Paste 2024 – AB Fourie & D Reid (eds)

doi:10.36487/ACG_repo/2455_44

Effect of brine, slag and lime inclusion on Fosterville Gold Mine cemented paste backfill strength

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Abstract

This paper presents an investigation conducted to evaluate the feasibility of utilising saline water (brine) in cemented paste backfill at Fosterville Gold Mine in Victoria, Australia. The primary motivation for this study arises from sustainability concerns related to the storage of brine generated by the operation's reverse osmosis (RO) facility. The test work encompasses physical characterisation of tailings, rheological assessments, and strength testing involving various binder and slag combinations. Both brine and raw water are explored as potential diluents. Incorporating brine into binders revealed alterations in yield stress and strength in comparison to the conventional use of raw water, in addition to the long-term strength behaviour related to brine inclusion and binder type and content. Initial increments in slag content within binders corresponded to reduced strength; however, a threshold exists beyond which early strength significantly improves. Higher binder content emerges as a key driver for strength enhancement. Lime use enhances strength particularly when RO brine is employed. General purpose (GP) cement-only binders exhibit strength increments with higher total binder content. Slag and GP cement blend samples display lower early strength but eventually outperform GP cement-only samples, with specific blend compositions demonstrating unique strength profiles at longer curing durations. Test work and operational outcomes underscore the generality (with some exceptions) of unconfined compressive strength improvement with longer curing times, higher total binder content, and increased slag blend content, while highlighting the unique and sometimes inconsistent impact of brine inclusion on the mechanical properties of paste backfill. This test work formed the main basis of Fosterville Gold Mine management to optimise the paste fill mix design to meet the challenging paste backfilling operation requirements while optimising operating cost. Findings provide valuable insights into the prospective utilisation of brine and diverse binder compositions in the Fosterville paste backfill project for more holistic resource management and environmental stewardship.

Keywords*:* *case study, yield stress, paste fill strength, paste fill test work, reverse osmosis brine, binder blends, slag*

1 Introduction

1.1 Fosterville Gold Mine

The Fosterville Gold Mine (FGM) is a high-grade, low-cost underground gold mine located 20 km from the city of Bendigo and 130 km north of the city of Melbourne, Victoria, Australia. FGM utilises open stoping with the application of paste fill (PF) to extract gold ore from most of its underground stopes. Once a stope has been mined out, the void is backfilled with PF to ensure stability in accordance with planned future vertical and horizontal function exposures, including regional stability.

Fosterville is a non-discharge site, and a sustainability challenge is the current storage of brine from the reverse osmosis (RO) water treatment facility. To identify alternate uses for this waste product, Fosterville have assessed the efficacy of using saline water (the brine from the RO facility) in the backfill paste mix. The test work presented in this paper was undertaken assess the suitability and ongoing opex costs that may be expected from using brine in paste backfill.

1.2 Mining method

FGM utilises open stoping with the application of PF to extract gold ore mainly from the Phoenix orebody. In the upper levels where paste infrastructure is not available, such as in the Harrier orebody, cemented rockfill (CRF) is mainly used. Selection of the specific mining method within the open stoping regime is based on ore zone geometry and geotechnical conditions.

Stoping widths and strike length vary and are dictated by grade distribution in the block model. Internal waste is incorporated within the stope block design. The open stope reserve wireframe design parameters applied were:

- Strike length dictated by grade distribution in block model
- Width from ~3.0 to ~15 m
- Height of ~15–25 m vertical from drawpoint floor up to the drive above
- Internal waste incorporated within the stope block design.

1.3 Mill processing

Run of mine (ROM) ore is reclaimed from stockpiles on the ROM pad and fed to a bin by front-end loader, blending the ore in the process. Ore is then processed through crushing and milling, flotation, gravity recoverable gold, oxidation BIOX, leaching and elution and gold electrowinning.

The flotation/neutralisation residue is combination of flotation tails which is ground ore and neutralised liquor containing precipitated solids from the oxidation process. This is approximately 93% of the ore milled and is sent to the PF plant when paste is required, otherwise it is diverted and stored within an above-ground tailings storage facility, or within an in-pit facility.

1.4 Paste processing

Tailings from the processing plant are pumped to the paste plant thickener. Flocculant is added and the paste plant thickener underflow is pumped to the filter feed tank then to the vacuum disc filter.

The resulting filter cake is sent to the paste mixer and combined with a portion of filter feed slurry, brine and/or raw water and binder to generate a required mix consistency (yield stress or density) and delivered underground. The paste plant has a rated production capacity of 65 m^3 per hour of PF targeted to produce a paste mix range between 200–300 Pa yield stress. Adding a suitable binder or binder mix to PF enables paste to be self-supporting, such that ore extraction directly adjacent to or below the fill mass is possible, maximising the recovery of ore within the mine. The FGM paste filling operation requires early strength, thus a high binder content for faster curing, to allow mining development works beside and/or under the paste filled stope several days after paste filling due to limited areas of production.

Raw water for the paste plant, when RO brine water is not sufficient, is supplied from the existing raw water supply while brine water is pumped from the brine water dam. Brine water use is maximised as make up water in the production of paste due to the limited impoundment area in the dam and the zero external discharge site requirement.

1.5 Paste delivery underground

The paste delivery system accepts paste produced by the paste mixer into the paste hopper. Paste arriving at the paste hopper is either directed into the borehole to be reticulated underground or into the drain bund if the paste is out of specification.

The paste hopper is fitted with weight and level indication. The weight indication in the paste hopper controls the flow control valve on the discharge pipe to the borehole to prevent vacuum in the reticulation lines underground.

In the event of shutdown or disruption to paste production, there is a paste flushing system that is activated to direct water from the flush water tank to the borehole and that is followed by a flow of high-pressure air to the borehole to clear out residual paste from the underground delivery system.

The PF underground reticulation starts at the top of the surface borehole located beside the paste plant hopper. The 1,040 m long borehole, dipping at 70°, is cased with ceramic-lined steel pipes throughout the length. The surface borehole breaks through at the P4190 level which is centrally located above the main Phoenix orebody and serves as the main distribution lines as it cascades down to the levels below consisting of a series of interconnected horizontal pipes and boreholes between levels. Currently, the lowest level where paste is being backfilled is at P3840 level.

The underground reticulation pipelines are installed with instrumentation such as flowmeters, dump valves, pipe pressure sensors, diverter valves and CCTV cameras where required. CCTV cameras are installed in drawpoints to monitor bulkheads while CCTV cameras in the fillpoints are to monitor paste discharge and level. The paste reticulation geometry takes advantage of gravity to deliver PF to the stope voids.

2 Materials

2.1 Fosterville tailings

Several tailings samples were collected throughout the duration of this test work program. The on-line stream of Fosterville combined flotation and neutralisation tailings investigated had the composition as shown in Table 1. The mineral content of the tailings is predominantly quartz and muscovite with some gypsum.

Due to the presence of mica platelets, in addition to the high fines particle size distribution, obtaining high paste strengths is difficult, thus binder addition rates for the FGM paste are generally high to meet strengths required. The presence of some gypsum, although minimal in quantity also affects strength development.

The tailings had a pH ranging between 7–8 and the specific gravity of all samples tested ranged from 2.77 to 2.81.

Table 1 Fosterville Gold Mine tailings composition for paste production

Mineral or group	Sample 1 Reclaimed tails (%)	Sample 2 Floatation/neutralised tails (%)	Sample 3 Floatation tails (%)
Clay mineral	1	<1	<1
Kaolinite	0	<1	0
Chlorite	1	4	2
Serpentine	0	0	<1
Annite-biotite-phlogopite	7	8	12
Muscovite	11	11	11
Calcic and sodic amphibole	2	1	0
Clinopyroxene	1	0	0
K-feldspar and/or rutile	1	1	1
Sodic plagioclase	2	2	2
Alpha quartz	50	60	55
Calcite and Mg-calcite	1	1	1
Dolomite-ankerite	14	10	4
Magnesite	1	0	2
Siderite type carbonate	4	0	11
Gypsum	4	2	0
Copiapite	<1	0	0

Particle size distribution (PSD) measurements were conducted using a Malvern Mastersizer 3000 laser diffraction particle size analyser with a particle size measurement range of 0.01 to 3500 µm. Fosterville typical cumulative and differential PSDs are shown in Figure 1. Tailings contained 50–60% passing 20 µm and thus conformed to the accepted PF suitability 'rule of thumb' of more than 15% passing 20 µm (Stone 2014) but has a significantly high fines content upper range. Differential PSD shows peaks around 5 and 75µm.

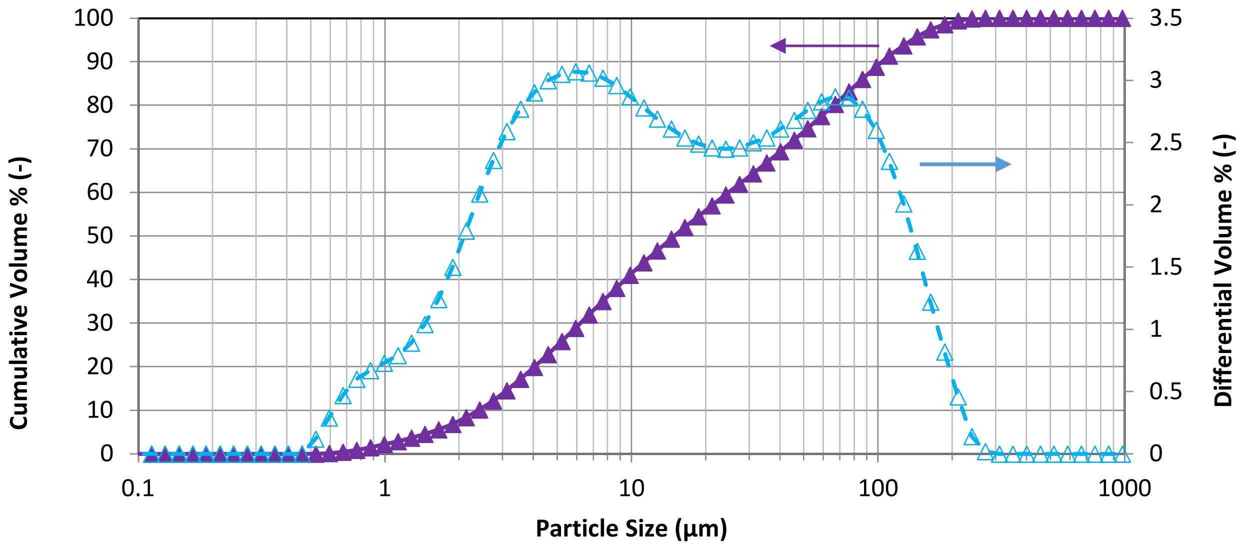

Figure 1 Fosterville tailings cumulative and differential particle size distribution

2.2 Paste preparation water

The water treatment operation at Fosterville consists of an RO high-pressure selective separation membrane system producing a high purity RO permeate and a high salinity brine waste stream. The salt content of RO brines is typically twice that of natural sea water (De Vito et al. 2011). FGM currently uses a combination of raw water and brine water for paste production. The compositions of Fosterville RO Brine is shown in Table 2 and raw water in Table 3.

The raw water has an almost neutral pH and a very low total dissolved solids (TDS) content. The RO brine is more alkaline but also has a very high TDS (47,000 mg/l) which is counterproductive to attaining higher paste strengths.

FGM currently uses RO brine as the main make up water in the paste production due to the limited impoundment at the dam. Brine water from the processing, as per environmental regulation requirement, needs to be impounded or encapsulated. Hence it is used in paste production for backfilling underground.

Safe storage/disposal of RO brines via encapsulation into cemented paste has been investigated with positive strength outcomes (Mahlaba et al. 2011; Opong et al. 2022).

Table 2 Fosterville brine water composition

Assay element	Unit	Value
Antimony	mg/L	0.16
Arsenic	mg/L	0.024
Calcium	mg/L	1,400
Chloride,	mg/L	22,900
Electrical conductivity, 25°C	µS/cm	60,400
Free cyanide	mg/L	0.002
Iron	mg/L	0.09
pH	pH Units	8.17
Potassium	mg/L	315
Sulphate as SO^{4-}	mg/L	7,450
Thiocyanate	mg/L	1
Cyanide	mg/L	0.005
Total dissolved solids	mg/L	47,300
WAD cyanide	mg/L	0.002

Table 3 Fosterville raw water properties

Assay element	Unit	Value
pH value	pH unit	7.74
Electrical conductivity @ 25°C	µS/cm	10,300
Total dissolved solids	mg/L	6,400
Suspended solids (SS)	mg/L	12
Chloride	mg/L	2,850
Hydroxide alkalinity as $CaCO_3$	mg/L	<1
Carbonate alkalinity as $CaCO_3$	mg/L	<1
Bicarbonate alkalinity as $CaCO_3$	mg/L	264
Total alkalinity as $CaCO_3$	mg/L	264
Sulphate as SO^{4-} turbidimetric	mg/L	1,410
Calcium	mg/L	230
Magnesium	mg/L	302
Sodium	mg/L	1,630
Potassium	mg/L	58
Antimony	mg/L	5.78
Arsenic	mg/L	0.298

2.3 Binder, slag and lime

General Purpose Cement (GPC) and lime were provided by Independent Cement and Lime Pty Ltd in Victoria Australia. Ground granulated blast furnace slag used was provided by the same company and used as a supplementary Cementous material.

3 Methodology

3.1 Core preparation

Cemented paste backfill (CPB) specimens were formulated with varying binder doses using combinations of GPC, slag and lime with either raw site water or RO brine water diluent. The ranges of additives for each test series are shown in Table 4.

The preparation process involved mixing of tailings materials, binders, and water until achieving a homogenous paste consistency. The flow characteristics of the paste mixtures were assessed by measuring the yield stress, adding water gradually until reaching the prescribed yield stress value of approximately 210 Pa.

Subsequently, the CPB mixtures were placed into cylindrical moulds measuring 50 mm in diameter and 130 mm in height. Special attention was given to filling the moulds uniformly with the paste backfill mixture to minimise potential voids. To eliminate air pockets within the CPB samples, a vibrating table was employed, aiding in achieving consistent density across the samples.

The filled moulds were placed in a controlled curing environment maintained at 35°C and 90% relative humidity for the prescribed duration prior to unconfined compressive strength (UCS) testing.

All cores were prepared to a nominal yield stress value of 210 Pa. The total solids concentration this related to depended on the specific constituents and their concentrations but was generally in the range of 64 to 68 wt%.

Table 4 Range of parameters investigated for unconfined compressive strength testing

Test series	Parameters tested	Binder content (%)	GPC in binder (%)	Slag in binder (%)	Raw water (%)	Brine (%)	Lime (%)
11	binder dose and yield stress	4–10	100				
13	binder dose, brine use	4–10	100	0	0 or 100	0 or 100	0
14	binder dose, GP cement/slag ratio	6–10	30-100	0-70	100	0	0
15	mixed binder dose, brine use, lime inclusion	6–8	23 or 30	67 or 70	0 or 100	0 or 100	0 or 10
16	binder dose, slag inclusion	6–12	30 or 100	0 or 70	75	25	0

3.2 Rheology – yield stress

Yield stress measurements were conducted using a Haake VT550 rheometer and the vane-shear method (Nguyen & Boger 1983, 1985). A vane of suitable dimensions for the yield stress range under consideration was selected and rotated at a rate of 0.2 rpm. The yield stress is calculated using the maximum torque reading vane dimensions. For selected samples of both raw tailings and paste blends prepared, the yield stress was measured as a function of solids concentration to produce yield stress profiles. These profiles were then used to determine the yield stress (hence solids concentration) for paste preparation for subsequent strength testing.

3.3 Unconfined compressive strength testing

Following core preparation as per Table 4, UCS tests were conducted at predetermined curing durations using an Avery Dennison UCS testing machine with a maximum loading capacity of 50 kN. CPB specimens were initially trimmed to remove the water-rich surface for consistency and to achieve a targeted L:D ratio of 2:1 (+/- 10%). The mass and dimensions (length and diameter) were measured to calculate cross-sectional area and bulk density per specimen. Loading was consistently applied at a displacement rate of 1 mm/min, ensuring controlled conditions throughout the test.

4 Results and discussion

4.1 Particle size distribution

Laser PSD results for selected tailings both as received and with various additives are provided in Figure 2. Most samples displayed a similar PSD, even with the addition of various binders. This is due to the particularly fine nature of the raw tailings; the binders are also very fine, so addition does not result in a major shift of the PSD. With the notable exception of Series 14 (with a mean PSD of 50 µm), the samples tested had mean PSDs in the range of 33 to 38µm.

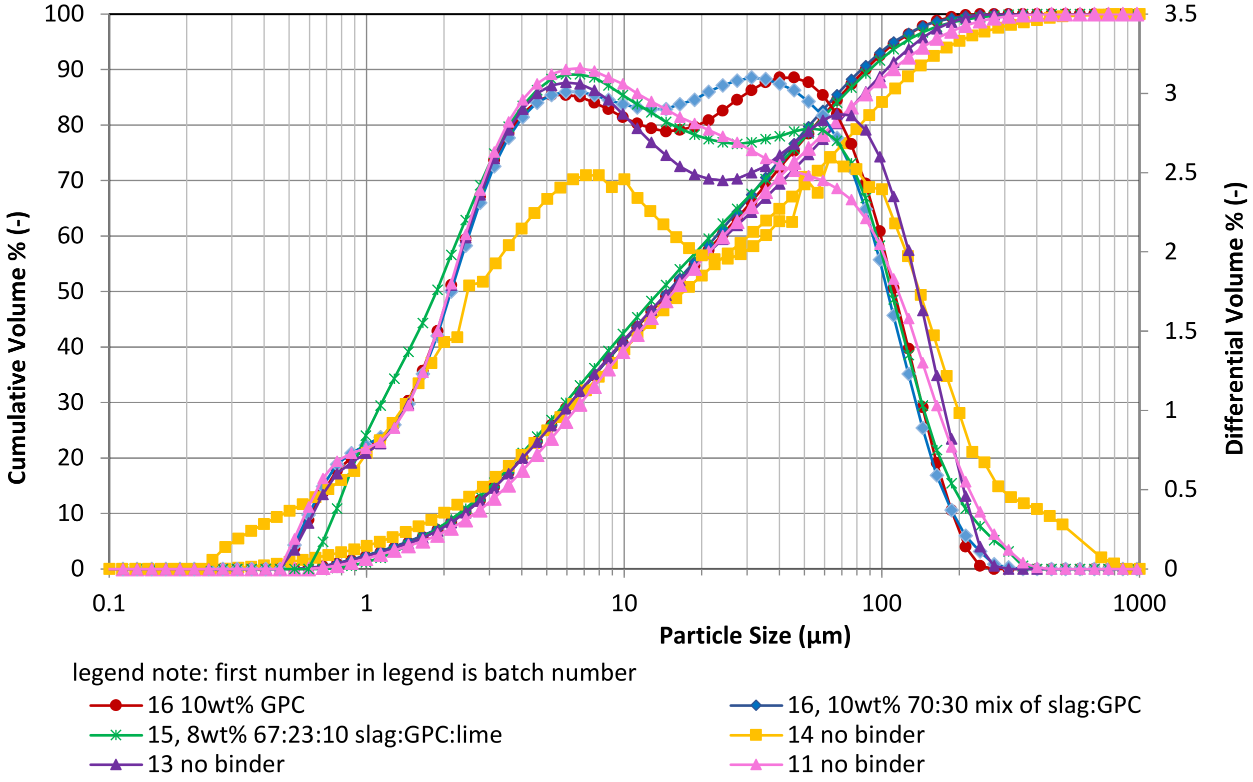

Figure 2 Fosterville tailings cumulative and differential particle size distributions

4.2 Rheology – yield stress

The vane yield stress profiles of samples shown in Figure 2 are provided in Figure 3.

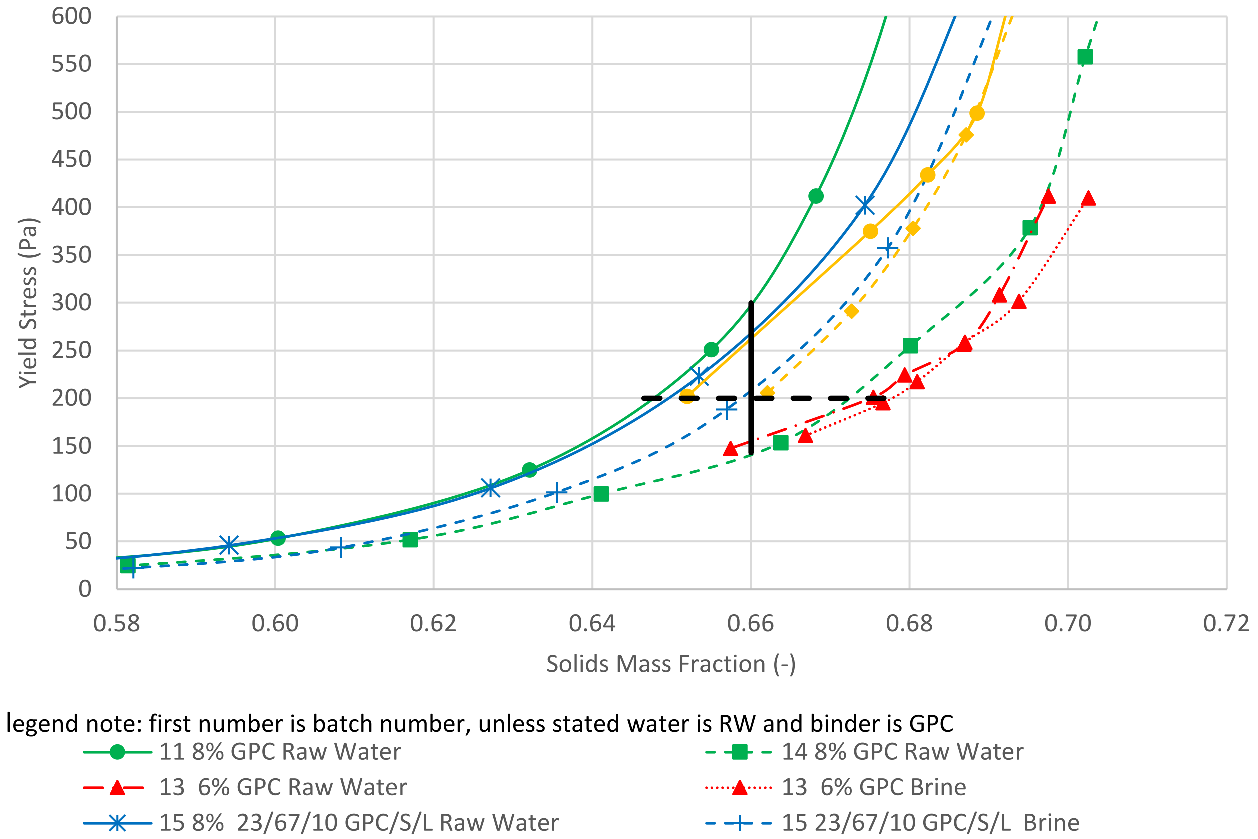

Figure 3 Fosterville tailings yield stress as a function of solids concentration with various additives

4.3 Unconfined compressive strength

4.3.1 Binder content and prepared yields stress

UCS data for paste prepared to yield stress values ranging from 125 to 300 Pa, and with binder contents ranging from 4 to 10wt% (dry basis), are shown in Figure 4. For this test series, the binder was GP cement-only. Overall, the strength increases with initial yield stress, binder content and curing time. As binder content increased, the overall strength gain increased significantly across all curing durations. The highest strength after curing for 28 days is 1.86 MPa for the core prepared with 10wt% binder and yield stress of 300 Pa. The lowest strength after curing for 28 days is 0.42 MPa for the core prepared with 4wt% binder and yield stress of 125 Pa. The strength of most samples increased throughout the 28 day of curing duration. The 225 Pa, 6wt% binder results are somewhat inconsistent with others however the cause for this is unclear.

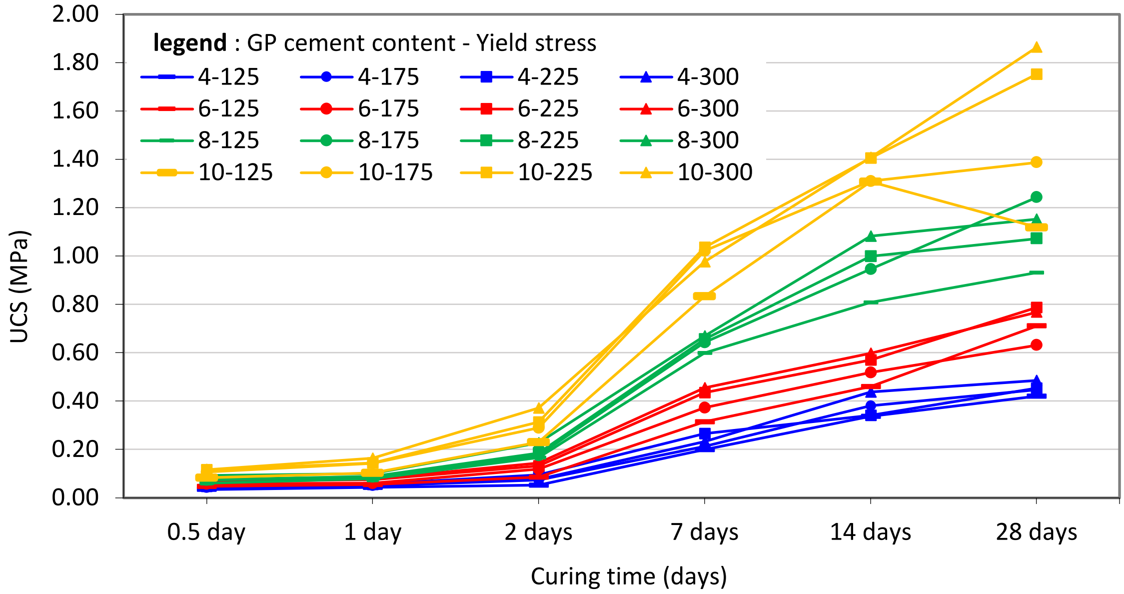

Figure 4 Binder content and total solids (yield stress) effect

4.3.2 Reverse osmosis brine use

The effect of substituting brine for raw water was investigated with varying binder content (Figure 5). For this test series the binder was GP cement-only. For samples containing 4, 6 and 8wt% the UCS increased with both binder content and curing time. Strength was 7 to 26% higher for samples prepared with raw water than with brine and was generally greater at longer curing times. However, the 10wt% binder sample did not show a significant difference in strength due to water type up to three days curing, but 71 day tests showed the brine containing sample showing a 20% increase in UCS compared to the raw water sample. The cause is unclear.

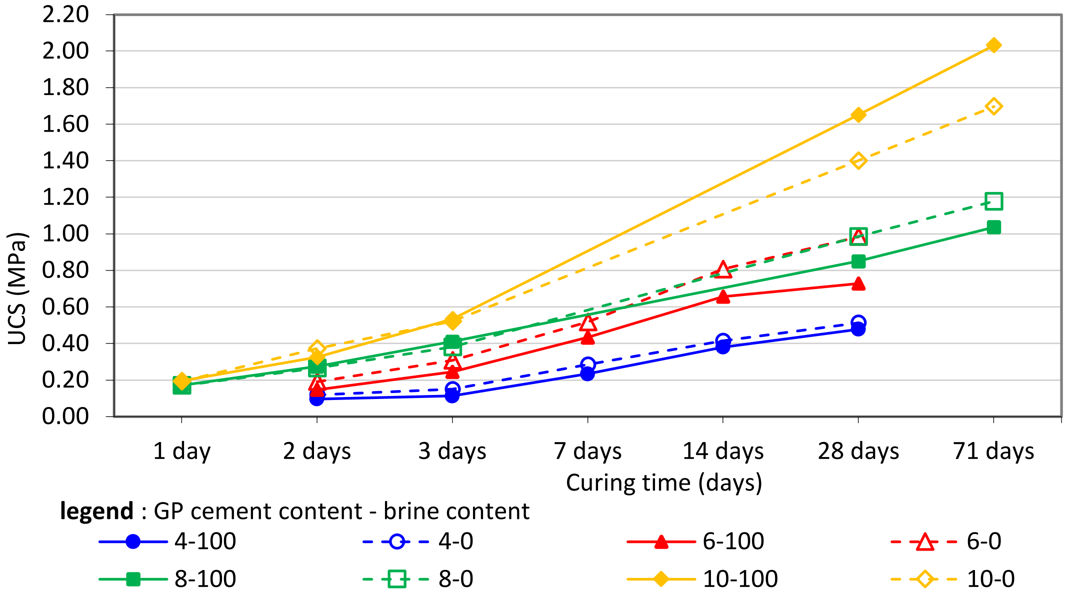

Figure 5 Binder content and water type (Raw or RO Brine)

4.3.3 Slag use

Blending iron slag into the GP cement was investigated by substituting up to 70% of GP cement with slag. Raw water was maintained as the diluent in this next test series.

As shown in Figure 6, for short curing times, increasing slag blend content from 0 to 30 or 50% led to a to a reduction in paste backfill samples' UCS. However, 70% slag-30% GP cement blend showed higher strengths for 6 and 8 wt% total binder content, but low strength for 10% total binder content. These results indicate that slag retards early-stage UCS development. This trend reverses between seven and 14 days of curing and the strength thereafter increases with both overall binder content and slag content.

Overall, with the exceptions highlighted above, the UCS generally increases with curing duration, GP cement and increasing slag blend content.

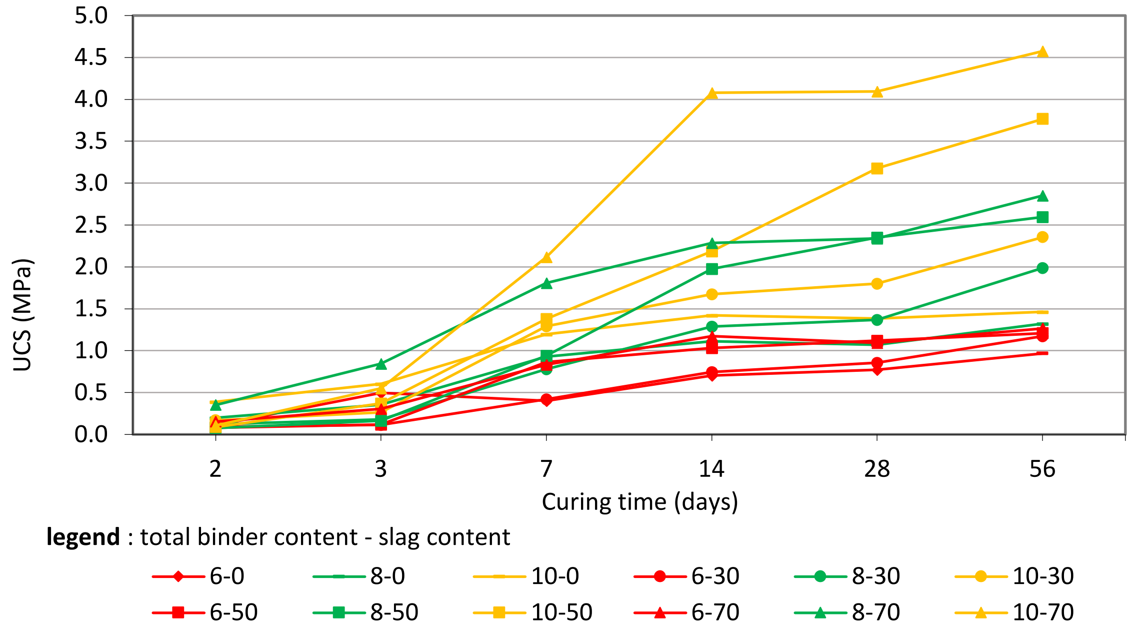

Figure 6 Binder content and slag proportion effect with raw water

4.3.4 Lime addition

Lime addition was investigated by adding 10% of lime to a GP cement/slag blend binder. The overall binder content ranged from 6 to 8wt% and either raw water or RO brine were the diluent. UCS data is shown in Figure 7.

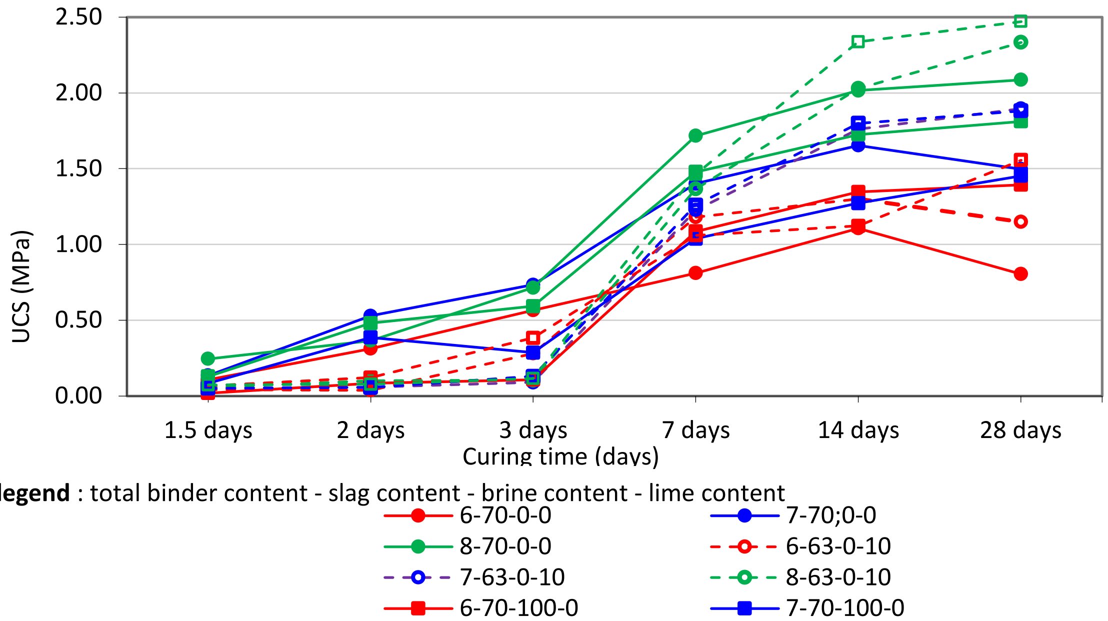

Figure 7 Binder/slag content with brine or raw water with and without lime

An increase in total binder content generally increased the strength. For samples prepared using raw water and using RO brine, the addition of lime and the related decrease in GP cement and slag content supressed strength development at short curing durations, up to three days. Thereafter, the rate of strength growth increased, and the strength became equal to or greater than for samples without lime addition after approximately 14 days in raw water and after seven days in brine.

In raw water, many of the samples showed a reduction in strength after 14 days of curing. This strength reduction was not seen for samples prepared using RO brine. The highest 28-day paste strength was achieved using 8wt% of 27wt% GP cement, 63wt% slag, 10wt% lime binder blend, prepared in RO brine. However, the cost and complexity of preparing this blend must be balanced against the need for the observed strength improvements.

4.3.5 Slag addition with 25/75 reverse osmosis brine/raw water blend

With the diluent fixed at 25/75 RO brine/raw water, the effect of 70% slag substitution for GP cement was tested. A wider total binder dose range of 6 to 12wt% was tested in this case, shown in Figure 8.

Tailings using a GP cement-only binder showed that total binder content increased the strength for all curing times. For samples prepared using the slag and GP cement blend binder, high binder concentrations resulted in low early curing time strength (i.e. < 2 days) but then high strengths thereafter compared to low slag and GP cement binder concentrations.

After seven days curing, higher strengths were recorded for the slag and GP cement blend binder than for the GP cement-only blend. Twenty-eight day UCS values were 3.8MPa for the tailings containing the slag and GP cement binder and 2.7Mpa for the tailings containing GP cement-only. However, at 28 days curing, slag and GP cement binder strength appeared to be plateauing or even reducing for some binder concentrations whereas strengths were still increasing at 28 days for the GP cement-only samples.

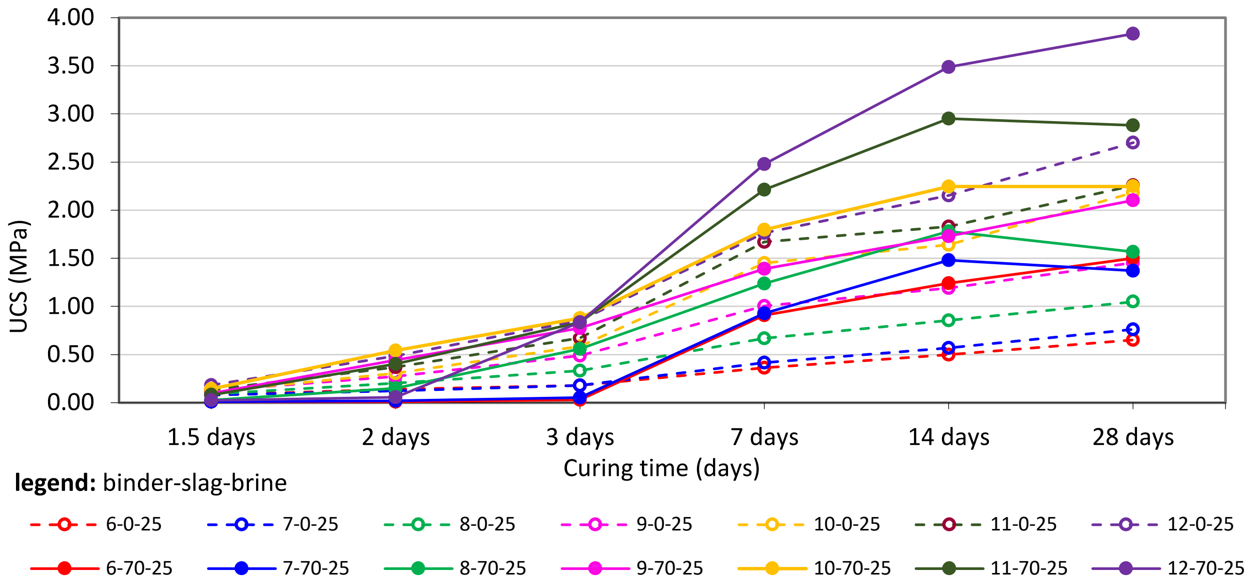

Figure 8 Binder content and slag proportion effect with fixed water blend

4.3.6 Strength performance summary

A summary of 28-day strengths is shown in Figure 9. For the conditions tested, the highest strength achieved was 4.1MPa for 10%, 70/30 slag and GP cement blend binder in raw water. Considering the operation's brine utilisation requirement, adopting a 25/75 RO brine/raw water blend, the highest strength was achieved using 12% 70/30 slag and GP cement blend binder.

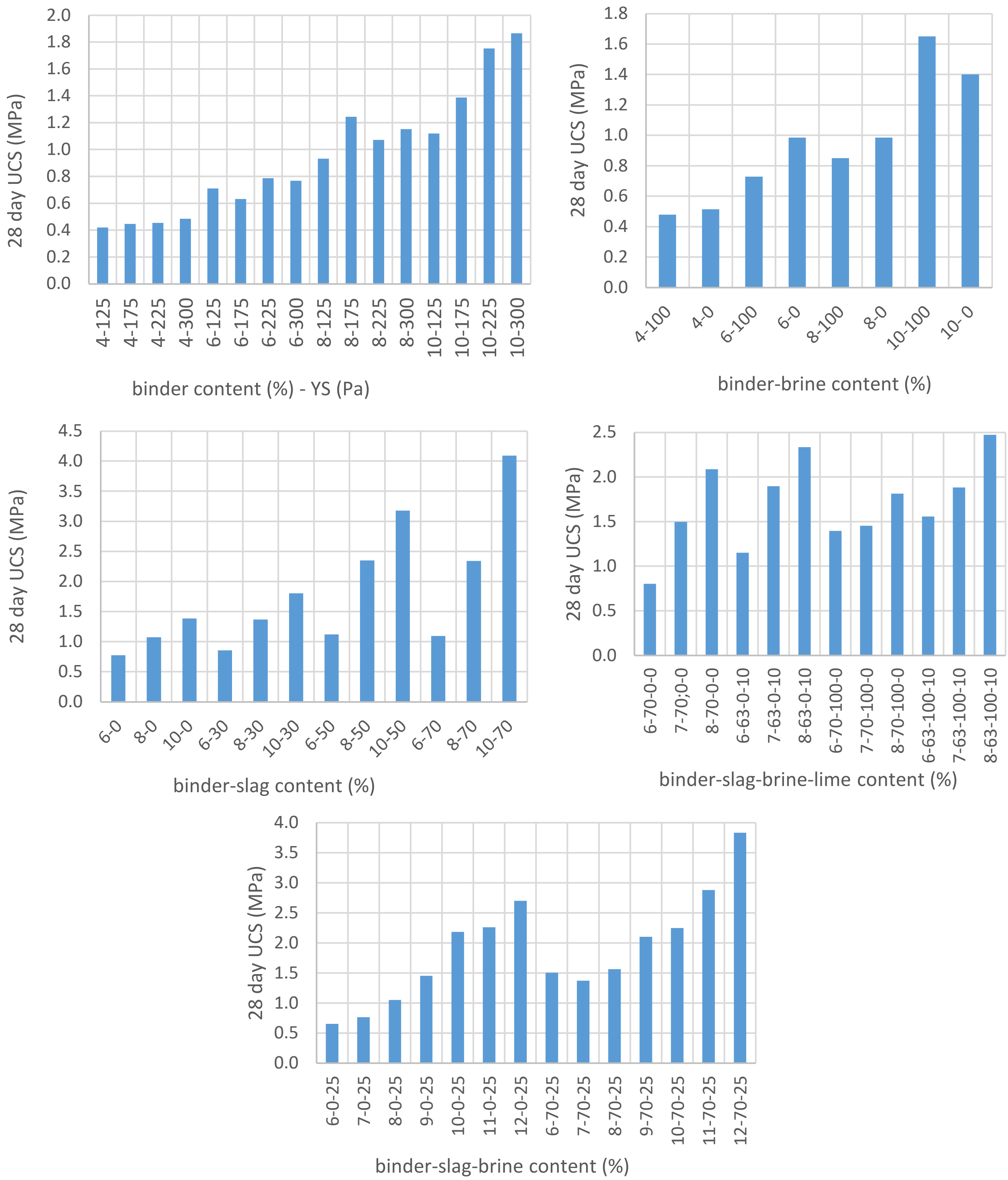

Figure 9 Fosterville paste fill 28 day strength results for water and binder combinations tested

5 Current paste fill operation

The FGM paste filling operation requires high strength several days after paste filling for mining development works beside and/or under the paste filled stope to proceed. On site, quality control samples results using brine water have shown reduction in early paste strength when slag is used. Therefore, instead of using 9% slag and GP cement blend binder (70% slag and 30% GP cement) with raw water to reach the required early strength (two, three, five and seven day cured), FGM is using 10% slag blend binder to compensate for the strength reduction observed using RO brine water. On the upper lifts of stopes binder is normally reduced, depending on the curing time required before development activities commence.

Figure 10 shows the effect of raw water versus RO brine in the paste in early curing and use of pure GP cement with raw water. The 10% binder (slag and GP cement) blend binder performs better than GP cement alone, irrespective of the water type used. Despite lime addition showing some strength advantages, contribution to strength did not warrant the additional cost. The final mix chosen is addressing the brine utilisation requirement in addition to slag blend binder saving around AUD 13/tonne compared to GP cement alone (saving ~AUD 850,000/year) whilst still meeting strength requirements at the required optimum curing time. Currently, an admixture is being trialled to further optimise use of binder whilst maintaining the required strength at the required curing time.

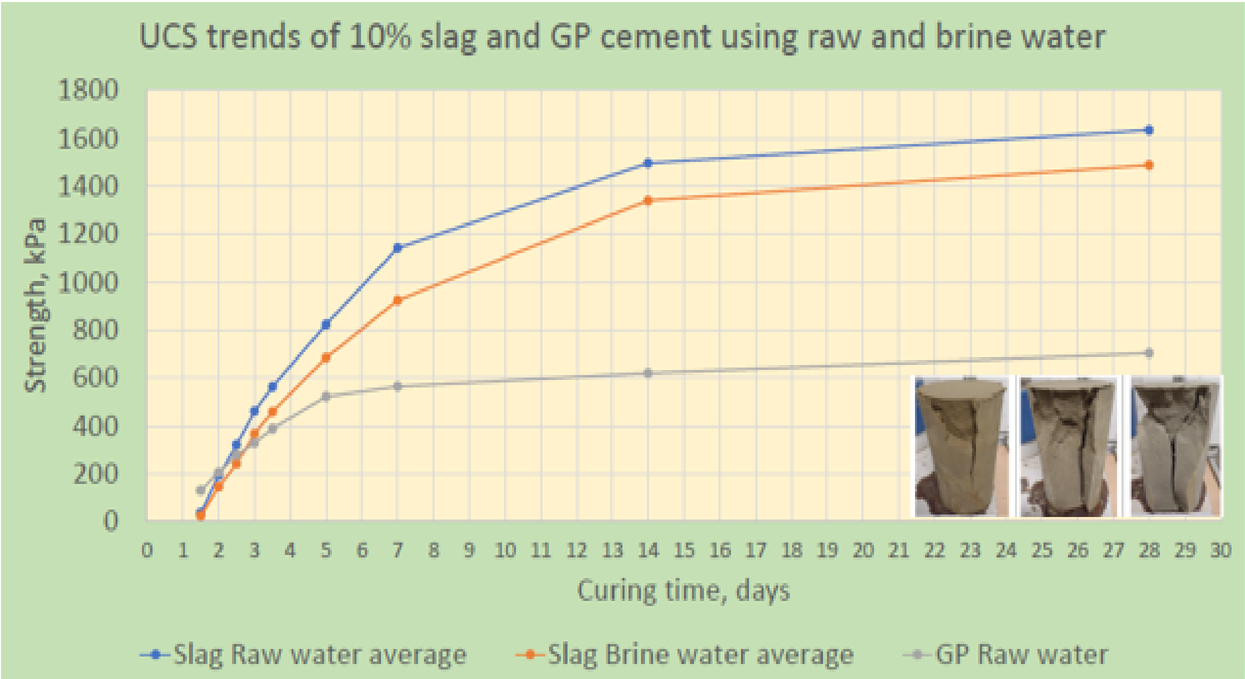

Figure 10 General purpose cement and slag blend binder strength trend comparing use of raw and brine water

6 Conclusion

The comprehensive investigation into various binder and water types and doses, and their impact on FGM paste backfill UCS material has yielded valuable insights for optimising strength development in mining operations. Observations highlight a direct correlation between strength and key parameters such as binder content, curing time, and initial yield stress. Overall, an increase in these factors enhances paste strength, evident in the consistent trend observed across different test series.

Notably, the influence of binder content exhibited a significant role in strength gain, especially with higher binder concentrations resulting in superior strength performance after 28 days of curing. Similarly, the substitution of RO brine for raw water and the introduction of slag into the GP cement binder matrix showcased nuanced effects on strength development. While the utilisation of brine initially lowered strength compared to raw water, the extended curing period revealed a reversal in the trend, emphasising the complex interplay between materials and curing times.

The addition of lime presented mixed results, suppressing early strength but later proving advantageous, although the cost–benefit ratio warrants consideration. The trials with slag and GP cement blends demonstrated a dynamic impact on UCS, indicating a temporal influence on strength development that necessitates careful optimisation.

The culmination of these findings has led to the identification of a tailored blend – 10% slag and binder containing 70% slag and 30% GP cement – addressing both early-stage strength requirements and brine utilisation concerns, achieving the desired strength within the optimal curing duration. This optimised mixture not only fulfills operational needs but also introduces substantial cost savings, illustrating a balanced approach between material performance, environmental imperatives, and economic feasibility.

Ongoing trials with admixtures aim to fine-tune binder utilisation while maintaining requisite strength at specific curing times, ensuring a sustainable and efficient paste filling operation aligned with operational demands. This research offers a nuanced understanding of paste backfill material dynamics, paving the way for informed decision-making and continual improvements in mining operations.

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