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Mining with backfill: predicting backfill strength requirements, long-term behaviour, and placement

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Abstract

The main challenge in mining with backfill is to design a flowable backfill capable of ensuring good stability of the backfilled stopes after placement and hardening. This would require, among other things, a good understanding of the physics (particle size distribution curve) and the mineralogy (presence of sulphides and/or clay minerals) of the mine waste, the correct determination of the required strength (based on the factor of safety), the correct definition of the rheological parameters (slump S, critical solids mass concentration %$C_{w\text{-}cr}$*, adequate shear yield stress* τ_Y *and viscosity* μ*), the proper selection of the backfill mix recipe (formulation taking into account the physico-chemical properties of the mixture ingredients), the correct design of the backfill retaining barricades (horizontal pressure), the good understanding of the hydromechanical properties (self-weight consolidation), the better control of the filling sequences (dissipation of the pore water pressure), the long-term compressive and shear strengths of the backfill, the reduction of the backfilling operation costs (possibility of reducing the amount of binder used), the prediction of the cemented rockfill and paste backfill strength.*

Keywords: *cemented mine backfill, required strength, critical solids mass concentration, compressive strength, rheological parameters, self-weight consolidation*

1 Introduction

Underground backfilling contributes to the profitability of mining while ensuring maximum safety for mine workers. This is why mine backfills have become a staple in modern underground hard rock mining operations worldwide over the past two decades. However, their adequate use requires a multidisciplinary approach to studying their physical, chemical, mechanical, and rheological properties and their thermal effect. This underground mine backfilling must, however, meet both transport (fluidity) and stability (mechanical strength) criteria, once placed and considered for seismicity (liquefaction potential). Following these criteria eliminates some operational risks, such as blockage of the backfill distribution line or failure of the backfill mass that could result in infrastructure damage and/or human injury. The keynote speech will review all the challenges listed by addressing the current state of knowledge, the challenges that have already been met and those that remain, as well as new avenues to explore or emerging methods.

2 Design of the required strength of cemented mine backfill

The first challenge in implementing underground mine backfill is properly designing the required strength of the cemented mine backfill according to its prescribed role. It has been 40 years since the confined block model was proposed by Mitchell et al. (1982), and despite the plethora of new solutions in the literature, it remains the most widely used in the mining industry mainly because of its simplicity and ease of use. However, because of the limitations of all existing models, including considering different boundary conditions of backfilled mine stopes and other modes of interfacial failures, a new generalised solution for the required strength of cemented mine backfill (Cmb) was proposed by Belem et al. (2022). This generalised analytical solution can be used for cemented hydraulic fill (CHF), paste backfill (CPB) and rockfill (CRF) and uses a similar approach to Mitchell et al. (1982) with more flexibility. The generalised relation for the required uniaxial compressive strength ($UCS_{generalised}$) is given as follows:

$$UCS_{\text{generalised}} = \frac{q\mathbf{S} + \gamma H^{*}\mathbf{W}}{[\mathbf{F}]^{-1} + \mathbf{C} + \mathbf{T}} \tag{1}$$

where:

q = surcharge load (N.m^{-2}), **S** = surcharge load multiplying factor,

γ = wet unit weight of Cmb (N.m^{-3}), **W** = block weight multiplying factor,

H^{*} = backfill block sidewall equivalent height (m),

F = safety factor term,

C, T = cohesive and tensile strength terms.

This solution considers four contact configurations of confined block boundary conditions:

- cohesive & frictional contacts at the two sidewalls and tensile contact at the backwall,
- cohesive & frictional contacts at the two sidewalls and the backwall,
- tensile contacts at the two sidewalls and the backwall,
- tensile contacts at the two sidewalls and cohesive & frictional contact at the backwall.

The main advantage of the new solution is its adaptability to more complex settings such as more than one free face, different sidewalls contact conditions, different stope dimensions, and drained or undrained conditions. The proposed solution also considers the importance of tensile strength at the backwall contact of a stope that contributes to the backfilled stope's overall stability. It also ponders the situation where the cohesion of the interfaces is smaller than that of the backfill material.

3 Backfill rheology and pipeline transport

After determining the required strength of the cemented backfill, the rheological and transport parameters through an underground pipeline distribution line should be determined. At this stage, it is imperative to consider the mode of distribution of the backfill, which can be by gravity or pumping. Indeed, the rheological parameters (static and dynamic shear yield stresses, plastic viscosity) and factors (Boger's cylinder or standard Abrams's cone slump) will be different depending on whether the flow is by gravity or by pumping. In the conventional method, the static shear yield stress (τ_Y) is determined using a rheometer with a vane spindle for solids mass concentration (%C_w) ranging from 70 to 85% (depending on the relative density of the tailings used). The target %C_w is then determined either by the corresponding slump (S) and τ_Y or through flow-loop tests showing the lowest pressure drop ($\Delta p/L$).

An alternative method would be to consider that the Cmb obeys the Herschel-Bulkley fluid law, which is given as follows:

$$\tau = \tau_Y + K\left(\dot{\gamma}\right)^{n} \tag{2}$$

where:

τ = shear stress (Pa),

K = consistency (Pa.s^{n}),

$\dot{\gamma}$ = shear rate (1/s),

n = flow index (if $n < 1$, yield pseudoplastic fluid, shear thinning behaviour).

Rheological tests are then carried out to determine different rheograms for %C_w varying between 70 and 85% and by determining the corresponding flow index (n). The critical mass solids concentration (%$C_{w\text{-}cr}$) can then be determined (cf. Li et al. 2017) so that the backfill will have a shear thinning behaviour ($n < 1$) during its pipeline transport. The %$C_{w\text{-}cr}$ value could also be correlated with the slump (S) and the shear yield stress (τ_Y).

4 Procedure for the selection of the type of binding agent

Once the required strength and the rheological parameters of the cemented backfill are known, it becomes imperative to select the type of binder that will allow the backfill to reach the prescribed strength at the desired curing times. It is clear, however, that if the backfill is to be placed in permafrost, the type of binder to be used should be type HE (high early strength) Portland cement. For the other cases, the main issue is using the most cost-effective binding agent without compromising the strength target. This is the main reason for using binders with supplementary cementitious materials or SCM (e.g., fly ash, blast furnace slag, etc.). Moreover, in the current context where the mining industry would like to do its part in decarbonisation, the trend would be to use low carbon footprint binding agents or eco-binders. These eco-binders can contain treated biomass ashes, calcined clays, or any other industrial by-product that can be reused. For this purpose, the relative hydration index (H_a) was defined as follows (Belem & Sahi 2017; Sahi et al. 2015, Belem et al. 2010):

$$H_a = A\left(Hm_b\right)^B \tag{3a}$$

$$Hm_b = \frac{\sum_{i=1}^{N} y_i(\mathrm{CaO})_i}{\sum_{i=1}^{N} y_i(\mathrm{SiO_2})_i + \sum_{i=1}^{N} y_i(\mathrm{Al_2O_3})_i + \sum_{i=1}^{N} y_i(\mathrm{Fe_2O_3})_i} \tag{3b}$$

where:

Hm_b = the hydraulic modulus of the binder,

A, B = constants (A = 0.4248 and B = 0.9985),

y_i = the fractional proportion of the i^{th} cement or SCM in the blend; CaO, SiO_2, Al_2O_3 and Fe_2O_3 (in %).

By comparing the H_a value of a reference binder (e.g., $H_{a\text{-Ref}}$ = 0.43) with those of new types of binding agents, it is possible to select the most suitable binding agent for a given backfill mix.

5 Backfill mix proportioning

The solid mass concentration of the backfill ($C_{w\text{-fill}}$), the binding agent ratio B_w (= $M_{binder}/M_{dry\text{-tails}}$), the total mass of cemented backfill (M_T), the water content of the wet tailings ($w_{wet\text{-tails}}$), the masses of wet tailings ($M_{wet\text{-tails}}$), binding agent (M_{binder}), total water in the mix (M_w), and mixing water ($M_{w\text{-add}}$) to be used are then calculated as follows:

$$M_{\text{wet-tails}} = C_{\text{w-fill}}\left(1 + w_{\text{wet-tails}}\right)\left(\frac{M_{\mathrm{T}}}{1 + B_w}\right) \tag{4a}$$

$$M_{\text{binder}} = B_w \times M_{\text{dry-tails}} = B_w C_{\text{w-fill}}\left(\frac{M_{\mathrm{T}}}{1 + B_w}\right) \tag{4b}$$

$$M_{\mathrm{w}} = M_{\mathrm{T}}\left(1 - C_{\text{w-fill}}\right) \tag{4c}$$

$$M_{\text{w-add}} = M_{\mathrm{T}}\left[\left(1 - C_{\text{w-fill}}\right) - C_{\text{w-fill}}\left(\frac{w_{\text{wet-tails}}}{1 + B_w}\right)\right] \tag{4d}$$

6 Design of waste rock barricades

Most mine backfilling operations with cemented paste backfill using waste rock barricades (WRBs) as retaining structures are in two steps (rather than continuous) due to a lack of confidence in their stability.

This is explained by the lack of knowledge of the WRB parameters, such as the shear resistance or shear strength at the interface (τ_{int}), the horizontal total pressure on the barricade (σ_b), the factor of safety (FS), etc. As a result, the mining industry is adopting a conservative approach of oversizing the WRBs (FS > 4). However, these safe practices remain insufficient if mining engineers cannot provide the FS of the WRB in the event of their failure or instability followed by the paste backfill spill. Because in practice, the WRBs are oversized (top length L_{top} > 2 m), and to avoid calculating L_{top} < 2 m, the FS value must satisfy the following necessary condition based on limit equilibrium analysis (Belem et al. 2019):

$$FS > \frac{2\tau_{\mathrm{int}}}{\sigma_b}\left(\frac{1}{w}+\frac{L_{btm}}{L_{top}}\left[\frac{1}{w}+\frac{1}{h}\right]\right) \tag{5}$$

where:

L_{btm} = the bottom length of the WRB (m),

w = = the width of the access drift or drawpoint (m),

h = the height of the access drift or drawpoint (m).

7 Underground placement and long-term behaviour

After the backfill has been placed in the mine stope, the self-weight consolidation phenomenon occurs. The extent depends strongly on the particle size distribution of the tailings. This phenomenon, along with the pressure distribution in the backfilled stope and the evolution of the long-term hydromechanical behaviour, can be analysed in the laboratory by physical modelling using small-scale models or in-situ through instrumentation using various sensors (tassometer, total earth pressure cells, piezometer). It is imperative to consider the static and dynamic liquefaction potentials of early age backfill while also being able to predict the short and long-term mechanical properties of the backfilled stopes.

8 Conclusion

Different studies have been undertaken to tackle the complexity of cemented mine backfills, and various solutions have been found to keep mining up-to-date with backfill methods. These range from predicting the required strength of the backfilled stope and the cemented backfill's long-term strength to characterising the rheology, transport, and liquefaction potential considerations.

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