SELF-WEIGHT CONSOLIDATION OF CEMENTED PASTE BACKFILL IN 3-M HIGH COLUMNS

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ABSTRACT

This paper investigates and simulates the effect of underground placement conditions of cemented paste backfill (CPB) on the evolution of its physical and mechanical properties. Experimental set-ups that consist of PVC/Makrolon® GP polycarbonate sheet columns, each 3 m high, were built and filled with CPB at two different backfill plants. These set-ups allow simulating undrained (UD), laterally partially-drained (LPD) and laterally fully-drained (LFD) conditions and the measurement of resulting self-weight consolidation settlement of CPB. The results show that maximum drainage water percentages of 15% and 8% of the CPB total initial water were observed for the LFD and the LPD columns. The results also suggest that *in situ* backfilled stopes behave in a similar way to that of LFD or LPD conditions.

Keywords: Cemented paste backfill, Drainage, Self-weight consolidation, Filling rate, Column tests

INTRODUCTION

Cemented paste backfilling technique, which uses a viscous mixture made of mine tailings filter cake, a binding agent and mixing water, is becoming a common practice in underground hard rock mines worldwide. However, the nature of cemented paste backfill (CPB) material is very complex. Indeed, the geotechnical and geochemical properties of CPB material are in continuous change since their preparation to their placement underground and hardening [1]. Recent studies showed that for a given mix recipe and curing time the unconfined compressive strength (UCS) of *in situ* CPB core samples can be 2 to 6 times higher than samples of the same CPB mix poured into plastic molds [2]–[5]. Also, the same observations were made for CPB samples prepared and cured in laboratory conditions compared to *in situ* underground CPB samples [6], [7]. These differences in compressive strength could be attributed partly to the CPB hardening conditions [8] in the stope such as: stope size and geometry, stope walls convergence against the fill mass and its resulting shrinkage [9]. Other factors of influence are the water bleeding and the gravity-driven consolidation settlement (self-weight consolidation) of the CPB mass which may depend on its physical-geochemical properties and also on the physical properties of the surrounding rock mass (fracturing). It was reported that this self-weight consolidation settlement can reach more than 1 m [4] and is usually considered to positively affect the CPB strength development [2], [3]. A relatively large number of experimental studies are reported in the literature on the self-weight consolidation of granular slurries, debris, dredge materials or waste rock and mine tailings [10], [11]. The originality of the present study, however, is that it considers high density slurry (solids mass concentration ranging between 70% and 85% w/w). Only limited numbers of investigation on the consolidation behavior of CPB have been completed to date [2], [12]–[15].

The purpose of this paper is to a the physical and mechanical properties of CPB prepared at two mines paste backfill plant, poured and cured into 3-m high PVC/Makrolon® polycarbonate sheets transparent columns following three drainage scenarios: fully-drained, partially-drained and undrained conditions. The main objective is to better understand the effect of self-weight consolidation settlement of CPB on its physical and mechanical properties.

MATERIAL AND METHODS

CPB self-weight consolidation columns

In-stope CPB self-weight consolidation can occur through different drainage scenarios either laterally (across the stope walls) or at the base of the stope (usually impervious). In this study, the gravity-driven consolidation tests were performed at the LVT and LRD mine backfill plants in Quebec, Canada. To simulate CPB placement in underground mine stope and its self-weight consolidation, three PVC/Makrolon® GP transparent polycarbonate sheet columns having 31.5 x 30.5 cm^2 section and 300 cm height were manufactured. The columns allow simulating the stope backfilling sequences as well as various drainage configuration scenarios (laterally and vertically).

Drainage scenarios

The drainage of CPB is allowed through a seal of geotextile, and is prevented using a rubber seal. For LRD mine backfill CT1, a single drainage scenario was studied: lateral drainage (fully drained laterally where drainage is allowed along the entire height of the column) and vertical drainage (at the base of the columns) occurring simultaneously (Fig. 1a).

For LVT mine backfill CT2, three drainage scenarios were studied: a laterally fully-drained (LFD) column where drainage is allowed along the entire height of the column (base case), a laterally partially-drained (LPD) column where drainage is allowed only on the lower half of the column (intermediate case) and undrained (UD) column where drainage is not allowed (Fig. 1b). The drainage water (vertically and laterally) is collected in different bottles to be weighted. Also, pore water pressure in the backfill CT1 columns was measured using pressure sensors installed at 70 cm and 180 cm from the base of the columns (see Fig. 1a).

Backfill materials

The CPB used at LVT mine was made up of slightly deslimed tailings (by 5% of minus 20 μm particle size) and mixed with recycled mine process water while at LRD mine, full stream tailings and lake water were used for CPB preparation. At the end of the mixing process the LVT mine CPB has a final standard cone slump height of 19.8 cm (7.8”), while this value was set to 26.7 cm (10.5”) at LRD mine.

The paste backfill mixture (CT1) used to fill column 1, column 2 and column 3 were prepared at the LRD mine backfill plant. Three different backfill mix recipes were prepared and each column was filled with a single recipe: column 1 with 100% of GU (general use Portland cement), column 2 with blended binder 50%GU/50%Slag and column 3 with blended binder 50%GU50/%HS (HS is high sulfate resisting Portland cement). The final mixtures contained 5 wt% of binder and solid content C_w(%) of 76 wt%. The resulting total unit weight is 22.1 kN/m^3 while the dry unit weight is 16.8 kN/m^3 (see Table 1).

The paste backfill mixture (CT2) used to fill the UD, LFD and LPD columns were prepared at the LVT mine backfill plant. A single backfill mix recipe was used with a blended binder 20%GU/80%Slag. The final mixture contained 4.5 wt% of binder and solid content C_w(%) of 75.8 wt%. The resulting total unit weight is 21.4 kN/m^3 while the dry unit weight is 16.2 kN/m^3 (see Table 1).

METHODS

Sequential filling of the columns

LRD mine columns (backfill CT1)

The three columns were filled with the backfill CT1 in two sequences of filling as shown in Fig. 1a. The filling rate r_f and filling time t were derived from LRD mine practice. Indeed, the rate of rise for LRD mine medium sized stope (30 m high) was $r_{f(stope)}$ = 1.21 m/h for a total duration of t = 24 h, which would correspond to $r_{f(column)}$ = 0.121 m/h or 12.1 cm/h for a 3-m high column (scale factor of 10). Rather than trying to fill the columns at this filling rate, it was choose to fill them in two sequences each of 1.45 m, with a time interval between the two sequences of 12 h (a total period of 24 h). Thus, the first layers (or sequences) of 1.45 m thick in the three columns were all filled during the first 12 hours of the first day, while the second layers (or sequences) were filled during the 12 hours following the second day for a total of 24 hours to complete filling of the columns (Figs. 2a, b).

The filled columns were left to cure in ambient air at the LRD paste backfill plant for a curing period of 94-day for the Column 1 CPB (GU), 98-day for the Column 2 CPB (50GU/50Slag), and 102-day for the Column 3 CPB (50GU/50HS).

Table 1 Various parameters of the backfills CT1 and CT2

	CT1 Column 1	CT1 Column 2	CT1 Column 3	CT2 UD col.	CT2 HDL col.	CT2 FDL col.
C_w(%)	76	76	76	75.8	75.8	75.8
V_T (L)	279	279	279	288	288	288
ρ_h (kg/m^3)	2150	2146	2151	2180	2180	2180
ρ_s (kg/m^3)	3624	3609	3625	3500	3500	3500
M_T (kg)	599.03	597.91	599.31	628.33	628.33	628.33
M_w (kg)	143.8	143.5	143.8	152.06	152.06	152.06
M_s (kg)	455.3	454.4	455.5	476.3	476.3	476.3
V_s (L)	125.62	125.91	125.65	136.08	136.08	136.08
V_{v0} (L)	153.4	153.1	153.4	151.9	151.9	151.9
e_0	1.22	1.22	1.22	1.12	1.12	1.12

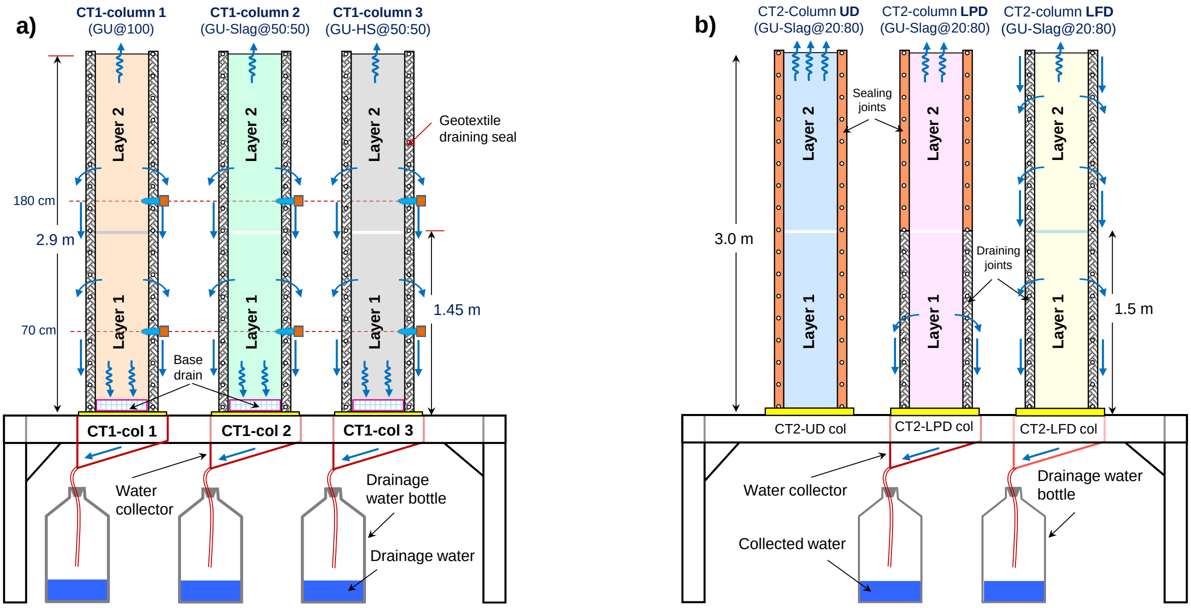

Fig. 1 Schematic diagram of the three consolidation columns used at: a) LRD mine backfill plant b) LVT mine backfill plant (modified from [16] and [17]).

LVT mine columns (backfill CT2)

The columns were filled with the backfill CT2 in two sequences of filling as shown in Fig. 1b and in the similar way than backfill CT1. The filling rate r_f and filling time t were derived from LVT mine practice: the rate of rise for LVT mine of 30 m high stope was $r_{f(stope)}$ = 1.25 m/h for a total duration of t = 24 h, which would correspond to $r_{f(column)}$ = 0.125 m/h or 12.5 cm/h for a 3-m high column. The columns were filled in two sequences each of 1.5 m, with a time interval between the two sequences of 12 h for a total period of 24 h (Figs. 2a, b).

Twenty five hours after the columns are filled, the drainage water from LFD and LPD columns and the bleeding water from the UD column are collected and weighed. The CT2 CPB self-weight consolidation settlement was manually measured for each column at a time interval of about 1 hour. The total duration of the measurements was 5 days. The filled columns are then maintained under the backfill plant ambient conditions for a total curing time of 45 days.

Plastic molds filling and curing condition

In order to compare lab-scale (plastic molds) and intermediate scale (columns) samples performance, 3 undrained and 3 drained plastic molds (7.6 cm diameter and 15.2 cm height) were poured with each mix recipe of backfill CT1 (columns 1, 2 and 3) as control samples at LRD mine backfill plant. This makes a total of 6×3 = 18 molds of CT1 CPBs (Fig. 2c). At the LVT mine backfill plant, however, 6 plastic molds (10.16 cm diameter and 20.32 cm height) were filled with the CT2 CPB material.

All the filled molds CT1 (LRD mine) and CT2 (LVT mine) paste backfill were caped and placed in a controlled humidity chamber at relative humidity RH ≥90% and 23 ±2°C. The curing times were 10, 28 and 59 days for CT2 paste backfill and 94, 98 and 102 days for CT1 paste backfill.

Columns dismantling and test samples coring

After each dedicated curing time, the PVC columns were carefully dismounted for recovering paste backfill columns. Each CPB column is then transversally cut out into a number of blocks between 10 and 12 using an electric disc cutter. The blocks are numbered starting from the top of each column. The coring of test specimens from each paste backfill block was carried out at the backfill plant using a concrete core cutter (Fig. 3).

Attempt has been made to obtain 3 test specimens per block, but generally 2 test specimens were obtained per block. A total of 60 and 68 core specimens were taken from the LVT mine backfill CT2 and LRD mine backfill CT1, respectively. The obtained test specimens were wrapped in paraffin film (preventing them from drying), labelled and stored in a humidity chamber at the same curing conditions than for the plastic mold specimens (RH >90% and T = 23 ±2°C).

Fig. 2 Photographs showing the columns filling and plastic molds filled with CT1 and CT2 paste backfill.

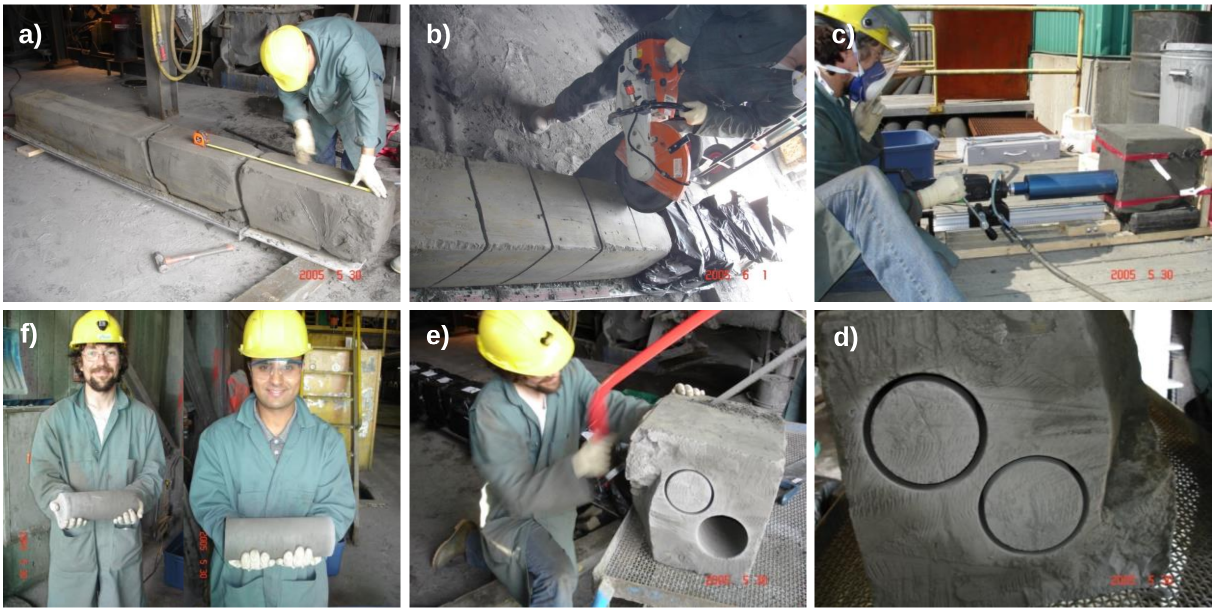

Fig. 3 Columns dismantling: a) blocks sizing, b) blocks cutting, c) specimen coring, d) end of coring, e) specimen cutting, f) obtained test specimens.

Unconfined compression tests

The unconfined compression tests were performed on all test specimens for determining their uniaxial compressive strength (UCS). These tests were carried out using a servo-controlled mechanical press (MTS 10/GL) having a normal loading capacity of 50 kN and tests were performed at a displacement rate of 1 mm/min. The aspect (height-to-diameter) ratio of all test specimens was around 2.

RESULTS

Self-weight consolidation results

The results of the CPB drainage water collection, self-weight settlement and volumetric strain measurements are listed in Table 2. The self-weight consolidation settlement and drainage of all filled columns occurred mainly within the first 48 hours. That means that little or no drainage/settlement occurs beyond 72 hours after the column filling.

Table 2 CPB self-weight consolidation data

Type of column	%drainage water (%)	Settlement ΔH_f (cm)	Vol. strain ε_v (%)
LFD column	15.8	16.4	5.5
LPD column	8.9	8.5	2.8
UD column	-	7.5	2.5
Column 1	17.5	12	4.1
Column 2	25.8	14.4	5.0
Column 3	19.7	12.4	4.3
LVT mine	-	100 – 150	3.3 – 5.0

LVT mine backfill (CT2) self-weight consolidation

The percentage of drainage water was 15.8% for the laterally fully-drained (LFD) column and 8.9% for the laterally partly-drained (LPD) column. This drainage corresponds to the final self-weight consolidation settlement (ΔH_f) of 16.4 cm (ε_v = 5.5%), 8.5 cm (ε_v = 2.8%) and 7.5 cm (ε_v = 2.5%)

for LFD, LPD and UD columns, respectively. The observed CPB final settlement (ΔH_f) measured from the top of the columns is also listed in Table 2. The observed LVT mine stope CPB settlement varies between 100 cm and 150 cm for a typical stope of 30 m high. Figs. 4d, e, f show the variation of the final volumetric strain ε_v (= $\Delta H_f/H_0$ = $\Delta V/V_0$) calculated for the paste backfill CT2 as a function of elapsed time since the beginning of the filling.

LRD mine backfill (CT1) self-weight consolidation

The percentage of drainage water was 17.5% for the Column 1, 25.8% for the Column 2 and 19.7% for the Column 3 (see Table 2). The corresponding calculated volumetric strain ε_v(%) for these drainages were 4.1%, 5% and 4.3% for the Columns 1, 2 and 3, respectively. Figs. 4a, b, c show the variation of the final volumetric strain ε_v calculated for the paste backfill CT1 as a function of elapsed time since the beginning of the filling.

From Fig. 4 it can be noticed that the calculated ε_v(%) from the settlement (ΔH_f) is much lower than the one from the drainage water. Indeed, calculated settlement-based strains were 5.0% and 5.5% for backfill CT1-column 2 and backfill CT2-LFD column, respectively. However, the calculated drainage water-based strains were 13.5% and 8.5% for backfill CT1-column 2 and backfill CT2-LFD column, respectively.

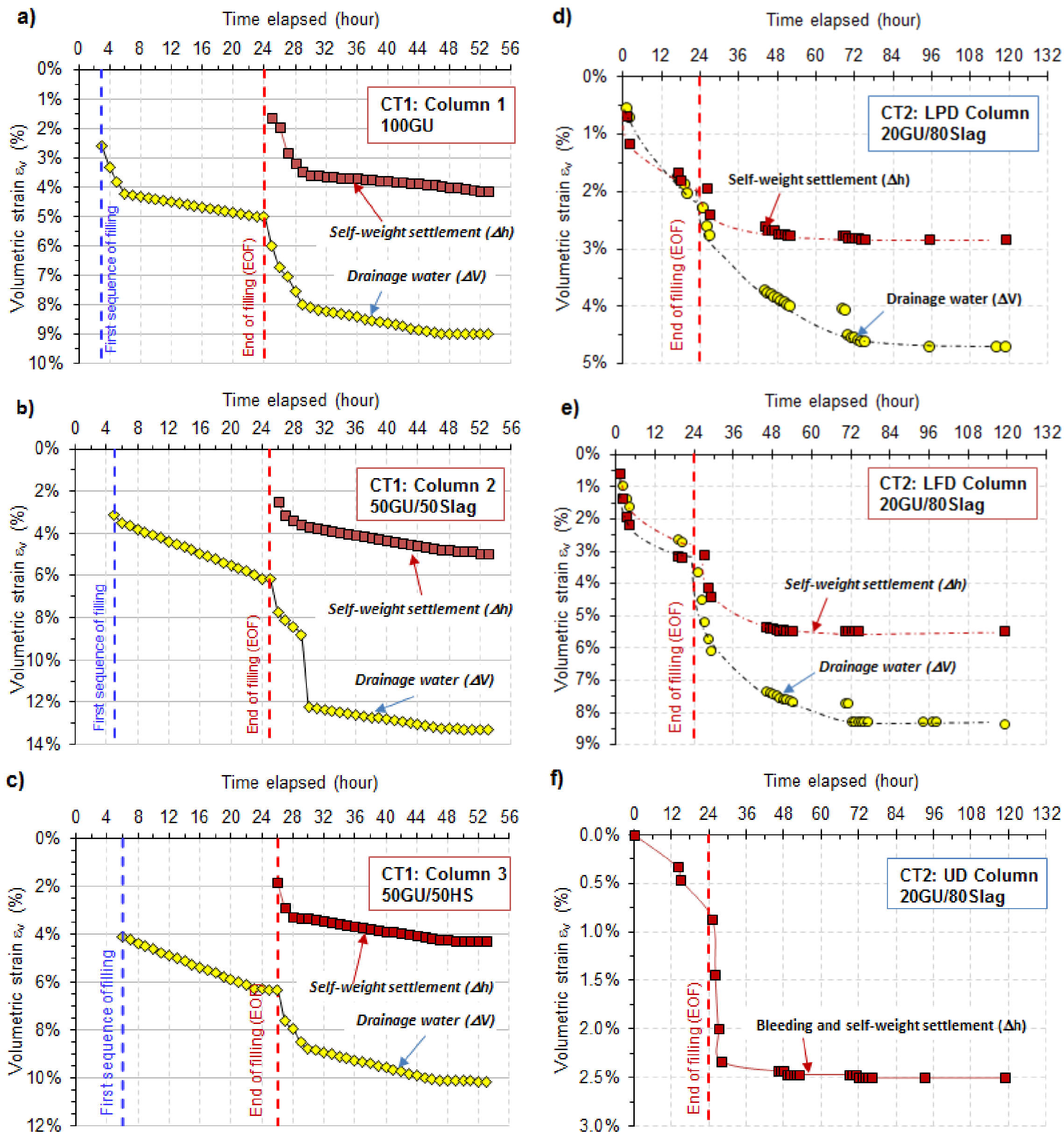

Fig. 4 Volumetric strain calculated from drainage water and settlement for backfills CT1 and CT2.

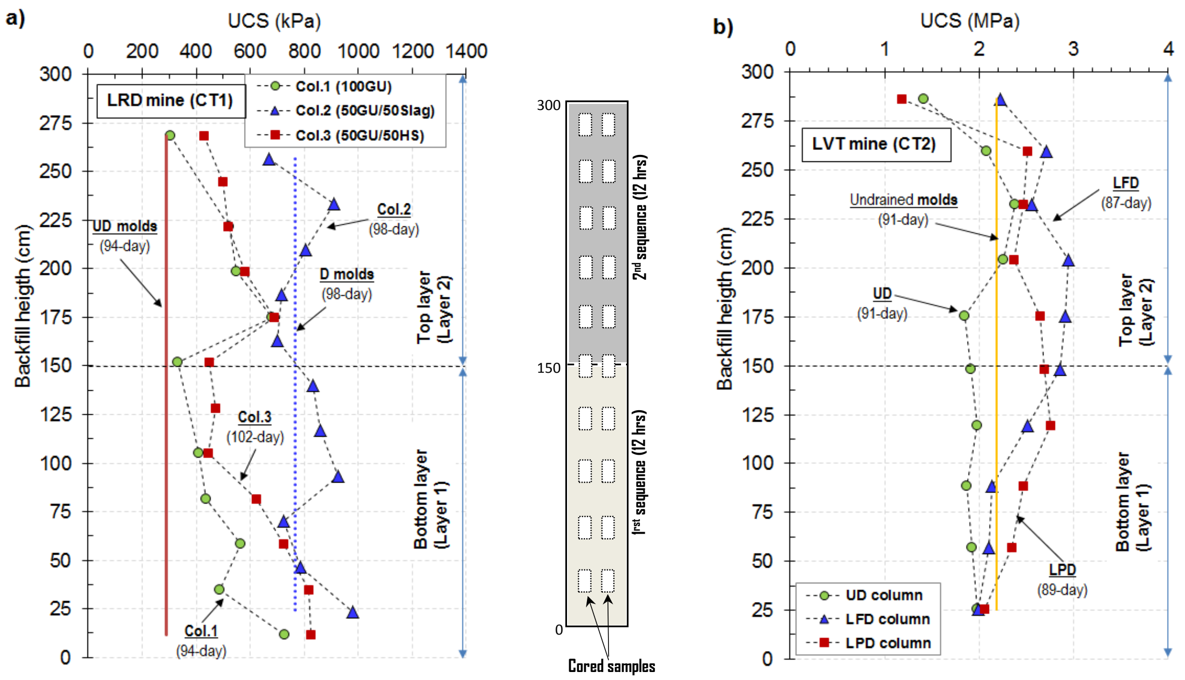

Fig. 5 UCS profiles of cemented paste backfill in 6 columns tested at LRD and LVT mines.

However, only the values from settlement data are matching the *in situ* ones. The marked difference between the calculated drainage water-based and settlement-based volumetric strains could be explained by the column filling sequencing. In fact, this difference may be due to the consolidation process occurring during the 1st sequence of filling (bottom layer) before the 2nd sequence of filling (top layer).This difference is much more pronounced in the case of backfill CT1 at LRD mine (combination of vertical and lateral drainage) than for backfill CT2 at LVT mine (lateral drainage only).

UCS test results

Table 3 summarizes the UCS values obtained from both plastic mold backfill specimens (undrained UD and drained D) and the column CPB core specimens (CT2 backfill from LVT mine and CT1 backfill from LRD mine).

Table 3 UCS values of the column and mold CPBs

Columns	UCS (kPa)			
	Range	Average	UD mold	D mold
Column 1 (94-day)	304 – 725	501	291	515
Column 2 (98-day)	670 – 978	809	586	767
Column 3 (102-day)	428 – 825	588	362	650
LFD (87-day)	2000 – 2900	2492	2140	-
LPD (89-day)	1200 – 2700	2348	2160	-
UD(91-day)	1400 – 2400	1963	2180	-

Fig. 5 presents the variation in the UCS of the column CPB core specimens as a function of their location in each column at LRD mine (Fig. 5a) and LVT mine (Fig. 5b). The vertical straight lines shown in Fig. 5 correspond to the UCS average values obtained from the drained (D) and undrained (UD) molds CPB specimens.

LRD mine backfill (CT1) strength development

Fig. 5a shows that the average UCS value from undrained mold CPBs is the lowest value of all, while the average UCS value from drained mold specimens corresponds to an average UCS value from Column 2 CPB specimens. Also, the UCS of drained mold specimens is always higher than the one of undrained mold specimens. This is suggesting that plastic molds underestimate the average values of UCS in the columns or even in real stopes. In addition, the UCS from Column 2 CT1 backfill specimens (after 98-day curing) is higher than the one from Column 3 CT1 backfill specimens (after 102-day curing) which in turn is higher than the one from Column 1 CT1 backfill specimens (after 94-day curing). It appears that the highest strengths were obtained on backfill specimens prepared with GU-Salg@50:50 recipe, regardless of the depth: $UCS_{(GU\text{-}Slag)} > UCS_{(GU\text{-}HS)} > UCS_{(GU)}$.

The results show that the UCS of column-consolidated backfill samples slightly increases with depth. For GU (Column 1) and GU-HS (Column 3) backfill specimens, this increase follows the trend of overburden stress (γh). From Fig. 5a it can be observed that the average UCS values from undrained mold specimens, commonly used in quality control (QC) and design processes, correspond to the one of the top specimens of columns. This confirms the fact that UCS values obtained from plastic mold specimens can be considered as very safe. It can also be noticed that the average UCS value from column-consolidated paste backfill is closer to the one of drained mold specimens. This suggests that the more realistic laboratory UCS values should be obtained from drained mold samples only.

LVT mine backfill (CT2) strength development

Fig. 5b shows that the average UCS value from undrained mold CPBs is almost always higher than the one of undrained column CPB and is lower than the UCS value of the LFD and LPD paste backfill. This result suggests that backfilled stopes are probably laterally partly or fully drained. But it should be noted however that the molds do not take into account the sequencing of CPB filling in the columns and were not cured under the same conditions than the columns. For example, the top of the columns was remained opened during curing process under LVT mine backfill plant ambient air conditions while the plastic molds were sealed and stored in a lab controlled humidity chamber at RH >90% and T = 23 ±2°C.

It can be observed from Fig. 5b that the variation in UCS seems to be dictated not only by the curing time and the column configuration, but also by the sequencing of filling. As a matter of fact, the UCS value of the LHD column paste backfill CT2 is higher than the one of the LPD column paste backfill CT2 in the first layer (0–150 cm), and is lower than the one of LFD backfill in the second layer (150–300 cm). Just after the first layer filling sequence (0–150 cm) the paste backfill drains a part of its water in the case of the LFD and LPD columns, but bleeds part of its water in the case of the UD column.

Since the second layer filling sequence (150–300 cm), the LPD paste backfill could drain its water only through the backfill sub-layer of 150 cm thick, while the LFD paste backfill can drain its water through this sub-layer as well as through the permeable geotextile joint. For the UD column, the initial bleeding water at the top of CPB sub-layer is imprisoned by the second CPB layer and once the column is filled there is again a water separation on the top surface of the CPB, a part will evaporate and other will re-integrate the CPB.

CONCLUDING REMARKS

This paper presents the results of a prospective experimental study on self-weight consolidation behavior and strength development of cemented paste backfill poured into settling columns of 3-m high. The tests were performed at two different mines paste backfill plants, namely LRD (CT1 backfill) and LVT (CT2 backfill) mines. Four different backfill mix recipes formulation (100GU, 50GU/50Slag, 50GU/50HS and 20GU/80Slag) and four column drainage scenarios (UD, LPD, LFD and LFD + vertical drainage) were tested. Conventional plastic molds were also used in order to get lab-scale control specimens.

The results showed that the total percentage of drainage water and the maximum observed self-weight consolidation settlement occur mainly within the first 48 to 72 hours since the columns are filled. The maximum drainage percentage varied between 9% (CT2-LPD column) and 26% (CT1-Column 2) of the initial total water of CPB.

The maximum measured CPB self-weight consolidation settlement ΔH_f was of 16.4 cm (CT2-LFD column) and the minimum was of 7.5 cm (CT2-UD column). The corresponding volumetric strains ε_v(%) varied between 2.5% (CT2-UD column) and 5.5% (CT2-LFD column). The field observed volumetric strain of CPB at LVT mine varies between 3.3% and 5.0%, which is suggesting that *in situ* backfilled stopes behave in a similar way to the laterally fully-drained (LFD) or the laterally partly-drained (LPD) conditions.

The unconfined compression tests results showed that the compressive strength (UCS) of the undrained mold specimens, commonly used in quality control and design processes, correspond to the one of specimens from the top of columns. The average UCS value of column-consolidated paste backfill is closer to the one from drained mold specimens (suggesting that the more realistic laboratory UCS values should be obtained from drained mold specimens only).

The maximum UCS value was obtained at the bottom of columns, probably due of highest self-weight consolidation (compactness). The LVT backfill strengths are clearly much higher than the strengths of the LRD backfill.

Under equal conditions, it appears that the highest strengths were obtained on backfill specimens prepared with GU-Salg@50:50 formulation, regardless of the depth: $UCS_{(GU\text{-}Slag)} > UCS_{(GU\text{-}HS)} > UCS_{(GU)}$.

Further *in situ* investigations using adequately instrumented columns are needed to better understand the effect of self-weight consolidation of paste backfill on its short- and long-terms mechanical, physical and geochemical behaviors.

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