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Reducing CO_2 accumulation in cemented paste backfill with optimised solids–cement equivalency and chemical admixtures

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Abstract

Backfilling in mining constitutes approximately 30% of the mine's total operational expenses. Cemented paste backfill (CPB) has become a favourable backfilling method due to its capability to provide highly secure structural properties. However, a significant cost associated with CPB is the cementitious binder, which generally constitutes up to 2 to 10% of the overall paste mass. Cement is an essential constituent imparting strength to the paste, ensuring sufficient mechanical properties to support the filled stopes and securing a safe underground environment. The consumption of this binder directly reflects the material cost, as well as the accumulation of carbon footprint generated during its production and transport. Therefore, reducing cement content without compromising the performance of the paste fill operation generates both environmental and economic benefits.

Amid the industry's goal of minimising carbon footprint, this research explores the potential of compensating cement by augmenting the solids content of the paste mix, facilitated by the addition of chemical admixtures to improve the paste's fresh properties. The study involved observing several paste mixes, assessed over an extended time to determine the best optimum balance between cement and solids content, while also considering the cost-effective dosage of the admixture.

The introduction of admixture enhanced the paste properties, improving fluidity and reducing pressure and friction within the pipelines, enabling an increase in solids content between 0.4 to 1.5% in magnitude. This compensated for a 0.3% points reduction in cement content without compromising the unconfined compressive strength of the cured paste. Reduction in cement led to substantial savings equating to 165 t of cement and 154 t in carbon dioxide accumulation for every 100,000 wet tonnes of paste batched. Together with alternative CO_2 savings, such as reduced freight and increased volume of reused tailings, optimisation of paste mix designs showcases the potential to yield significant environmental and economic benefits.

Keywords: *backfill, cemented paste backfill, carbon dioxide reduction, cement reduction, sustainability, paste mix optimisation, admixtures*

1 Introduction

It is estimated that a backfill operation accounts for approximately 30% of the mine's overall operational expense (Bloss 2014), and a significant portion of this cost is allocated to the consumption and transportation of the materials used. Cemented paste backfill (CPB) has become a popular method of backfilling with its ability to provide enhanced ground support and stability with increasing numbers of mines operating at deeper depths, together with regulatory pressures to practice safer and more sustainable mining operations.

The paste is designed and adjusted uniquely to each project according to the required wet and cured mechanical properties, with considerations of water, tailings, and infrastructure available on site. Optimised paste design ensures smooth batching and flow which ultimately leads to flexible and efficient mine planning and safe backfilling operations. The key material of CPB is cement, also referred to as binder, and it often constitutes approximately 2 to 10% of the overall paste mass. The cement is the biggest determinant influencing the strength development of the paste making it one of the most crucial components in securing a safe underground environment. However, due to the sheer mass of paste batched in large CPB operations in the likes of Newmont Tanami Operations (NTO), even a small reduction of cement consumption can directly lead to appreciable material cost savings, and more importantly, a reduction in carbon footprint. With the industry's push to minimise carbon dioxide emissions and with the trending transition into greener, sustainable mining operations, methods to reduce the consumption of cement without affecting the CPB performance were investigated.

Water-reducing chemical admixtures are often used in concrete to improve workability without increasing the volume of water and jeopardising the strength. The same technology can be used in CPB with correct compatibility between the admixture and the tailings used on site. This increased fluidity and workability of paste leads to pressure reduction within the pipeline, allowing for an increase in the solids content which also improves the performance of unconfined compressive strength (UCS), ultimately enabling a cut in the cement.

The objective of this research was to confirm the volume of cement that could be reduced by optimising the solids–cement ratio by incorporating chemical admixtures into paste design. The focus is also to maintain the mechanical properties of the cured paste, as well as the operational feasibility of the backfilling process, and ultimately to quantify the material cost benefits and the reduction in carbon dioxide accumulation.

2 Methodology

2.1 Material and equipment

The chemical admixture was connected to a calibrated P-Base WEG pump to be dosed directly into the raw water line, which was synchronised to the paste plant's operation software, Citect system, allowing real-time reading and recording of the flow meter and automated adjustments according to the configured dosage rate and cement content. This equipment is shown in Figure 1.

(a) (b) (c)

Figure 1 (a) Paste batching plant of NTO; (b) Admixture and dosing pump used for this trial; (c) Dosing point of admixture

2.2 Measurement of cemented paste backfill operating parameters

All key parameters representing the performance of the paste fill operations, including pipeline pressure, friction, and flow rate, are numerically displayed through the Citect system in the operator room Simultaneously, paste fill parameters such as solids content, tailings moisture content, cement content, and admixture dosage are also controlled in real-time. All necessary data were recorded for analysis.

2.3 Measurement of mechanical properties of cured paste

The flow characteristics of the wet paste were observed by measuring the slump and flow conforming to the standard ASTM C143. As for UCS specimens, one cylinder was collected per testing of each material age; σ1d, 2d, 3d, 7d, 28d, and were stored in a controlled, humidified chamber. The testing procedure of the cured paste conformed to the standard test method of AS 1012.9. For this trial, the UCS results were benchmarked against the values currently achieved at NTO, with the target set to reach equivalent or more with the implementation of admixtures.

3 Scope of trials

The effectiveness of the admixture in the paste is observed by analysing the changes to the pressure and friction within the piping, and the amount of solids content allowed to be increased to maintain optimum pressure. This increase in solids content enhances the strength of the hardened paste, which creates a margin to reduce the cement content. The trials were divided into two sections; firstly, to check the effect of admixture is reflected on the flow characteristics of the paste, then secondly to observe the degree to which solids content can be increased with admixture, and its changes to the UCS. An overview of the trials conducted are presented in Tables 1 and 2, outlining the scope of this trial.

Table 1 Overview of conducted cemented paste backfill operation trials

Trial no.	CPB mix design	Admixture dosage	Objectives/remarks
1	Solids content: 70.8% Cement content: 3.8%	200 mL/wet tonne (wt)	Effect of admixture on pipeline pressure and friction
2	Solids content: 72.7% Cement content: 4.8%	200 mL/wt	Effect of admixture on paste flow rate

Table 2 Overview of conducted cemented paste backfill unconfined compressive strength trials

Paste mix no.	Cement reduction	Solids increase achieved	Admixture dosage	Objectives/remarks
1	3.8% → 3.8%	70.8% → 71.8%	200 mL/wt	Observed an increase in solids with admix, along with corresponding change on UCS of paste (no change in cement)
2-1	3.8% → 3.6%	70.7% → 71.9%	200 mL/wt	Observed an increase in solids with admix, along with the corresponding change in UCS using a 'generic' paste mix
2-2	3.8% → 3.6%	70.7% → 72.2%	200 mL/wt	
3	4.8% → 4.6%	72.7% → 73.3%	200 mL/wt	Observed an increase in solids with admix, along with the corresponding change in UCS using a high-binder paste mix
4	4.8% → 4.5%	72.6% → 73.2%	250 mL/wt	Observed an increase in solids with admix, further reduced cement content along with corresponding change in UCS using a higher binder paste mix
5	3.8% → 3.5%	72.4% → 73.8%	250 mL/wt	Observed an increase in solids content with admix, further reduced cement content along with the corresponding change in UCS using a 'generic' binder paste mix

4 Results

4.1 Effect of chemical admixture on pipeline pressure and friction

To confirm the effect the admixture had on the pipe pressures, it was dosed into the control paste at the rate of 200 mL/wt. Figure 2 displays the difference in pipeline pressures and friction readings of pipeline 1020L, the main reticulation line, before and after the addition of admixture into the paste.

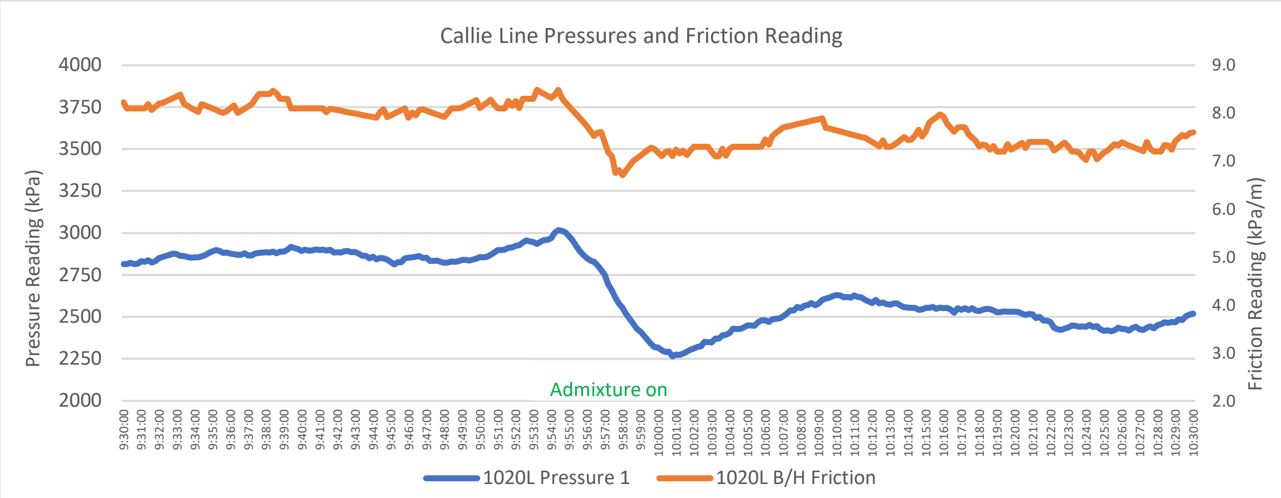

Figure 2 Pressure and friction reading of pipeline 1020L before and after dosing chemical admixture at rate of 200 mL/wt of paste

As seen in Figure 2, both pressure and friction within the pipe 1020L are almost immediately lowered after the introduction of the admixture. The continuous reading of lowered parameters confirms that the introduction of admixture does improve the flow characteristics of the paste and creates a margin for solids to be increased to maintain sufficient pressures within the reticulation. From this trial, the average pipeline pressure on the 1020L pipe was reduced from 2,878 to 2,495 kPa due to the presence of admixture at 200 mL/wt of paste. This equates to a pressure reduction of 13.2%.

4.2 Effect of admixture on paste flow rate

Slump and slump flow of the paste must remain below a certain threshold to avoid issues such as bogging and other operational challenges. The flow of the paste was continuously monitored throughout the entirety of the trial to ensure the paste's wet properties are consistent, without the risk of bogging.

Using the paste mix with a cement-rich content of 4.8% and solids content at 72.7%, pressure and paste flow on the 1020L pipe were examined with various admixture dosages. Data was used as a representative sample to monitor the impact of the admixture on paste flow.

Figure 3 illustrates the pressure and flow readings on the 1020L pipe during the admixture trial, where variations were made in the solids content, binder content, and dosage of the admixture.

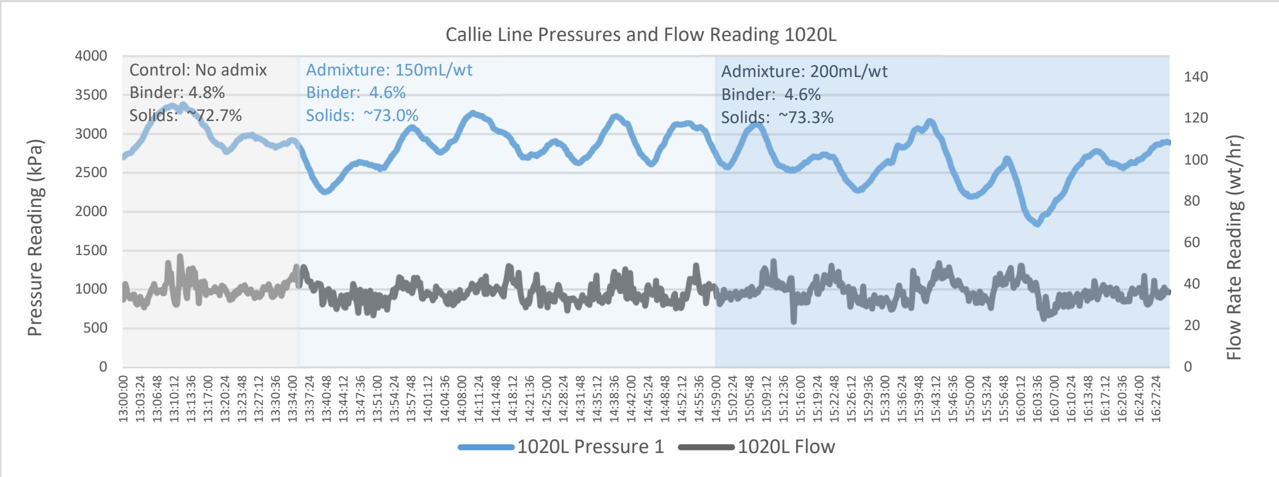

Figure 3 Pressure and flow rate reading of pipeline 1020L with various solids, binder content, and dosages of admixture

As seen from the results, the pressure readings are notably balanced as the solids contents are increased to match the pressure drops caused by the use of admixture. Additionally, the paste flow demonstrates a remarkable level of consistency. Again, the graph represents the flow rate of the cement-rich paste batched throughout this trial. This data indicates that the changes in wet properties of the paste due to the implementation of the admixture do not negatively affect the flow rate of the paste.

4.3 Correlation between solids–cement content and fresh properties of paste

The wet properties of the paste have a significant influence on how smoothly the paste fill is executed. Each paste mix was tested for its slump and slump flow to observe the correlation between the solids content and wet properties of the paste. From preliminary trials, adding admixture at a dosage of 200 mL/wt without any changes to the solids content was found to increase the paste slump and the slump flow by 25 mm and 60 mm, respectively.

Table 3 displays the slump and slump flow before and after the increases in solids content due to the addition of chemical admixtures. Table 4 displays the condition of each paste mix.

Table 3 Changes in wet properties of the paste with implementation of admixtures and changes in solids content

Paste mix no.	Solids increase achieved w/ admix	Cement content reduction	Admixture dosage	Slump (mm)		Slump flow (mm)	
				Control	w/ admix	Control	w/ admix
1	70.8% → 71.8%	3.8% → 3.8%	200 mL/wt	35.0	25.0	165	140
2-1	70.7% → 71.9%	3.8% → 3.6%	200 mL/wt	25.0	15.0	145	135
2-2	70.7% → 72.2%	3.8% → 3.6%	200 mL/wt	25.0	15.0	145	135
3	72.7% → 73.3%	4.8% → 4.6%	200 mL/wt	30.0	20.0	160	130
4	72.6% → 73.2%	4.8% → 4.5%	250 mL/wt	25.0	30.0	135	130
5	72.4% → 73.8%	3.8% → 3.5%	250 mL/wt	30.0	25.0	130	125

Table 4 Fresh properties of paste at each mix design

<table>
<tr><th>Paste mix no.</th><th>Paste mix</th><th colspan="2">Control mix</th><th colspan="2">Paste with admixture and solids increase</th></tr>
<tr><td>1</td><td>Control:
S: 70.8%
C: 3.8%

w/admix: 200 mL
S: 71.8%
C: 3.8%</td><td></td><td>Slump:
35.0 mm
Sl flow:
165 mm</td><td></td><td>Slump:
25.0 mm
Sl flow:
140 mm</td></tr>
<tr><td>2-1</td><td>Control:
S: 70.7%
C: 3.8%

w/admix: 200 mL
S: 71.9%
C: 3.6%</td><td rowspan="2"></td><td rowspan="2">Slump:
25.0 mm
Sl flow:
145 mm</td><td></td><td>Slump:
15.0 mm
Sl flow:
135 mm</td></tr>
<tr><td>2-2</td><td>Control:
S: 70.7%
C: 3.8%

w/admix: 200 mL
S: 72.2%
C: 3.6%</td><td></td><td>Slump:
15.0 mm
Sl flow:
135 mm</td></tr>
<tr><td>3</td><td>Control:
S: 72.7%
C: 4.8%

w/admix: 200 mL
S: 73.3%
C: 4.6%</td><td></td><td>Slump:
30.0 mm
Sl flow:
160 mm</td><td></td><td>Slump:
20.0 mm
Sl flow:
130 mm</td></tr>
<tr><td>4</td><td>Control:
S: 72.6%
C: 4.8%

w/admix: 250 mL
S: 73.2%
C: 4.5%</td><td></td><td>Slump:
25.0 mm
Sl flow:
135 mm</td><td></td><td>Slump:
30.0 mm
Sl flow:
130 mm</td></tr>
<tr><td>5</td><td>Control:
S: 72.4%
C: 3.8%

w/admix: 250 mL
S: 73.8%
C: 3.5%</td><td></td><td>Slump:
35.0 mm
Sl flow:
165 mm</td><td></td><td>Slump:
35.0 mm
Sl flow:
165 mm</td></tr>
</table>

From the results, it is observed that as the solids content is increased to reach the original pressure values, so does the wet properties of the paste. Findings of solids increase achieved with the use of admixtures are as follows:

- 200 mL/wt of admixtures allowed increases in solids content within the range of 1.0 to 1.5% points, or on average by 1.23% points when dosed into paste with 3.8% base cement content. Paste with higher base cement content at 4.8% showed an increase in solids by 0.6% points at the same dosage.
- 250 mL/wt of admixture allowed increases in solids content by 1.4% points when dosed into a paste with 3.8% base cement content. Paste with higher base cement content at 4.8% also allowed an increase in solids by 0.6% at the same dosage.
- Effect of admixture is more prominent with paste with lower cement content as more chemicals are present per particle of cement. No significant improvement in solids increase with increased dosage of admixture by 50mL/wt.

4.4 Correlation between solids–cement content and the unconfined compressive strength

To ascertain the viability of the cement reduction achieved through the incorporation of admixtures, it is essential to ensure that the UCS of the cured paste remains either equal to or higher than that of the paste before the addition of admixtures or any alterations to the design. Designating the paste without any admixtures as the 'control', the UCS of cured paste samples was measured both before and after changes to the paste design. This comprehensive assessment aimed to confirm that the increase in solids content, facilitated by the use of admixtures, sufficiently supplements the reduction in cement content.

Findings of UCS performance with solids increase and cement reduction achieved with the use of admixtures are as follows:

- Paste with 3.8% cement content and admixture dosage of 200 mL/wt, presented an average increase in solids content by 1.35% points and improved the average overall UCS of cured paste by 7.6%, whilst achieving cement reduction of 3.
- Paste with 4.8% cement content admixture dosage of 200 mL/wt, presented an increase in solids content by 0.6% points and improved the overall UCS of cured paste by 24.36% whilst achieving cement reduction of 3.4%. UCSs of paste with higher base cement content increased higher than of lower base cement content, despite smaller changes to the solids content.
- Further cement reduction by 0.3% points with higher admixture dosage at 250 mL/wt also proved to provide an increase in UCS. The UCSs of paste with a base cement content of 3.8% and 4.8% increased by 20.6% and 20.6% due to an increase in solids content by 0.6% and 1.4% points, respectively.
- The lowest cement reduction achieved was -6.10% equating to 1.68 kg per wet tonne of paste, whilst achieving higher UCS by 25.6% than the control.

Table 5 displays the changes in paste mix design allowed with the implementation of admixtures and its respective UCS results, whilst Table 6 presents the changes achieved in cement content. The reduction of UCS in paste mix 1 is considered an outlier due to discrepancy in the density between the paste with and without admixtures caused by insufficient tampering during sampling of the test specimen.

Table 5 Changes in paste mix design allowed with implementation admixtures and its respective UCS results

Paste mix no.	Solids content increase allowed w/ admixtures	Binder reduction (control % → target binder %)	Admixture dosage	Compressive strength (kPa)	1 day	2 days	3 days	7 days	28 days
1	70.8% → 71.8%	3.8% → 3.8%	200 mL/wt	Control (S:70.8% | C:3.8%)	210.1	188.4	616.3	1,185.4	2,067.0
				w/ admix (S:71.8% | C:3.8%)	142.6	514.4	739.8	1,109.0	1,778.0
				UCS v control	**-32.1%**	**173%**	**20.0%**	**-6.45%**	**-14.0%**
2-1	70.7% → 71.9%	3.8% → 3.6%	200 mL/wt	Control (S:70.7% | C:3.8%)	188.4	520.8	753.8	1,392.9	1,930.0
				w/ admix (S:71.9% | C:3.6%)	224.1	553.9	804.7	1,325.4	2,131.0
				UCS v control	**18.9%**	**6.4%**	**6.8%**	**-4.8%**	**10.4%**
2-2	70.7% → 72.2%	3.8% → 3.6%	200 mL/wt	w/ admix (S:72.2% | C3.6%)	206.3	570.4	816.2	1,384.0	2,155.0
				UCS v control	**9.5%**	**9.5%**	**8.3%**	**-0.6%**	**11.7%**
3	72.7% → 73.3%	4.8% → 4.6%	200 mL/wt	Control (S:72.7% | C:4.8%)	192.3	441.8	646.8	1,294.9	2,187.0
				w/ admix (S:73.3% | C:4.6%)	252.1	522.0	865.8	1,536.8	2,625.0
				UCS v control	**31.1%**	**18.2%**	**33.9%**	**18.7%**	**20.0%**
4	72.6% → 73.2%	4.8% → 4.5%	250 mL/wt	Control (S:72.6% | C:4.8%)	238.1	550.0	742.3	1,483.3	2,170.0
				w/ admix (S:73.2% | C:4.5%)	345.1	615.0	972.8	1,641.2	2,764.0
				UCS v control	**44.9%**	**11.8%**	**31.0%**	**10.6%**	**27.4%**
5	72.4% → 73.8%	3.8% → 3.5%	250 mL/wt	Control (S:72.4% | C:3.8%)	147.7	441.8	488.9	1,009.7	1,953.0
				w/ admix (S:73.8% | C:3.5%)	–	533.0	743.0	1,207.0	1,759.0
				UCS v control	**–**	**20.6%**	**52.0%**	**19.5%**	**-9.9%**

Table 6 Changes achieved in cement content with the implementation of admixtures

Solids content increase allowed w/ admixtures	Binder reduction (control % → target binder %)	Admixture dosage	Cement content		Cement mass per wet tonne of paste (kg)		Cement reduction	
			Control	w/ admixture	Control	w/ admixture	Cement reduction rate (%)	Cement reduction mass (kg/wt)
70.8% → 71.8%	3.8% → 3.8%	200 mL/wt	3.8%	3.8%	26.90	27.28	+1.4%	+0.38
70.7% → 71.9%	3.8% → 3.6%	200 mL/wt	3.8%	3.6%	26.87	25.88	**-3.7%**	**-0.982**
70.7% → 72.2%	3.8% → 3.6%	200 mL/wt	3.8%	3.6%	26.87	25.92	**-3.5%**	**-0.946**
72.7% → 73.3%	4.8% → 4.6%	200 mL/wt	4.8%	4.6%	34.90	33.72	**-3.4%**	**-1.178**
72.6% → 73.2%	4.8% → 4.5%	250 mL/wt	4.8%	4.5%	34.85	32.94	**-5.5%**	**-1.908**
72.4% → 73.8%	3.8% → 3.5%	250 mL/wt	3.8%	3.5%	27.51	25.83	**-6.1%**	**-1.682**

4.5 Trial results summary

The Callie lines' records provide clear evidence of the decrease in pressure and friction upon activating the admixture pump, confirming the water-reducing effect of the admixture. This effect enhanced the flowability of the paste, allowing for an increase in solids content to provide sufficient UCS whilst reducing the cement content.

- The implementation of chemical admixture at a dosage of 200 mL/wt resulted in a notable alteration in the fresh properties of the paste, leading to a reduction in the average pipeline pressure by 13.2%.
- Higher increases in solids content are enabled with paste with lower base cement content due to the higher effective volume of admixtures per mass of cement. Balanced consumption of admixture itself must also be considered to ensure the cost feasibility.
- Paste with 3.8% cement content and admixture dosage of 200 mL/wt, presented an average Increase in solids content by 1.35% points and improved the average overall UCS of cured paste by 7.6%, whilst achieving cement reduction of 3.6%.
- Paste with 4.8% cement content admixture dosage of 200 mL/wt, presented an increase in solids content by 0.6% points and improved the overall UCS of cured paste by 24.36% whilst achieving cement reduction of 3.4%.
- Further cement reduction by 0.3% points with higher admixture dosage at 250 mL/wt also proved to provide an increase in UCS. The UCSs of paste with a base cement content of 3.8% and 4.8% increased by 20.6% and 25.2% due to an increase in solids content by 0.6% and 1.4% points respectively.
- Ongoing data collection efforts are anticipated to further validate the performance of these improved paste mixes on an extended timescale.

5 Carbon dioxide accumulation of cemented paste backfill

The production of 1.0 kg of Ordinary Portland cement is estimated to generate, on average, 0.93 kg of carbon dioxide (Lehne & Preston 2018). Given its exceptionally high emission rate, cement production and usage contribute significantly, comprising 5.0 to 8.0% of total global anthropogenic CO_2 emissions (Andrew 2019).

In the context of CPB, although the cement content within each paste may seem relatively small, the sheer volume of paste batched magnifies the impact of even minor reductions in cement consumption, leading to a substantial decrease in CO_2 emissions and fostering greener and more sustainable backfilling operations.

From the conducted trials, it was verified that the increase in solids content, facilitated by the dosing of admixture, safely compensated for a 0.3% point reduction in cement without compromising the overall UCS of the cured paste or the backfill operation itself. Of course, the actual mass of cement savings varies with each mix design. For this case, using a paste mix with solids content at 70.8%, and an allowed increase of 1.35% points as a reference, the reduction in cement and CO_2 is calculated.

Table 7 provides an overview of the potential savings in cement consumption and the corresponding reduction in carbon dioxide emissions for each volume of paste batched, based on the obtained trial results.

Table 7 Potential cement and CO_2 savings per tonne of paste batched

Mass of paste batched (t)	Potential cement savings (t)	CO_2 savings (t)
1,000	1.65	1.54
5,000	8.26	7.68
10,000	16.52	15.36
50,000	82.57	76.79
100,000	165.15	153.59

6 Summary

The introduction of chemical admixtures into the CPB of NTO resulted in immediate improvements in the paste's wet properties, enhancing its fluidity and reducing pressure and friction within the pipes. This allowed for an increase in solids content within the range of 0.4% to 1.5% points. The increase in solids content effectively compensated for a 0.3% points reduction in cement content in terms of UCS. These findings demonstrate the potential of admixtures in achieving cement reduction while maintaining or enhancing the strength properties of the paste.

Furthermore, the increases in solids content achieved through the implementation of admixture were shown not to compromise the operational stability of the paste fill system, avoiding issues such as bogging or other complexities. The analysis of operational parameters and UCS results reveals the potential for further reduction in cement content, leading to further material and CO_2 savings. These findings highlight the viability, economic and environmental benefits of optimising the paste composition while maintaining the desired performance and operational efficiency.

A confident reduction of binder by 0.3% points was estimated to yield cement consumption savings of 165 t for every 100,000 wet tonnes of paste batched. This reduction also equates to a CO_2 saving of 154 t, contributing to environmental sustainability and mitigating carbon emissions. These substantial savings in cement consumption and CO_2 emissions further underscore the economic and environmental benefits of incorporating paste admixtures and implementing cement reduction strategies in paste fill operations. Further data collection is planned to substantiate and confirm the long-term benefits observed in this study, together with the aim to optimise the dosages of the admixture to further reduce material costs.

We would like to express our sincere gratitude and appreciation to all members of the paste plant team at NTO, who provided significant support and assistance in collecting crucial data, enabling the completion of this paper. Thank you all for your valuable contributions and support.

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