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Reduction of strength losses in paste backfill with sludge cake

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Abstract

Mine tailings containing pyrite and other acid generating rock have a large environmental impact associated with acid mine drainage. Cemented paste backfill (CPB) containing pyritic tailings has been used in several underground mining applications in the Iberian Pyrite Belt. Utilising the high pyrite tailings is often the only economically feasible and practical option for the CPB. In addition, it has the benefits of reducing the environmental impact for tailings management and storage requirements on the surface while providing stability to the underground mine.

However, the associated long-term strength losses due to oxidation of the pyrite in CPB mixtures and the associated expansive reactions caused by the acid generated need to be considered and planned for accordingly so that stopes can be safely exposed and mined before too much strength is lost and without rising binder consumption. To a large extent, supplementary cementitious materials and low-aluminate cements have been used to limit long-term strength losses. However, strength deterioration cannot be stopped altogether.

In a study by Paterson & Cooke for a future mine located in the Iberian Pyrite Belt, an investigation into the addition of the mine waste water treatment precipitated cake (sludge cake) in the CPB was conducted in parallel to testing CBP without the inclusion of sludge cake (i.e. 100% tailings). The polymetallic tailings (Zn, Cu and Pb) have a pyrite content exceeding 90%, which is typical of the region. This high pyrite content in the tailings causes long-term mechanical strength losses. The testwork demonstrated that, with the addition of sludge cake, the strength losses were reduced significantly.

This case study incorporated the addition of sludge cake into the backfill plant design and the underground piping reticulation system. The possibility to form CPB recipes with the addition of sludge cake to the mix requires a holistic view on the design of the backfill system; stope discharge locations are constantly changing and, therefore, the pumping pressure requirements.

Keywords: *cemented paste backfill, underground mine, backfill plant, underground reticulation system, unconfined compressive strength, rheology, strength loss*

1 Introduction

Cemented paste backfill (CPB) allows for tailings to be placed underground, providing a mining operation with many benefits including reduction of the surface storage area, reduced environmental impact and more. For the future Los Frailes underground mine located in the east end of the Iberian Pyrite Belt (IPB), an investigation into the addition of the mine waste water treatment precipitated cake (sludge cake) in the CPB was conducted in parallel to testing CBP without the inclusion of sludge cake (i.e. 100% tailings), and with two different binders, namely CEM I and CEM III.

2 Project background

Minera Los Frailes and the Aznalcóllar mining complex have reserves and probable resources of approximately 80 million tonnes of polymetallic sulphides (zinc, copper and lead, as well as gold and silver). The two open pits that comprise it, Aznalcóllar and Los Frailes, were partially exploited by surface mining methods between 1975 and 2001, the year in which it was closed.

In order to boost mining activity in the region and take advantage of the potential of existing resources for the benefit of citizens, the Andalusian Government, at the beginning of 2014, launched an international public tender for the reopening of the mine. In addition to offering the best technical feasibility, the proposals had to comply with maximum security parameters as well as economic, social and environmental sustainability.

Long-term strength is often a challenge in operating mines in the IPB. While relatively high strength is obtained with CPB, produced with filtered tailings and the available local binder, this strength is often reduced over the long term (Benzaazoua et al. 2002).

Los Frailes and Aznalcóllar open pits are filled with water from runoff which has reacted to produce acid mine drainage. This water will be treated using lime, which will result in the production of a precipitated gypsum and hydroxide cake referred to as sludge cake. This sludge cake will require storage on the surface, in addition to the tailings generated from the mine operation.

The mine was initially looking into the use of CPB for storage of the tailings, however, an opportunity was identified to provide storage for the sludge cake. The filtered tailings, sludge cake, the dry binder and the filter bypass stream all will feed a continuous mixer under normal operation. Trim water can also be added at this point in the process to fine-tune the solids concentration if required. The solids concentration of the combined streams to the mixer is managed so that it is higher than the final CPB required, thereby enabling the introduction of filter bypass and/or trim water to the mixer to provide the final adjustment of the mixture consistency.

This case study aims to present two key aspects of applying this storage solution. The first aspect is the testing and results of the CPB investigation, implementation of the inclusion of the sludge cake into the CPB and understanding the rheological behaviour of the paste mixture, since it is a conditioning aspect for the underground reticulation pipeline hydraulic design. The second key aspect of the case study is to present the unconfined compressive strength (UCS) results, which demonstrate a specific benefit that the sludge cake addition brings to the backfill system.

Previous work by Paterson & Cooke on this project suggested that the addition of the sludge cake did not prevent the backfill from curing and so a large testwork campaign was developed to understand the engineering implications of the addition of sludge cake into the backfill.

3 Testwork campaign

A full flow sheet process plant pilot campaign was conducted at the mine, which provided the bulk tailings sample used throughout the testwork presented in this case study. The backfill testwork considered two main aspects of backfill, namely rheology and UCS strength. The testwork included a matrix of testing to compare both sludge cake addition and 100% tailings.

The results of the material characterisation of the tailings and sludge cake are summarised in Table 1. The particle size distributions of the two samples are very similar, however, the tailings have a relatively high solids density, not only in comparison to the sludge cake but also when compared to typical copper tailings, which commonly have a density of 2.75 t/m^3 to 3.20 t/m^3. The mineralogy of this sample is typical of those taken in the IPB, where many of the mines operate with tailings having a 70 to 90% pyrite content.

Table 1 Material characteristics summary

Sample parameter	Process tailings	Sludge cake
Dry solids density (t/m³)	4.65	2.24
Particle size passing 80%	24	36
Particle size passing 50%	9	15
Particle size passing 20%	3	5
Mineralogical summary: Process tailings: The ore minerals within the sample are dominated by sphalerite, with trace amounts of galena, chalcopyrite and tetrahedrite. The main gangue mineral is pyrite, which constitutes 90 wt% of the sample, with trace amounts of quartz, iron oxides, carbonates, arsenopyrite, and mica and clay group minerals. Sludge cake: The sludge cake consists of various species of calcium and magnesium sulfates (90%) with carbonates and silicates making up the rest. Trace amounts (>0.5%) of heavy metal precipitates are also present.		

The testwork was divided into two main areas of investigation. The first was rheology and the second was testing to determine the CPB's UCS.

As part of the CPB testing, two locally available binders were tested. These binders were classed as a CEM I 52.4 R SR3 containing >95% clinker and a CEM III/A 42.5 N SRC. The CEM I SR has been a well-established binder in the region, utilised by several backfill plant operations. The CEM III is a blast furnace cement. The specifications of the binders used are presented in Table 2.

Table 2 Binder specification

Parameter	Description	Parameter	Description
CEM I	Portland cement with addition of minor constituents to a maximum of 5%	CEM III/A	Blast furnace cement. A = quantity of main constituents other than the binder, indicating from 6 to 20%
52.5	Strength class indicating minimum characteristic strength at 28 days, expressed in MPa	42.5	Strength class indicating minimum characteristic strength at 28 days, expressed in MPa
R	Strength sub class indicating quick strength gain	N	Strength sub class indicating normal
SR	Sulphide resistant	SR	Sulphide resistant
SR0, SR3, SR5	Sulfate resistant cement with a tricalcium aluminate content of less than 0%, 3% or 5% respectively	–	–

3.1 Rheology

The first part of the investigation for this case study was into the rheology of the material, both with and without sludge. This testing component aimed to develop a relationship between yield stress and the solids mass concentration for a particular CPB mix. Samples of cemented paste were prepared at the required solids concentration and Boger slump tests (Boger & Pashias 1996) were performed, which provided a relative measure of stiffness of the samples. Figure 1 shows the Boger yield stress for each type of binder, with and without the addition of sludge cake, and includes results with three different cement dosages each. However, for drawing simplicity, the rheology trending curves are presented considering the whole set of data for each type of mix to illustrate the rheological shift seen when adding the sludge cake in the preparation of cemented paste. This means that for a specific rheology, the solids mass concentration of this rheology shifts by a certain amount. Rotational viscometry tests were also performed on the CPB mixtures, confirming the Boger slump rheology and the trend of these results. Although rotational viscometer results (yield stress and Bingham plastic viscosity) were used in the hydraulic modelling, they are not included in this paper due to project confidentiality.

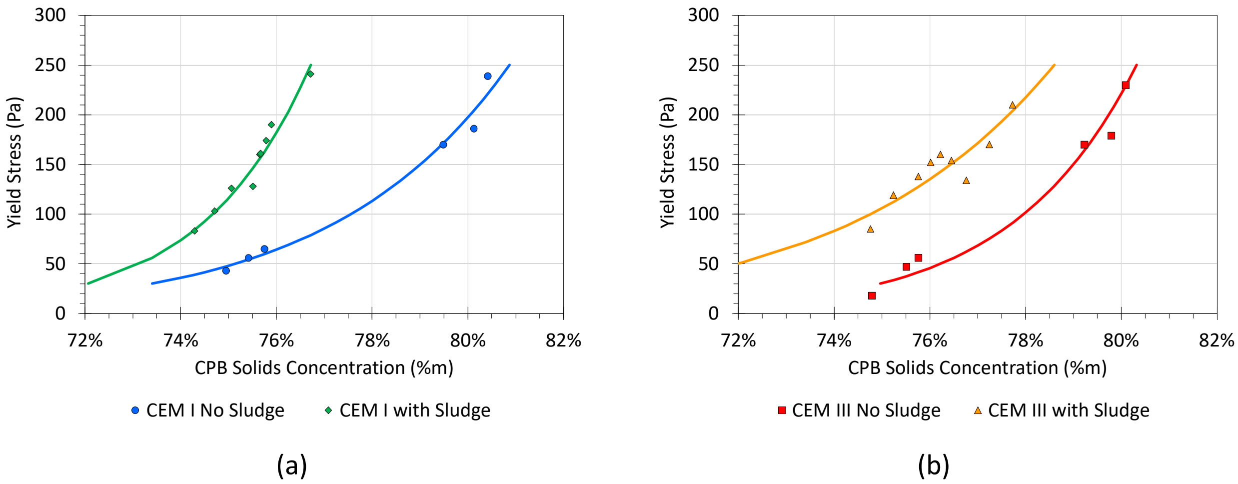

Figure 1 Cemented paste backfill rheology: (a) CEM I results; (b) CEM III results

There is a clear correlation between sludge content and yield stress: when increasing the sludge content in the backfill mixture, the yield stress tends to increase for a given solids mass concentration. It is important to understand the rheological behaviour of the paste mixture as it is a conditioning factor for the underground reticulation pipeline hydraulic design, paste transport evaluation and head requirements under a laminar flow regime (Cooke 2002).

3.2 Unconfined compressive strength testing

UCS testing is the typical method for the comparison and design of CPB materials. UCS testing was conducted on the tailings sample generated from the pilot plant and sludge cake provided from the onsite treatment plant. The testwork suite covered extensive variations of mixes to provide a wide range of mix consistencies and cement dosages. The sludge cake was added, as applicable, at a fixed ratio which represented the expected material balance during live production at the mine. This was 5.5% by mass of dry sludge cake to dry mass of tailings.

The UCS testing was conducted at 7, 28, 56 and 120 days, although not enough sample material was available to test every curing period. However, testing of 28-day and 120-day samples was included for all mixes. Each mix was cast in a 50 × 125 mm cylinder mould and cured until testing. All cylinders where cast in triplicate and remained in their moulds throughout the curing period. Curing took place in a temperature- and humidity-controlled chamber which throughout the testing maintained a temperature of 20 to 25° and 100% humidity via heaters and water evaporators. The only decreases in temperature and humidity occurred on curing days when the box was accessed.

After demoulding, the cylinders were trimmed to ensure a flat, parallel surface on their top and bottom. Each sample was then trimmed to maintain a ratio of height to diameter of 2:1. Each mix was prepared from the bulk tailings sample, which was dewatered to the desired solids concentration and mixed with the sludge cake (when applicable) and with the binder to generate various backfill mixes.

The amount of binder added and the water content were varied to generate a range of ratios of water to binder. This also resulted in different consistencies of the mixes, ranging from a targeted thin paste to thick paste.

The solids concentration by mass of each mix was calculated using the following formula:

$$C_m = \frac{M_{TS}}{M_{Tm}} = \frac{(M_s + M_a + M_b)}{M_{Tm}} \quad (1)$$

where:

C_m = solids concentration by mass (%m).

M_{TS} = total mass of solids in the mix (dry mass of solids) (kg).

M_{Tm} = total wet mass of mix (kg).

M_s = mass of solids (dry mass of tailings) (kg).

M_a = mass of aggregate (dry mass of sludge cake) (kg).

M_b = mass of binder/cement (dry mass of binder) (kg).

The binder content for each mix was calculated using the following formulas:

$$C_b = \frac{M_b}{M_{TS}} = \frac{M_b}{(M_s + M_a + M_b)} \quad (2)$$

$$M_b = \frac{C_b(M_s + M_a)}{(1 - C_b)} \quad (3)$$

where:

C_b = binder/cement content (dosage) (%b)

3.3 UCS results

The results from the UCS testing are presented in Tables 3 and 4 for three mixes from each of the cement types for samples without and with sludge cake respectively. The strength at 120 days is compared to the strength achieved at 28 days as a percentage, with a negative value indicating a loss in strength. For clarity, this is a representative dataset of the overall larger test campaign data. The results are also visually presented in the graphs in Figures 2 and 3.

Table 3 Strength results without sludge cake

Cement type	**CEM I**			**CEM III**		
Binder content (%b)	7%b	5%b	3%b	7%b	5%b	3%b
Water:cement ratio	3.6	5.1	8.7	3.6	5.1	8.7
CPB solids mass concentration (%m)	80.4%m	80.1%m	79.5%m	80.1%m	79.8%m	79.2%m
UCS strength (kPa)						
7-day curing	1,508	545	467	1,004	383	53
28-day curing	3,092	1,571	771	2,550	991	259
120-day curing	2,016	318	100	1,865	526	159
Strength change 28-day vs 120-day	–53%	–394%	–674%	–37%	–88%	–63%

Table 4 Strength results with sludge cake

Cement type	CEM I			CEM III		
Binder content (%b)	7%b	5%b	3%b	7%b	5%b	3%b
Water:cement ratio	4.5	6.5	10.8	4.2	5.9	11.1
CPB solids mass concentration (%m)	75.8%m	75.7%m	75.7%m	77.7%m	77.2%m	74.8%m
UCS strength (kPa)						
7-day curing	1,931	813	–	233	–	–
28-day curing	2,330	1,454	578	2,710	929	73
56-day curing	2,530	1,268	578	3,631	1,537	145
120-day curing	2,721	1,573	552	3,189	1,421	355
Strength change 28-day vs 120-day	14%	8%	-5%	15%	35%	79%

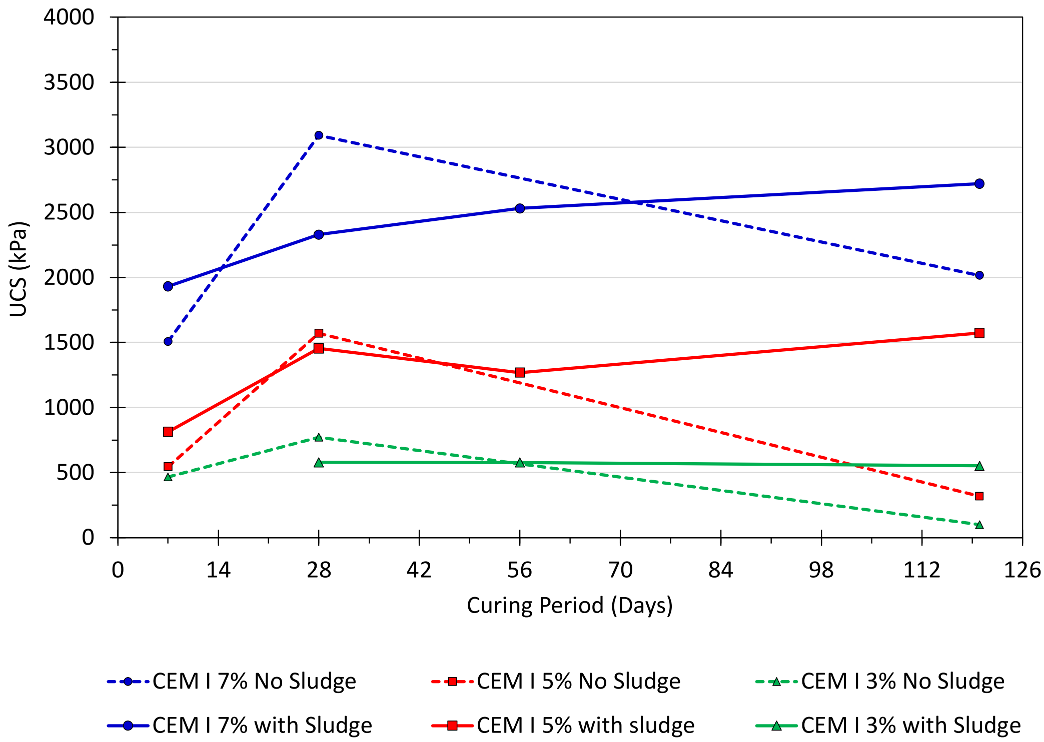

Figure 2 CEM I unconfined compressive strength results

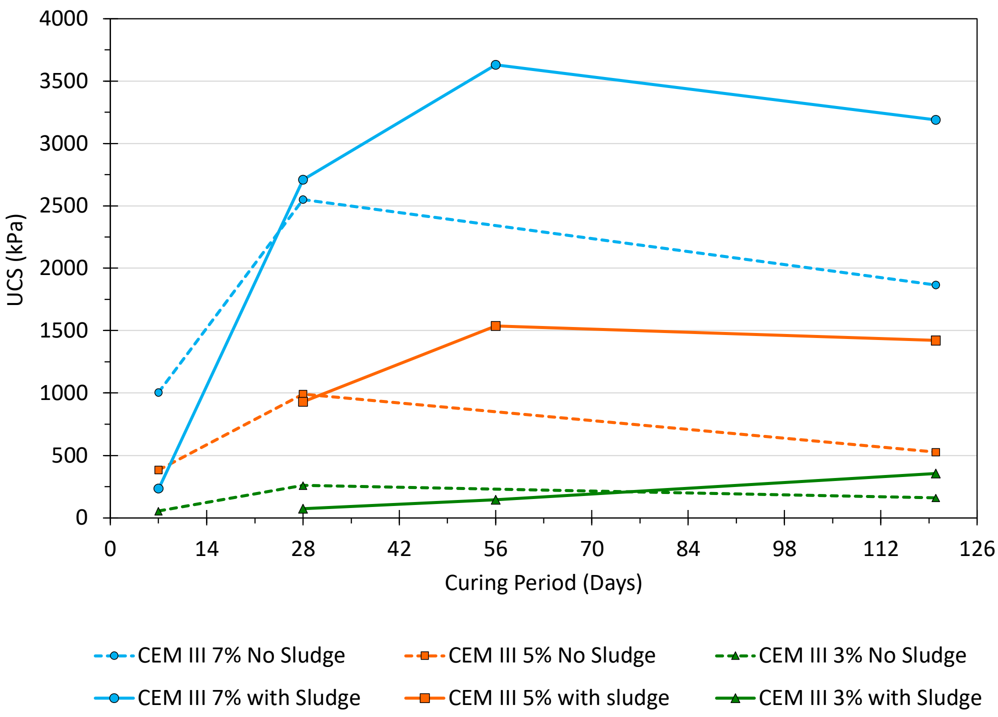

Figure 3 CEM III unconfined compressive strength results

The test data demonstrates that the CPB with the sludge material maintains a high strength over the long-term testing of 120 days. The CPB material using the CEM III was less affected by strength loss but the inclusion of the sludge still resulted in a higher strength when compared to 28-day strength. The CEM I used widely in the IPB was significantly affected by strength loss between 28 days and 120 days, and the sludge cake inclusion reduced these losses. Also, the effect of binder addition and strength loss reduction are more significant at higher binder dosages.

A pair of UCS test cylinders were kept in their moulds in a temperature/humidity curing chamber for up to 290 days; one with sludge cake addition (left-hand samples on Figure 4) and another without sludge cake addition (right-hand samples on Figure 4). After demoulding the sample they were exposed to air at room temperature and, as shown in Figure 4, large crystals developed on the non-sludge cake backfill mixes.

Figure 4 UCS cylinders 290 days – formation of crystals on samples without the addition of sludge cake when exposed to air at room temperature (right-hand samples)

The root causes and reactions that are likely influencing these results are discussed in the next section and explain why the addition of sludge cake can reduce the mechanical strength losses over the long term.

3.4 Discussion of sulfate attack and mitigation by the addition of sludge

The mechanism of sulfate attack has been well documented in literature (Scrivener & Taylor 1996; Taylor 1997; Lea 2019; Zhang et al. 2013). Sulfate attack can be divided into three main mechanisms:

- Gypsum formation.
- Ettringite formation.
- Acid attack due to sulfates.

Depending on the source of the sulfates, the degradation mechanism is termed either internal sulfate attack (ISA), i.e. the sulfates are present in the mix; or external sulfate attack (ESA), i.e. the sulfates are present in the host environment. The sulfate attack of concern to pyritic tailings is the ISA variety.

3.4.1 Gypsum formation

Gypsum formation occurs when sulfates react with calcium hydroxide to form calcium sulfate, an expansive product. However, the volume change is not large and the resulting stresses are generally not considerable, especially on very porous matrices such as backfill. Gypsum formation can be reduced by using supplementary cementitious materials (SCM) that consume excess calcium hydroxide.

3.4.2 Ettringite formation

The mechanism of potential concern is the volume change that occurs when calcium aluminates from the cement react with sulfates to form ettringite, a tetrasulfoaluminate mineral. During early hydration, the formation of ettringite will be beneficial for early strength and can be accommodated by the backfill.

However, once the cemented paste has set, the volume change will lead to stresses and microcracks, reducing strength. Therefore, the formation of ettringite must be divided into two stages: early and delayed ettringite formation.

Delayed ettringite formation (DEF) occurs when unhydrated aluminates or monosulfoaluminates react with sulfates to form ettringite and cause expansion. In ISA, this mechanism occurs if the sulfates are contained in the aggregate and are released or decompose after the initial hydration. In this case, DEF is caused due to sulfates being present but not available during the hydration period.

If sulfates are present in the mix but are available during hydration (soluble), the sulfates will more readily consume all aluminates and cause early ettringite formation (EEF). This will lead to a matrix that contains little to no unhydrated aluminates, which will reduce the potential for the subsequent onset of DEF.

3.4.3 Acid attack

In pyritic tailings, the oxidation of pyrite creates sulfuric acid that lowers the matrix pH and reacts with (and leaches) calcium ions, resulting in the formation of calcium sulfate, causing loss in strength. This reaction lowers the matrix pH, causing calcium silicate hydrate (CSH) instability and a reduction in the calcium content of the CSH matrix.

3.4.4 Mitigation of sulfate attack by sludge addition

The addition of sludge can be shown to reduce DEF as well as acid attack.

The gypsum formation (described in Section 3.4.1) likely does not represent a major attack mechanism in the CEM III binder due to the SCM consuming the majority of calcium hydroxide in the mix. However, it is still a major attack point for the CEM I binder where the calcium hydroxide produced from the primary cementitious reactions is not consumed by supplementary cementitious reactions in the mix and is available to react with the sulfuric acid produced. This explains why the sludge addition is not as effective for the CEM I mixes.

The addition of the sludge, and specifically gypsum in the sludge, is expected to promote EEF due to the abundance of sulfates available during hydration. This reduces or even eliminates the aluminates available in the long term, which would reduce DEF strength loss for both the CEM I and CEM III.

The other heavy metal hydroxides and carbonates present in the sludge cake represent species that are more susceptible to the acid attack and which essentially buffer the acid being generated, thus reducing the direct acid attack mechanism on the CSH. It is also possible that the calcium sulfate consumes acid produced by creating calcium bisulfate.

4 Backfill strength operating envelope assessment

A multivariable relationship, or backfill strength 'operating envelope', can be developed from the results of the rheology and UCS tests. The operating envelope is a visual guide to the desired range of acceptable operating parameters in the system. It refers to the various recommended limits of operation within the system.

The operating envelope includes the following multivariable relationships (refer to Figure 5):

- UCS versus the water-to-cement ratio in the top right-hand side. This includes the various mixes prepared with CEM I and CEM III, with and without the addition of sludge cake. The aim of this relationship is to target the UCS strength and determine the required water-to-cement ratio of the mix in the vertical axis.
- CPB mass solids concentration versus water-to-cement ratio in the top left-hand side. This includes the resulting binder content curves (%b), allowing evaluation of the options to minimise binder content when possible.
- CPB mass solids concentration versus yield stress in the bottom left-hand side. The aim of this relationship is to evaluate both the thick and thin paste consistency of the backfill mix, so that the underground reticulation system allows for hydraulic transportation.

From this relationship, the effect of changing a single variable may be quickly determined and the limitations of the material can be assessed. This also allows multiple samples to be directly compared while considering the key influences on a backfill mix recipe, the required strength, the water-to-cement ratio, binder addition and resulting rheology.

The evaluation considered the results from the 28-day and 120-day testing. For the 28-day assessment, the UCS was set to a reference strength of 1,000 kPa and the resulting yield stress in an operating range of 100 Pa (thin consistency) up to 200 Pa (thick consistency). The water-to-cement ratio and binder addition required were then compared for each mixture.

Figure 5 shows the multivariable relationship for the CPB mixes considering 28 days of curing time, including yield stress, solids concentration, the cement–water ratio and UCS, and with an operating envelope between 100 to 200 Pa yield stress and a reference backfill strength of 1,000 kPa. Table 5 presents the results from the multivariable relationship for the CPB recipe at the 28--day period.

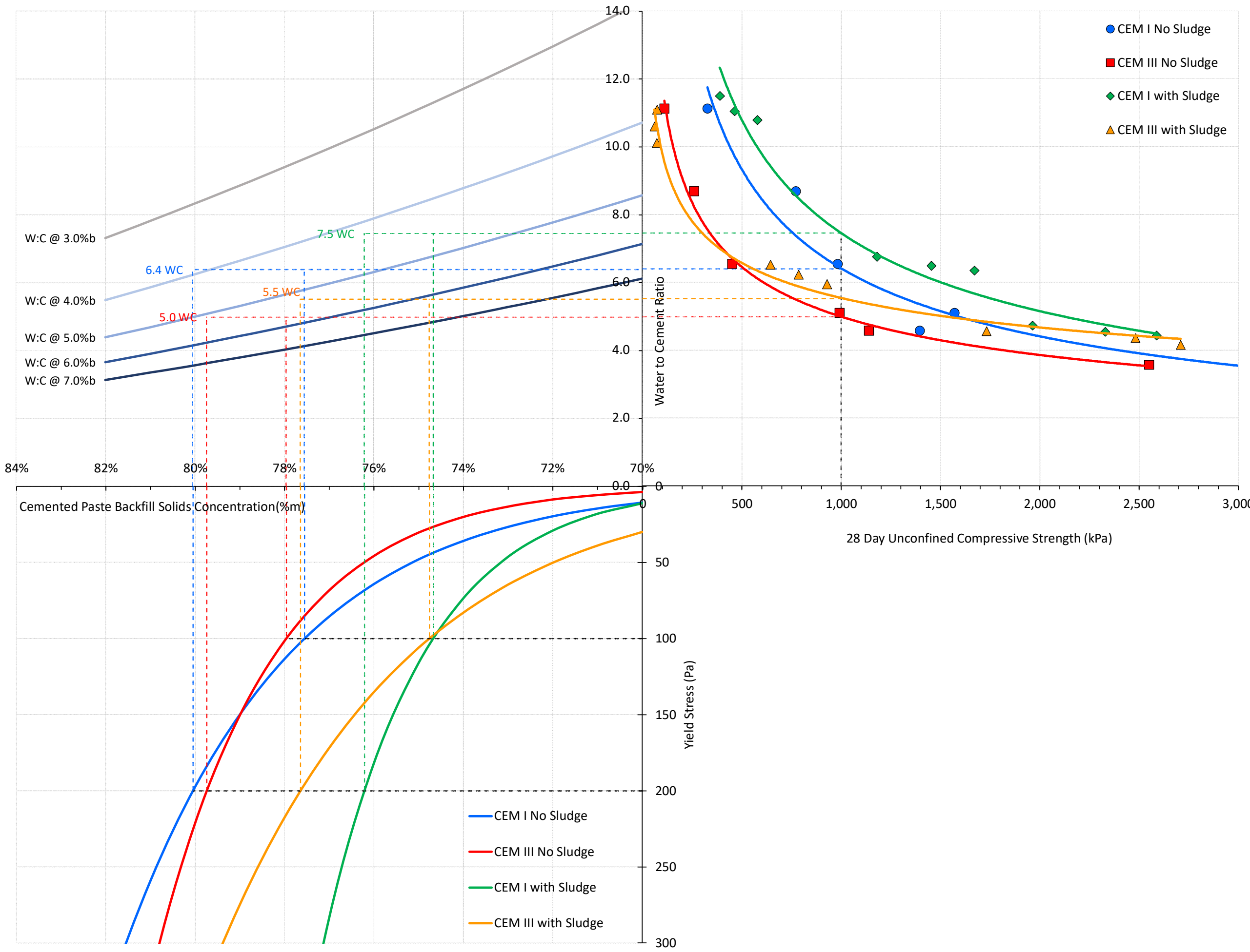

Figure 5 Multivariable relationship CPB recipe – 28-day period

Table 5 Backfill strength operating envelope – 28-day period

Mix	Reference target strength at 28 days (kPa)	Yield stress (Pa)	CPB solids concentration (%m)	Water-to-cement ratio	Binder dose required (%b)
CEM I no sludge	1,000	100 to 200 (thin) (thick)	77.6 to 80.1	6:4	4.5 to 3.9
CEM I with sludge			74.7 to 76.2	7:5	4.6 to 4.2
CEM III no sludge			78.0 to 79.7	5:0	5.7 to 5.1
CEM III with sludge			74.8 to 77.6	5:5	6.1 to 5.2

Figure 6 shows the multivariable relationship for the CPB mixes considering a 120-day curing time period, including an operating envelope between 100 to 200 Pa yield stress and a reference backfill strength of 1,000 kPa. Table 6 presents the results from the multivariable relationship for the CPB recipe at the 120-day period.

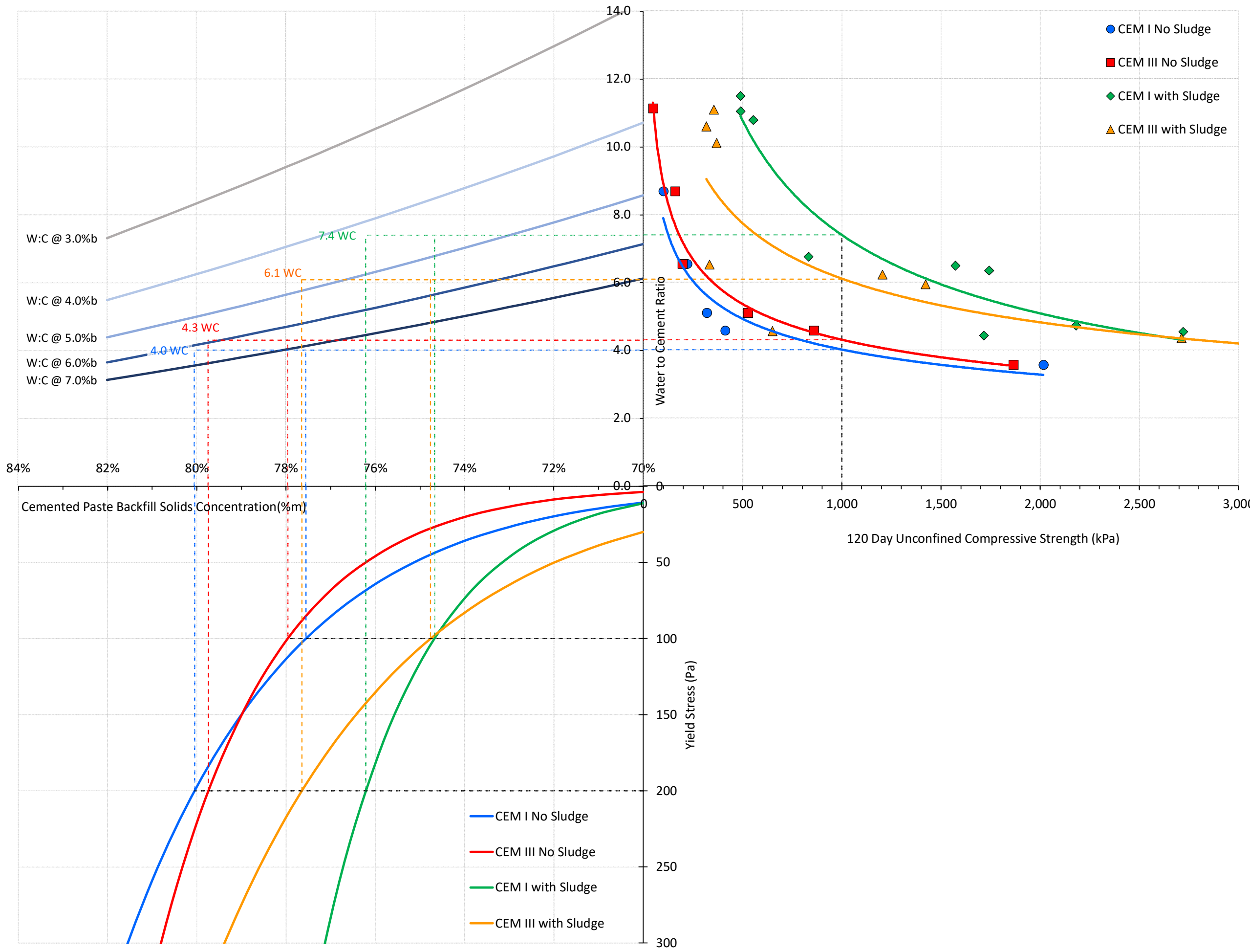

Figure 6 Multivariable relationship CPB recipe – 120-day period

Table 6 Backfill strength operating envelope – 120-day period

Mix	Reference target strength at 120 days (kPa)	Yield stress (Pa)	CPB solids concentration (%m)	Water-to-cement ratio	Binder dose required (%b)
CEM I no sludge	1,000	100 (thin) to 200 (thick)	77.6 to 80.1	4:0	7.2 to 6.2
CEM I with sludge			74.7 to 76.2	7:4	4.6 to 4.2
CEM III no sludge			78.0 to 79.7	4:3	6.6 to 5.9
CEM III with sludge			74.8 to 77.6	6:1	5.5 to 4.7

5 Conclusion

The inclusion of the sludge cake material into the mixture is beneficial to the long-term strength as it provides mechanisms that mitigate the strength loss. However, it has a negative influence on the rheology and, therefore, must be used selectively for areas that do not require target UCS and/or additional energy for hydraulic transportation.

The sludge addition is expected to buffer the acid generation due to the hydroxides and carbonates; thereby reducing direct acid attack on the CSH. In addition, the gypsum in the sludge will promote EEF and reduce any DEF, thereby further reducing strength loss. However, it is not expected to help with gypsum formation in the CEM I mixes, thus explaining the reduced effectiveness of sludge addition as compared to the CEM III mixes.

Generally, the results indicate that CEM I offers a greater strength to the backfill than CEM III, which is particularly noticeable in the short-term 7–28-day period. The 7-day results demonstrate a significant strength gain in the CEM I mixes compared to the CEM III mixes, reaching a strength of 100–200 kPa, while CEM I gained up to 2,000 kPa (see Figures 2 and 3).

When more sludge cake is added to the mixture, the water content of the paste increases and, therefore, the binder dosage increases to maintain the desired water-to-cement ratio. The inclusion of higher ratios of sludge cake and the requirement for additional binder to offset the change in solids concentration to maintain the water to cement ratios will change the rheology of the paste.

When sludge cake is added to the CPB, the required volume of tailings storage on the surface (the tailings storage facility) increases, therefore consideration must be given to the overall material balance.

A pair of UCS test cylinders were exposed to the air at room temperature and large crystals developed on the non-sludge cake backfill mixes. The root causes and reactions that are likely influencing these results are discussed in this paper, and explain why the addition of sludge cake is able to reduce mechanical strength losses over the long term.

Through further flow loop testwork, the correlations between solids content, yield stress and the water-to-cement ratio could be further refined and adjusted to completely reveal the hydraulic requirements for the underground reticulation pipeline system design.

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