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Enhancing cemented paste backfill using chemical admixtures to create economic and environmentally sustainable paste fill

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Abstract

Cemented paste backfill (CPB) has emerged as a crucial component in underground mining operations, offering essential support in the underground mine and assisting in tailings disposal. This, in turn, ensures mine safety and sustainability. However, CPB can contribute to a sizeable portion of total mining operational costs, necessitating the exploration of innovative approaches to enhance performance and minimise environmental impact. In response, this study conducted extensive field trials at a Western Australian gold mine, with the aim of optimising CPB mix designs by incorporating the chemical admixture MasterRoc MF 707. The main goals were to increase solids content, reduce binder content, and assess the effects of the admixture on flow properties and early strength development.

The field trials followed a systematic approach, starting with laboratory tests that displayed the potential of MasterRoc MF 707 in enhancing CPB rheological properties. Large-scale trials progressed at the operating paste plant in three distinct stages: plug pour, main body pour, and solids increase and binder decrease. At each stage, critical parameters such as yield stress, pipe pressures, mixer torque, and unconfined compressive strength (UCS) of the cured paste were carefully monitored to assess the effectiveness of the chemical admixture.

Stage 1 of the field trials focused on the plug pour. The introduction of MasterRoc MF 707 resulted in a significant reduction in yield stress of more than 50% and mixer torque by 9.5%. Moreover, pipe pressures were reduced by 50%. The early strength development was particularly promising, with 100 kPa achieved within 24 hours, leading to more efficient backfilling operations. Further UCS testing revealed that the 7, 14, and 28-day strengths outperformed the control sample by up to 40%.

In Stage 2, the main body pour displayed similar positive trends to the plug pour. With a 41.6% reduction in pipe pressures and a 52% decrease in yield stress, this study demonstrates the potential for reducing the amount of binder reduction used while still maintaining operational parameters. UCS testing confirmed a substantial increase in strengths, with the admixture-enhanced designs outperforming the control at various lower binder content levels.

Stage 3 aimed to optimise the mix designs further by increasing the solid content and reducing the binder content. Cost analysis demonstrated potential savings in binder costs with the utilisation of admixtures. Furthermore, an assessment of CO_2 emissions revealed significant reductions, which contribute to a more environmentally friendly mining practice.

Overall, this study presents evidence that the chemical admixture, MasterRoc MF 707, can enhance CPB mix designs, offering multiple benefits such as improved rheological behaviour, increased early strength, cost savings through binder reduction, and reduced environmental impact. By using innovative technologies and practices, the findings show the potential for successfully integrating chemical admixtures to enhance CPB.

Keywords: *cemented paste backfill, yield stress reduction, binder reduction, chemical admixture, UCS strength increase, carbon footprint reduction*

1 Introduction

The Kanowna Belle gold mine, operated by Northern Star Resources, is situated in the eastern goldfields region, approximately 23 km northeast of Kalgoorlie in Western Australia. The deposit lies within the Archaean Norseman-Wiluna Greenstone belt. The Kanowna Belle underground mine employs the use of cemented paste backfill (CPB) as a means of ensuring stability and support in the mined-out areas. This backfill material is transported through the paste reticulation system to the excavated stope.

Admixtures have a history spanning several years, with their application well-documented in CPB. Some examples include Martic et al. (2011) and Weatherwax et al. (2011).

The evolution of chemical admixture technology has advanced over time, leading to the innovations we see today. The chosen admixture for this specific project is a recently introduced product in Australia which serves as both a hydration controller and a strength enhancer for UCS, making it an ideal choice for this particular application.

The designated strength criteria for the CPB at Kanowna Belle is 100 kPa for the plug pour, prior to commencing the body pour, and 405 kPa for development. The design CPB strength requirements are dependent on parameters such as footprint, volume, future adjacencies, and future development.

The purpose of this review is to accomplish two primary objectives:

1. Decreased binder content: through the reduction of binder quantity employed in the CPB, the operation can achieve cost savings for the CPB. It is imperative to note that the strength of the paste fill remains uncompromised and continues to meet the required performance specifications.
2. Reduction of development periods: by achieving the required performance specifications faster, it is possible to decrease the curing time required before exposing the paste fill, whether it be mining adjacent stopes or developing through it. This reduction in development periods can enable the continuation of other mining activities, providing the operation with increased and/or more reliable production.

The review involved conducting laboratory testing, field trial testing, and analysis to assess the performance of the CPB under different solid contents. Additionally, the study explored the effects of introducing chemical admixtures to the paste fill to enhance its rheology and unconfined compressive strengths (UCS). The CPB underwent testing for UCS and yield stress.

The outcomes of these tests demonstrated the possibility of reducing the binder content while still meeting the specified UCS. It is imperative to strike a balance between cost reduction and guaranteeing the safety of the backfilled regions. The results of the test program show that CPB, optimised with chemical admixtures, has the potential to deliver operational efficiencies, cost reductions, and sustainability gains to the Kanowna Belle gold mine in the future.

2 Laboratory trials

Laboratory trials were conducted at the Kanowna Belle laboratory as a proof of concept before proceeding to field trials. The primary objective of the laboratory trials was to evaluate various chemical admixture solutions in comparison to the standard control mix design, with the main goals being to observe the impact of the various admixtures on the UCS of the CPB, as well as its rheological properties and ability to retain flow.

As part of the testing process, samples of filter disc tailings, binder, and process water were collected from the CPB plant. These samples were used to create different mix designs by incorporating various admixture solutions.

Key objectives of the trials were specifically assessed via measurement of:

1. The rheological properties of the CPB should be evaluated to ensure the effective transportation and placement of the backfill material. The experiments entailed the utilisation of a rheometer to

measure the yield stress of the CPB with various admixture solutions at different doses. Yield stress is a crucial parameter of CPB that defines the amount of force necessary to initiate flow.

2. The monitoring of flow retention was conducted during the testing process. This process is monitored by conducting yield stress testing consistently over a set period to ensure there are no changes in yield stress, as it is crucial to ensure or enhance flow retention to guarantee the effective transportation and placement of the CPB.
3. The feasibility of increasing the solids content whilst maintaining or enhancing rheological properties, leading to the same or lower yield stress with a higher solid content. Higher solid contents have the potential to enhance the UCS of the backfill material, thereby resulting in shorter development times.
4. The UCS development of the CPB was monitored over various ages. This testing enabled assessment of the rate at which the compressive strength increases over time, as well as to determine whether the admixtures used have any beneficial, or detrimental, effects on the development of UCS. The objective is to attain or surpass the current performance of the site's CPB.
5. The determination of the most cost-effective admixture solution. It is crucial to strike a balance and assess the trade-off between enhanced improved performance and economic feasibility before implementing the findings on a larger scale.

By conducting laboratory trials, and evaluating the outcomes, the most economically efficient admixture solution was identified for field trials, and further work to optimise the CPB mix design. The objective is to enhance the flow properties and increase the UCS while minimising costs, thereby optimising the cost efficiency and cost-effectiveness of CPB operation at Kanowna Belle gold mine.

2.1 Rheology testing

The rheology testing was conducted after the preparation of all tailing samples, which were dried, sieved and blended to ensure a homogenous and representative blend of tailings was used for the CPB mixes.

The investigation into the rheology involved using a variety of paste fill designs, each with a different solid content, while keeping the binder content consistent. By manipulating the solid content, the objective was to investigate the influence of yield stress parameters of the CPB at various solid content levels.

To measure the yield stress a Thermo Scientific HAAKE Viscotester 550 was used in the rheology testing. This device is fitted with a vane rotor and is used to assess the rheological behaviour of non-Newtonian fluids, such as CPB. Unlike Newtonian fluids (e.g. water) they do not have a constant viscosity and exhibit different flow characteristics under varying shear rates.

The vane rotor was inserted into the prepared CPB samples. The HAAKE Viscotester 550 measured the resistance (yield stress in Pa) at different solid content levels allowing an understanding of the yield stress changes at different paste compositions. A consistent shear rate of 0.5 rpm was maintained throughout all testing.

To ensure repeatability, all tests were conducted by the same individual utilising the vane rheometer and the same vessel, with the vane inserted at the specified depth according to the manufacturer's guidelines. Control samples were also collected to validate the effectiveness of the tests. This same process is used for laboratory trials and live large-scale trial. When analysing the rheology testing results in Figure 1, on the control sample, the following observations were made:

1. As the solid content is decreased from higher values to below 76%, there is a significant drop in yield stress. This is due to the dilution of the paste fill density by increasing the water to binder ratio (W/B) which leads to a decrease in yield stress.
2. Slower rate of change can be observed when the solid content falls below 74%. In this case, the decrease in yield stress becomes less pronounced. This finding suggests that maintaining a solid

content between 73 and 75% may be the optimal operational range for underground paste transportation in the control sample.

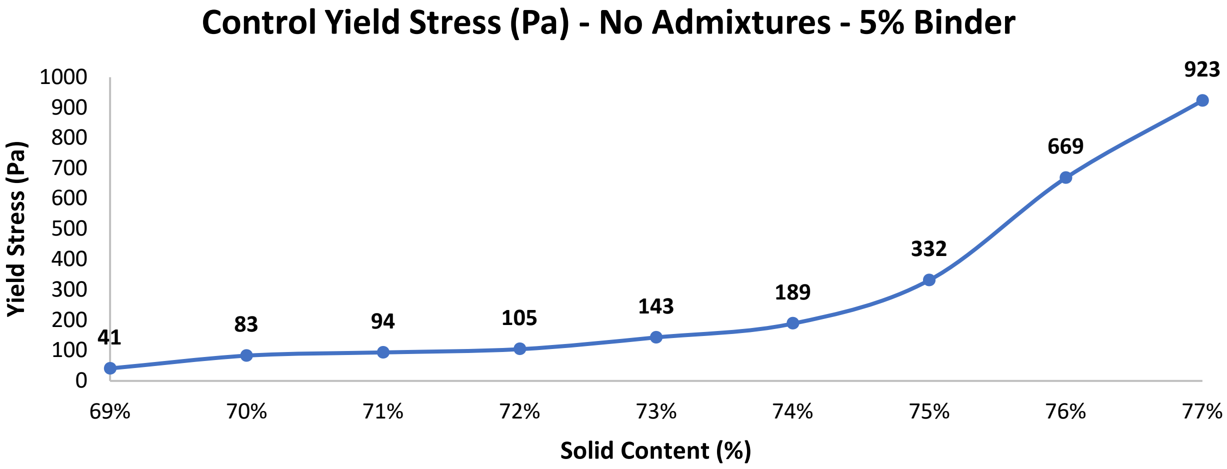

Figure 1 Control yield stress at different solid contents

During the testing, a flattening of the yield stress was observed when solids content decreased to under 73% solids; the likely explanation being one or a combination of the following:

1. Settlement in the CPB mix design: as the solid content decreases and the W/B ratio increases, the CPB mix design is influenced by the reduced presence of solids, and higher proportion of water can accelerate the settling process. Settlement can cause undesirable effects such as increased bleed and segregation of the CPB.
2. The choice of vane rotor size may influence the measured yield stress values. Smaller vane rotors may not effectively capture the behaviour of pastes with low solid contents, leading to an apparent flattening of the yield stress curve.

2.2 Rheology testing: introducing admixtures

Once the rheological behaviour of the control samples had been benchmarked, additional batches were mixed, incorporating different admixtures and various doses. Dose rates were determined by a per wet tonne (w/t) basis.

Based on the results presented in Figure 2, it is evident that the addition of chemical admixture solutions has a significant impact on the flow properties of the CPB. The focus of the testing was to assess which admixture would be the most efficient and cost-effective solution to lower the yield stress of the CPB.

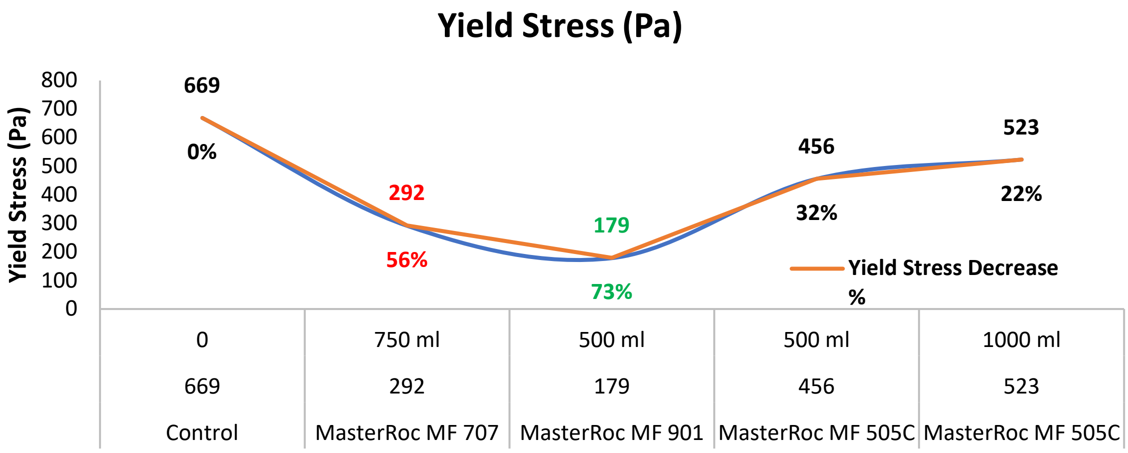

Figure 2 Yield stress with admixtures and the control without admixture – 5% binder content and 76% solid content

Observations derived from Figure 2:

1. MF 707: the initial admixture solution, dosed at 750 mls per w/t, resulted in a 56% reduction in the yield stress of the control sample of CPB. This suggests that the utilisation of MasterRoc MF 707 can effectively enhance the flow characteristics of the CPB.
2. MF901: the second admixture solution, dosed at 500 mls per w/t, demonstrated a significantly greater decrease in yield stress compared to the control sample, with a reduction of 73% in yield stress. This observation provides evidence of the effectiveness of MasterRoc MF 901 in improving the flow characteristics of the CPB.
3. MF 505C: the third admixture solution resulted in a 22% reduction in yield stress when applied at a dosage rate of 1,000 mls per w/t. Although this admixture solution has demonstrated a decrease in yield stress, compared to the control sample, it is not as efficient as the previous two admixtures due to the increased dose rate of the MF505C economically this admixture would not be suitable.

2.2.1 Implications for the content of binders and solids

By employing chemical admixtures, it is possible to achieve a greater solid content by while simultaneously preserving the desired flow characteristics.

The decrease in yield stress observed in all three admixture solutions provides the opportunity to enhance the flexibility of the CPB mix design. This can be achieved by increasing the solid content and decreasing the binder content, while ensuring that the yield stress remains within the operational parameters of the CPB plant.

The capacity to decrease the amount of binder used, while simultaneously maintaining or enhancing CPB performance, offers two significant advantages:

1. The reduction in binder content results in cost savings, in terms of materials, as binders are more costly constituents of the CPB mix design. Reducing the utilisation of binders can significantly enhance the cost-effectiveness of the CPB operation.
2. Reduction in binder content results in positive environmental outcomes, as binders make the largest contribution towards the CPB's carbon footprint. Therefore, the reduction in binder usage enhances the sustainability of the CPB, and the entire operation.

The results obtained from the rheology testing, with a specific focus on observations presented in Figure 2, demonstrate that the admixture solutions MF 707 and MF 901 exhibit the highest level of efficiency in reducing the yield stress of the CPB. By employing one of these admixture solutions, and appropriately modifying the solid and binder proportions, it is possible to attain a more economical and environmentally friendly CPB operation at Kanowna Belle gold mine, without compromising the relevant performance specifications.

2.3 Unconfined compressive strength testing

Once rheological testwork had been completed, the emphasis of the project shifted to assessing the strength development profiles of the various CPB mixes via UCS testing (Standards Australia 2014).

The results in Figure 3 and Table 1 show the influence of chemical admixtures on UCS of the CPB. The study centred on a consistent mix design, maintaining a solid content of 76% and a binder content of 5%. Various admixtures were introduced and compared to the control with the outcomes displaying a significant increase in UCS, compared to the control sample.

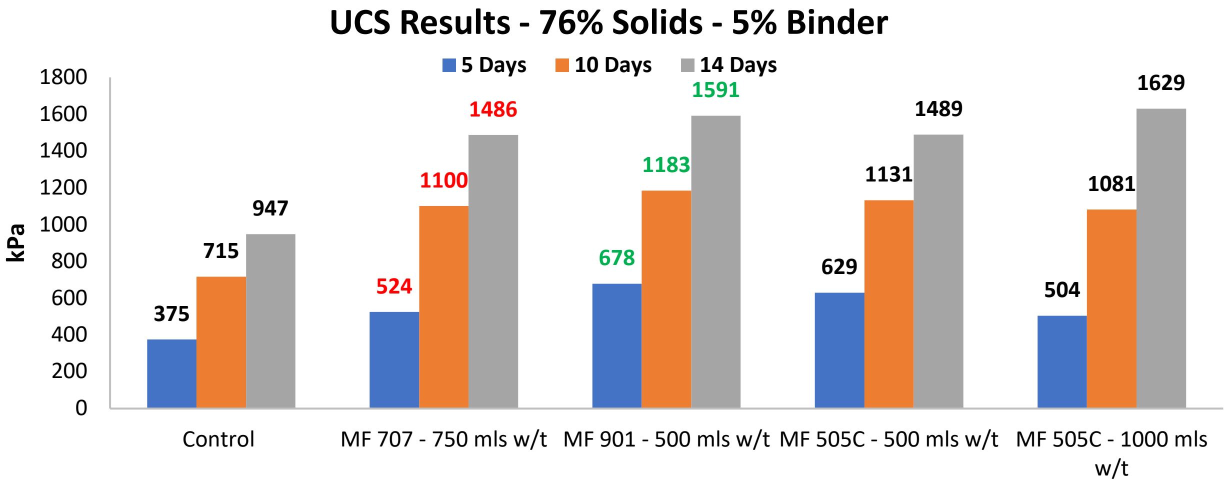

Figure 3 Unconfined compressive strength (UCS) enhancement using chemical admixtures

Key observations can be made from Figure 3 & Table 1. UCS improvement with all additions, MasterRoc MF 707, MasterRoc MF 901, and MasterRoc MF 505C showed significant improvements in UCS strength compared to the control sample. MasterRoc MF 707 demonstrated a 57% increase in UCS at the 14-day mark, MasterRoc MF 901 exhibited an increase of 68% in the same period, and MasterRoc MF 505C showed a 72% increase in UCS.

Table 1 Unconfined compressive strength (UCS) values at varied dose rates per wet tonne of cemented paste backfill

UCS age (days)	Control	MF 707–750 mls	MF 901–500 mls	MF 505C-500 mls	MF 505C–1,000 mls
5	375	524	678	629	504
10	715	1100	1183	1131	1081
14	947	1486	1591	1489	1629

2.3.1 Implications for the cemented paste backfill design and operations

The impact of the chemical admixtures on UCS strength offers several opportunities for CPB design and operational practices:

1. The significant increase in UCS strength indicates improved structural integrity and support, provided by the paste fill. This has the potential to enhance the stability and safety of underground operations.
2. The utilisation of admixtures, to enhance the UCS, offers the potential to investigate additional reductions in binder content while maintaining the required strength characteristics. Lower binder content not only reduces costs, but also aligns with sustainable mining practices by reducing the use of binders and the associated carbon footprint, effectively reducing the embodied carbon of the CPB.
3. Results indicate that by optimising the mix design of CPB with suitable admixtures, it is possible to achieve higher UCS while also realising cost savings. A more efficient use of materials and improved operational productivity can contribute to a cost-effective paste fill operation at the mine.
4. Improved production rates: with higher UCS strengths, the potential for shorter development periods, and faster stope filling processes, can lead to improved production rates in the mining operation.

The prospect of enhancing UCS is notably promising, suggesting the potential for achieving higher strength levels without elevating solid content or binder content. As illustrated in Figure 3 and detailed in Table 1, the addition of a chemical admixture alone resulted in a substantial increase in UCS strength, demonstrating the efficacy of the admixture without the need for additional solid or binder content.

This finding implies that by incorporating appropriate admixtures, it is feasible to enhance the design of CPB to attain higher UCS values, creating the opportunity to meet the required performance specifications while achieving a reduction in binder content.

Figure 3 and Table 1 show the effect of admixtures on UCS strength in the CPB, however, further research, testing, and implementation on a larger scale are necessary to validate and optimise the findings for practical applications.

2.4 Conclusions from laboratory trials

Laboratory trials suggest that chemical admixtures, specifically MF 707, holds promise for enhancing the efficiency of CPB operations at Kanowna Belle gold mine. Notable improvements in strength, achieved without increasing solid or binder content, offer optimistic prospects for future CPB designs and operations. The use of these admixtures could optimise effectiveness, cost efficiency, and sustainability in paste fill operations while ensuring safety in underground mining.

The findings include:

1. Flowability enhancement: MF 707, MF 901, and MF 505C exhibited superior flowability, with a plasticising effect improving rheological characteristics for easier transportation and placement in underground stopes
2. Positive impact on strength development: utilising chemical admixture solutions, especially MF 707 and MF 901, significantly improved the overall strength development of CPB, as shown by the enhanced UCS values
3. Binder reduction potential: MF 707, MF 901, and MF 505C demonstrated a plasticising impact, allowing for a practical reduction (15 to 30%) in the required binder quantity while increasing solids content, maintaining strength and rheological properties

4. Cost-efficient choice: cost analysis revealed MasterRoc MF 707 as the most economically efficient admixture for Kanowna Belle gold mine, surpassing MF 901 in economic performance. Its adoption presents an opportunity to enhance operational efficiencies and cost-effectiveness in CPB operations.

In conclusion, MF 707 emerges as the most suitable and economically viable admixture solution, offering enhanced flowability, reduced yield stress, and improved strength development. The findings also suggest opportunities for performance improvement in CPB, reducing costs and environmental impact. Further validation at a larger scale is recommended based on these promising results.

3 Field trials

The primary aim of the field trial was to validate the favourable outcomes achieved during the laboratory trials and assess the effectiveness and durability of the chemical admixture MasterRoc MF 707 under actual operating conditions. The objectives of the field trials were as follows:

1. A comparative analysis of the chemical admixture’s performance in field conditions against the standard design.
2. Evaluate the influence of the admixture on the flow properties of the CPB during two distinct stages, namely the plug pour and body pour.
3. Explore the potential of increasing the solid content by utilising admixtures while preserving, or improving, its flow properties.
4. Binder reduction: assess the possibility of binder reduction when solid content is increased to optimise the CPB design.
5. Determine any potential decrease in pressure along the paste reticulation line upon the introduction of the admixture to the CPB.

3.1 Field trial process

The field trials were conducted in three distinct phases to assess multiple facets of the CPB using a chemical admixture.

3.1.1 Stage 1

The initial stage of the process involved the plug pour, which aimed to create a stable plug using the CPB before proceeding with the main body pour. The trials entailed a comparison of the performance of the admixture, with the standard mix design during the plug pour process, while maintaining a constant solid content and binder content.

Key parameters:

- Flow properties during plug pour (yield stress).
- Pressure measurements in the paste reticulation system.
- A comparative analysis of system performance with, and without, the inclusion admixture.
- Evaluating UCS with, and without, the addition of admixture.

3.1.2 Stage 2

The second stage of the trial involved the body pour process, with the main objective being to assess the effects of admixtures in comparison to the control. Both the solid content, and binder content, were kept constant throughout the evaluation.

Key parameters:

- Flow properties observed during the pouring body (yield stress).
- Pressure measurements in the paste reticulation system.
- Comparing system performance with, and without, admixture.
- Assessing UCS strengths with, and without, admixture.

3.1.2 Stage 3

The objective of this stage was to examine the potential of reducing binder contents through binder optimisation whilst still achieving the required UCS and maintaining the operational parameters. The focus was on increasing the solid content, and reducing the binder, for the plug pour and body pour.

Key parameters:

- Flow properties, specifically the measurement of yield stress.
- Pressure measurements in the paste reticulation system.
- Assessing UCS strengths.
- Comparing CPB mix designs, with admixtures performance assessed against the control mix.

The field trials aimed to validate the findings of the laboratory trials and assess the performance of the chemical admixture in real-world mining conditions in a non-critical area of the underground mine.

3.2 Stage 1: plug pour field trial – rheology

The plug pour rheology field trials involved the evaluation of the chemical admixture's performance in comparison to the current plug pour CPB design (control). Throughout the trials, the solid content was maintained at a constant level of 75.3%, while the binder content remained at 6%. The findings, depicted in Figure 4, demonstrated the beneficial impact of the admixture on the rheological properties of the CPB.

Key findings derived from initial stage of field trials are as follows:

1. Yield stress of the CPB was reduced from 236 (control sample) to 117 Pa when the chemical admixture was introduced. This is a 50% reduction in yield stress which is comparable to the laboratory trials.
2. Mixer amps was reduced from 52 to 47. The chemical admixture led to a 9.5% reduction in mixer torque. This reduction in torque indicates that the admixture led to a more homogenous, and easily workable, CPB mixture.
3. Pipe pressure reduction was observed with a reduction from 550 to 274 psi; the 50% reduction in pipe pressure was evident in the CPB operating system. The lower pressure in the reticulation system indicates that the CPB flows more efficiently with the use of an admixture, but also allows for scope to increase solid contents.

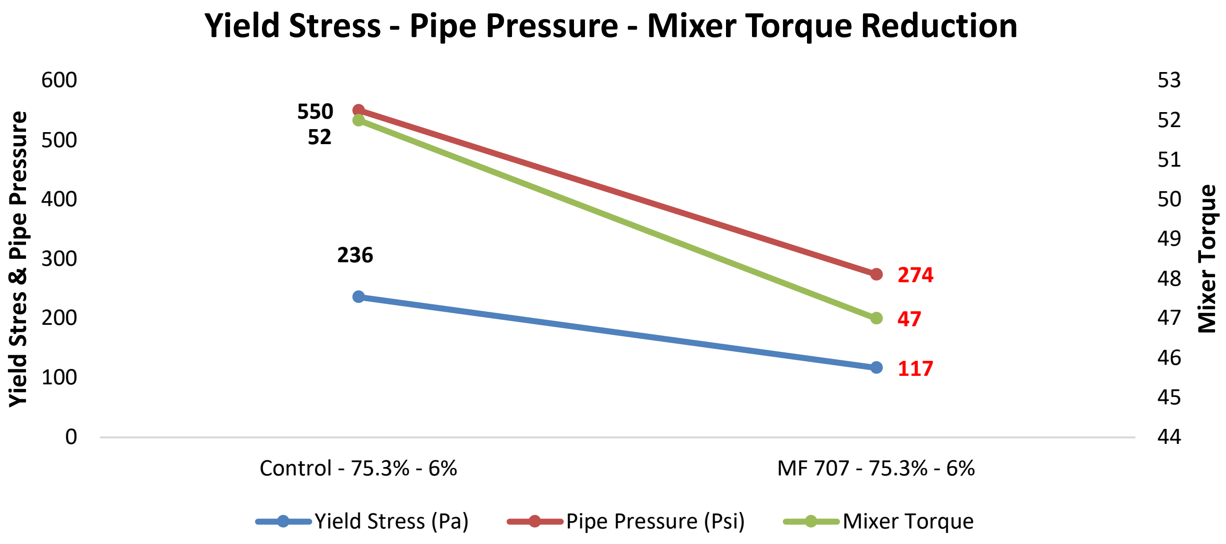

Figure 4 **Stage 1: yield stress, pipe pressure and mixer torque reduction**

3.2.1 Stage 1: plug pour field trial – rheology summary

The collective findings offer support of introducing the chemical admixture for favourable enhancements in the rheological properties of the CPB. The notable decrease in yield stress, coupled with lower mixer torque and pipe pressures, indicates an improved flowability. This data is crucial for justifying the decision to increase solid contents and reduce binder contents.

Key conclusions drawn from Figure 4 include:

1. The yield stress of the CPB was reduced by more than 50%, highlighting the substantial impact of the chemical admixture MasterRoc MF 707 on the rheology of the CPB.
2. The decrease in mixer torque implies a reduction in energy consumption, thereby contributing to lower CO_2 emissions due to the reduced power required for effective paste mixing.
3. Additionally, it was observed that even with the lower mixer torque, an increase in volume of paste being mixed was evident as the tonnes per hour mixed increased with the introduction of admixtures.
4. Lower pipe pressures not only signify reduced energy requirements for paste movement but also enhance flexibility in CPB paste reticulation modelling. This, in turn, may lead to decreased wear and tear on the reticulation system, thanks to the coating of particles by the chemical admixture.
5. With a significant reduction in yield stress, there is an opportunity to increase solid contents and restore pipe pressures to the original operating conditions. This adjustment allows for the potential increase in UCS strength due to a denser material.

3.2.2 Stage 1: plug pour field trial – unconfined compressive strength results

Results of UCS testing comparing CPB mix design with chemical admixture to control design without admixture are shown in Figure 5 and Table 2. Trials maintained a solid content of 75.3% and a binder content of 6%. Two samples were collected for each age strength, and an average was calculated. UCS samples were stored at 35°C and tested using a uniaxial unconfined compressive testing machine.

Key findings from the initial stage of UCS testing:

1. Control samples without admixture did not record UCS strength at the 1-day mark; they were too plastic to crush, so crushing occurred on day two. The sample with chemical admixture reached 178 kPa in one day, demonstrating its ability to accelerate the strength development process.

2. The 7-day sample with the admixture achieved a UCS strength of 1,545 kPa, a 40% increase over the control sample at the same age, validating the effect of the admixture on the CPB's overall performance.
3. At the 14-day mark, the sample with admixture achieved a UCS strength of 1,191 kPa, an 8% growth over the control sample at the same age. This drop in strength appears to be an anomaly as strengths at 28 and 56 days increase.
4. All samples containing the admixture exhibited higher strength than the control sample at the same age, up to 56 days. This finding shows the consistent, and sustained, positive influence of the admixture on the long-term strength development of the CPB.

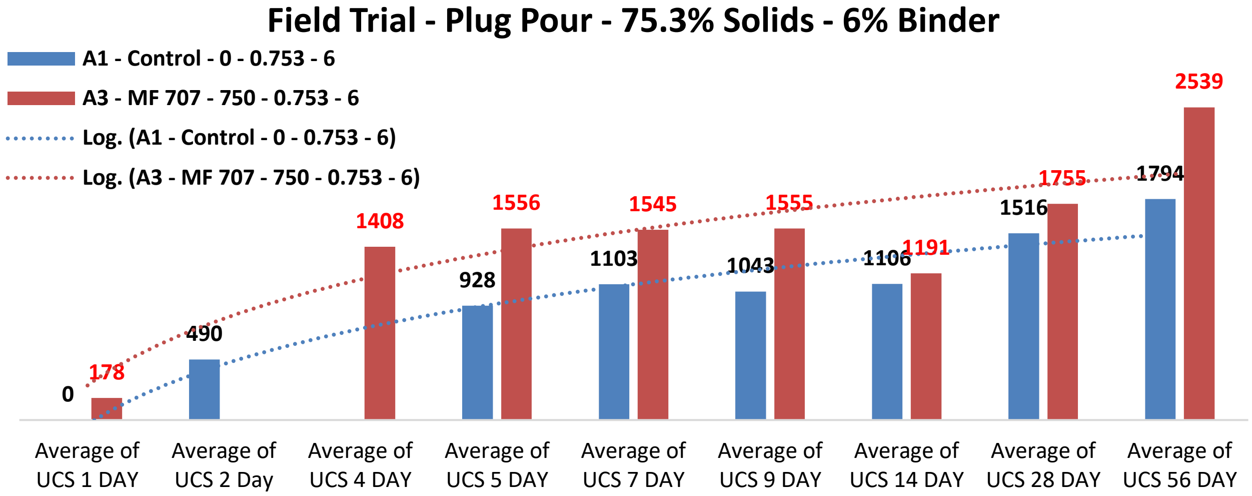

Figure 5 Stage 1: plug pour unconfined compressive strength results

Table 2 Stage 1: plug pour unconfined compressive strength results

UCS age (days)	A1 – control	A3 – MF 707	UCS % increase
1	0	178	178% ↑
2	490	NA	NA
4	NA	1408	NA
5	928	1556	67% ↑
7	1103	1545	40% ↑
9	1043	1555	49% ↑
14	1106	1191	8% ↑
28	1516	1755	16% ↑
56	1794	2539	29% ↑

3.2.3 Stage 1: plug pour field trial – UCS results summary

The testing results of the UCS have significant practical implications for the CPB operation at Kanowna Belle gold mine.

1. With enhanced early strength, 100 kPa in 24 hours achieved by the sample with admixtures. This can accelerate the back filling operations by beginning the main body pour earlier, improving mining efficiencies.

2. The effects of the admixture on UCS strength offer the possibility of exploring binder reductions without compromising on strength.

Overall, the UCS testing results show the influence of chemical admixtures on strength development of the CPB, with significant improvements in early strength and sustained strength development up to 56 days.

3.3 Stage 2: body pour field trial – rheology

The plug pour rheology field trials involved the evaluation of the chemical admixture's performance in comparison to the current body pour CPB design (control). Throughout the trials, the solid content was maintained at a constant level of 76.5%, while the binder content remained at 3%. The findings, depicted in Figure 6, demonstrate the beneficial impact of the admixture on the rheological properties of the CPB.

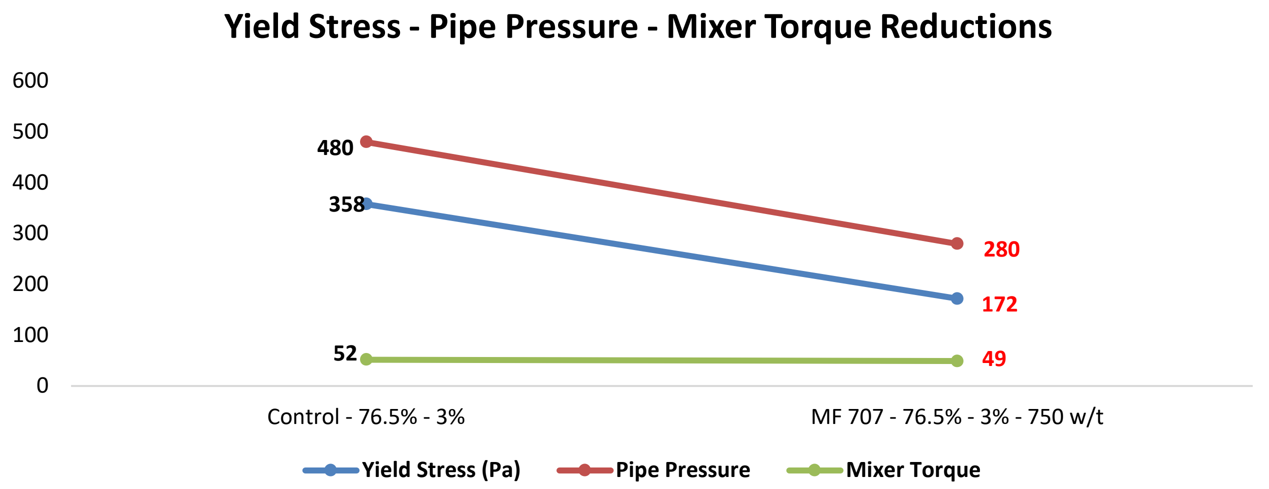

Figure 6 **Stage 1: yield stress, pipe pressure and mixer torque reduction**

Key findings derived from the Stage 2 field trials found in Figure 6 are as follows:

1. The yield stress of the CPB was reduced from 358 to 172 Pa, indicating a decrease of 52%. This observed decrease indicates enhanced fluidity of the paste fill.
2. A decrease in pipe pressure was observed upon the introduction of the admixture, resulting in a reduction from 480 to 280 psi. Lower pipe pressures indicate enhanced paste rheology upon introduction of the admixture.
3. The torque of the mixer was reduced from 52 to 49. A decrease in mixer torque indicates a decrease in resistance during the mixing process, which can result in enhanced mixing efficiency and reduced energy consumption.

3.3.1 Stage 2: body pour field trials – UCS results

The results of the UCS testing conducted during Stage 2 of the field trials indicate improvements in the strength of the paste fill when comparing the CPB control mix design with the chemical admixture design.

The trials were conducted using a consistent solid content of 76.5% and a binder content of 3%. The inclusion of the chemical admixture has demonstrated notable beneficial impacts on the UCS of the CPB, as depicted in Figure 7 and Table 3. Two samples were collected for each age strength, and an average was calculated. UCS samples were stored at 35̊C and tested using a uniaxial unconfined compressive testing machine.

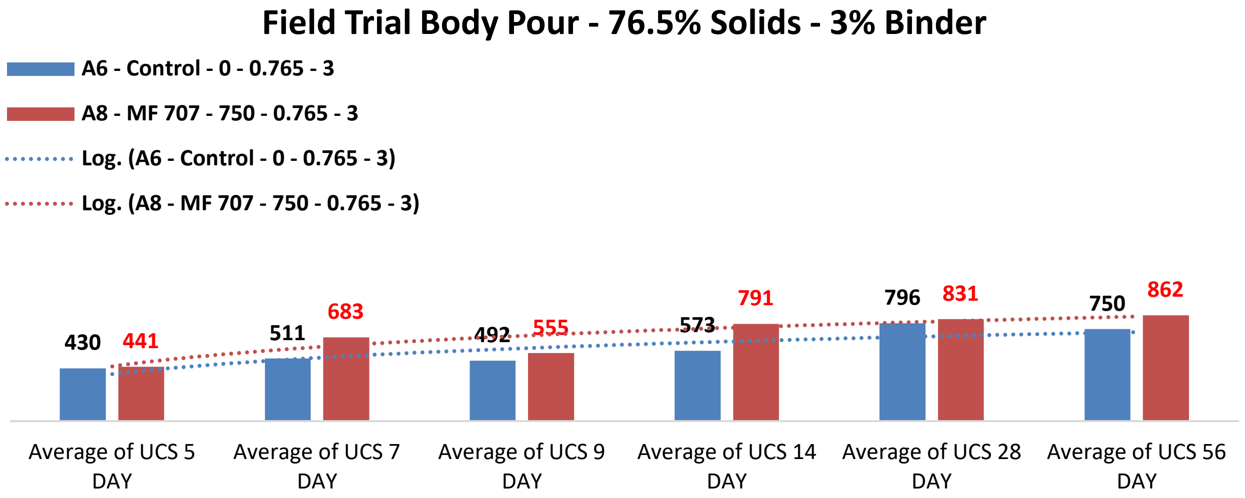

Figure 7 **Stage 2: body pour unconfined compressive strength**

Key observations derived from the Stage 2 UCS testing:

1. By the fifth day, all UCS cylinders successfully exceeded 405 kPa, thereby satisfying the prescribed strength criteria for development. The design incorporating the admixture achieved a compressive strength of 441 kPa, exhibiting a slight improvement of 3% compared to the control sample.
2. The sample with the admixture surpassed the control sample UCS at the 7-day mark, with UCS strength of 683 kPa, indicating a 33% increase.
3. The 9-day results indicate that MF 707 still outperformed the control sample, but both samples exhibited a reduction in strength. Site reports have not indicated any prior degradation of strength, and the long-term strength has consistently increased. This result appears to be an anomaly.
4. At the 14-day interval, the design incorporating the admixture exhibited sustained superior performance compared to the control sample, achieving a compressive strength of 791 kPa, representing a notable 38% increase. The consistent enhancement in strength development further substantiates the positive influence of the chemical admixture on the performance of the CPB.
5. The long-term strength results up to 56 days indicate that the design incorporating the admixture consistently surpasses the control sample. This statement highlights the enduring advantages of the admixture.

The results of the UCS tests conducted during Stage 2 of the field trials demonstrate that the chemical admixture has a notable and beneficial impact on the early and long-term strength development of the CPB.

Table 3 **Stage 2: body pour unconfined compressive strength (UCS)**

UCS age (days)	A6 – control	A8 – MF 707	UCS % increase
5	430	441	3% ↑
7	511	683	33% ↑
9	492	555	13% ↑
14	573	791	38% ↑
28	796	831	5% ↑
56	750	862	15% ↑

3.3.2 Stage 2: body pour field trials – unconfined compressive strength results summary

The presented data suggests the potential for optimising the CPB mix design by increasing solid content and decreasing binder content while maintaining or potentially enhancing UCS. This optimisation could lead to cost savings in materials, reduced environmental impacts, and improved mining efficiencies.

Key findings include:

1. The introduction of MF 707 alone resulted in a significant increase in UCS without the need to adjust binder or solid contents.
2. This information implies that increasing solid content further could enhance the UCS strengths of the body pour.

3.4 Stage 3: binder optimisation

In Stage 3 of the field trials, the primary objective was to optimise the plug pour and body pour CPB mix designs through an increase in solid content, and a decrease in the binder content, while maintaining similar operating parameters to the control. The objective of this stage was to achieve a more cost-efficient and sustainable CPB.

The process encompassed the subsequent steps:

1. The addition of MF 707 to the CPB mix was proposed to enhance its rheological characteristics, such as flowability and yield stress.
2. The intent was for the cost savings to be generated by a reduction in binder content to more than offset the cost of the admixture, producing CPB with equivalent or better performance, at a lower cost.
3. The solid content of the CPB mix was increased while the binder content was decreased. The binder content values were incrementally reduced by 1% at a time, and the solid content was gradually increased to assess the effect on the yield stress readings. The objective was to attain a yield stress value comparable to the control.
4. Monitoring operating parameters is crucial when increasing the yield stress. Once a yield stress comparable to the control is achieved, the plant is operated for a specific duration to allow the reticulation line pressures and mixer torques to stabilise. This ensures that the CPB operation is within the desired operating parameters.
5. Confirmation of the operating parameters was conducted once the CPB plant had stabilised. Another measurement of yield stress was performed to verify that the CPB mix design was within the desired operating parameters. Furthermore, the pressures within the reticulation system and the torque of the mixer were measured to evaluate the performance of the paste fill in the system.
6. UCS sampling was also undertaken to assess the strength development of the CPB using the optimised mix design. The objective was to ensure that the early and long-term strength of the paste fill material met, or exceeded, the prescribed UCS.

The data collected during Stage 3 enables the assessment of the optimised CPB mix design, with increased solid content and a decreased binder content. The field trials aimed to enhance the flow properties, decrease the yield stress, and improved UCS, while ensuring that the necessary operational parameters for effective back filling and underground mining activities were met.

The outcomes obtained from the third stage of the trials play a crucial role in assessing the practicality and advantages of implementing the optimised mix design on a larger scope. The data collected was used to evaluate the performance, cost-effectiveness, sustainability, and safety of the CPB operation at the Kanowna Belle Gold Mine, as well as its potential positive impact on mining efficiencies and production rates.

3.4.1 *Stage 3: rheology*

The following data is provided for the plug pour and main body pour of the CPB designs, including both samples with admixture and the control sample without admixture. The trials were conducted with the objective to optimise the CPB mix designs by increasing solid content, and reducing binder content, by using a chemical admixture.

Rheology results for the plug pour are noted as follows and presented in Figure 8:

1. When the admixture was introduced to the control, a noticeable decrease in yield stress, pipe pressures, and mixer torque was observed. The observation indicated that the incorporation of admixture had a favourable impact on the rheological characteristics of the CPB, leading to enhanced flowability and facilitated transportation.
2. Following the addition of the admixture, the solid content was increased and the binder content was decreased, resulting in an increase in the parameters that aligned with the control sample, yield stress, pipe pressure and mixer torque. This observation indicated that the CPB mix design, despite alterations to the solid and binder contents, remains within the established operating parameters, due to the inclusion of the admixture.

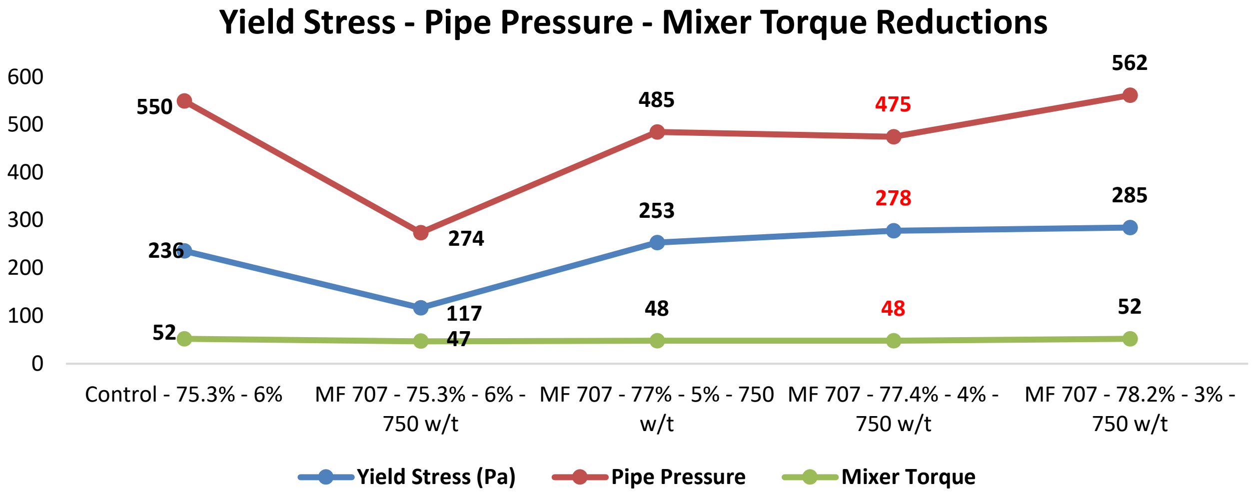

Figure 8 Stage 3: operating ranges for plug pour with varied cemented paste backfill designs

Several findings from the plug pour with the admixture are as follows:

1. When the binder content was reduced from 6 to 5% and the solid content was increased to 77%, a 1.7% increase in solids from the control was observed while achieving compliance with operating parameters.
2. When the binder content was reduced from 6 to 4% and the solid content was increased to 77.4%, an increase of 2.1% in solids was observed while still maintaining compliance with the specified operating parameters.
3. When reducing the binder content to 3% and increasing the solid content to 78.2%, an increase of 2.9% was observed whilst adhering to the operational parameters.

3.4.2 *Stage 3: rheology – summary*

Key findings pertaining to the main body pour presented in Figure 9:

1. Like the plug pour, the addition of the admixture to the control resulted in a noticeable decrease in yield stress, pipe pressures, and mixer torque during the main body pour.

2. After adjusting the solid content and binder content using the admixture, the parameters showed an increase that aligned with the control.

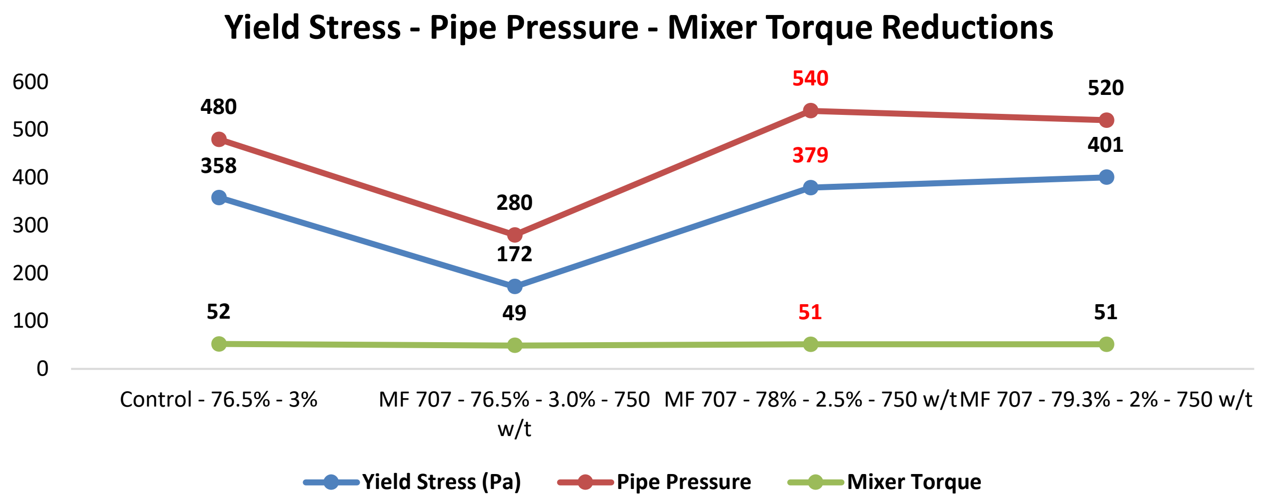

Figure 9 Stage 3: operating ranges for main body pour with varied cemented paste backfill designs

Overall, preliminary findings indicate that the incorporation of the chemical admixture has a positive impact on the rheological properties of the CPB. Moreover, the capability to increase solid content and reduce the binder content, while preserving the operating parameters, presents the possibility of achieving greater cost efficiency.

3.4.3 Stage 3: unconfined compressive strength

The data provided for the plug pour and main body pour of the CPB designs demonstrate the performance of the CPB with admixture compared to the controls without admixture. The results obtained from UCS tests at various ages and binder percentages indicated the effectiveness of these designs in terms of UCS.

Two samples were collected for each age strength, and an average was calculated. UCS samples were stored at 35°C and tested using a uniaxial unconfined compressive testing machine.

Key observations regarding the plug pour are delineated as follows, and shown in Figure 10 and Table 4:

1. At the age of one day, all designs containing admixture and lower binder contents exhibited higher strength compared to the 6% binder control, which did not demonstrate any recorded UCS.
2. The mix design containing 5% binder and admixture demonstrated enhancement in UCS strength at 7 and 14 day ages, surpassing the control sample by 26 and 39%, respectively. The mix design containing 4% offered favourable performance, demonstrating improvements compared to the control.
3. At the ages of 28 and 56 days, the mix design containing 5% binder and admixture demonstrated an increase in UCS of 23 and 20%, respectively. The mix design incorporating 4% binder displayed improved performance, compared to the control.

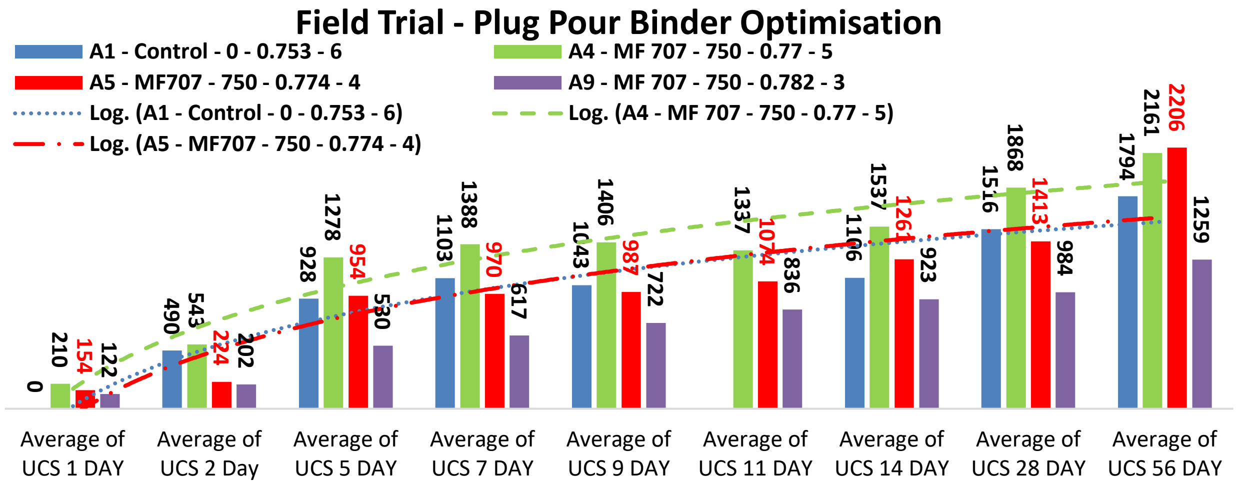

Figure 10 Stage 3: binder optimisation of plug pour unconfined compressive strength (UCS)

Table 4 Stage 3: binder optimisation of plug pour unconfined compressive strength (UCS)

UCS age (days)	A1 – 6% control	A4 – 5% MF 707	UCS % change	A5 – 4% MF 707	UCS % change	A9 – 3% MF 707	UCS % change
1	0	210	210% ↑	154	154% ↑	122	122% ↑
2	490	543	11% ↑	124	74% ↓	202	58% ↓
5	928	1,278	38% ↑	954	3% ↑	530	43% ↓
7	1,103	1,388	26% ↑	970	12% ↓	617	44% ↓
9	1,043	1,406	35% ↑	987	5% ↓	722	31% ↓
11	NA	1,337	NA	1074	NA	836	NA
14	1,106	1,537	39% ↑	1,261	14% ↑	923	16% ↓
28	1,516	1,868	23% ↑	1,413	7% ↓	984	35% ↓
56	1,794	2,161	20% ↑	2,206	23% ↑	1,259	29% ↓

Key observations regarding the body pour are presented below in Figure 11 and Table 5.

1. At the age of three days, it was observed that the mix designs incorporating admixture and lower binder contents demonstrated higher strength compared to the 3% control. This highlights the beneficial influence of the admixture on the early strength development for the main body pour.
2. At the age of five days, the mix design containing 2.5% binder and admixture exhibited a 30% increase in UCS compared to the control with 3% binder. Similarly, after seven days, the mix design containing 2.5% binder and admixture revealed a 67% higher strength compared to the control mix design with 3% binder.
3. However, it was observed that the strength gains of the mix designs, specifically the 3% control without admixture and 2% with admixture, reached a plateau at 28- and 56-day ages.

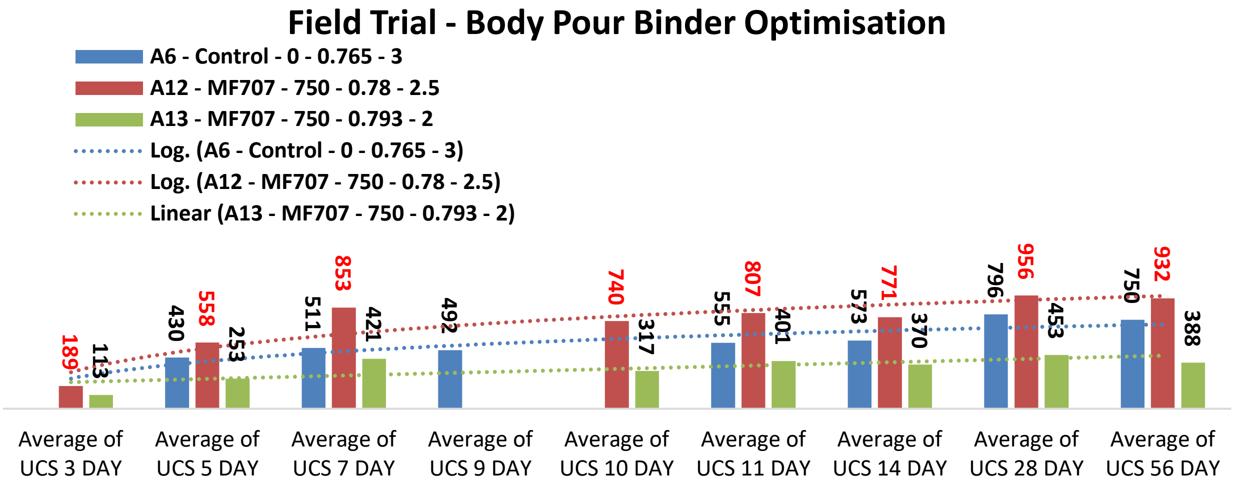

Figure 11 Stage 3: binder optimisation of body pour unconfined compressive strength (UCS)

Table 5 Stage 3: binder optimisation of body pour unconfined compressive strength (UCS)

UCS age (days)	A6 – 3% control	A12 – 2.5% MF 707	UCS % change	A13 – 2% MF 707	UCS % change
3	0	189	189% ↑	113	113% ↑
5	430	558	30% ↑	253	41% ↓
7	511	853	67% ↑	421	17% ↓
9	492	NA	NA	NA	NA
10	NA	740	NA	317	NA
11	555	807	45% ↑	401	28% ↓
14	573	771	35% ↑	370	35% ↓
28	796	956	20% ↑	453	43% ↓
56	750	932	24% ↑	388	48% ↓

3.4.4 Stage 3: Unconfined compressive strength – summary

The introduction of the admixture positively influenced the initial strength development of the plug pour, enabling an earlier commencement of the main body pour and subsequently improving mining efficiencies.

Upon analysing the data, it can be demonstrated that adopting the mix design with 4% binder and admixture for the plug pour is feasible, surpassing the performance of the control at various stages. This mix design offers a significant 33% reduction in binder content and demonstrates improved early and late strengths.

The analysis of the body pour results indicated that a binder reduction to 2.5% (equivalent to a 16% decrease in binder content) was a viable option for the main body pour. This reduction still allows for improved UCS results compared to the control.

In summary, the data showed that incorporating admixtures along with lower binder content can enhance UCS strengths for both the plug pour and main body pour. These findings present possibilities for a more cost-efficient and sustainable mining practice while meeting and exceeding the required performance criteria for the CPB mix designs.

4 Cost analysis of optimised paste fill

The cost analysis of the optimised paste fill designs at Kanowna Belle gold mine demonstrated promising results, indicating potential cost savings and operational efficiencies. The cost analysis yielded several significant findings which are outlined.

Plug pour cost analysis is depicted in Figure 12.

1. The reduction of binder content from the 6% control to 4% with admixture leads to a decrease in binder quantity of 33%. This reduction in the utilisation of binders is of considerable importance, as it has the potential to lead to cost savings.
2. By reducing the binder content from 6% to 4%, with the addition of admixture, a potential cost saving of 17% per w/t produced at the mine can be achieved. This revealed that by reducing the amount of binder, the cost of the admixture is balanced, thereby making the optimised mix design economically viable.
3. The mix design incorporating 5% binder and 750 mL per w/t of MasterRoc MF 707 admixture sits at a cost neutrality, suggesting that this combination does not incur additional expenses to site, even when higher strengths are occasionally needed for operational purposes.

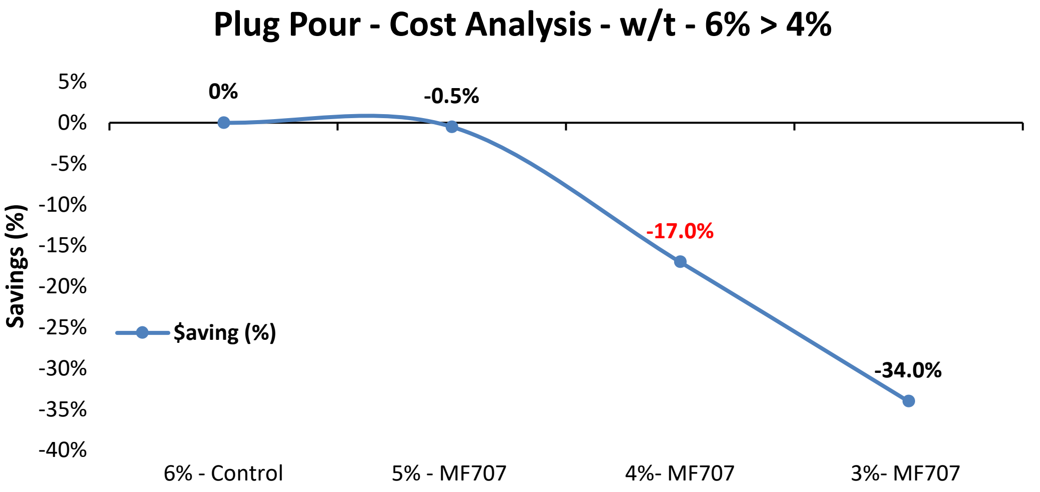

Figure 12 Cost analysis: savings per wet tonne (w/t) for the plug pour

The cost analysis for the plug pour revealed that implementing a reduction in binder content from 6 to 4%, with the use of a chemical admixture, is a financially viable option. This not only reduces the binder cost per w/t of CPB but also provides additional advantages, including the ability to initiate the body pour earlier, achieve higher UCS strengths, enhance the Factor of Safety, and facilitate development at an earlier stage, resulting in more efficient mining cycles.

The main body pour cost analysis is presented in Figure 13.

1. The reduction of binder content from 3 to 2.5% lead to a decrease in binder quantity of 15%. The decrease in binder content, however, resulted in an additional expense of 13% per w/t produced at the mine when utilising admixture.
2. While there is an increase in cost on the surface reducing the binder content, the mix design incorporating 2.5% binder and admixture exhibited notable enhancements in UCS compared to the control. This situation presents possibilities for additional optimisation, by potentially decreasing the dosage rates of admixtures and solid contents to discover a solution that is either cost saving or cost neutral.

3. The incorporation of an admixture in the improved CPB presents an additional opportunity – the ability to explore previously inaccessible scenarios, enabling the penetration of rock-filled stopes with an enhanced CPB. This opens the potential for mining previously sterilised stopes.

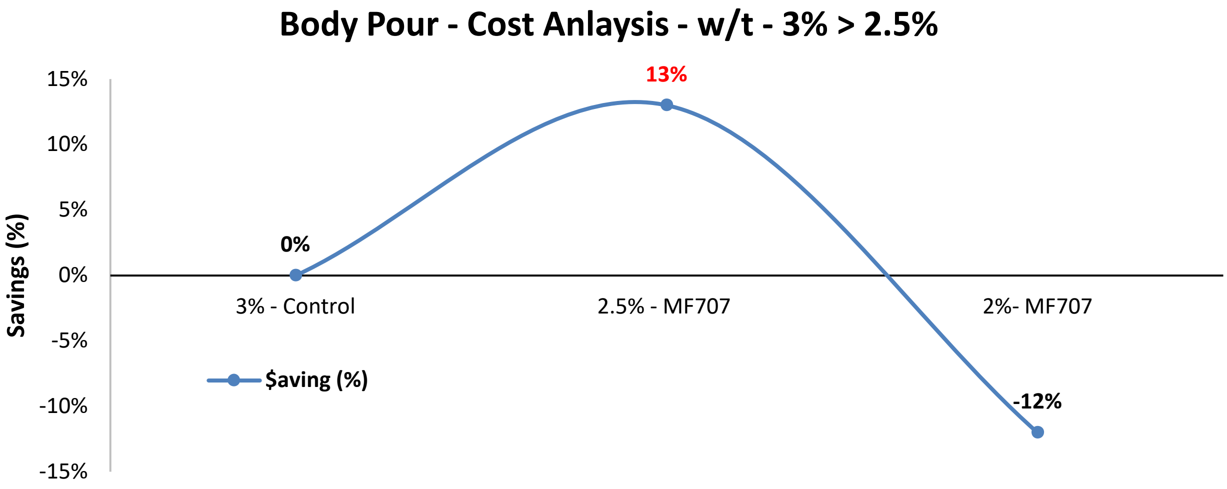

Figure 13 Cost analysis: savings per wet tonne (w/t) for body pour

The cost analysis failed to consider additional potential operational savings resulting from enhanced efficiencies. These potential savings could be quantified over an extended duration and encompass various aspects, including, but not limited to, the following:

- Lower energy consumption.
- Reduction in maintenance cost.
- Enhanced production capacity in terms of tonnes per hour.
- Lower labour costs could be observed.
- Potential for decreased ore dilution and the possibility of making previously sterilised ore mineable.
- Capex is paid back in three months for the extra system that is installed to pump the admixture just on the savings from the plug pour.
- Opex is already accounted for in the savings by considering the total cost per w/t including the saving in binder and cost of admixture.

Operators have reported that reducing the binder content from 6 to 4% decreases torque requirements on the binder auger. This reduction in torque leads to fewer problems during the filling process. Furthermore, the inclusion of the admixture improves efficiency when cleaning the mixer and hopper at the end of the shift.

The cost analysis revealed that the optimised mix designs, which incorporate reduced binder content and admixtures, present a promising opportunity for cost savings and enhanced mining efficiencies at Kanowna Belle gold mine. While there may be initial additional expenses associated with for the main body pour using a 2.5% binder, there are potential opportunities for optimisation and operational savings that can compensate these costs, such as lower downtime and more efficient stope fill rates.

5 Mining sustainability

Upon the completion of the live trials, an analysis of relevant data was conducted to determine the extent to which the optimisation of paste fill contributes to the reduction of CO_2 emissions and/or embodied carbon, thereby contributing to environmental footprint reduction. Reducing the amount of binder content can have a substantial effect on the reduction of CO_2 emissions. This is particularly important because cement production is a well-known contributor to greenhouse gas emissions. When evaluating CO_2 emissions, there are several key factors to consider:

1. The reduction of binder content is a key strategy for mitigating CO_2 emissions in paste fill. By incorporating admixtures and optimising mix designs, it is possible to decrease the amount of binder used, resulting in reduced CO_2 emissions.
2. To calculate the reduction in environmental footprint, it is crucial to have knowledge of the CO_2 emission factors associated with cement production, as the composition of the cements can vary significantly. CO_2 emission factors quantify the quantity of CO_2 released for each unit of material produced. The aforementioned factors may exhibit variations depending on the type of cement, admixture, and other components employed.
3. The quantification of CO_2 savings can be achieved by comparing the CO_2 emission factors of the original paste fill design (control) with the optimised designs that have lower binder contents and incorporate admixtures. The decrease in the utilisation of binders, the decrease in energy consumption during the production process, and the potential environmental advantages resulting from the use of admixtures, all play a significant role in the overall reduction of CO_2 emissions.
4. The decrease in binder content also leads to additional CO_2 savings in the transportation phase, as less binder needs to be delivered to the site, contributing to a reduction in associated transportation-related emissions.
5. The findings of the analysis on CO_2 emission reduction can be integrated into the operations sustainability reporting. Sharing the achieved environmental benefits resulting from the optimisation of paste fill can serve as a demonstration of commitment to sustainable mining practices.

Conducting a comprehensive evaluation of the reduction in CO_2 emissions, resulting from the optimisation of paste fill, is essential in demonstrating the environmental advantages of implementing designs with lower binder content and the utilisation of admixtures in the paste fill operation.

5.1 Mining sustainability: CO_2 reduction

The reduction in CO_2 emissions is achieved through the utilisation of admixtures and the subsequent reduction in binder content during the optimisation of paste fill. The presented data illustrates that the implementation of these optimised mix designs can result in significant environmental advantages, particularly in the reduction of CO_2 emissions:

- LH binder produces 463 kgs of CO_2 per w/t produced as per BGC Cement (2023).
- MasterRoc MF 707 produces 1.88 kgs of CO_2 per litre produced per EPD.

The calculations demonstrate that reducing the binder content from 6 to 4% leads to a decrease in CO_2 emissions by 6.6 kgs per w/t of paste produced, resulting in a savings of 31%. Similarly, when the binder is decreased from 3 to 2.5%, there is a corresponding reduction in CO_2 emissions of 1.45 kgs per w/t of paste produced, resulting in a 14% decrease in CO_2 emissions.

When evaluating the monthly production of 30,000 tonnes of paste fill and distributing it with a 30% allocation to the plug pour and a 70% allocation to the body pour, the projected monthly and yearly CO_2 savings can be estimated as follows:

- 14.85 tonnes of CO_2 emissions saved per month for the plug pour.
- 3.90 tonnes of CO_2 emissions saved per year for the body pour.

This results in an estimated annual reduction of 1076.24 tonnes of CO_2 emissions, as illustrated in Table 6.

Table 6 CO_2 savings to cemented paste backfill operation

CO_2 savings (t)	Plug pour	Body pour	Total CO_2 saved (t)
Day	1.95	1.00	2.95
Week	13.67	7.00	20.67
Month	59.23	30.45	89.68
Annum	710.84	365.40	1076.24

While the preliminary calculations presented do not encompass an entire lifecycle assessment of the CPB, and certain factors such as the transportation of binders or admixtures to site have not been considered, the results still offer a valuable perspective on the immediate reduction in CO_2 emission that could be achieved through the implementation of optimised mix designs.

The reduction of CO_2 emissions, through the utilisation of admixtures and the reduction of binders in the paste fill, can be regarded as a favourable measure towards promoting environmental sustainability in mining operations. By consistently implementing these optimised designs, the mine can provide a significant contribution towards a sustainable and environmentally conscious mining industry.

As the ongoing operation aims to optimise and refine the paste fill mix designs and explore further reductions in binder content and admixture dosages, this exploration holds the potential for achieving even greater reductions in CO_2 emissions and additional long-term environmental benefits. Such endeavours contribute to the overarching objective of establishing a mining practice that is more sustainable and environmentally friendly.

6 Conclusion

In conclusion, the field trials conducted to enhance the mix designs of CPB at Kanowna Belle gold mine have produced extremely promising outcomes. The incorporation of the chemical admixture, MasterRoc MF 707, has demonstrated significant impact on enhancing the rheological characteristics and early strength gain of the CPB, resulting in improved mining efficiencies. Through a methodical approach of incrementally raising the solid content and reducing the binder content, the team effectively attained performance levels that were either on par with, or surpassed, those of the control sample. Moreover, this approach resulted in a substantial reduction in the environmental footprint.

Findings derived from the field trials are as follows:

1. The utilisation of the admixture MasterRoc MF 707 demonstrated a positive impact on the rheological properties of the CPB, resulting in a significant reduction in yield stress, mixer torque, and pipe pressures. This facilitated the exploration of increased solid contents and reduced binder contents.
2. UCS testing demonstrated that the CPB with the admixture exhibited improved early strength, reaching a strength of 100 kPa within in 24 hours. This allowed for an earlier start of the main body pour and resulted in improved mining efficiencies.
3. Both the plug pour, and body pour, demonstrated exceptional long-term strength development, further substantiating the suitability of the optimised designs.
4. Cost analysis showed that a binder reduction of 6 to 4% for the plug pour, a 16% cost saving with the use of admixtures, was economically viable.
5. The optimisation of the body pour requires further investigation to achieve cost neutrality or provide financial benefits to the operations. It is important to note that this does not currently include other potential operational savings.

6. The inclusion of an admixture in the enhanced CPB introduces an additional prospect – the capacity to investigate previously unreachable scenarios, allowing the penetration of rock-filled stopes with an improved CPB. This creates the possibility of mining stopes that were previously considered sterilised.
7. The binder reduction with admixture also resulted in a considerable reduction in CO_2 emissions. Paste fill production with the optimised mix designs could save approximately 1,076.24 tonnes of CO_2 emissions per annum.

The successful outcome of these trials highlights the potential of chemical admixtures in optimising CPB mix designs and achieving significant environmental and economic benefits.

Further optimisation and refinement of the mix designs, dosages of admixtures, and solid contents have the capability to unlock even greater financial and environmental benefits. The mining industry continues to strive for more sustainable mining practices, and the learnings from these field trials could have broader implications for similar operations worldwide. By embracing innovation and sustainable solutions, mining companies can not only reduce their environmental impact but also improve their economic performance and operational efficiency.

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