

Volumetric change measurement for Cemented Paste Backfill under high isotropic compression: laboratory challenges and tips



Mohammadamin Jafari, Mohammad Shahsavari & Murray Grabinsky
The University of Toronto, Toronto, Ontario, Canada

ABSTRACT

Over the past decade, study of Cemented Paste Backfill (CPB), which is a mixture of mine tailings, binder, and water, has been increased. Despite all research has been done so far, many researchers have had difficulty in the study of the constitutive behavior of this material. The main reason is related to this fact that conducting laboratory scale test on this material, which can have a uniaxial compressive strength of less than 25 kPa in lower cement content and curing time, is troublesome. In this paper, challenges faced during conducting a high isotropic compression test on this material along with some design tips are discussed.

RÉSUMÉ

Au cours de la dernière décennie, les études qui portent sur le remblai à pâte cimenté (RPC), qui consiste en un mélange de résidus miniers, de ciment et d'eau, ont beaucoup augmentées. Malgré toutes les recherches effectuées jusqu'à présent, un grand nombre de chercheurs ont rencontré des difficultés à investiguer le comportement constitutif de ce matériau. Ceci est avant tout lié au fait que la réalisation des analyses au laboratoire sur ce matériau, qui peut avoir une résistance à la compression uniaxiale (RCU) de moins de 25 kPa à une faible teneur en ciment, est problématique. Dans cet article, nous présenterons des difficultés rencontrées lors de la mise en place d'un test de compression isotrope élevé sur ce matériau, ainsi que certains conseils pour la conception de cette expérience.

1 INTRODUCTION

In recent decades, research on cemented silt has become increasingly important in the deep mining industry. In this industry, after extraction of the ore body, large void spaces are created in the ground called stopes. Stopes are backfilled using mine wastes (e.g., mine tailings) to provide ground support for further excavations and also to reduce the volume of tailings that are disposed on the ground surface. One of the backfilling materials that has gained popularity over the past decades is cemented paste backfill (CPB) which is a mixture of mine tailings (mostly is categorized as silt), cement, and water.

CPB is prepared in the paste plant on the ground and then is delivered through pipelines into the mine stope with a controlled filling rate. At an early age, CPB behaves like a non-Newtonian fluid and does not have any strength. During this stage, the paste is still plastic, and it is able to flow. As time passes, cement particles start reacting with water as soon they come into contact with one another and this reaction produces cement hydrates. In favorable conditions, hydration continues to occur, and the cement hydrates gradually grow and form interlocking strands. This process leads to the setting of the fresh CPB mixture, stiffening, and progressive strength gaining of CPB as a solid material. The progress of hydration is often referred to as the degree of hydration.

Many researchers have focused their studies on predicting pore pressure and consolidation process of CPB in stopes. They have conducted experimental studies and proposed different mathematical frameworks to predict consolidation process of this hydrating hydraulic

filling at the early age as well as after the material gains stiffness (Fahey et al. 2010, Helinski et al. 2011, Ghirian and Fall 2013, Veenstra 2013, Wu et al. 2014, Cui and Fall 2015, Doherty 2015, Cui and Fall 2017, Walske and Doherty 2017).

Study of CPB has not been limited to early age stage of this material. Nowadays, activities are being done in deep parts of the earth (more than 4 km) where rockbursts are more likely to occur due to the high stresses around stopes at such depths. In addition to rockburst, the blasting activities near to filled stopes subject CPB to sudden dynamic loadings. These loading conditions show that conducting research studies to have profound knowledge about the mechanical behavior and engineering properties of stiffened CPB (as a support system in the stopes) under extreme pressures is necessary. Examples of such studies are Lu and Fall (2016), Lu and Fall (2017) which combined Perzyna viscoplastic framework with two invariants cap model to investigate the response of stiffened CPB under blasting.

The first step in choosing a proper constitutive equation for a material is to study the response of the material in laboratory-scale tests. Although the uniaxial compressive strength (UCS) of CPB in terms of correlations between the cement content and curing time has been studied quite extensively (Fall et al. 2005, Kesimal et al. 2005, Ercikdi et al. 2009, Yilmaz et al. 2009, Yi et al. 2015), other mechanical properties such as effect of cemented bond breakage on the behavior of CPB under isotropic compression has not been studied yet. Not including such effect in the constitutive equation

framework can result in an unrealistic prediction of CPB behavior under mechanical loading.

To study the behavior of CPB under high-pressure isotropic compression, a high-pressure triaxial cell was designed and fabricated which is discussed in this paper. Moreover, the challenges in conducting this test and CPB response to high isotropic compression are discussed here.

2 SAMPLE PREPARATION CHALLENGES

Water contents and void ratios measured from field blocks taken from Williams, Cayeli, and Kidd mines and studied by le Roux et al. (2005), Thompson et al. (2012) and Grabinsky et al. (2013) show that the cured CPB void ratio varies between 0.84 to 1.27. Preparation of a uniform sample, especially for higher void ratio, is not easy in the laboratory-scale. Jafari et al. (2017) discussed some key shortcomings associated with customary CPB sample preparation (which has significant fractions of fines) to be: (1) segregation of particles especially in samples with considerable sand fraction; (2) non-uniformity in density and void ratio along the sample height; (3) large air bubbles trapped in samples that reduces the degree of saturation and disturbs the uniformity; and (4) non-uniformity in spatial distribution of cement particles.

Crowder (2004) and le Roux et al. (2005) proposed a similar sample preparation method for uncemented and cemented tailings, respectively. Based on their method, first tailings, cement, and water are mixed based on a desired water content; once the CPB mixture is ready, it is poured into a mould in three stages and in each stage, large air bubbles are removed using a glass rod. After filling the mould, the desired dead-weight is placed on top of the sample and based on collected water drained from the mould, the void ratio is determined. This method can give a uniform sample for samples with lower water content; however, it has been observed in the sample with high water content, there is a notable difference between the void ratios on top and bottom of the sample. To overcome this problem, the sample can be placed in a rotating wheel machine during the first hours of its curing (before the set time of cement). Due to the rotation, there is no preferred direction for particles to deposit and the sample is more uniform (to study more about the CPB sample preparation challenges and its application see Jafari et al. (2017), Jafari et al. (2018)).

CPB samples are usually prepared by being poured into a mould that is cut out of a PVC pipe and left to be cured for the desired time. Extruding CPB samples which can have UCS values as low as 25 kPa (for the sample with 3% cement content and 1-day curing time) is not easy causing damages to samples most of the times. To overcome this problem, a simple mould was designed and fabricated by which the sample can be removed from the mould with minimum damage (Figure 1). Combination of O-Rings at the top and bottom of the sample associated with O-ring cord along the split mould grooves prevents any water loss during sample preparation and curing process. The sample extracted from this mould has 34.2 mm diameter and 70-80 mm height.

3 HIGH-PRESSURE ISOTROPIC EQUIPMENT

To study the response of CPB under isotropic compression a high-pressure triaxial cell was designed and fabricated. Details related to the cell and its instrumentation are provided in the following.

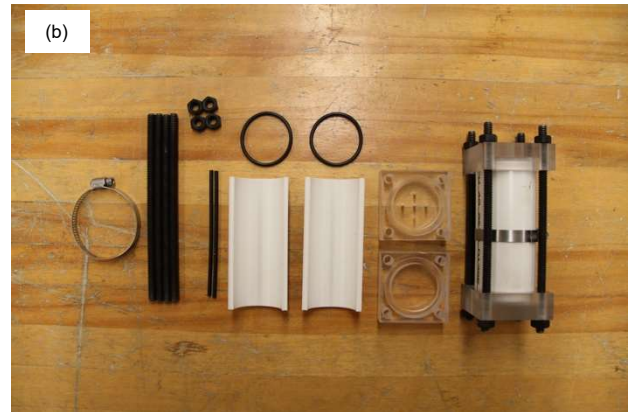
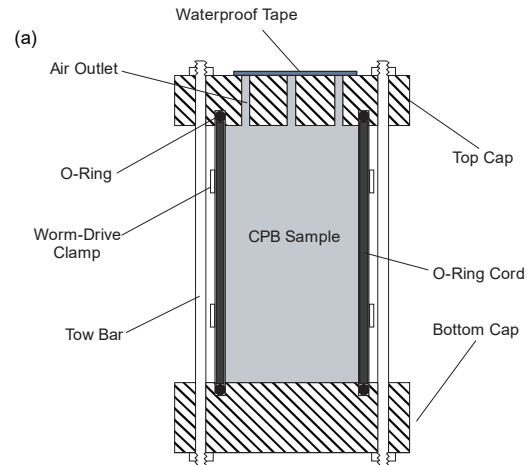


Figure 1. Designed split mould: a) Schematic figure; b) accessories

3.1 Triaxial Cell

The isotropic cell used in this study has a capacity of 20 MPa. Different parts of the designed triaxial cell are shown in Figure 2. All parts of this cell were made from stainless steel (A/SA312). Generally, there are three main parts in this cell: top cap, cylindrical wall, and the base of the cell. The thickness of top, base, and cylindrical wall of the cell are 14.5, 25.4, and 11 mm, respectively. The top cap is attached to the cylindrical wall using screws, and four tie bars were used to attach the cell base to the cylindrical wall. To seal top and base of the cell, two Oil-Resistant Buna-N O-Rings with 1/8 Fractional Width, Dash Number 252, and 3/16 Fractional Width, Dash Number 355, were used respectively.

3.2 Sensors and calibrations

The cell pressure is controlled from the feedback of a pressure transducer with 1000 ± 1 kPa limits for cell pressure less than 1000 kPa and a pressure transducer with 20000 ± 20 kPa limits for cell pressure higher than 1 MPa. The combination of these sensors enhances cell pressure accuracy in the high range of pressure. Two

electrical pressure transducers with 1000 ± 1 kPa limits are installed at the top and bottom of the sample. Also, a frictionless rolling diaphragm type (designed by GCTS) volume change device (VCD) with 0.01 ml resolution was used to measure the volumetric change of samples. VCD resolution enabled volumetric strain measurements to the nearest 0.01%. Figure 2 (b) shows the configuration of each sensor connected to the base of the cell.

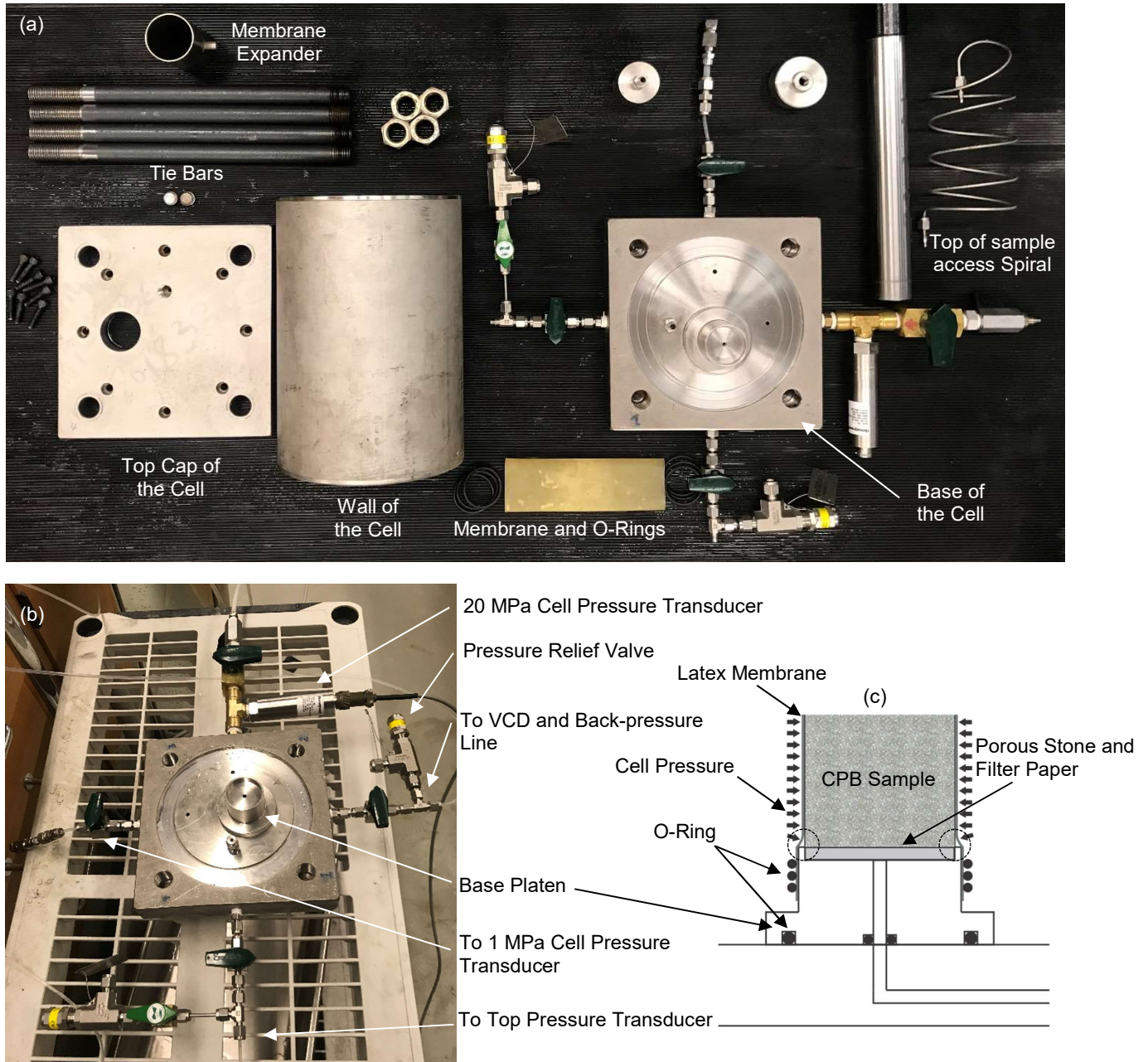


Figure 2. Isotropic high-pressure cell; (a) different parts of the cell; (b) instrumentation of the base; and (c) schematic view of the base platen

Although using 1000kPa pore water pressure transducers gives high accuracy in controlling and

measuring pore water pressure of the sample, if any hole or rupture is created in the membrane in higher effective

confining pressure, all the sensors and equipment used to apply the back-pressure will be damaged. To overcome this problem, two Stainless Steel Low-Pressure Proportional Relief Valve, SS-RL3S4 Swagelok, were installed before each sensor (Figure 2 (b)). The setpoint of these valves was adjusted to 950 kPa.

To ensure fully saturated condition, the samples were always saturated by applying back-pressure (typically near 600 kPa) according to ASTM D4767-04. During the test, the pore pressure was monitored from the top cap pressure transducer, and the drainage was allowed from the bottom part of the sample. Isotropic compression tests were conducted by applying consecutive increments of pressure. By monitoring pore pressure using the top cap pressure transducer, the new increment was applied when the excess pore pressure was dissipated and an increase in volumetric strain was insignificant. Here, a spiral made of stainless-steel pipe was used to connect the top of the sample to the pore water pressure transducer inlet at the base of the cell (Figure 2 (a)). The numbers of rotation in this spiral allow for deformation in the axial direction of the sample with an insignificant amount of force (applying 200 gr causes approximately 7 mm axial displacement).

All sensors were calibrated before testing, and the calibrations were checked frequently. To calibrate the pressure transducers, a differential pressure transducer, OMEGA DPI-603 Pressure Calibrator, was used. Figure 3 presents the reading pressure of each sensor after calibration.

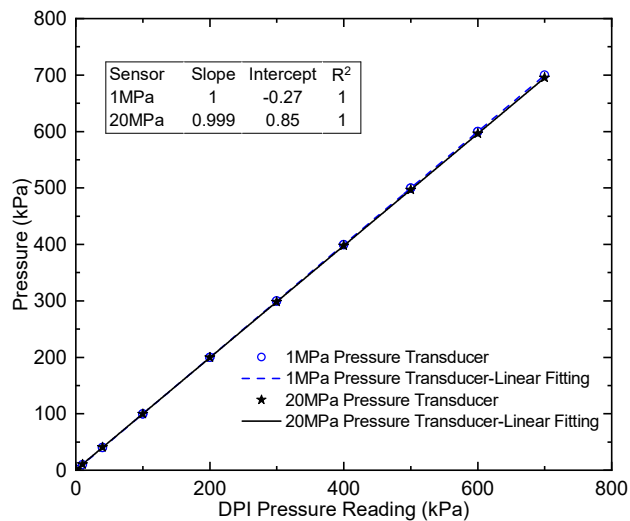


Figure 3. Calibration of the pressure transducers

3.3 Porous stone and latex membrane

In conventional triaxial compressive testing of soils, where the effective confining pressure is mostly smaller than 700 kPa, porous stones are usually placed between the platen and the sample. However, higher confining pressures are more likely to create holes in the membrane caused by the edge of the porous stone. To overcome this problem,

the porous stones were embedded in the top and base platen (Figure 2 (b) and (c)).

Another important element to study the behavior of CPB under high pressure is choosing the right membrane. Membrane penetration is one of the common sources of errors in volume change measurement in the granular materials. The latex membrane penetrates the surface irregularities of the sample by applying the confining pressure (Newland and Allely 1957, Frydman et al. 1973, Baldi and Nova 1984, Nicholson et al. 1993). Based on Lade and Hernandez (1977) considering the fact that D_{50} , C_u , and C_c of this soil are 0.0023 mm, 10.33, and 1.55 respectively, this source of error can be neglected.

Membrane resistance is another source of error associated with rubber membranes in compiling triaxial test data; during the consolidation stage, most of the load is carried by the sample and only a small portion is taken by the membrane. Research has shown that this small portion of the load is independent of sample stiffness but proportional to the stiffness of the membrane (Duncan and Dunlop 1968).

Based on these issues, it was decided to choose a membrane which is thin enough to reduce the effect of membrane resistance and thick enough to tolerate near to 10 MPa confining pressure. Different membranes were tested and a latex membrane with 0.6 mm (0.025 inches) thickness was chosen.

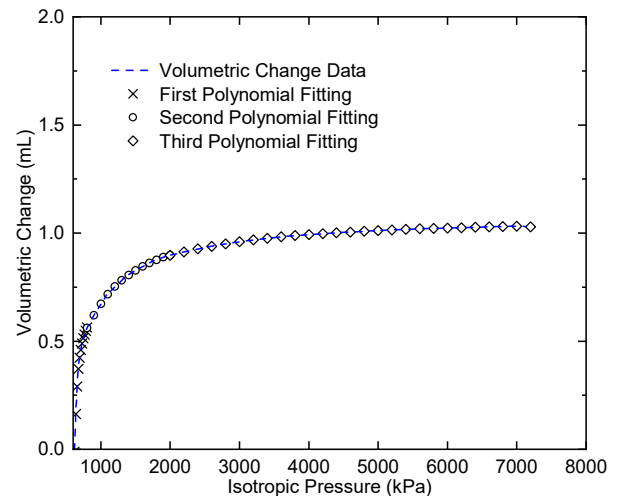


Figure 4. Isotropic compression test on the metal sample

4 CORRECTION OF VOLUMETRIC CHANGE

The errors associated with measurements of volumetric change under isotropic high-pressure loading conditions can be divided into two groups: (a) those related to porous stones and filter papers compliance; and (b) errors associated with the membrane. Porous stones and filter papers were fully saturated during testing; considering high pressure that was applied to them, these parts were compressed, and water was drained from them. As a result, higher volumetric change was measured. In

addition, at the beginning of each test, water was flushed into the sample from the base platen to remove air bubbles surrounding the sample. During the water flushing process, a portion of the water was trapped between the sample and the membrane. Most of this water was trapped around the top and bottom edges of the sample (as shown in Figure 2 (c) with the circles). This water was drained during the test as well and could affect the results.

To overcome the mentioned source of errors and improve the accuracy of volumetric change measurement, a stainless-steel cylinder with the diameter and height of samples was fabricated. This metal piece was placed in

the cell exactly with the procedure used for the CPB sample. Back-pressure of 600 kPa was applied to make sure that there is no air bubble around the metal sample. Then the cell pressure was increased, and volumetric change was measured. As can be seen in Figure 4, most of the volumetric change occurs at the lower isotropic pressure, which is mainly related to the drainage of the water trapped between the sample and membrane. However, at the higher pressure, the rate of volumetric change is decreased, and the portion of volumetric change mostly can be related to the compliance of porous stone and drained water from filter papers.

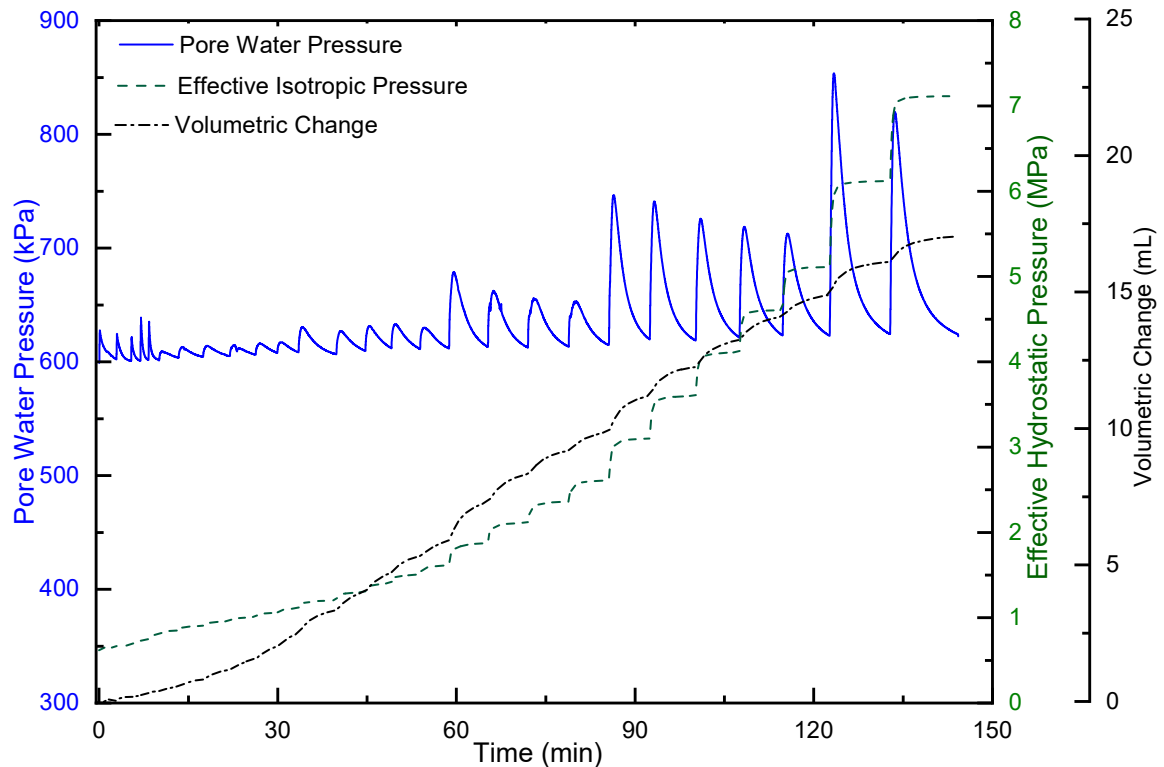


Figure 5. An example of equipment results after volumetric change correction

To correct volumetric change measurements, three polynomial equations with the degree of nine were fitted to three parts of this data (as presented in Figure 4). These three polynomial equations were selected in order to accurately determine the value of a volumetric correction for each isotropic pressure. The resulting value was subtracted from the total volumetric change recorded by the equipment. An example of a corrected volumetric change graph is shown in Figure 5. Visual comparison of the two data sets shown in Figure 6 shows that without the correction, the volumetric change is consistently overestimated. The overestimation is evident, and it will have an impact on the initial slope mentioned in the next section.

5 TYPICAL BEHAVIOR OF CPB UNDER ISOTROPIC COMPRESSION

Typical isotropic compression behavior of CPB is shown in Figure 7. The volumetric strain is negligible at lower isotropic pressures. This can be attributed to the resistance of the cemented bond that dominantly controls the response of CPB in a lower range of pressure before reaching the yield point. CPB shows a linear behavior in this part, which is called the pre-yield compression line. Here, yield stress is considered the stress level where the material behavior starts to deviate from the linear behavior. Beyond the yield point, cementation bonds start to break, and consequently higher magnitude of

volumetric change is observed. In higher pressures, after breakage of cementation bonds, volumetric change of CPB shows linear change with the increase of isotropic pressure, which is called post-yield compression line.

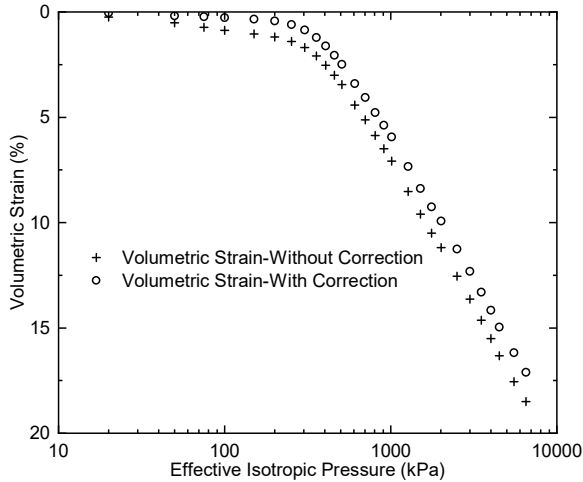


Figure 6. Volumetric strain versus effective isotropic pressure in semi-log space

The results of isotropic compression test on the CPB samples with 7.5% cement content are presented in Figure 8. The abbreviations in the legend of the figure mean CC: Cement Content (percent cement mass by mass of dry tailing); and CT: Curing Time. Figure 9 shows the slopes of post-yield compression lines (PYCLS) for these data. These slopes are seen to increase with curing time. This increase in the magnitude of the slopes may be expressed as a linear function of the logarithm of curing time, i.e. $PYCLS = a - b \log(CT)$, with the best-fit values of a and b shown in Figure 9.

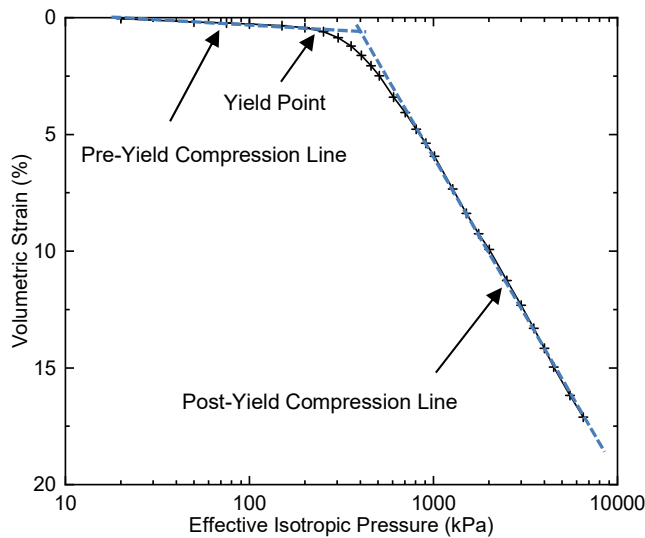


Figure 7. A typical behavior of CPB sample under isotropic compression

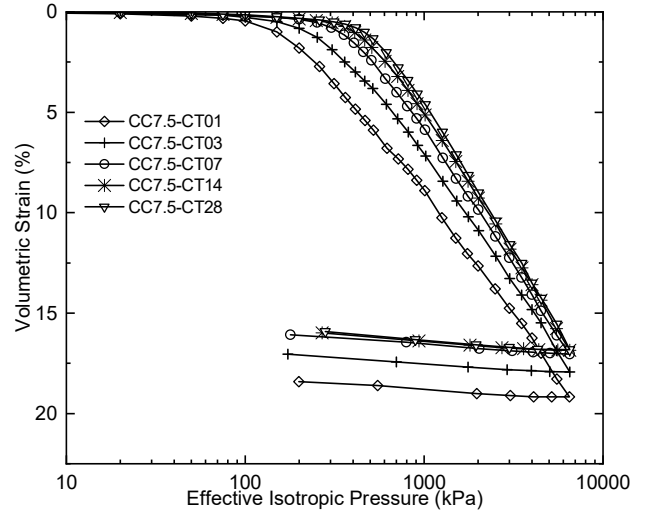


Figure 8. Isotropic compression response of CPB samples with 7.5% cement content (CC) at different curing times (CT)

6 CONCLUSIONS

A triaxial cell was designed to conduct high isotropic compression test on CPB material. Two different sources of errors associated with volumetric change measurement were identified and corrected for. The results show that without measuring and defining these sources of error, the volumetric change measurement is overestimated especially at the lower isotropic pressure.

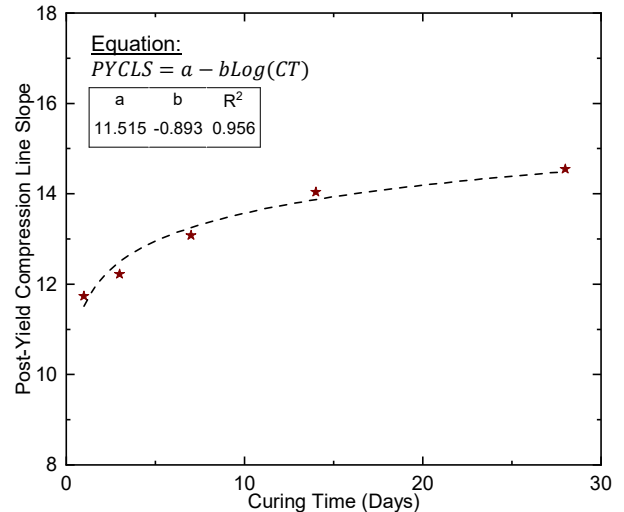


Figure 9. Variation of Post-Yield Compression line slope for different curing times

After correcting the volumetric change measurements, the resulting volumetric strain shows a bilinear relationship with respect to effective isotropic pressure in the semi-log space. The first line is related to the elastic

behavior of CPB governed by cementation bonds. At the yield stress, the cementation bonds start to break. After breakage of all of the cementation bonds, the volumetric change changes linearly with the increase of effective isotropic compression. For a given cement content, the latter slope is seen to increase logarithmically with respect to curing time.

7 ACKNOWLEDGMENT

The authors wish to express their gratitude to Barrick Gold Corp and Natural Sciences and Engineering Research Council Canada (Collaborative Research and Development Grant #514220-1) for financial support to this research as a part of a larger investigation into the behavior of high-performance cemented paste backfill.

8 REFERENCES

Baldi, G. and Nova, R. 1984. Membrane Penetration Effects in Triaxial Testing, *Journal of Geotechnical Engineering*, Vol. 110, No. 3, pp. 403-420.

Crowder, J. J. 2004. Deposition, consolidation, and strength of a non-plastic tailings paste for surface disposal, *University of Toronto*, Toronto, Canada.

Cui, L. and Fall, M. 2015. A coupled thermo–hydro-mechanical–chemical model for underground cemented tailings backfill, *Tunnelling and Underground Space Technology*, Vol. 50, pp. 396-414.

Cui, L. and Fall, M. 2017. Multiphysics Model for Consolidation Behavior of Cemented Paste Backfill, *International Journal of Geomechanics*, Vol. 17, No. 3, pp. 04016077.

Doherty, J. P. 2015. A numerical study into factors affecting stress and pore pressure in free draining mine stopes, *Computers and Geotechnics*, Vol. 63, pp. 331-341.

Duncan, J. M. and Dunlop, P. 1968. The significance of cap and base restraint, *J. Soil Mech. and Found.*, Vol. 94 (1),

Ercikdi, B., Kesimal, A., Cihangir, F., Deveci, H., and Alp, İ. 2009. Cemented paste backfill of sulphide-rich tailings: Importance of binder type and dosage, *Cement and Concrete Composites*, Vol. 31, No. 4, pp. 268-274.

Fahey, M., Helinski, M., and Fourie, A. 2010. Consolidation in accreting sediments: Gibson's solution applied to backfilling of mine stopes, *Géotechnique*, Vol. 60, No. 11, pp. 877-882.

Fall, M., Benzaazoua, M., and Ouellet, S. 2005. Experimental characterization of the influence of tailings fineness and density on the quality of cemented paste backfill, *Minerals Engineering*, Vol. 18, No. 1, pp. 41-44.

Frydman, S., Zeitlen, J., and Alpan, I. 1973. The Membrane Effect in Triaxial Testing of Granular Soils, *Journal of Testing and Evaluation*, Vol. 1, No. 1, pp. 37-41.

Ghirian, A. and Fall, M. 2013. Coupled thermo-hydro-mechanical–chemical behaviour of cemented paste backfill in column experiments. Part I: Physical, hydraulic and thermal processes and characteristics, *Engineering Geology*, Vol. 164, pp. 195-207.

Grabinsky, M. W., Bawden, W. F., and Simon, D. 2013. In situ Properties of Cemented Paste Backfill from three mines, *GeoMontreal*, Montreal

Helinski, M., Fahey, M., and Fourie, A. 2011. Behavior of Cemented Paste Backfill in Two Mine Stopes: Measurements and Modeling, *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 137, No. 2, pp. 171-182.

Jafari, M., Shahsavari, M., and Grabinsky, M. 2017. Cemented Paste Backfill Laboratory study: Sample preparation challenges, *GeoOttawa*, Ottawa

Jafari, M., Shahsavari, M., and Grabinsky, M. 2018. Effect of lubricated-end-platens on the behavior of cemented paste backfill under triaxial loading *GeoEdmonton*, Edmonton

Kesimal, A., Yilmaz, E., Ercikdi, B., Alp, İ., and Deveci, H. 2005. Effect of properties of tailings and binder on the short-and long-term strength and stability of cemented paste backfill, *Materials Letters*, Vol. 59, No. 28, pp. 3703-3709.

Lade, P. V. and Hernandez, S. B. 1977. Membrane Penetration Effects in Undrained Tests, *Journal of the Geotechnical Engineering Division*, Vol. 103, No. 2, pp. 109-125.

le Roux, K. A., Bawden, W. F., and Grabinsky, M. W. 2005. Field properties of Cemented Paste Backfill at the Golden Giant mine., *Transactions of the Institution of Mining and Metallurgy, Section A: Mining Technology* Vol. 114(2):65-80,

Lu, G. and Fall, M. 2016. A coupled chemo-viscoplastic cap model for simulating the behavior of hydrating cemented tailings backfill under blast loading, *International Journal for Numerical and Analytical Methods in Geomechanics*, Vol. 40, No. 8, pp. 1123-1149.

Lu, G. and Fall, M. 2017. Modelling blast wave propagation in a subsurface geotechnical structure made of an evolutive porous material, *Mechanics of Materials*, Vol. 108, pp. 21-39.

Newland, P. L. and Allely, B. H. 1957. Volume Changes in Drained Triaxial Tests on Granular Materials, *Géotechnique*, Vol. 7, No. 1, pp. 17-34.

Nicholson, P. G., Seed, R. B., and Anwar, H. A. 1993. Elimination of membrane compliance in undrained triaxial testing. I. Measurement and evaluation, *Canadian Geotechnical Journal*, Vol. 30, No. 5, pp. 727-738.

Thompson, B. D., Bawden, W. F., and Grabinsky, M. W. 2012. In situ measurements of cemented paste backfill at the Cayeli Mine, *Canadian Geotechnical Journal*, Vol. 49, No. 7, pp. 755-772.

Veenstra, R. L. 2013. A Design Procedure for Determining the In Situ Stresses of Early Age Cemented Paste Backfill, *University of Toronto*, Toronto.

Walske, M. L. and Doherty, J. 2017. Incorporating chemical shrinkage volume into Gibson's solution, *Canadian Geotechnical Journal*, Vol. 55, No. 6, pp. 903-908.

Wu, D., Fall, M., and Cai, S.-j. 2014. Numerical modelling of thermally and hydraulically coupled processes in hydrating cemented tailings backfill columns, *International Journal of Mining, Reclamation and Environment*, Vol. 28, No. 3, pp. 173-199.

Yi, X. W., Ma, G. W., and Fourie, A. 2015. Compressive behaviour of fibre-reinforced cemented paste backfill, *Geotextiles and Geomembranes*, Vol. 43, No. 3, pp. 207-215.

Yilmaz, E., Benzaazoua, M., Belem, T., and Bussière, B. 2009. Effect of curing under pressure on compressive strength development of cemented paste backfill, *Minerals Engineering*, Vol. 22, No. 9, pp. 772-785.