing, combined with the discrete time windows available for the tests (which should not affect the running business performance), reduces the representativity of the data in the early stages of industrial trials. For this reason, in our graph, the admixture trend (in yellow) combines testing with two dosages, 2 and 3% admixture. Further industrial trials would allow the authors to separate the lines in two, as a result of (valid) statistical representation of best fitting trends. In the figure, each point has been plotted with three test results for accuracy.

The light blue dashed line represents the average strengths obtained in mix designs without admixture using cement contents of 12%, so the performance can be compared with the samples with admixture.

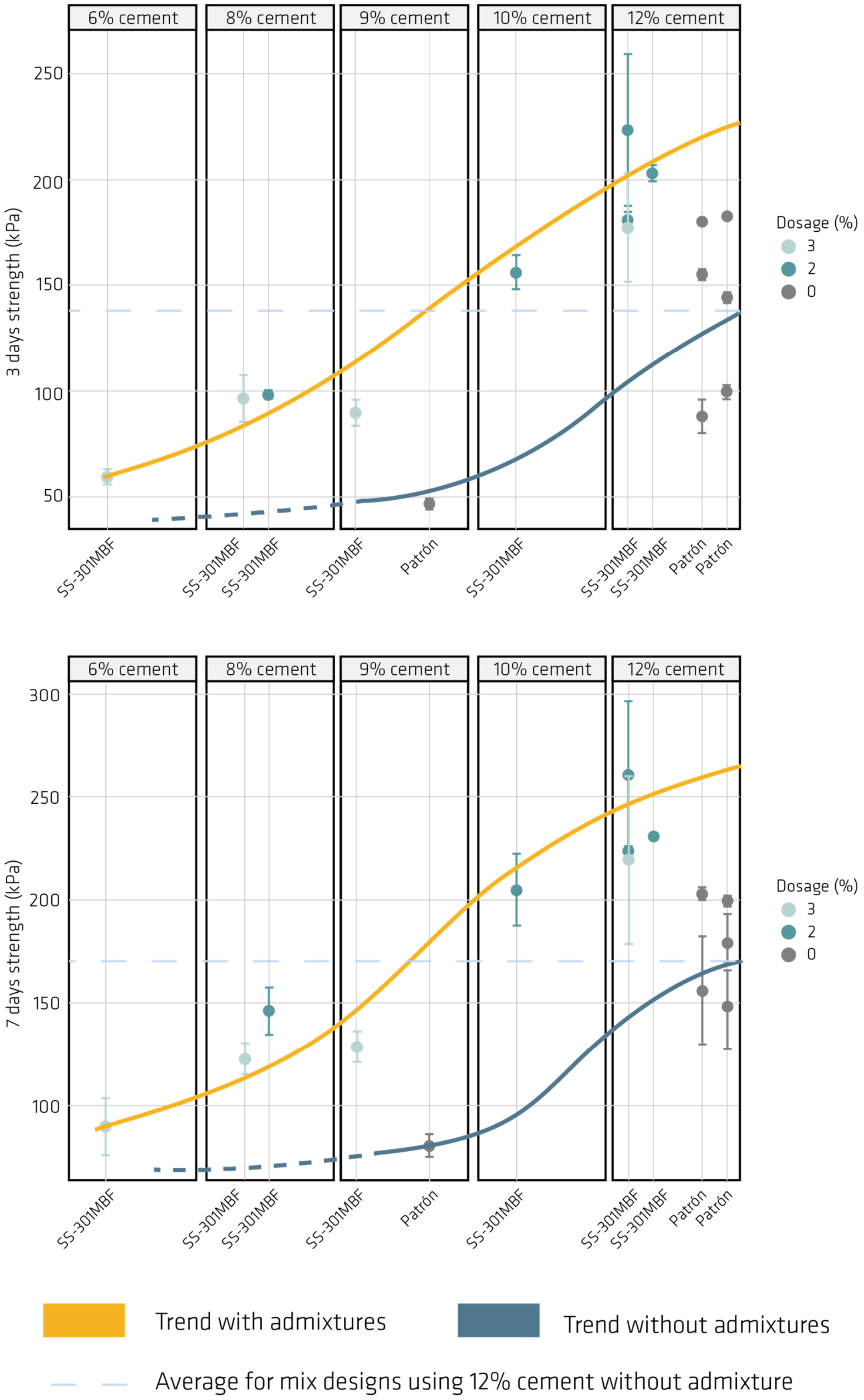

Figure 4 **Uniaxial compressive strength test results after 3 days and after 7 days. The dotted line compares between the strength obtained without admixture and higher cement contents and with admixture and lower cement contents**

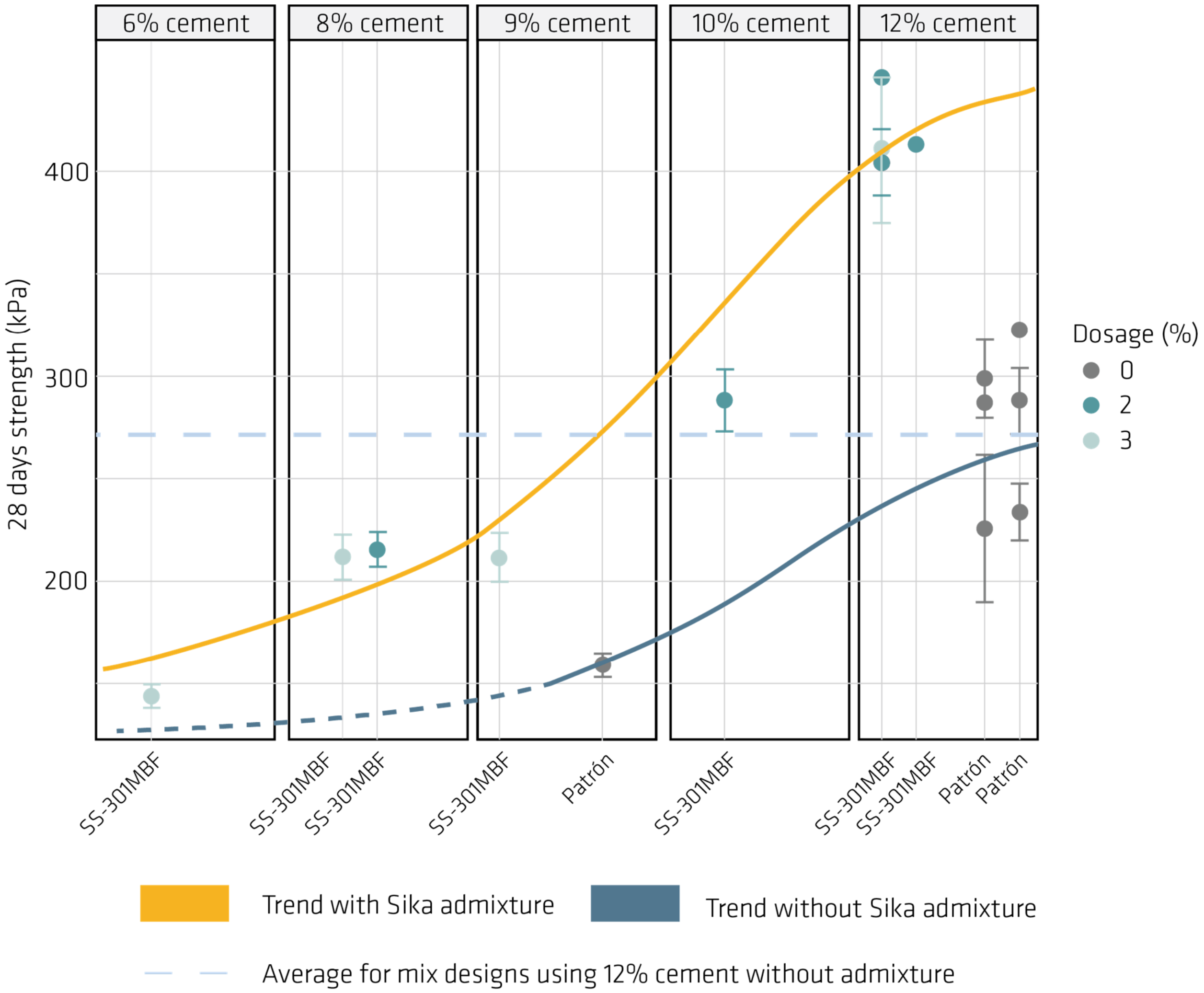

Figure 5 **Uniaxial compressive strength test results after 28 days. The dotted line compares between the strength obtained without admixture and higher cement contents and with admixture and lower cement contents**

Other relevant parameters have been monitored in this study (Figure 6), such as the percentage of solids and the cake/slurry ratio.

According to the results, the Sika Stabilizer- 301 MBF EC admixture allows an increase of 1.5% in solids (Figure 6a), as well as a decrease in the water required for mixing and pumping (yield stress decrease despite solids' increase, Figure 6b).

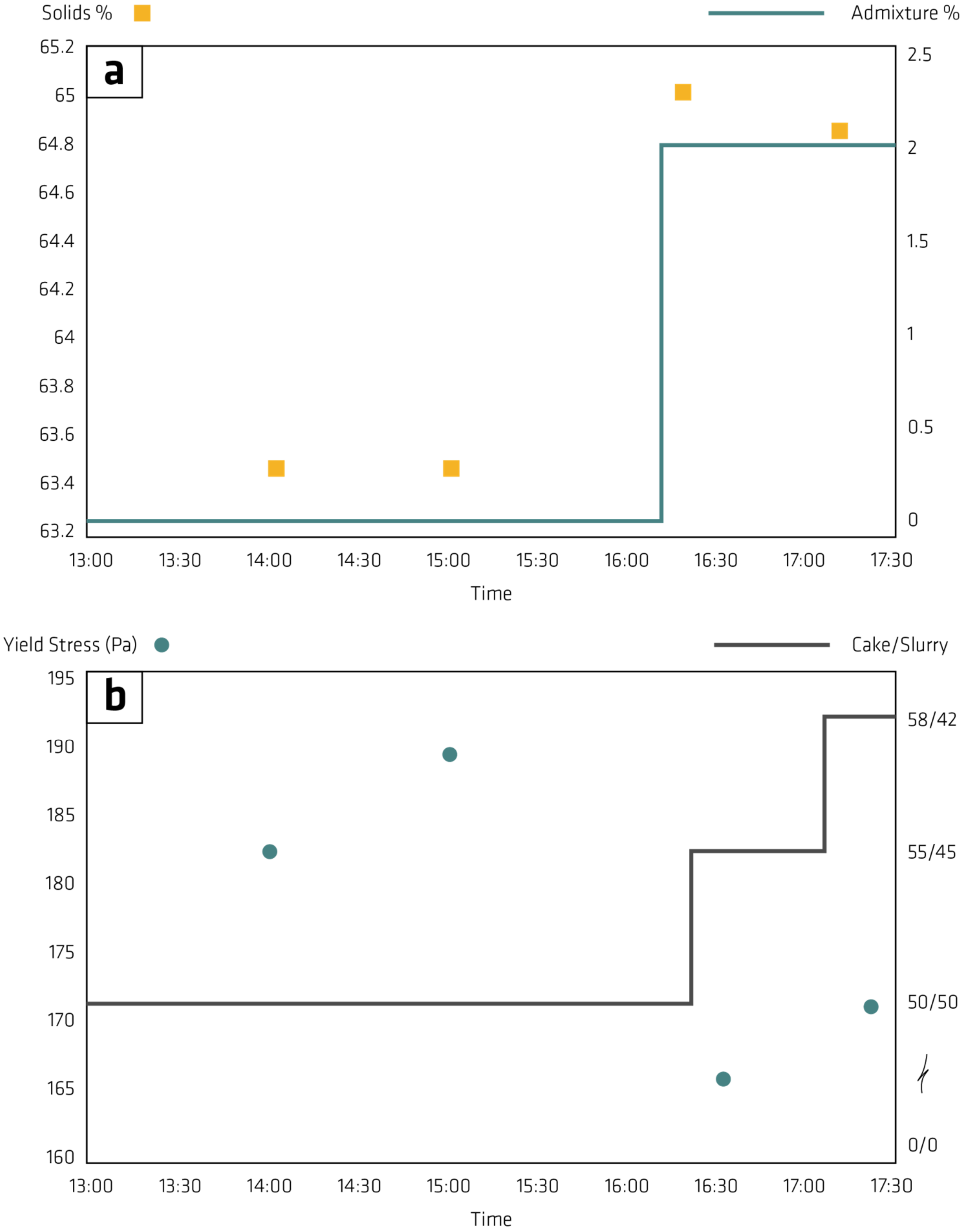

Figure 6 Relevant parameters during the industrial tests carried out in December 2021. (a) Increment of the solid content in fresh paste when the admixture is added to the system; (b) Decrease of the yield stress (Pa) in fresh paste when admixture in added to the system. When adding the admixture, the yield stress decreases even though the solid content increases. This fact eases the pumping pressure while increasing the resistance of the hardened paste

4 Discussion

The UG gold mine is situated beneath a post-mineralisation sedimentary cover rock approximately 200 m thick. This intermediate-sulfidation epithermal gold-silver deposit is believed to be influenced by the Las Peñas fault system, encompassing both eastern and western faults. The mineralisation is phyllosilicate-rich, featuring robust, multi-phase quartz-sulphide ± carbonate stockwork veining and brecciation.

4.1 Characterisation and laboratory tests

Phyllosilicates and particle size are widely known to negatively affect paste rheology (e.g. Ndlovu et al. 2011; Dikonda et al. 2021). The high concentration of phyllosilicate phases in the mine tailings (Table 1, chlorite, muscovite, smectite and kaolinite) is therefore problematic for MBF operations. These mineral phases are detrimental to the paste rheology and strength development as they lower the density, can potentially adsorb admixtures, and are prone to exfoliation, which increases the water and cement demand of the paste (Deb et al. 2017).

As such, the use of specific admixtures that target these phases is a requirement to decrease the cement content in the system.

The capacity of phyllosilicates to sequestrate admixtures (e.g. Borrego-Sánchez et al. 2022) also reflects the importance of tailor-made, problematic, phase-suppressing technologies which lower the water demand while improving the behaviour of the paste. Sulphide minerals are bad because of oxidation in the presence of water and air, producing sulphate ions and acidity in the cementitious mix.

The negative effect of these sulphate ions is due to the combined effects of the following factors: (i) sulphate absorption by calcium silicate hydrate (C-S-H) bonds, creating lower quality bonds; (ii) the formation of expansive minerals such as gypsum and ettringite, and these mineral phases coarsen the pore structure of the cementitious mix, this ensues in lower strength development yields; (iii) furthermore, ettringite also inhibits cement hydration, resulting in longer setting times and fewer hydration products. (Li & Fall 2016)

The low amounts of sulphides (see Table 1) makes paste acidification negligible.

The PSD affects the characteristics of paste in both, fresh and cured state.

According to the Golder Paste Technology tailings classification system (Deb et al. 2017) paste tailings are categorised into three classes, namely coarse, medium, and fine tailings (Table 2). As a general rule, CPB must contain a <20 µm fraction larger than 15%, and this fraction allows for a non-segregating mixture, avoiding bleeding and facilitating transport of the paste through a pipeline (Deb et al. 2017).

Table 2 Paste tailings clasification according to particle size (Deb et al. 2017)

Tailings size category	Passing 20 µm content (wt%)	Strength development (constant w/c ratio)	180 mm slump solid concentration (wt%)
Coarse	15–35	High	78–85
Medium	35–60	Low	70–78
Fine	60–90	Poor	55–70

Indices such as the coefficient of uniformity (CU) and coefficient of curvature (CC) are employed to determine the grade quality of a sample, and they are generally used to characterise and qualify the PSD of the tailings to be used for backfilling (Equations 1 and 2). It has been studied that paste backfill samples have the highest strength with a CU of approximately between 4 and 6, showing improved packing density, reduced porosity, and generally high friction angle (Deb et al. 2017) and a CC between 1 and 3.

Equation 1 is the C_U:

$$C_U = \frac{D_{60}}{D_{10}} \quad (1)$$

where:

D_{10} = grain size at 10% passing

D_{60} = grain size at 60% passing.

Equation 2 is the CC:

$$CC = \frac{D_{30}^2}{D_{60} \times D_{10}} \quad (2)$$

where:

D_{10} = grain size at 10% passing

D_{30} = grain size at 30% passing

D_{60} = grain size at 60% passing.

The tailings sample from the UG gold mine are medium to fine sized according with the Golder Paste Technology tailings classification system, which is in agreement with the results obtained from the study of 34 different mine tailings previously analysed by Sika (Figure 7). Moreover, the sample presents a CU of 22.1, which is not in between the ideal parameters, as well as the CC, which yields a value of 0.6.

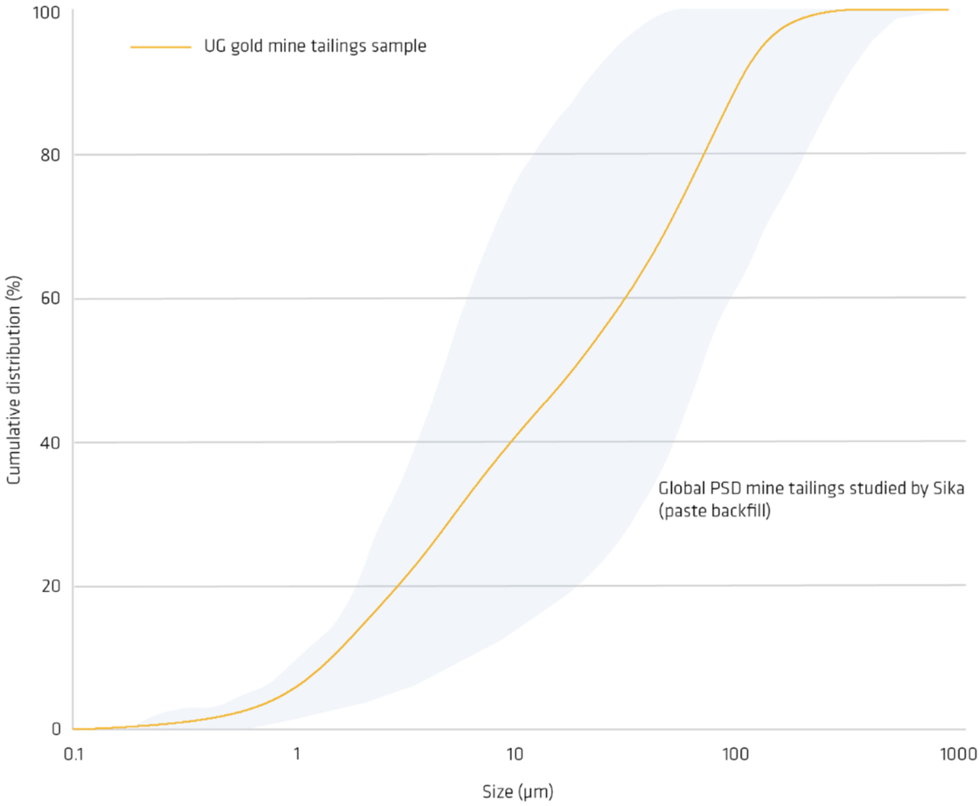

Figure 7 Cumulative particle size distribution (PSD) analyses by laser diffraction of the UG gold mine tailings sample. The solid yellow line corresponds to the analysis performed. Comparison with 34 tailings analyses of other mines previously studied by Sika is also provided (light blue field)

The PSD indicates a moderate water absorption and admixture adsorption by the UG gold mine tailings when compared with their even finer counterparts. If finer milling is required in the future as a response to ore liberation procedures, the resultant finer tailings would have a direct effect in the water and admixture demand, and the paste mix design must be readjusted. Under this case scenario, coupled with the mineralogy that is rich in phyllosilicates, it might require fine recipe adaptations in the future.

According to laboratory tests, the best fitting admixture was determined and named Sika Stabilizer - 301 MBF EC. The laboratory tests using admix 1, 2 and 3 yield a slump flow much greater than the reference, and lumps dispersion was observed during mixing. However strength tests proved the performance of the Sika Stabilizer - 301 MBF to be the optimal (Figure 2). The formula has been optimised ulteriorly by Sika Ecuatoriana with local raw materials, yielding the final Sika Stabilizer - 301 MBF EC product.

4.2 Industrial trials

The use of Sika admixtures increases the solids ratio and decreases the amount of water, improving the strength at all ages (Figures 3, 4, and 5).

As illustrated by the dashed line in Figures 4 and 5, the average strengths in samples with 12% cement without admixtures are comparable to the strengths obtained in samples with Sika admixture with cement contents of 9%. The trends also reflect similar strengths in samples without admixture using 9% cement and samples with Sika admixture with <6% cement (see 7-day plot, Figure 4). This fact indicates that 25% of cement can be saved due to the use of the Sika Stabilizer - 301 MBF EC. Given that the mine places 1 million tonnes of paste underground annually and typically consumes around 96,000 tonnes of cement, this translates to a saving of 24,000 tonnes of cement. From a sustainability standpoint, this saving yields two primary advantages: first, a comparison between the carbon footprint of producing 1,800 tonnes of the admixture versus that of 24,000 tonnes of cement; and second, the impact on transportation. Specifically, there is a 92.5% decrease in the mass required to be transported to the mine, highlighting significant environmental and logistical benefits.

The comparison of the trends at 3, 7 and 28 days (Figures 4 and 5) shows that the trend lines of the strengths with and without Sika admixture gradually drift apart (see increasing space between the yellow and blue lines in all three plots). This is caused by the use of Sika admixture which further increases the strengths over time. This fact is also observed in experiments where the cement content is kept constant (Figure 3).

Figure 3 illustrates how the strength trends of samples with 2 and 3% admixture dosages, although yielding very different initial strengths (3 and 7 days) overlap after 28 days. This stark difference might be useful to adapt paste designs in plugs, where higher initial strengths are required (e.g. Grabinsky et al. 2023), however, more data need to be compiled to assess the behaviour of the paste with different admixture dosages (i.e. 2 and 3%) with cement percentages lower than 12%

Gruszczyński et al. (2021) describes the positive effect the use of flocculants (e.g. admixtures) have in the slope of depositing tailings. As admixtures reduce lumps and improve the flow of the tailings due to the superplasticising effect, a more efficient pumping and stope filling is observed when using Sika Stabilizer - 301 MBF EC.

5 Conclusion

Industry tests indicate that Sika Stabilizer - 301 MBF EC admixture improves the workability of the mix design and increases the strength of the paste once hardened.

Operational benefits include:

- Lower head pressure
- Reduction of slurry lumps
- Constant flow rate
- Instant fluidisation of the slurry
- Increase in the ratio of solids in the slurry

- Less water needed for the mix.

Benefits in hardened state include:

- Increased strengths at all ages
- Reduction of 25% of cement required to achieve given strengths
- Reduction of the carbon footprint.

The tailor-made solution Sika Stabilizer-301 MBF EC reduces the amount of cement required to achieve the required strength in the UG gold mine MBF operations. Sika admixtures are therefore not only economically advantageous for the client but are also a sustainable solution.

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