Predictive models for unconfined compressive strength of cemented paste backfills taking into account self-weight consolidation

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ABSTRACT
This paper present numerous UCS results obtained from plastic moulds, CUAPS (curing under applied pressure system) apparatus and *in situ* core specimens of cemented paste backfill. It was confirmed that the UCS from CUAPS-cured cemented paste backfill specimens were consistently higher than the one from plastic mould-cured cemented paste backfill specimens for a given backfill mixture recipe. Two semi-empirical general equations were proposed in order to predict the UCS of CUAPS-consolidated backfills from known UCS of plastic mould backfill specimens and the CUAPS-predicted UCS at a corresponding backfill depth. These two equations were both defined as a function of curing time and binder content. In addition, these equations can take into account the arching effect on the strength development within a backfilled stope. It has been demonstrated that these predictive equations can be used with 60% and 75% confidence limit.

RÉSUMÉ
Ce papier présente de nombreux résultats obtenus à partir d'UCS de remblais cimentés en pâte de moules en plastique, des appareils CUAPS (durcissement sous pression appliquée) et des carottes in situ. Il a été confirmé que les UCS de remblais consolidés à l'aide du CUAPS étaient constamment plus élevés que ceux obtenus à partir des remblais des moules en plastique pour une recette de mélange de remblai donné. Deux équations générales semi-empiriques ont été proposées afin de prédire les UCS de remblais consolidés à l'appareillage CUAPS à partir des UCS obtenus des spécimens des moules en plastique et l'UCS du remblai in situ correspondant à une profondeur donnée connaissant l'UCS des remblais des moules en plastique. Ces deux équations sont tous deux définis en fonction du temps de cure et de la teneur en liant. En outre, ces équations peuvent prendre en compte l'effet de la consolidation gravitaire sur le développement de la résistance dans un chantier remblayé. Il a été démontré que ces équations prédictives peuvent être utilisés avec entre 60% et 75% de niveau de confiance.

1 INTRODUCTION

Cemented paste backfill (CPB) is used in most modern mines around the world for underground open stope filling. CPB provide secondary ground support and a safe working floor for miners and machinery, and hence, allows a complete extraction of ore bodies. It also allows disposing significant amount (up to 50%) of mine tailings underground, which in turn decreases surface tailings storage requirements, thereby reducing environmental hazards and costs linked to future tailings management (e.g., Potvin et al., 2005; Belem and Benzaazoua, 2007). CPB is prepared by mixing the required amounts of filtered mine tailings (70–85 wt% solids) and mix water (recycled process water or tap water) to obtain the required slump (6–10") for transport purpose. A certain amount of binding agents, usually varying from 2% to 7% by dry mass of tailings, is added to achieve compressive strength. Binding agents typically consist of general use Portland cement (GU) blended with different types and amounts of supplementary cementitious materials such as blast furnace slag or fly ash (Benzaazoua et al. 2002, 2004; Kesimal et al. 2005). The CPB material prepared at the surface backfill plant is then transported by gravity and/or pumped underground. The structural stability of CPB-filled stopes depends on backfill long-term shear strength performance. The required long-term strength (in terms of unconfined compressive strength, UCS) and stability depend on different factors, such as stope geometry, mining method and CPB end-use application (waste disposal, pillar recovery, ground support, self-supporting, drift seal in backfill mass, or working floor). UCS is usually the key parameter used as a quality control one in the assessment of the CPB shear strength properties, and generally varies between 0.1 and 4 MPa (Belem and Benzaazoua 2007).

To determine the required strength for paste backfill design, UCS is generally obtained from laboratory-prepared CPB specimens. Backfill specimens are usually poured into conventional plastic capped moulds and cured under undrained or drained conditions in a humidity chamber at constant relative humidity and temperature. However, many laboratory and *in situ* tests have shown that for a given mix recipe and curing time, the UCS of *in situ* CPB specimens can be 2 to 6 times higher than the UCS of laboratory samples using the same CPB mixture poured into conventional plastic moulds (Belem et al., 2002; le Roux et al., 2002; Cayouette, 2003; Revell, 2004). This unforeseen difference between laboratory and *in situ* results cannot be ignored when optimizing a CPB recipe since this could allow reducing the amount of binder to use (Belem et al., 2002).

The reasons supporting this discrepancy between the UCS of mould specimens and in situ stope core specimens could be explained by the combined effects of placement, curing under stresses, drainage, self-weight and/or time-dependent consolidation and cement hydration (Belem et al., 2002, 2010; Helinski et al., 2006, 2007a; Yilmaz et al., 2008a, b, 2009, 2011). However, in most cases, only the paste backfill ingredients (e.g., tailings, cement and water) are considered in the investigations of CPB properties. Only few studies in the literature have attempted to better understand the effects of self-weight consolidation on the evolution of CPB properties (Pierce 1997; Belem et al. 2002; le Roux 2004). Some investigations used experimental set-ups that allow backfill specimens to consolidate and acceleration of the rate of hydration due to drainage, thus improving the CPB strength properties (e.g., Mitchell and Smith, 1981; Belem et al., 2002, 2006; Helinski et al., 2006, 2007a; Fourie et al., 2007; Yilmaz et al., 2009). In this regard, the so-called CUAPS apparatus (curing under applied pressure system) was designed and developed for the purpose of preparing laboratory CPB specimens that realistically mimic *in situ* conditions (i.e., CPB-filled stopes) at the *Université du Québec en Abitibi-Témiscamingue* (UQAT). This apparatus was initially intended for examining the strength development of the CPB specimens cured under equivalent overburden or self-weight pressure (Benzaazoua et al., 2006; Yilmaz et al., 2008a, 2009). Ghirian and Fall (2015) tried to present another apparatus called CUS (curing under stress) apparatus which remain basically a copy of the original CUAPS apparatus.

The objective of this paper is to perform self-weight consolidation of CPB specimens using an improved CUAPS apparatus, which mimics the *in situ* stope conditions and allows the assessment of CPB properties. The paper presents numerous UCS results obtained from plastic moulds, the CUAPS apparatus and in situ core specimens. Two empirical models were proposed in order to predict i) the UCS of CUAPS-consolidated backfill specimens from known UCS obtained with plastic mould-cured CPB specimens, and ii) the UCS of equivalent *in situ* backfill from CUAPS data at a corresponding backfilled stope depth. The proposed two empirical models were both defined as a function of curing time and binder content. These models can take into account the arching effect on the compressive strength development within a backfilled stope. In addition, the model predictions were compared to different plastic moulds, CUAPS apparatus and in situ UCS data of CPB taken from the literature.

2 MATERIALS AND METHODS

2.1 Cemented paste backfill mixture ingredients

2.1.1 Mine tailings sample

Sulfide-rich tailings were sampled from a polymetallic hard rock mine (Au, Ag, Cu, Zn) located in the province of Quebec, Canada. The tailings sample has a specific gravity G_s of 3.71 and a BET specific surface area S_m of 2170 $m^2.kg^{-1}$. This tailings sample has a liquid limit of 23% and a plastic limit close to zero and is categorized as non-plastic silt (ML) in the USCS classification (Table 1). Similar values have been reported by Bussiere (2007). Grain size distribution (GSD) of the tailings was obtained using a Malvern Laser Mastersizer S2000 (Figure 1).

Table 1. Physical characteristics of the mine tailings

Element (unit)	Value
Initial gravimetric water content *w* (%)	23.45
Specific gravity G_s	3.71
BET specific surface area S_s (m^2/g)	2.17
Liquid limit *LL* (%)	23
Clay size particles (< 2μm; %)	4.7
Silt size particles (2–50 μm; %)	66.13
Sand size particles (50–2000 μm; %)	29.18
Fines content (< 20 μm; %)	43.87
D_{10} (effective particle size; μm)	4.26
Coefficient of uniformity, C_U	7.88
Coefficient of curvature, C_C	1.04
USCS classification	ML

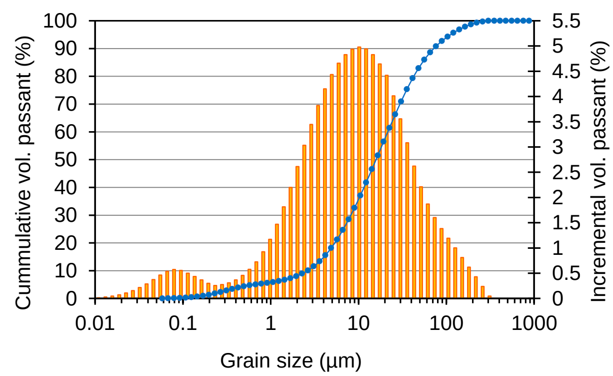

Figure 1. Grain size distribution (GSD) of the mine tailings sample

Chemical composition analysis showed that iron Fe, total sulfur S, aluminum Al, and calcium Ca contents were 27.4 wt%, 20.6 wt%, 2.8 wt%, and 0.57 wt%, respectively. Mineralogy of the tailings was obtained by X-ray diffraction (XRD; Bruker AXS D8 Advance Diffractometer): pyrite (47.1 wt%), quartz (31.6 wt%), chlorite (8.9 wt%), and paragonite (7.3 wt%).

2.1.2 Binding agent

The binder type used (GU-Slag@20:80) for CPB mixtures preparation was a blend of 80 % ground blast furnace slag (GBFS) and 20 % general use Portland cement (GU). Three binder contents of 3, 4.5, and 7 wt% were used to produce the CPB mixes.

2.1.3 Mixing water

The mixing water used was tap water. The pH, Eh (redox potential), and EC (electrical conductivity) of the mixing water were analyzed using a Benchtop pH/ISE Meter, Orion Model 920A with a Thermo Orion Triode combination electrode (Table 3), and were determined to be 7.8, +0.43 V, and 0.3 mS/cm. The Eh was first determined using a Pt/Ag/AgCl electrode and then converted into the standard hydrogen electron potential.

2.2 Cemented paste backfill preparation

The required amounts of CPB ingredients (filter cake tailings, binding agent, and mixing water) were thoroughly mixed and homogenized in a double spiral concrete mixer for about 7 minutes to ensure homogeneity of the final paste. Initial water content for all CPB mixes was set at 28.2 % (the equivalent solid mass concentration is 78 %). The binder proportions were 3, 4.5, and 7 wt% with corresponding water-to-binder (w/b) ratios of 9.7, 6.5, and 4.3 respectively. Immediately after mixing, CPB specimens were cast in both conventional plastic (non-perforated bottom ends) molds and CUAPS molds. Both plastic and CUAPS molds had a diameter-to-height (D/H) ratio of 2 (DxH: 102 x 204 mm). Backfill paste was poured into plastic and Perspex molds in three layers, each tamped 25 times with a steel rod to remove most of the air bubbles within the specimen. CPB specimens in capped plastic and CUAPS molds were placed in a humid chamber and cured for 7, 14, and 28 days at 24°C and ≥ 80% RH (relative humidity) to simulate typical curing conditions in underground mines (Figure 2).

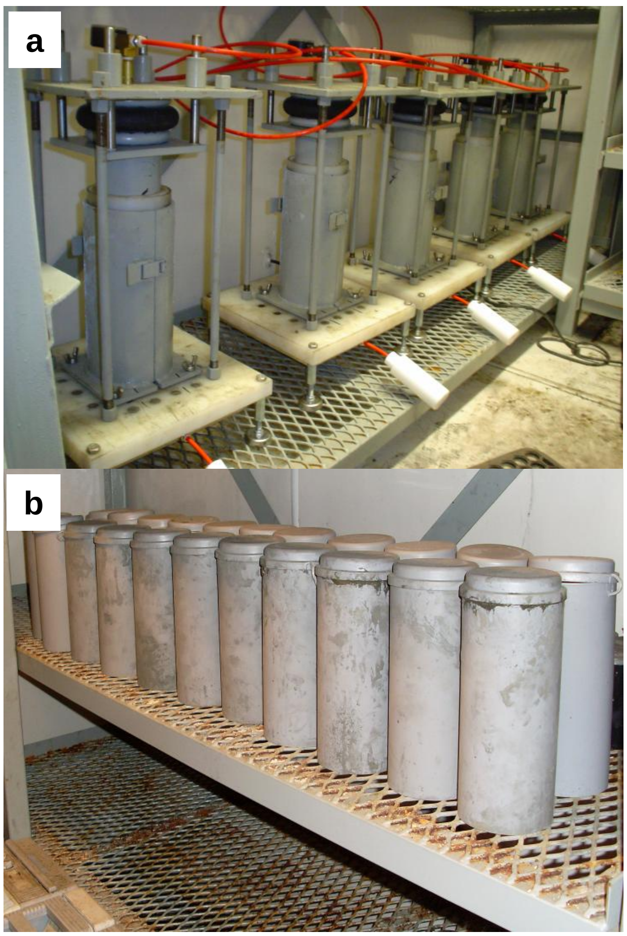

Figure 2. Photos showing ***a***) CUAPS and ***b***) conventional plastic moulds with CPB specimens curing in a humid chamber (after Yilmaz et al., 2011)

The CUAPS apparatus (a total of 10 were used) allows simulating *in situ* placement properties and curing conditions for laboratory-prepared CPB specimens. The CUAPS consists of three main parts: a sample holder (Perspex mold), a pneumatic pressure loading plate equipped with a piston, and a lower plate provided with a drainage port with an outlet for collecting water. A detailed description of the CUAPS apparatus is beyond the scope of this paper, but interested readers are referred to Benzaazoua et al. (2006), Yilmaz et al. (2009, 2010) and Yilmaz (2009).

2.3 Experimental program

2.3.1 Self-weight consolidation of CPB

To investigate the effects of curing under pressure (self-weight consolidation) on the strength of CPB materials during curing, the CUAPS apparatuses were used (Benzaazoua et al., 2006; Yilmaz et al., 2010). After mounting the CPB specimen contained in the Perspex mold, no pressure is applied for the first half an hour, after which pressure is applied and gradually increased to 400 kPa. The final pressure corresponds to an equivalent overburden stress of 17.6 m in height of CPB within an underground stope and having a bulk unit weight γ of 22.7 kN/m^3. Each CUAPS-consolidated specimen was left to cure under the final pressure of 400 kPa for relatively short-term curing times (7, 14 and 28 days). These tests aimed at better simulating the effect of different stope filling rates and backfill heights on the resultant strength properties of CPB. The scenario considers backfilling of underground stope at four different heights of 5, 10, 15 and 20 m for a total duration of 50 h. Table 2 summarizes the calculations of the equivalent overburdens or vertical pressures $p_v = \gamma h$ (kPa) and corresponding CPB filling rate r_f (m/h), assuming no arching effect. Each sample was then left to cure for 7, 14 and 28 days under final overburden pressures of 113.5, 227, 340.5 and 454 kPa which correspond to the backfilled stope heights of 5, 10, 15 and 20 m, respectively.

Table 2. Calculated equivalent CPB heights, overburden pressures and filling rates for self-weight consolidation using CUAPS (adapted from Yilmaz et al., 2010)

Backfill height in the stope *h* (m)	Equivalent overburden stress p_v (kPa)	Equivalent filling rate r_f (m/h)
5	113.5	0.1
10	227.0	0.2
15	340.5	0.3
20	454.0	0.4

2.3.2 Unconfined compression tests on CPB

After the curing times of 7, 14, and 28 days, the CPB specimens (extracted from plastic and CUAPS Perspex molds) were subjected to uniaxial compression tests (based on ASTM C39 method) in order to determine the unconfined compressive strength (UCS) using a computer controlled press (MTS 10/GL) with a load capacity of 50 kN and a deformation rate of 1 mm/min. Axial deformation was digitally recorded by a real-time data acquisition system. The UCS corresponds to the maximum stress (peak at failure) reached during compression. For a given CPB mix recipe, only one test was performed for CUAPS-consolidated specimens, whereas triplicate tests were performed for plastic mold-unconsolidated specimens. However, the reproducibility tests showed reliable and repeatable results across CUAPS specimens (Yilmaz et al., 2009).

3 RESULTS

3.1 Compressive strength of CPB specimens

Table 3 presents the UCS values of all tested CUAPS-consolidation and plastic molds unconsolidated (drained and undrained) CPB specimens. It is apparent that there is a relationship between the curing conditions (self-weight consolidated and unconsolidated) and the strength development within CPB specimen. Self-weight consolidated specimens always produce higher UCS values than unconsolidated (drained and undrained) specimens for a given binder content. In comparison, the UCS values of CUAPS-consolidated specimens having a binder content of 3 wt% were respectively 57.9%, 64.3% and 58.2% higher than those of unconsolidated-undrained specimens for the curing times of 7, 14 and 28 days. With the binder contents of 4.5 and 7 wt%, these values were 52.3%, 54.4% and 51.8% higher, and 50.5%, 27.1% and 19.8% higher (Yilmaz et la., 2011). It can be noticed that as the binder content increases up to 4.5 wt%, the percentage of UCS increase of consolidated specimens is higher. The addition of 7 wt% binder increases the UCS value by a factor of approximately 1½ between 7 and 28 days of curing. The reasons behind why consolidated CPB specimens give higher UCS values than unconsolidated-undrained ones (which are commonly used for CPB stability analysis and design) could be explained by the effective curing conditions based on the combined effects of applied pressures (self-weight consolidation) during curing and removal of excess water which accelerates the rate of the binder hydration, leading to more pozzolanic reactions and C-S-H gel formation for a given curing time, and thus provide higher UCS (Yilmaz et al., 2011).

Table 3. Summary of the UCS results for CUAPS-consolidated and plastic molds unconsolidated (drained and undrained) CPB specimens (from Yilmaz et al., 2010, 2011)

Curing time (days)	UCS CUAPS-consolidated CPB		
	3 wt%	4.5 wt%	7 wt%
7	793.8	1506.0	3015.2
14	2024.8	2864.9	3194.5
28	2311.9	3080.7	3428.9
	UCS Plastic mold (undrained) CPB		
7	334.3	718.4	1493.0
14	721.9	1306.6	2328.8
28	967.2	1486.0	2751.4
	UCS Plastic mold (drained) CPB		
7	425.6	803.6	1721.7
14	1005.5	1620.6	2661.2
28	1305.4	2196.3	3215.3

3.2 Semi-empirical models development

3.2.1 Model for predicting CUAPS data from mold data

Since the common practice is to obtain UCS values from plastic molds (drained or undrained) CPB specimens, it is appropriate to propose a relationship allowing the prediction, for a first approximation, of UCS accounting for the effect of curing under self-weight consolidation. It is first assumed that the UCS_{cuaps} obtained after curing under applied pressure (equivalent to an effective stress since the pore pressure was allowed to dissipate) is the algebraic sum of the UCS_{hyd} due purely to the hydration and which can be obtained from drained or undrained plastic mold specimens ($UCS_{hyd} = UCS_{mold}$) and the UCS_{pv} due solely to the influence of applied pressure (rearrangement of the solid grains prior to the beginning of hydration). This is expressed by the following equation:

$$UCS_{cuaps(kPa)} = UCS_{mold} + UCS_{pv} \quad [1]$$

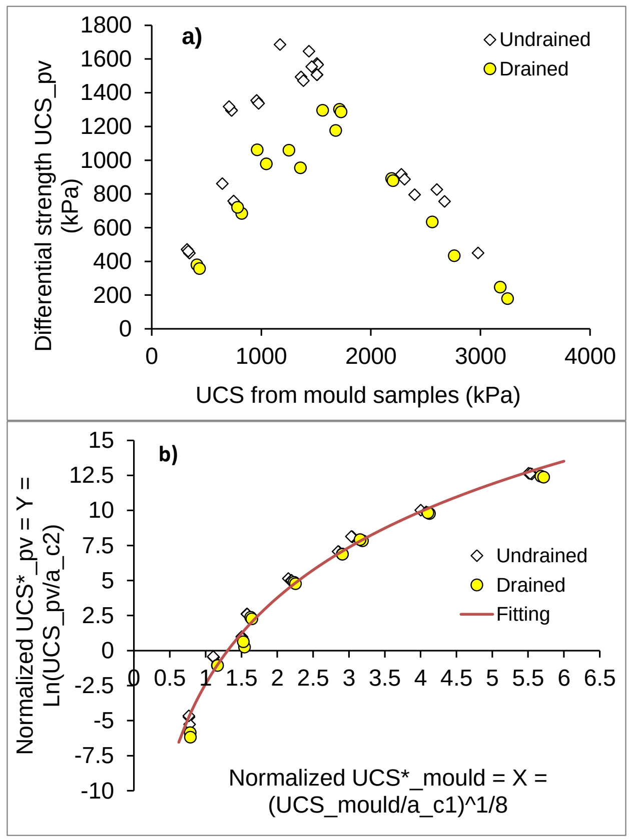

Figure 3. Variation in differential strength UCS_{pv} with the UCS obtained from mold specimens: a) direct relationship; b) normalized variables

From Eq. [1] it can be seen that the UCS due solely to pressure application UCS_{pv} is the difference between UCS_{cuaps} and UCS_{mold} (= differential strength $\Delta UCS = UCS_{cuaps} - UCS_{mold} = UCS_{pv}$). It remains then to predict this "differential strength". However, at this stage of the author's knowledge it's believed it would be easier to propose an empirical model for predicting UCS_{pv} from known UCS_{mold} (drained or undrained mould backfills) to be used in Eq. [1] rather than an analytical solution.

Figure 3a is a plot of the differential strength UCS_{pv} against UCS_{mold} and it can be seen that no exploitable correlation exists. Before doing a regression analysis to get an empirical relationship, a «master-curve» should be obtained from Figure3a through variable change by normalizing UCS_{pv} and UCS_{mold} in a way of keeping consistent units. For this purpose, let us first define a normalized time factor $t_n = t^*B_w/t_{min}$, which is the combination of curing time and binder content effects, where *t* is curing time (day), t_{min} is a minimum curing time taken arbitrarily to be equal to 1 day and B_w is the fractional binder content (percentage of binder divided by 100). Let define secondly the normalization parameters $a_{c1} = p_a^*(t_n)^8$ (for dependent variable UCS_{mold}, i.e. UCS_{mold}/a_{c1}) and $a_{c2} = p_v^*(t_n)^8$ (for independent variable UCS_{pv}, i.e. UCS_{pv}/a_{c2}), where p_a is the atmospheric pressure (= 101 kPa) and p_v is the final applied vertical pressure or effective stress (in kPa). The final variable change is $X = (UCS_{mold}/a_{c1})^{1/8}$ and $Y = Ln(UCS_{pv}/a_{c2})$, where the exponents 8 (in a_{c1} and a_{c2}) and 1/8, and the natural logarithm were chosen only in order to get the best possible fitting. Figure 3b is a plot of variable Y against variable X and it can be seen a clear good correlation between normalized UCS_{pv} and UCS_{mold}. The data in Figure 3b are well fitted with a natural logarithm function $Y = a + b\text{Ln}(X)$ (coefficient of correlation $r = 0.993$).

By replacing the variables X and Y by their expression into $Y = a + b\text{Ln}(X)$ and making some rearrangements the final empirical relationship for predicting UCS_{pv} from UCS_{mould} is given as follows:

$$UCS_{pv}(kPa) = \Omega \cdot p_v \cdot \left(\frac{t \cdot B_w}{t_{min}}\right)^m \cdot \left(\frac{UCS_{mold}}{p_a}\right)^n \qquad [2]$$

where Ω, *m* and *n* are fitting constants (unitless). For the data set used, the constant values Ω, m and n are: $\Omega = 0.1929$; $m = -0.2672$ and $n = 0.75$, with a very good coefficient of correlation $r = 0.9934$. It should be noteworthy that the range of vertical pressures 0–400 kPa is also typical compression stress values measured within the CPB-filled stopes (Belem et al., 2004; le Roux et al., 2005; Li and Aubertin, 2009).

Substituting Eq. [2] into Eq. [1] yields the proposed general semi-empirical model for predicting the equivalent CUAPS-consolidated CPB specimen's strength (UCS_{cuaps}) from known drained or undrained plastic mold specimen's strength (UCS_{mould}) given as follows:

$$UCS_{cuaps}(kPa) = UCS_{mold} + 0.1929 \cdot p_v \cdot \left(\frac{t \cdot B_w}{1\ day}\right)^{-0.2672} \cdot \left(\frac{UCS_{mold}}{101\ kPa}\right)^{0.75} \qquad [3]$$

Based on existing CUAPS test data, it was observed that Eq. [3] can be used with 60% confidence limit (±40% range). The advantage of Eq. [3] is that it is conservative enough to be used with a confidence limit of 60% with pressures above 400 kPa. Indeed, Figure 4 shows the evaluation of the theoretical variation of predicted CUAPS apparatus UCS (UCS_{cuaps_pred}) using Eq. [3] for a backfill prepared with the binder type GU-Slag@20:80 (specific gravity Gs of tailings is 3.72).

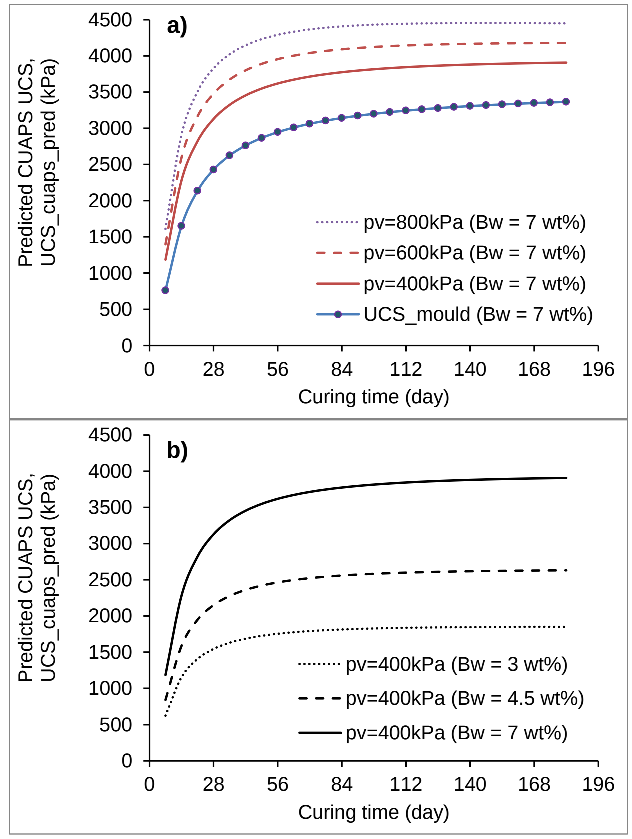

Figure 4. Variation of predicted UCS from CUAPS with: a) curing time and for different curing pressure and B_w = 7 %, b) curing time and for different binder content with p_v = 400 kPa

Figure 4a shows the evolution of UCS_{cuaps_pred} with curing time and for different curing stresses (stope depths) (400, 600 and 800 kPa) and a constant binder content of 7 %. It can be observed that the increase in curing stress leads to an increase in UCS_{cuaps_pred}. Figure 4b presents the evolution of UCS_{cuaps_pred} with curing time and for different binder content (3, 4.5 and 7 wt%) and a constant curing pressure of 400 kPa. From this figure, it can be seen the direct effect of binder content on UCS_{cuaps_pred} which hugely increases when the binder content is increased from 3 % to 7 %.

3.2.2 Model for predicting in situ data from mold data

Another way of doing is to try to directly predict the in situ strength from laboratory plastic mold data. As for the prediction of UCS_{cuaps}, it's assumed first that the UCS(h) obtained at a corresponding depth *h* in a backfilled stope with CPB containing $B_{w\%}$ binder and after a curing time *t* is the algebraic sum of the UCS_0 obtained on top of the stope ($UCS_0 = UCS_{top} = UCS_{mold}$) due purely to the hydration and which can be obtained from a plastic mold (drained or undrained) and the $UCS_{overburden}$ due solely to the influence of overburden pressure $\sigma_v(h)$ (= γh if no arching effect is taking into account) which can account for the arching effect. This is expressed by the following equation:

$$UCS(h) = UCS_{top(h=0)} + UCS_{overburden} = UCS_{mold(h=0)} + UCS_{overburden} \quad [4]$$

As in previous development, UCS_{mold} (= UCS_{top}) is easy to obtain then it remain $UCS_{overburden}$ to be predicted. The linear formulation in Eq. [4] is based on observation of field, meso-scale columns and CUAPS-predicted in situ data trends. From this equation it can be seen that the UCS due solely to overburden pressure $UCS_{overburden}$ is also the difference between UCS(h) and $UCS_{mold(h=0)}$. Table 4 contains the CUAPS simulated in situ strength and plastic molds UCS data for CPB prepared with 4.5 % of binder type GU-Slag@20:80.

Table 4. Summary of the UCS results for CUAPS-simulated in situ strength and plastic molds unconsolidated (undrained) strength (from Yilmaz et al., 2010)

Stope depth h (m)	Curing time t (day)	UCS(h) (kPa)	Binder content Bw%	$UCS_{mold(h=0)}$ (kPa)
5	7	357	4.5	167
5	14	1347	4.5	822
5	28	2090	4.5	1455
10	7	453	4.5	167
10	14	1939	4.5	822
10	28	2569	4.5	1455
15	7	619	4.5	167
15	14	2203	4.5	822
15	28	2802	4.5	1455
20	7	680	4.5	167
20	14	2563	4.5	822
20	28	3109	4.5	1455

Before doing a regression analysis to get an empirical model, a master-curve should also be obtained through variable change by normalizing $UCS_{overburden}$ (= UCS(h) – UCS_{mold}) and the overburden stress. For this purpose, the predefined normalized time factor t_n (= $t*B_w/t_{min}$) was retained. Let us define the normalization parameter $d_c = (t_n)^3$. The proposed variable change aimed at keeping a linear relationship and this is achieved by taking X = ($\sigma_v * d_c$) and Y = $UCS_{overburden} * d_c * (\gamma h)^{1/4}$, where the exponents 3 (in d_c) and 1/4 were chosen only in order to get the best possible fitting. The data from Table 4 are well fitted with a power law function: $Y = a*X^b$, where a and b are constants.

Replacing the variable X and Y by their expression into Eq. [4] and making some rearrangements the final empirical relationship for predicting $UCS_{overburden}$ from the overburden stress $\sigma_v = \gamma h$ or vertical stress with arching effect is given as follows:

$$UCS_{overburden}(h)_{kPa} = A \cdot \left(\frac{t \cdot B_w}{t_{\min}}\right)^{\alpha} \cdot (\sigma_v)^{\beta} \quad [5]$$

where A = strength proportionality parameter depending on the backfill type ($[kPa]^{1-\beta}$), t, t_{min} and B_w are previously defined, h = backfill depth (m), α and β = fitting constants. For the data set used (4.5 % of binder GU-Slag@20:80 and the range of simulated stope depth of 5–20 m), the constants A, α and β are: A = 25.61 $kPa^{(1-\beta)}$; $\alpha = -0.1814$ and $\beta = 0.6895$, with a very high coefficient of correlation r = 0.9989.

Substituting Eq. [5] into Eq. [4] yields the general proposed semi-empirical model for predicting the UCS(h) at equivalent depth h in a backfilled stope from the overburden pressure or arching vertical stress is given as follows:

$$UCS(h)_{kPa} = UCS_{mold(h=0)} + 25.61\left(\frac{t \cdot B_w}{1\ day}\right)^{-0.1814} \cdot (\sigma_v)^{0.6895} \quad [6]$$

The arching stress $\sigma_{v\_arching} = \sigma'_v$ because the pore pressure is supposed to be fully dissipated through self-weight consolidation. The analytical solution of vertical arching stress proposed by Aubertin et al. (2003) can be used with the at-rest state (K_0 condition), but any other vertical arching stress analytical equation can be used in Eq. [6] for predicting $UCS(h)_{arching}$. For the Eq. [6] to be useful it should be validated using both in situ data and meso-scale experimental data from different sources to ensure applicability to various CPB mixtures over a wide range of strength values and to provide a more general relationship. Fortunately, the literature documents a number of UCS data obtained from different sources such as in situ backfill core samples and meso-scale column-filled samples that take into account the stope depth effect (Cayouette, 2003; Belem et al., 2006; Thakur, 2008; El Aatar, 2009).

Figure 5 presents a comparison between measured and predicted depth-dependent UCS for different CPB materials. It can be observed that the UCS(h) is satisfactorily predicted using Eq. [6]. From this figure it can be also concluded that Eq. [6] can be used for predicting the depth-dependent UCS of CPB materials with at least 75% of confidence (±25% range). As Eq. [6] is validated over existing available data it can be used to compare the predicted *vs* the measured in situ UCS data from Louvicourt Mine backfilled stope #5618-2 (data from Cayouette, 2003). Figure 6 presents this comparison where it can be seen that 78% of the data point lie within the ±25 range.

Eq. [6] can also be used to evaluate the theoretical evolution of depth-dependent UCS of backfilled stopes for various curing time and binder contents. Indeed, Figure 7 shows the evaluation of the theoretical variation of predicted stope depth-dependent UCS(h) using Eq. [6] for the same previous CPB prepared with the binder type GU-Slag@20:80. Figure 7a shows the evolution of UCS(h) with backfilled stope depth h (no arching effect) and for different curing times (7, 14, 28, 56 and 91 days).

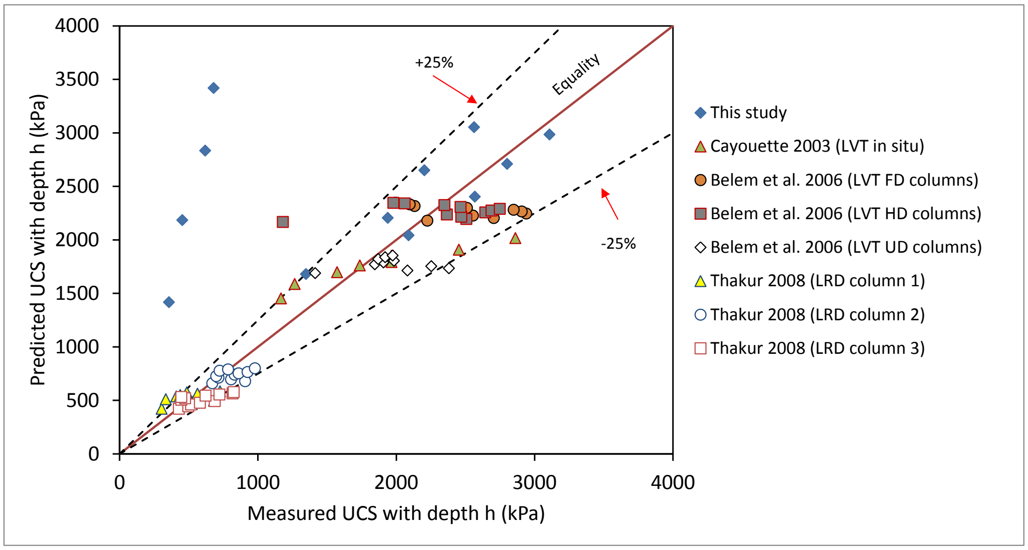

Figure 5. Comparison of predicted and measured depth-dependent UCS for different CPB mixture data taken from the literature

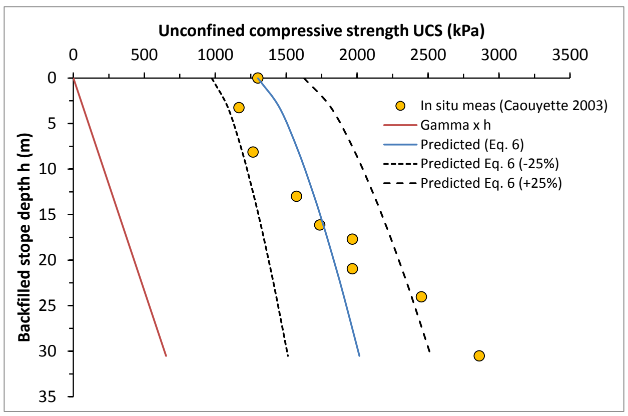

Figure 6. Comparison of predicted and measured depth-dependent UCS for Louvicourt Mine in situ backfilled stope (data from Cayouette, 2003)

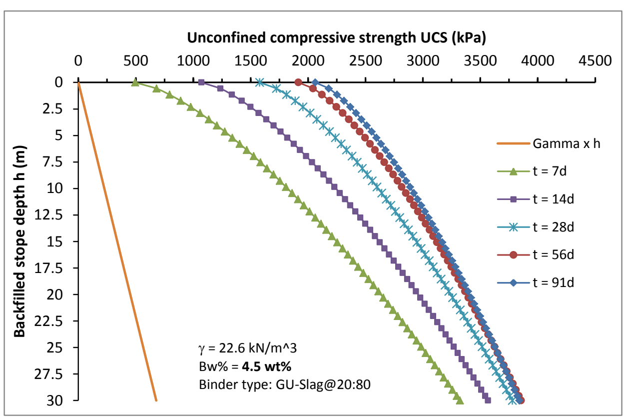

Figure 7. Theoretical variation of predicted UCS with backfilled-stope depth *h*: effect of overburden pressure and curing time

CONCLUDING REMARKS

Along with experimental validations, two semi-empirical general equations (Eqs. 3 and 6) were proposed in order to predict the UCS of CUAPS-consolidated backfills from known UCS of undrained or drained mold backfill specimens (Eq. [3]) and the in situ UCS(h) at a corresponding backfilled depth (Eq. [6]).

These two equations were both defined as a function of curing time *t* and binder content $B_{w\%}$. In addition, these equations can take into account the arching effect on the strength development within a backfilled stope. Also, Eq. [3] can be used with 60% confidence limit, while Eq. [6] can be used with 75% confidence limit.

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