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# Curing time effect on consolidation behaviour of cemented paste backfill containing different cement types and contents

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## HIGHLIGHTS

- Curing time effect on consolidation behaviour of cemented paste backfill (CPB) was investigated.
- Adding binder to the CPB mixtures increased compression resistance and reduced permeability.
- The coefficient of consolidation decreased gradually with increasing stiffness of the CPB materials.
- Application of successive pressure increments led to reduction in pore water pressure dissipation.
- Some empirical equations were proposed for estimating the CPB's consolidation properties.

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## ABSTRACT

The one-dimensional consolidation properties of early age cemented paste backfill (CPB) are useful for the estimation of design parameters for underground stope filling purpose as well as for numerical modelling purposes. Many studies have investigated the consolidation characteristics of mine tailings, but not in CPBs, mainly because consolidation was not initially considered as an essential property and the available testing equipment was not suitable. In this paper, the curing time effect of different types of binder and their content on the one-dimensional consolidation characteristics of CPB samples was investigated using an improved lab apparatus called CUAPS (curing under applied pressure system). As the drainage ability and the saturated hydraulic conductivity $k_{sat}$ are closely linked with consolidation, the change in the $k_{sat}$ at the end of the consolidation process was also investigated for tailings (control) and CPB materials. Results indicate that adding binder to the mixtures considerably affects the void ratio and increases compression resistance. The excess pore water pressure indicates that binder reduces the peak value reached for all pressure increments while the $k_{sat}$ decreases with time. Some empirical equations to estimate the one-dimensional consolidation characteristics of CPB samples are finally proposed and discussed.



## 1. Introduction

Cemented paste backfill (CPB) has become increasingly widespread, mainly because it reduces by 50–60 mass% the quantity of sulphidic tailings deposited on surface, increases ore recovery, and minimizes stoping sequences [1–3]. CPB usually consists of mixing dewatered and filtered "cake" total tailings (70–85 mass% solids) with single, binary and ternary hydraulic binders (typically 2–7 mass% for underground backfill) to meet the mechanical strength requirements. The preparation of CPB requires also mixing water for desirable consistency (15–25 cm slump) to assist plug flow of the resultant paste to its emplacement site. A number of works has been done on physico-chemical, mechanical and micro-structural properties of CPB materials at laboratory and meso scales [4–18]. Only a few studies have examined in situ properties of CPB, which differ greatly from those of laboratory-prepared and cured CPB samples [19–27]. It is common practice at most modern underground mines to hydraulically place the CPB within the mined-out stope in two sequences. The first sequence, called "plug fill", contains the highest binder content (7 mass%) and is left to cure under self-weight (or gravity-driven) consolidation for a few days (2–7 days), while the second

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sequence, called "residual fill", has lower binder content (typically 3–4.5 mass%) and is often left to cure under self-weight for a longer time. As a result, the plug fill will support an additional surcharge loading that could damage the formed cement bonds.

The settlement of saturated fresh mine backfill depends on the material's coefficient of consolidation $c_v$, which combines permeability coefficient (or saturated hydraulic conductivity $k_{sat}$) and stiffness, and on the filling rate [28–30]. As the stress ratio increases, void ratio decreases (including pore refinement and cementation by hydration and precipitation; [31,32] and the permeability decreases, thereby increasing the time required for water to flow out from the backfill voids [19,33,34,21,35–37]. However, the relationship between the filling rate and consolidation rate of fresh CPB during underground placement remains to be less understood. Only a few studies have examined the consolidation and saturated hydraulic conductivity behaviour of CPB [23,38–40].

A further key issue in freshly placed CPB material is the excess pore water pressure (PWP) that build-up during filling. If some consolidation is allowed to occur (through free drainage and PWP reduction) during filling, the result is effective stress development within CPB [28]. Following filling, the combined effects of what is assumed to be chemical shrinkage (also known as self-desiccation) and subsequent water drainage (increase of the effective stress) give rise to a reduction in total stresses due to the development of arching [28]. One can also speak that arching can take place even in the absence of self-desiccation and drainage. Specific research on self-desiccation in CPB can be found in Helinski et al. [21], Grabinsky and Simms [41], and Belem et al. [32]. Unconfined compressive strength (UCS) increases thereafter by a factor up to 2.4 or a difference of up to 58% compared to the UCS gained from the undrained CPB samples, depending on binder type and amount [33,35,42]. Thus, the knowledge of the consolidation characteristics of CPB is of great interest for a rational backfill design for underground mines.

The primary objective of this study was to investigate the one-dimensional consolidation characteristics of early age (a maximum curing time of 7 days) CPB materials prepared from a sulphide-rich mine tailings sample and a range of binder types and contents. A blended Portland cement (mixture of 20% GU Portland cement and 80% blast-furnace slag) was used as a reference binder since it provides the best CPB strength development. The originality of the present work lies in the attempt to understand the evolution of the CPB's consolidation parameters at early curing ages (i.e., compression index $C_c$, pore water pressure PWP, coefficient of consolidation $c_v$) using an innovative laboratory apparatus called CUAPS (curing under applied pressure system, [43,44] which is able to measure deformation within CPB. This information is essential to accurately predict the settlement of the CPB material placed in the mined-out stopes. A single regression model to predict consolidation parameters is also proposed and discussed.

**Table 1**
Physical and chemical properties of mine tailings used in this study.

| Physical parameter | Values | Chemical parameter | Values |
|---|---|---|---|
| Specific gravity $G_s$ | 3.71 | Iron, Fe (%) | 27.4 |
| Specific surface area $S_m$ ($m^2$/kg) | 2170 | Sulphur, S (%) | 20.6 |
| Clay size particles (<2 μm; %) | 4.7 | Aluminium, Al (%) | 2.8 |
| Silt size particles (2–75 μm; %) | 66.1 | Zinc, Zn (%) | 0.35 |
| Sand size particles (75–2000 μm; %) | 29.2 | Sodium, Na (%) | 0.3 |
| $D_{10}$ (effective particle size; μm) | 4.26 | Pyrite (%) | 47.05 |
| $D_{50}$ (average particle size; μm) | 24.27 | Quartz (%) | 31.6 |
| Coefficient of uniformity $C_u$ | 7.9 | Chlorite (%) | 8.9 |
| Coefficient of curvature $C_z$ | 1.1 | Paragonite (%) | 7.31 |
| Water content $w$ (%) | 23.5 | Muscovite (%) | 2.92 |
| Liquid limit $LL$ (%) | 23 | Talc (%) | 1.34 |

## 2. Material and methods

### 2.1. Mine tailings characteristics

The filtered total mine tailings sample (after cyanide destruction) was obtained from the LaRonde Mine milling complex (Quebec, Canada). It comes from the treatment of a polymetallic (gold–copper and zinc–silver mineralization) massive sulphide ore. The determination of the physical properties include specific gravity $G_s$, specific surface area $S_m$, water content $w$ (%), the grain size distribution (GSD) parameters, and the liquid limit $LL$. Table 1 lists some physical and chemical properties of the mine tailings studied. Based on the Unified Soil Classification System [45], the tailings material is non-plastic silt (ML). The mine tailings studied in this study have similar characteristics to other tailings reported in the literature [46–48].

### 2.2. Binder and mixing water characteristics

Binder and water were added to mine tailings to prepare the CPB mixtures. The three different binders used in the CPB mixtures were general use Portland cement (GU), blast-furnace slag (Slag) and type C fly ash (FA). GU was used alone, while GU and Slag, and GU and FA were blended in ratios of 20/80 and 60/40, respectively. The proportions were based on the ranges widely used by the mining industry for CPB preparation. The mixing water used was municipal tap water since the LaRonde mine use a fresh water. The specific gravity $G_s$ and specific surface area $S_s$ for GU, GU–Slag and GU–FA binder are 3.08 and 1.58 $m^2$/g, 2.92 and 2.84 $m^2$/g, and 2.88 and 1.66 $m^2$/g, respectively. Table 2 lists some physical and chemical properties of the binding agent and mixing water studied.

### 2.3. Experimental procedures

#### 2.3.1. Modified CUAPS apparatus

To investigate the mechanical strength properties of CPB materials cured under vertical stress in closely simulated in situ conditions (filling rate, placement and curing), an innovative lab apparatus called CUAPS (curing under applied pressure system) was developed by Benzaazoua et al. [43], inspired by an earlier simple set-up for curing under external vertical loads used by Belem et al. [33]. A schematic view of the CUAPS apparatus is presented in Fig. 1. The CUAPS apparatus consists of three main components: (i) a top loading device for applying vertical stress to the top of CPB sample at air pressures up to 600 kPa (with an LVDT for measuring vertical deformation and a loading piston), (ii) a Perspex mould forming the middle part (specimen holder and consolidation cell: ($D \times H$ = 101.5 × 203 mm) protected by a metal cylinder and (iii) a bottom drainage hole (which can be fitted with a PWP transducer) to drain excess pore water from the sample. The corresponding diameter-to-height ratio ($D/H$) is only 0.5. A full description of the CUAPS apparatus is beyond the scope of the present paper. However, detailed information on its features and some results can be found in Benzaazoua et al. [43], Yilmaz et al. [24,37,44], and Yilmaz [49].

#### 2.3.2. Paste backfill preparation: mixing, pouring and curing

To prepare the desired CPB consistency, the backfill ingredients (tailings, binding agent and tap water) were thoroughly mixed in a heavy-duty Hobart mixer (Model No. D 300-1) for approximately 12 min. The CPB samples were prepared using five different binder contents: 0 – control, 1, 3, 4.5 and 7 mass%, resulting in water-to-cement $w/c$ ratios ranging between 28.5 and 4.3 (note that only 1 and 4.5% binder proportions were used for the GU–FA and GU binders). The solid mass concentration for all samples was set at 78 mass%. The paste material was tested using the Abrams cone to achieve an average slump height of 177.8 mm for all CPB samples. Samples were then cast into the moulds in one-third increments. After the mould was filled, the paste was rammed in 25 blows using a small steel rod in order to eliminate any large trapped air bubbles within CPB, as described in the ASTM C143 standard [50]. The resultant average bulk unit weight $\gamma_{wet}$ of all fresh CPB samples was 22.3 kN/$m^3$. All samples were left to cure for 0, 1, 3 and 7 days in a controlled humidity room set at 23 °C ± 2 °C and 80% relative humidity. These external curing conditions replicate underground CPB-filled mine stope conditions.

#### 2.3.3. One-dimensional consolidation tests

The one-dimensional consolidation properties of CPB were determined by using the modified CUAPS apparatus with a maximum vertical effective stress of 400 kPa, which corresponds to typical compression stress values measured within mine backfilled stopes [20]. Immediately after samples were placed into the CUAPS consolidometer, a pre-contact pressure of 15 kPa was applied in order to place the loading piston and the top porous stone in contact with the top of the sample. An increasing pressure increment was then applied to consolidate the sample. According to ASTM Standard [51], a load (or pressure) increment ratio (LIR) of 1 was chosen. Thus, pressure increments of 25, 50, 100, 200 and 400 kPa were applied to the sample. Note that for each test an initial pressure of 0.5 kPa was applied right after each targeted curing time (0–7 days) to avoid log scale errors in the calculation. Each specimen was then loaded successively to a maximum pressure of