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Investigation of the short-term stress distribution in stopes and drifts backfilled with cemented paste backfill

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ABSTRACT

Cemented paste backfill (CPB) is largely used in underground mines worldwide. A key issue associated with application of CPB is to estimate the stresses in backfilled stopes and on barricades. Recent numerical and experimental results show that arching effect is absent shortly after the placement of CPB in stopes. However, stress decreases in barricade drift with increasing distance between the measurement points and drawpoint have also been observed, demonstrating arching effect shortly after the pouring of CPB. To explain these paradoxes, CPB is considered as Bingham fluid having a yield shear stress. Three dimensional analytical solutions are proposed to evaluate the short-term total stresses in backfilled stopes and on barricades, accounting for the CPB's yield shear stress-induced arching effect. Stress diminution due to such arching effect in the backfilled stopes and on barricades is indeed obtained. But the reduction becomes insignificant using typical yield shear stress and stope geometry. More analyses indicate that the typical yield shear stress values do not fully correspond to field conditions where the yield shear stress would increase exponentially due to apparent consolidation (loss of water by drainage, a phenomenon similar to the desiccation of overly saturated fine-grained materials).

1. Introduction

The application of cemented paste backfill (CPB) has increased significantly with time in mining industry worldwide. CPB plays the role of assuring the stability of stopes, increasing ore recovery rate, minimizing ore dilution and controlling ground subsidence associated with underground mining activities [1–6]. It is also beneficial from an environmental standpoint as it reduces the surface disposal of mine wastes [7–9].

Despite numerous advantages in application of backfill in underground mines, several cases of barricade failures reported in the literature indicated that the barricade design remains a serious concern [10,11]. This challenge is closely related to the pressure estimate in the backfilled stope and on the barricade. When a slurried backfill is placed into a stope, the particles tend to settle down driven by their self-weight, leading to generation of excess pore-water pressure (PWP) in the backfill. The drainage and consolidation accompanied with the dissipation of the excess PWP is a well-known phenomenon, called self-weight consolidation or sedimentation [12–19].

For hydraulic backfill that usually has quite high hydraulic conductivity and behaves mostly like sandy material, the self-weight consolidation can be achieved very quickly and accompanied by bleeding of a lot of free water. When the drainage of the barricade is not efficient enough compared to the water bleeding, a commonly observed phenomenon is the formation of water pond on the top of the backfill.

Compared to hydraulic backfill, the behavior of CPB is much more complicated because it usually has a lower permeability and behaves mostly as a material between a silty and clayey material. The drainage and consolidation of CPB last longer than that of hydraulic backfill. This is why much less water bleeding is observed in stopes backfilled with CPB. But it does not definitively mean low pressures on barricades as the bleeding water is not a reliable indicator of drainage and consolidation [19,20].

For a backfill given, once the self-weight consolidation starts, shear stresses are generated along the fill-wall interfaces and tend to hold the fill particles in place against their downward settlement. This leads to a load transfer from the backfill to the confining rock walls. The resulting stresses in the backfill then become smaller than those calculated based on the overburden solution (OS). This phenomenon is known as arching effect, firstly reported in powder industry [21,22]. In civil engineering, its application is mostly attributed to Marston who used arching theory to estimate

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the backfill loads on buried conduits in a trench [23]. Later, Terzaghi considered arching to assess the pressure distribution above a yielding strip (known as trap-door problem) [24]. In mining engineering, stress distributions in backfilled stopes have been analyzed numerically by Aubertin et al. [25–29]. Analytical solutions have also been proposed for estimating the stresses in a backfilled stope, mainly based on Marston solution. These include the extension of the Marston's 2D solution to 3D stopes, to 2D inclined stopes, and consideration of water pressure [28,30–35]. The arching effect in backfilled openings has been further confirmed by laboratory and in-situ measurements [36–45]. Arching solutions can thus provide useful stress estimation in backfilled stopes and on barricades.

However, paradoxical results were noticed on the short-term total stresses of CPB in stopes and on barricades. When horizontal arching effect is considered in barricade drifts, Li and Aubertin have shown that it would be advantageous (only from a safety point of view) to construct the barricade farther from the stope because the pressures on barricades are inversely proportional to the distance between the barricade and stope [46,47]. This is confirmed by field experimental results obtained by Grabinsky et al., who showed that the short-term total stress in barricade drift decreases indeed as the measuring points are farther away from the drawpoint [42,44]. On the other hand, some numerical and experimental results revealed that arching may be absent shortly after the placement of CPB in stopes [45,48–50]. In such case, the short-term total stresses and (excess) PWP in barricade drifts should only depend on the height of backfill in the stope, rather than the distance between the measuring points and the drawpoint. At a given depth in the stope and barricade drift, therefore, they can be calculated by OS as follows:

$$\sigma_v = \sigma_h = u = \gamma h \quad (1)$$

where σ_v and σ_h are the vertical and horizontal total stresses respectively, kPa; u the (excess) PWP, kPa; γ the unit weight of the CPB, kN/m^3; and h the backfill thickness above the calculation point, m.

In order to understand these contradictory observations, the rheological behavior of CPB is considered in the paper. It is well known that the CPB behaves like a Bingham plastic fluid with a certain yield shear stress to overcome before flow initiated [51–56]. The yield shear stress-induced arching effect has to be considered in CPB pipe transportation to assess head losses [52,57]. Pumping is applied when the horizontal segments of CPB pipe transportation are too long [58–60]. Similarly, it can be expected that a yield shear stress-induced arching effect takes place in narrow stopes and barricade drifts, leading to a pressure reduction in backfilled stopes and on barricades. This yield shear stress-induced arching effect, different from the traditional one due to shear strength (effective cohesion and friction), has never been considered for stress estimation in backfilled stopes and on barricades.

In this paper, the shear stresses due to CPB's yield shear stress at fill-wall interfaces are derived using Buckingham equation [61]. A 3D analytical solution is proposed based on Marston's approach [23,25,30,62]. Sample calculations are made to show the influence of CPB's yield shear stress and opening geometries on the short-term stress distribution in backfilled stopes and on barricades. The proposed solution is also compared with in-situ measurements available in the literature.

2. Rheology of CPB

Fluid materials are generally classified as Newtonian or non-Newtonian fluids [63]. Bingham proposed an analytical model to describe the non-Newtonian rheological behavior of slurries or pastes [64]. Hereafter, this type of non-Newtonian fluids is named Bingham plastic fluid. Previous publications have shown that CPB has a rheological behavior similar to fresh concrete and can be defined as a Bingham plastic fluid [51,53–55]. In the following two subsections, the yield shear stress of CPB and its induced shear stress along fill-wall interfaces are presented.

2.1. Yield shear stress of CPB

The concept of yield shear stress has been introduced in fluid material by Bingham and Green [65]. It is defined as the threshold shear stress to overcome before the fluid is fully mobilized. It is a key parameter for paste fill and tailings transportation design. Generally, the yield shear stress of CPB is sensitive to solid content, water content, content and type of binder, stage of hydration and pore fluid chemistry [56,58]. The correlation between yield shear stress and solid content has been used by Sofra and Boger to predict the pumping energy requirements in pipeline transportation [58].

For a Bingham plastic fluid like CPB, when an applied shear stress is smaller than its yield shear stress, it has an elastic behavior and the deformation is reversible. Once the applied shear stress exceeds the yield shear stress, the CPB starts to flow as a viscous material with constant viscosity. Boger et al. has reported different laminar flow models for thickened tailings and paste [53]. The most used one is the Bingham plastic model:

$$\tau = \tau_0 + K_b \dot{\gamma} \quad (2)$$

where τ is the required shear stress to fully mobilize the Bingham fluid, Pa; τ_0 the Bingham's yield shear stress, Pa; K_b the Bingham plastic viscosity, Pa s; and $\dot{\gamma}$ the shear strain rate (a gradient of velocity across the fluid layers), s^{-1}.

Several methods can be used to determine the rheological parameters τ_0 and K_b. For CPB, the mostly commonly used methods are slump test and viscometer [53,56,66]. Boger et al. indicated that the measured yield stress typically ranges from 100 to 800 Pa, whereas Simon and Grabinsky have reported some values as high as 1100 Pa [53,54,56,67].

2.2. Shear stress estimation along the wall of a confining structure

Buckingham proposed the following equation for Bingham plastic fluid under laminar flow regime in a pipe [61]:

$$\frac{8v}{D_i} = \frac{\tau_w}{\eta}\left[1 - \frac{4}{3}\left(\frac{\tau_0}{\tau_w}\right) + \frac{1}{3}\left(\frac{\tau_0}{\tau_w}\right)^4\right] \quad (3a)$$

where τ_w is the shear stress at pipe wall, Pa; v the average velocity of fluid mixture, m/s; η the plastic viscosity, Pa·s; and D_i the internal diameter of pipe, m.

Eq. (3a) can be solved to estimate the wall shear stress along the fluid–pipe interface for a given flow rate and pipe size. In pipe transportation design, as it is quite difficult to obtain an explicit solution, the quartic term $(\tau_0/\tau_w)^4$ is usually ignored and Buckingham equation is simplified as follows [68]:

$$\tau_w \approx 8v\eta/D_i + 4/3\tau_0 \quad (3b)$$

This is the modified Buckingham equation, used to determine the shear stress at the fluid–pipe interface for pipe transportation [68].

When the average velocity of fluid mixture is small, engineers tend to further simplify Eq. (3b) by assuming v to be nil and the wall shear stress at the fluid-pipe interfaces, τ_w is then estimated as:

$$\tau_w \approx 4/3\tau_0 \quad (3c)$$