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Optimal paste backfill specification development

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Abstract

Optimisation of paste backfill specifications is an area of development in mine backfill operations and is practiced at several sites, with backfill mixtures tailored specifically for each stope. This, however, remains the exception rather than the rule across the industry. Often mines employ suboptimal backfill recipes which do not properly leverage the three principal components of a backfill specification, namely: strength, rheology, and curing time. This is compounded by limitations in material characterisation data and the means to develop and integrate this within reliable hydraulic models.

Developing a strategy for determining this unique specification provides opportunities for improved backfill reticulation operation and binder minimisation while ensuring that the performance of the backfill aligns with the mining requirements and schedule.

The paper describes how, through the use of material test work data, relationships linking these three performance criteria together can determine the optimal paste backfill specification. Case example data is used to demonstrate the analysis process and how a software solution developed by Paterson & Cooke can be used to enable its application in everyday operation.

Keywords: *backfill optimisation, hydraulics, cement minimisation*

1 Introduction

Paste backfill is a blend of fine materials (typically mine tailings) mixed with water and a binder, which can be transported underground via a network of pipes and discharged into underground voids or stopes. Once in the stope, the blend of materials is expected to gain compressive and tensile strength to enable its exposure as part of the mining cycle. The strength required and the time allowed for this curing to occur varies, depending on a number of factors including the size and shape of the stope, the number and location of future exposures, and the time at which those exposures are planned to occur. Accordingly, paste backfill can be considered a product which must achieve a desired strength in a desired time, and this requirement may be called a specification. Further, it should be recognised that the specification will change throughout a mine as the requirements vary.

Another variable influencing the blend of tailings, water and binder is the product's rheology, which must also vary as the stope location varies in the mine relative to the paste preparation plant. Notwithstanding the application of chemical rheology modifiers, the most common variable influencing rheology is the water content. This in turn, however, influences the strength response of the paste backfill as there is an intrinsic relationship between the water-to-binder ratio and the strength–time performance of the material. Therefore, it is not only necessary to vary the specification to account for performance (strength and time) but also rheology.

Too often, however, paste backfill systems operate a limited number of fixed recipes, preventing them from taking account of the variations within the operation. Consequently, paste backfill delivered to the underground void may be at the wrong rheology and-or with the incorrect quantity of binder, thus not meeting the required strength–time criteria. The incorrect rheology will influence the product's flow-through the system, potentially constraining throughput if it is too thick or, when it is too thin, causing excessive wear or settlement, and blockages can occur. Fixed binder applications can consequently miss the opportunity to reduce binder addition or, potentially more importantly, result in under dosing, leading to lower-than-expected strength in backfill, and presenting safety and performance risks.

Carlier & Veenstra (2021) describe the development of a system at the Éléonore mine in Canada that addresses this requirement. In this operation, a unique system comprising recipe look-up templates was developed to allow for variations in material feeds, rheology and curing periods. BackfillPro®, a web-based application software solution developed by Paterson and Cooke in 2022, provides such a method for backfill operators to define the unique blend of water and binder to achieve a desired strength – time specification, along with dynamic hydraulic modelling to determine rheology for each filling location. This paper discusses the theory linking strength, time and rheology, and then presents a case study demonstrating its application.

2 Strength, time and rheology

Underpinning the ability to resolve upon each unique backfill specification is a tripartite relationship between binder content, water content and time. Importantly, this relationship is unique to each blend of materials which comprise the paste backfill. Consequently test work is essential in defining it and, indeed, maintaining the validity of that test work is necessary to maintain the accuracy of relationship.

2.1 Material test work data

Testing for a particular paste backfill blend would usually include preparation with various binder contents, backfill solids contents and curing periods. The variation in binder content and solids content and hence water content, provides the opportunity to understand the strength–time response at differing binder-to-water ratios. Should variations exist in the feed tailings, for example, changes in mineralogy or particle size, these must also be captured in the dataset.

Illustrative test work data is presented here to demonstrate the relationship between strength–time and rheology. The data is from testing of lead–zinc tailings, the particle density of which was recorded as 3.59 t/m^3 with a particle size distribution as illustrated in Figure 1.

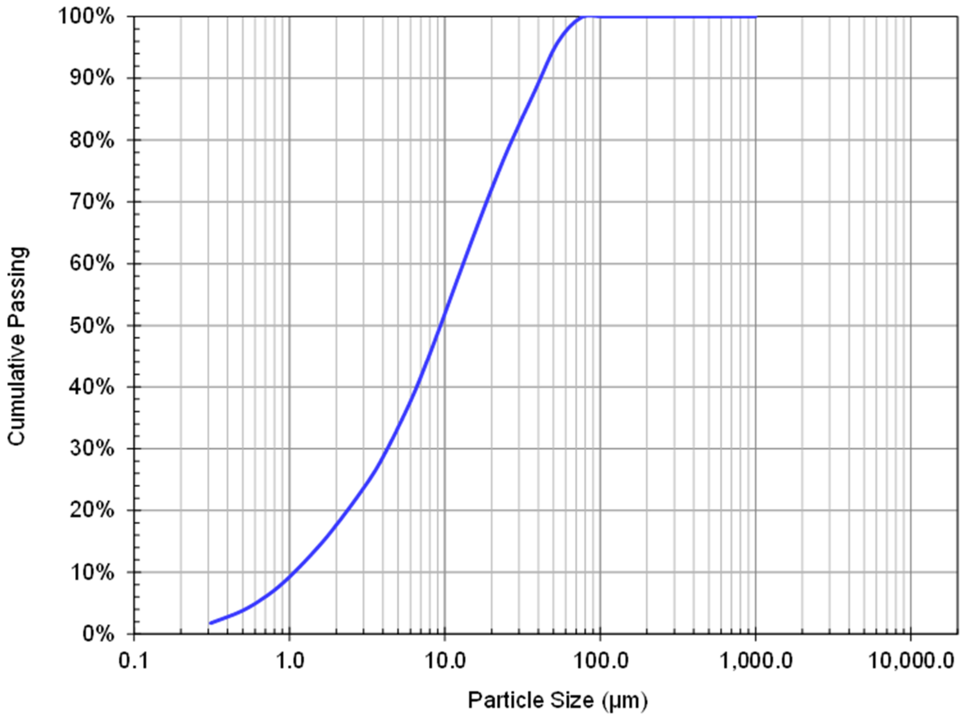


Figure 1 Tailings particle size distribution

Bulk mineral analysis of the tailings reports that the target phases in the sample include baryte, galena, sphalerite, bournonite, chalcopyrite and tetrahedrite. Baryte is the most abundant of these, present at 57.2 wt% in the sample, with galena, sphalerite, bournonite, chalcopyrite and tetrahedrite present but below 2 wt% each. The major gangue mineral present is dolomite (carbonates) and quartz with minor to trace abundances of pyrite, iron oxides and mica group and accessory phases.

Paste backfill unconfined compressive strength (UCS) testing was performed on the tailings comprised of three paste solids contents; each tested with two binder dosages providing six different water-to-binder ratios. Each of these were cured for 7, 14, 28 and 56 days, respectively.

The binder requirement for each mix was calculated using Equations 1 and 2:

$$\text{Binder \%} = \frac{\text{Binder weight}}{\text{Total dry solids} + \text{Binder weight}} \quad (1)$$

$$\text{Binder weight} = \frac{\text{Binder \%} * \text{Total dry solids}}{(1 - \text{Binder \%})} \quad (2)$$

Table 1 shows the resulting UCS data from the test work.

Table 1 Unconfined compressive strength testing results

Mix	Binder type	Binder dose	Total solids	Water-to-binder ratio	7 days UCS (kPa)	14 days UCS (kPa)	28 days UCS (kPa)	56 days UCS (kPa)
107	CEM III/A	5%	73.0%m	7.4	81	128	268	373
108		7%	73.4%m	5.2	179	291	528	856
109		9%	73.9%m	3.9	357	592	954	1,451
110		5%	77.9%m	5.7	153	266	459	595
111		7%	78.3%m	4.0	423	689	1,196	1,487
112		9%	78.6%m	3.0	709	1,476	1,708	2,491

These data can be resolved into a series of plots showing the strength development for each of the mix recipes, as well as their respective strength development with time (Figure 2).

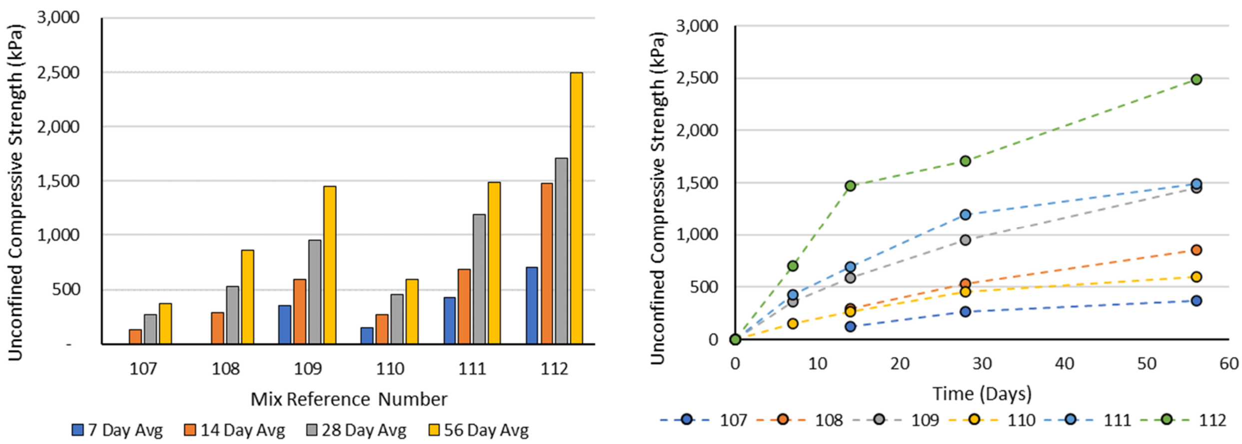


Figure 2 Unconfined compressive strength development with time

From these plots, several trends can be observed. Firstly, there is an improvement in strength relative to a reduction in the water-to-binder ratio, a relationship well established from the concrete industry (Neville 2011). Secondly, there is a progressive development in strength with time, with the most rapid strength development in the first seven days, beyond which the strength development slows before eventually plateauing. Both characteristics, while being well known and understood, can be leveraged to optimise the binder addition, allowing for targeting of strength at a particular time.

Plotting the binder-to-water ratio against UCS for each of the curing time intervals allows for development of relationships which can be used to make predictions of strength for varying water-to-binder ratios. This is illustrated for the same data in Figure 3.

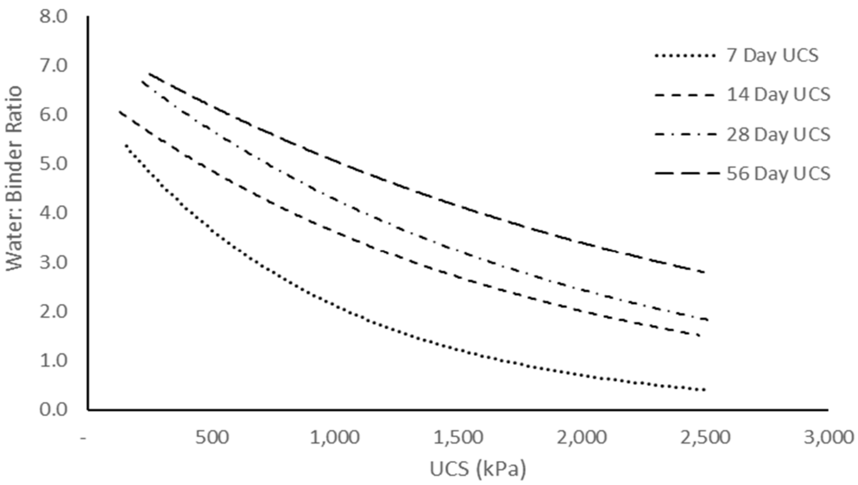


Figure 3 Water-to-binder ratio versus UCS

The final component in the tripartite relationship is to understand the relationship between paste backfill solids content and its rheology. This data was measured in the laboratory for each of the mix designs. The data obtained is reported below in Figure 4, with representative Boger slump tests shown to illustrate the approximate material consistency.

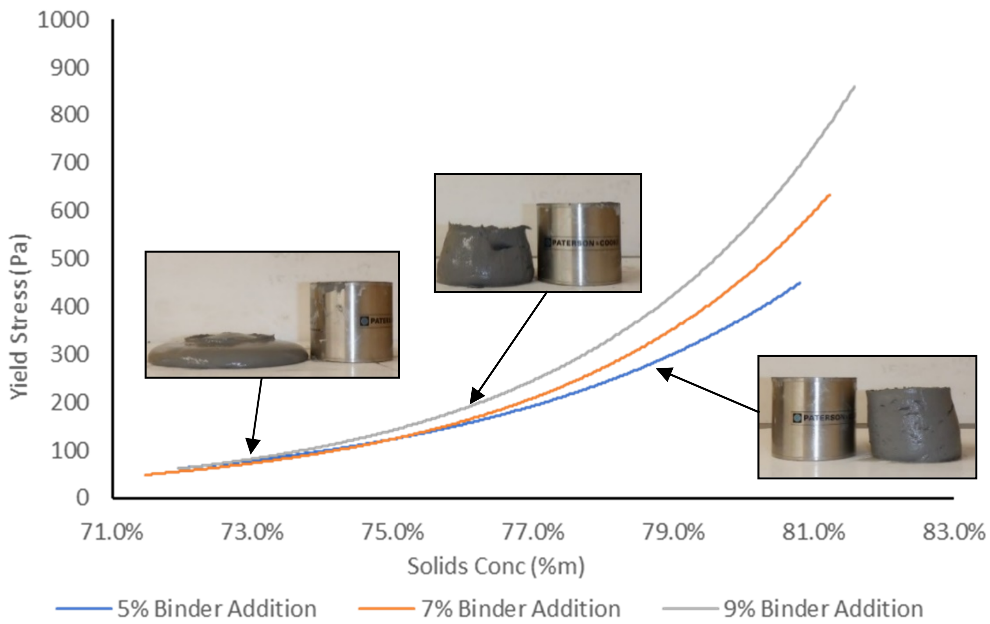


Figure 4 Mass solids concentration versus yield stress

While Figure 4 above shows yield stress against mass solids concentration, it is necessary to determine both yield stress and plastic viscosity to enable development of a suitable rheology model, such as the Bingham model (Ahmed et al. 2022). For this material, these relationships were developed using a bench scale rotational viscometer and are reported in Table 2.

Table 2 Rheological relationships

Binder addition	Bingham plastic model	
	Plastic viscosity	Bingham yield stress
5%, CEM III/A	$K_{BP} = \mu_w + 37406C^{40.135}$	$\tau_y = 12513C^{17.675}$
7%, CEM III/A	$K_{BP} = \mu_w + 46638C^{39.605}K_{BP}$	$\tau_y = 37478C^{20.402}$
9%, CEM III/A	$K_{BP} = \mu_w + 61000C^{38.1}K_{BP}$	$\tau_y = 56434C^{20.771}$
Applicable mass solids concentration range: 72.4%m < C < 79.3%m		

2.2 Building the relationship

From the above reported data, a unifying algorithm linking the relationship from Figures 3 and 4 can be developed. This is illustrated in Figure 5 below, and uses a third relationship combining the paste backfill solids content and the resulting water-to-binder ratio for multiple binder addition rates. Combining the parametric data in this way has previously been presented by Snyman et al. 2014.

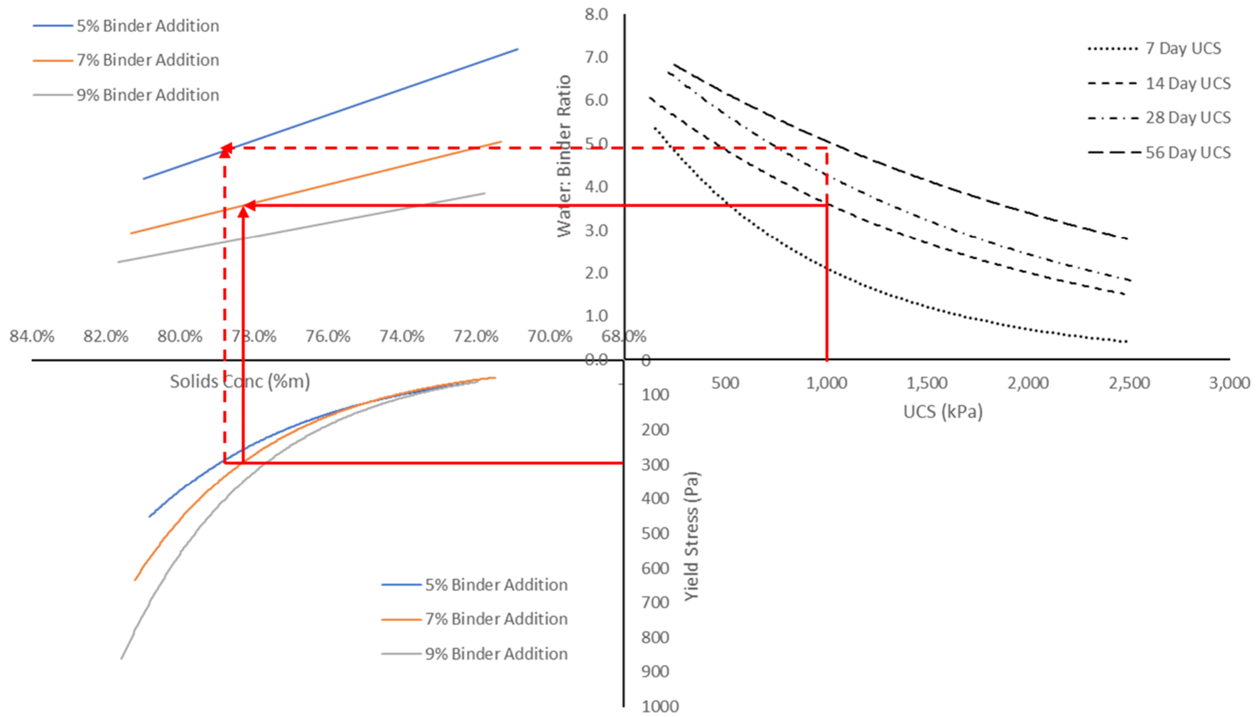


Figure 5 Unifying graph illustrating strength, time and rheology data

As illustrated above, it is possible to determine the required binder addition for a desired strength at a desired time interval for a known rheology. Changing any of the three variables–strength, time or rheology–results in a variation in the binder addition.

2.3 Determining the right backfill rheology

The final step in determining the unique backfill specification is to determine the necessary rheology for the backfill, and this will vary depending on the location of the void to be filled relative to the paste backfill plant. During the design stage of a backfill system it is common for the designer to assess several critical deposition routes to determine the overall operating envelope of the system to ensure adequacy of design. However, once in operation, it is common to find that hydraulic models are not routinely updated; nor are they used to assess the necessary rheology for each filling location. Instead, historic or 'universal' mix designs are applied, often with fixed rheologies and/or binder addition rates, with no allowance made for either the filling location or the influence on backfill strength as a result of changes to rheology.

Figure 6 below shows a hydraulic grade line plot which is typically used to illustrate the hydraulic conditions within the backfill reticulation system. The green line represents the pipeline profile, plotting vertical elevation against pipeline length, while the red line demonstrates the pipeline pressure rating, converted to that of a slurry head and plotted relative to the pipeline profile. Finally, the black line represents the hydraulic profile of the paste backfill, with its gradient representing the energy loss per metre of the fluid while flowing. A thicker paste will have a steeper line when compared to a thinner paste, so adjusting the water content allows for modification of this grade line to suit the selected discharge location.

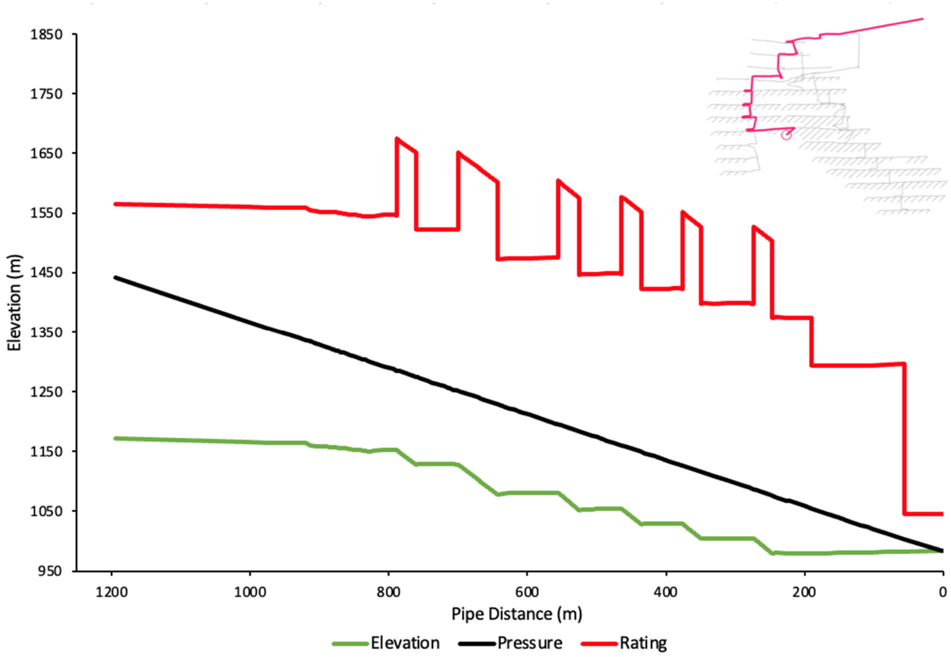


Figure 6 Hydraulic grade line. Filling on Level 975 with a total pipeline length of 1,194 m

In Figure 7 below, the same mine level is illustrated being filled as in Figure 6; however, now the stope location is 177 m closer to the final borehole. In both instances a pump capable of delivering up to 60 bar of discharge pressure is installed. Assuming the same final paste performance is required (for example, 500 kPa strength at 28 days) then, operating with the same rheology, the pump pressure would be reduced in this second case as illustrated. However, were the rheology to be adjusted to suit the discharge capability of the pump, the paste thickness could be increased and the binder dose reduced from 6.1 to 5.2% using the data presented previously. This revised hydraulic grade line is shown in Figure 7 as a dotted line. In all instances the hydraulic grade line must be maintained beneath the pipeline pressure rating.

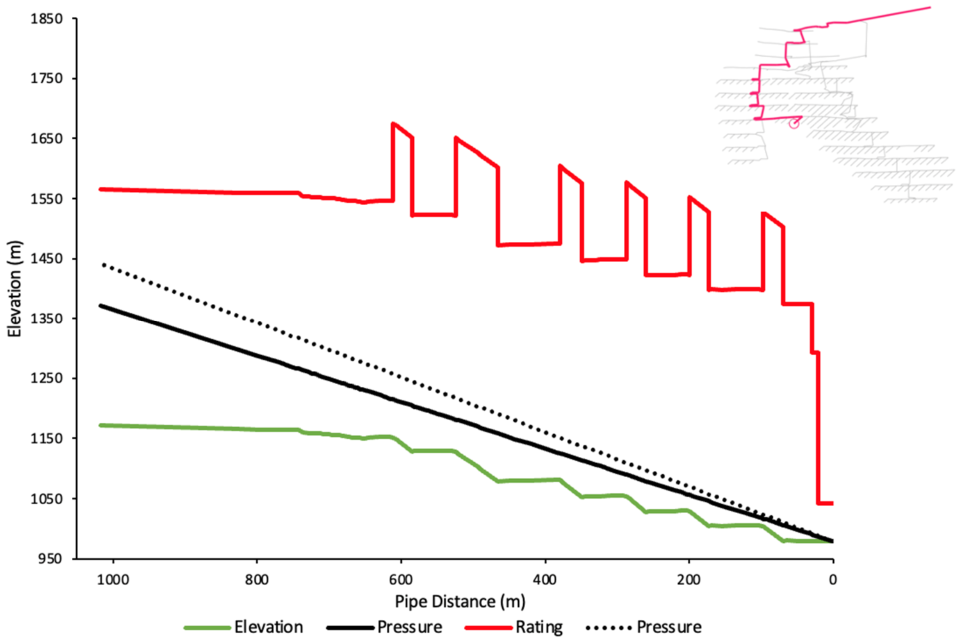


Figure 7 Hydraulic grade line. Filling on Level 975 with a total pipeline length of 1,017 m

Continuing this example, were the same rheology of paste to be used to fill a stope with a reduced horizontal to vertical pipeline profile, then slack flow may be experienced in one or more of the boreholes as illustrated in Figure 8, where the black line is seen to lie upon the green pipeline profile. Slack flow conditions arise when the absolute pressure inside a pipeline falls below the liquid or slurry vapour pressure. The slurry will flow with a free surface in the slack flow section, i.e. open channel or launder flow. If the pipeline slope is steeper than the hydraulic gradient when the pipeline is flowing full, the slurry will accelerate until it reaches a velocity such that the friction losses equal the pipeline slope. This velocity may be significantly higher than the full flow rate. This can result in rapid erosion of the pipeline invert. Again, in this instance, the rheology may be modified as shown (dotted line), thus avoiding the occurrence of slack flow and again offering the potential to reduce the binder content.

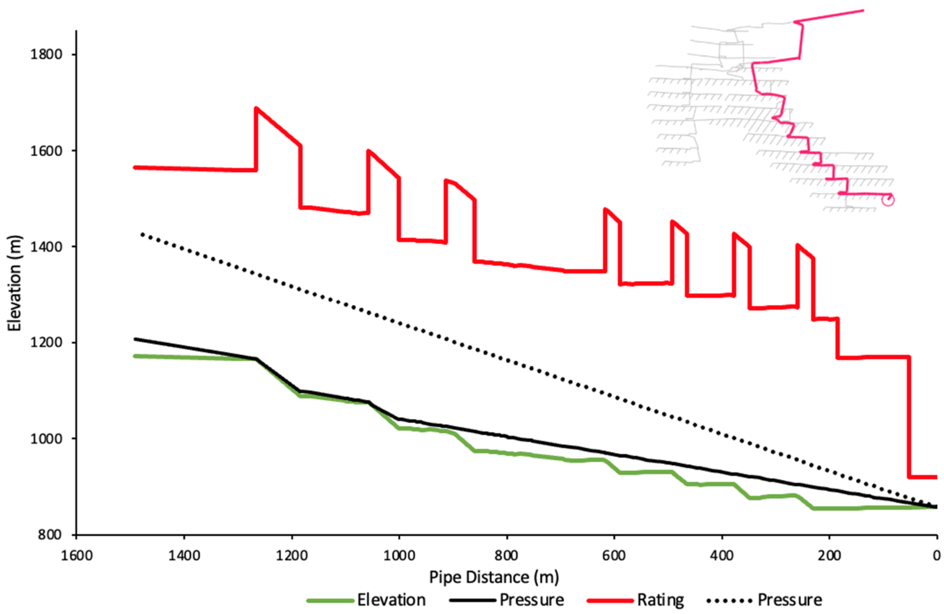


Figure 8 Hydraulic grade line plot illustrating slack flow

2.4 Summary

The preceding sections have sought to explain and demonstrate how the backfill specification may be determined and optimised for each stope. This takes account firstly of the performance required of the backfill, namely the strength required and when that strength is needed. If a delay in strength gain can be accepted, then binder can possibly be reduced. Equally, mining opportunity may be gained from earlier strength gain achieved by additional binder, the cost of which may be recovered by that mining opportunity. Next, understanding the rheology required to deliver the backfill to a stope not only ensures a properly operated reticulation system, avoiding slack flow and overpressure scenarios, but allows for minimisation of water content, which in turn minimises the binder necessary to meet the strength – time specification.

Software solutions which bring these components together should enable operators to perform this assessment rapidly and easily for each stope. A cautionary note, however, is that the relationships used in the assessment approach are underpinned by data and it is therefore necessary to develop and maintain a robust QA/QC record, ensuring quality and quantity of the data to give confidence in the results.

3 Case study

3.1 Background

To demonstrate the opportunity for value presented by this optimisation approach, a case study is used here to illustrate operational and cost improvements which may be derived from optimisation of the paste backfill specification. The case example used is an underground long hole stoping operation with a life of mine (LOM) of nine years producing at a nominal rate of 1.0 Mtpa. The LOM is shown below in Figure 9 and has provided for assessment the following data for each stope:

- Stope location (X, Y, Z coordinates of the stope centroid).
- Stope volume.
- Backfill strength and time requirements.
- Extraction date.

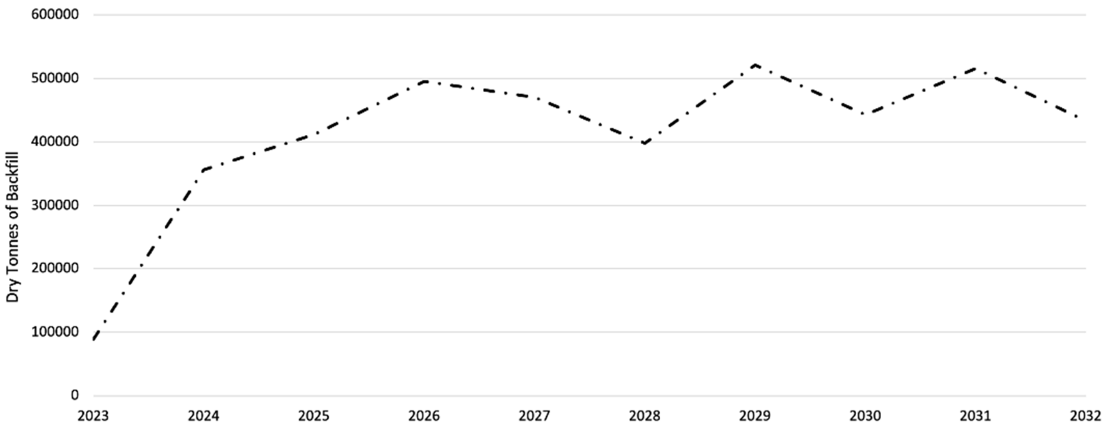


Figure 9 LOM backfill tonnage requirements

The reticulation layout is illustrated below in Figure 10. The paste backfill plant is located on the surface and accesses the mine via two routes, the primary one being an inclined borehole which is preceded by a length of near horizontal overland piping. A second access route is provided to the upper levels of the mine via a decline adjacent to the backfill plant.

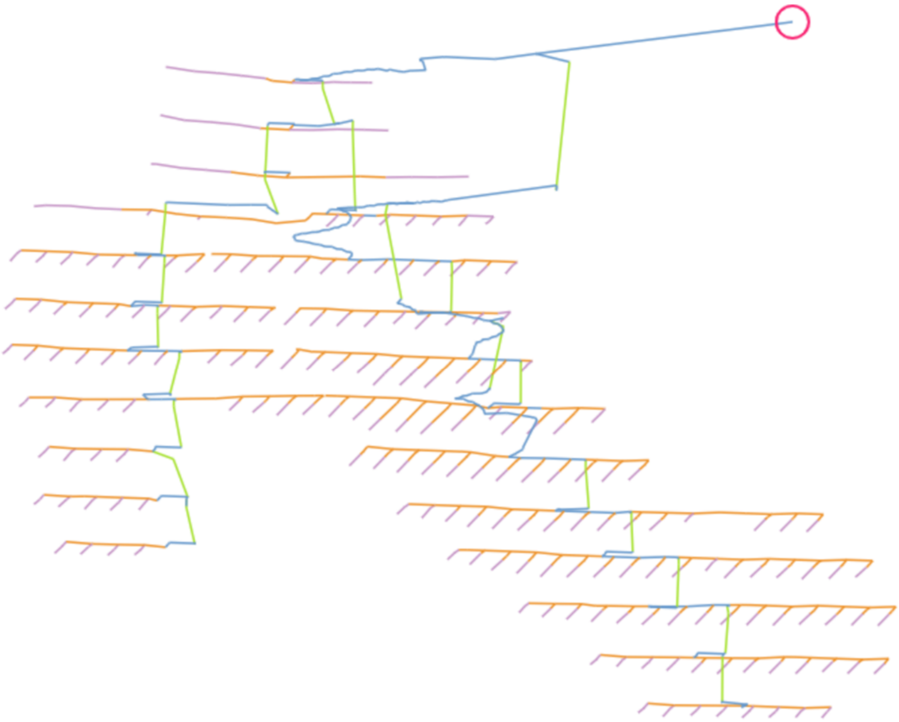
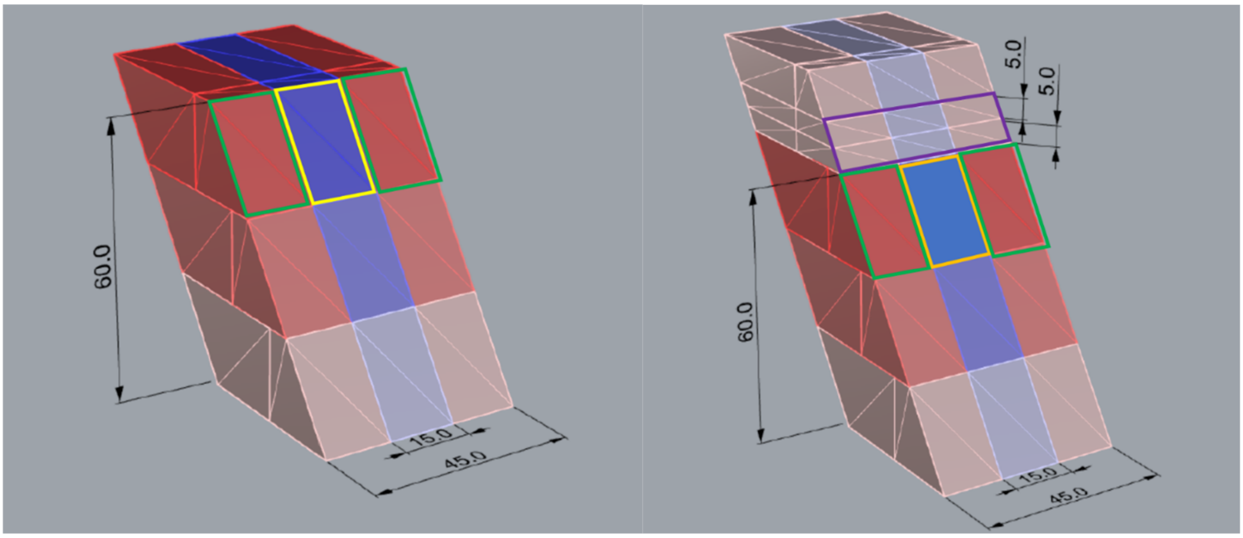


Figure 10 Underground reticulation network

3.2 Backfill strength modelling

The long hole mining method is developed between primary mine levels in a bottom-up fashion. This places a requirement on the backfill to provide for vertical wall exposures, as well as horizontal exposures for sill pillars when mining up to, and below, the base of a previous primary level. Consequently, the backfill strength requirement is for short-term vertical exposures and longer-term horizontal exposures. Within each stope two fill types are further defined, accounting for plug pours and stope body pours.

Numerical modelling was undertaken to develop strength requirements for both exposure scenarios, as illustrated in Figures 11 and 12 below.



(a) (b)

Figure 111 Stope numerical model illustrations. (a) Vertical; (b) Horizontal

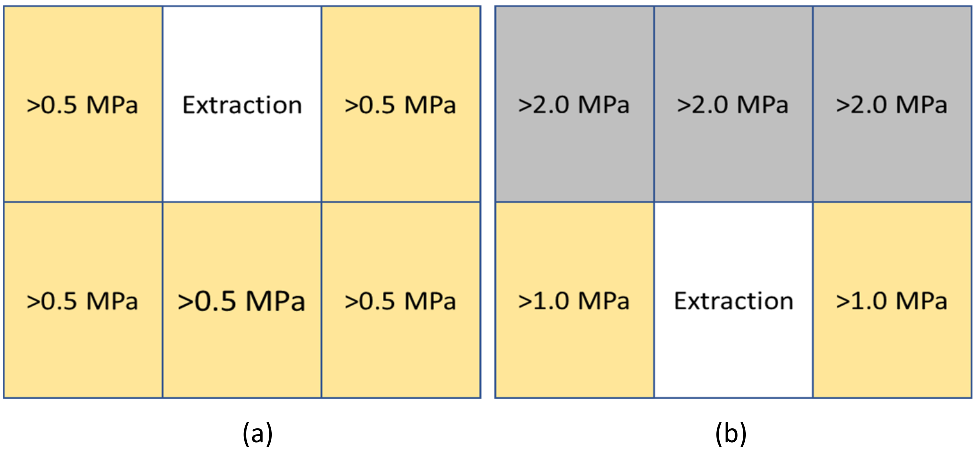


Figure 12 Stope numerical model simplified results. (a) Vertical; (b) Horizontal

The following timing is applied to the varying backfill strength requirements:

- Plug pours to achieve a minimum 500 kPa at seven days.
- Vertical exposure strengths to be achieved at 28 days.
- Horizontal exposure strength to be achieved beyond 56 days.

3.3 Mix designs

To meet the strength requirements, initial water-to-binder ratios were determined for conventional 7- and 28-day cure times using the test work data presented previously, and these are reported in Table 3. An initial optimisation is immediately possible as the mining schedule does not require the horizontal exposures until beyond 56 days, and consequently a revised water-to-binder ratio can be offered for these mix designs. This is also shown in Table 3, demonstrating a reduction in the binder addition requirement.

Table 3 Fill types and strength requirements, and water-to-cement ratio

Fill type	Pour type	Strength required	Curing period	Water: binder ratio	Revised curing	Revised water: binder
Vertical exposure (regular stope)	Plug	500 kPa	7 days	3.51	–	–
	Body	500 kPa	28 days	5.48	–	–
Vertical exposure (beneath sill stope)	Plug	500 kPa	7 days	3.51	–	–
	Plug	500 kPa	28 days	5.48	–	–
	Body	1,000 kPa	28 days	3.96	>56 days	4.66
Horizontal exposure (sill stope)	Plug	500 kPa	7 days	3.51	–	–
	Plug	2,000 kPa	28 days	2.86	>56 days	3.38
	Body	500 kPa	28 days	5.48	–	–
	Body	2,000 kPa	28 days	2.86	>56 days	3.38

3.4 Reticulation modelling

Initial reticulation modelling for the project took account of the 60-bar capacity pump installed at the backfill plant and focused on ensuring delivery of the various backfill recipes to the mine stopes. This meant designing for the most onerous reticulation location, with less onerous locations using the same mix design and rheology but with the pump operating at a lower discharge pressure. In this way the operation could ensure that the product delivered to each stope would meet the desired strength – time performance. This concluded on a nominal backfill recipe at 74.6 %m and the corresponding cement addition rates were determined for each of the pour requirements from the water-to-cement ratios (refer to Table 3).

While this approach provided confidence in it being able to backfill all stopes, it missed the opportunity to increase the mass concentration of the backfill to maximise the pump output pressure and minimise the binder. Using the BackfillPro® optimisation software an evaluation was run to assess every filling location in the mine, constraining the model to ensure a 60-bar pump discharge pressure was not exceeded. The software automatically balanced the hydraulic models to each stope by adjusting the rheology and, at the same time, adjusted the binder content to reflect the varying water content as the paste backfill density changed. Additionally, the software was able to account for the differing cure times from attribute data attached to each stope.

The resulting range of rheologies indicated by the software is illustrated in Figure 13, which shows the backfill tonnes placed at varying backfill densities. As a result of the water content variations and accounting for the necessary curing periods, an estimated 30,304 t of binder can be removed from the LOM forecast, equating to approximately USD 5 M over the LOM. This is greater than USD1 per tonne of backfill.

In addition to the cost saving, the adjustment of rheology ensures that the reticulation system will run without slack flow to all stopes. As a result of the mine layout, operating at the nominal recipe would have resulted in slack flow development in more than 30% of filling scenarios.

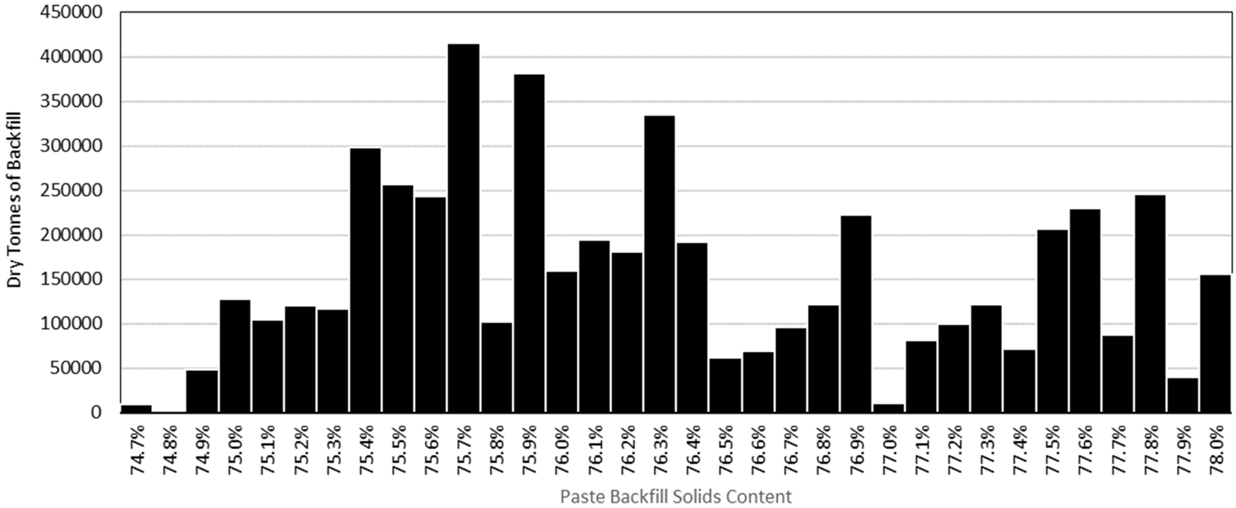


Figure 13 Distribution of paste backfill solids contents recipes

4 BackfillPro®

Paterson & Cooke developed BackfillPro® in response to a demand from backfill operators to have a day-to-day hydraulic modelling tool capable of assisting them in determining the preferred rheology for each stope. This development process allowed for inclusion of the binder optimisation tool, accounting for changes in rheology as well as the strength – time specification. As a result, the user can precisely specify the backfill mix recipe for each pour into a stope.

The software capability has been further extended to provide a backfill management capability. The user can upload monthly, annual or LOM stope plans and use the software to plan and schedule the filling accordingly. Exports of production and expenditure budgets can then be made. At the time of filling, pour notes can be generated to provide essential information to the backfill plant operator, with a capability to upload actual performance data as well as QA/QC data to maintain and improve the prediction accuracy.

To ensure the applicability of the software it has the capability to select optimal reticulation routes. It also allows user overrides when more than one such route exists, and can adjust friction loop lengths to further improve the hydraulic profile to a particular stope. It can also run with multiple different rheology profiles, accommodating situations when tailings feed material blends may change or when rheology modifiers are used, for example.

Figure 14 is a screen shot from the software illustrating the user interface. The optimal route selection is shown, as is the hydraulic grade line which updates in real time to variations in backfill rheology. The right side shows the optimisation tool which calculated the optimal recipe, combining strength, time and rheology.

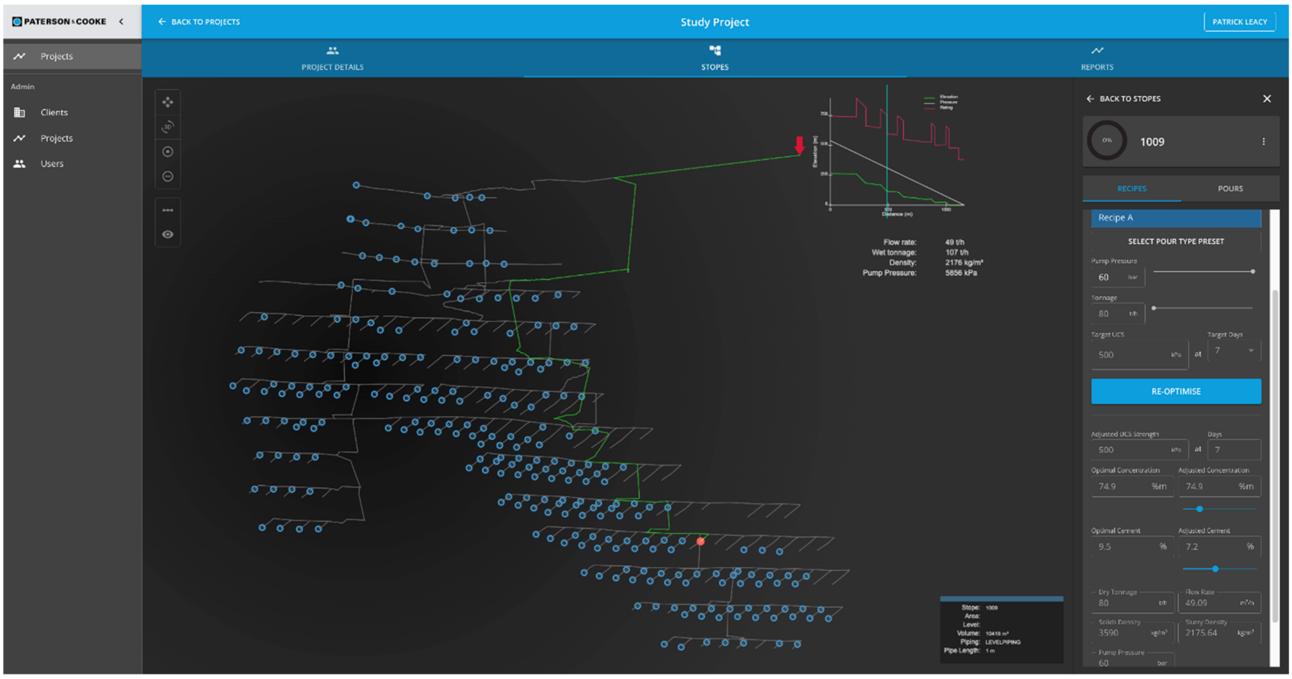


Figure 14 Illustration of BackfillPro® software interface

5 Conclusion

This paper has sought to firstly demonstrate why it is necessary to try to optimise the backfill specification, and then to discuss the underpinning principles which allow for this. The argument for optimisation relates to both technical and commercial drivers. It is essential that the mine stakeholders have confidence that the backfill can be delivered safely and efficiently to the stope, and that once there it will develop the necessary strength in the necessary time. The paper has illustrated how, when operating with a fixed recipe, there is the potential to fall short in all these criteria. From a commercial perspective, minimisation of binder is a well-understood lever in driving down backfill cost. By maximising the backfill solids content and adapting binder addition to its forecast strength – time development profile, the binder addition can be minimised. Additionally, when the rheology is correct, the reticulation system can be expected to run optimally, thus reducing wear and maintenance associated with slack flow operation.

The need for this approach is not new and has been reported by others. The software developed by Paterson & Cooke provides a web-based application that engineers and operators can use to create an optimal paste specification. Its capability has been further extended to include system and data management, recognising that this too is an important component in the operation of a successful backfill system.

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