EFFECT OF LOADING RATE ON CONSOLIDATION OF HYDRATING CEMENTED PASTE BACKFILL

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ABSTRACT
To reduce the surface footprint of mining operations and provide support for further excavations, the mined-out voids are backfilled with mine tailings. Over the past decade cemented paste backfill has gained popularity over other backfilling materials due to its high delivery rate and tight characteristics. Fresh CPB is held in the stope by a retaining structure (i.e. barricade). Barricade is subjected to lateral stresses and pore water pressures from within the CPB. A safe and economic design of the barricade is dependent on the proper knowledge of these stresses. The pore water pressure changes due to self-weight consolidation of the hydrating CPB. One of the parameters that affect the deformations and the rate of pore water pressure generation/dissipation is the backfilling rate. In this paper the effect of backfilling rate on consolidation characteristics and deformation of fresh and cured CPB is studied. CPB Samples with 5% binder content are loaded at 5, 10, and 20 kPa/hr loading rates to represent the typical in-situ backfilling scenarios of 0.25, 0.50, and 1.0 m/hr for a CPB with a unit weight of 20 kN/m^3, respectively. The deformations are recorded while samples were loaded and cured at the same time. These tests provide more information on the deformation characteristics of an accreting hydrating material and confirm the measured field void ratios at the end of the backfilling.

RÉSUMÉ
Les gradins des mines sont souvent remblayés à réduire l'impact des opérations des mines sur la surface et à permettre le support pour des excavations futures. Durant la dernière décennie le remblai à pâte cimenté (RPC) a été de plus en plus utilisé grâce à son taux de livraison et ses caractéristiques homogènes. Le RPC frais est restreint à mesure d'une barricade. La barricade est soumise aux contraintes latérales et à la pression de l'eau interstitielle. La conception sécurisée et économique de la barricade se dépende sur la compréhension de ces contraintes. La pression de l'eau interstitielle varie en fonction de la consolidation poids propre du RPC hydratant. Un des paramètres qui influence les déformations et la génération ou dissipation de pression de l'eau interstitielle est le taux de livraison de RPC. Dans la présente étude, l'effet du taux de livraison de RPC sur les caractéristiques de consolidation et la déformation du RPC frais et mûri sont interrogés. Les échantillons de RPC avec 5 pourcent contenu de liant sont chargées à 5, 10 et 20 kPa/h à mesure de simuler des scénarios typiques de livraison de RPC 0.25, 0.50 et 1.00 m/h avec un poids d'unité de 20 kN/m^3. Les déformations sont enregistrées durant que les échantillons ont été chargés et mûris simultanément. Ces essais ont fourni plus des détails sur les caractéristiques de déformation d'un matériel qui s'hydrate et qui s'accrète et affirment les taux de porosité enregistrés sur le chantier après le remblayage.

1 INTRODUCTION

The ore body excavation from underground rock masses, leaves large void spaces in the ground called stopes. To provide ground support for further excavations and reduce the amount of surface disposal of mine tailings, the stopes are backfilled with mine tailings. Cement is added to the backfilled mine tailings to enhance their mechanical properties and eliminate the need for leaving behind rock pillars. The mixture of cement, mine tailings and water is called cemented paste backfill (CPB). Over the past decade, CPB has gained popularity over other backfilling materials due to its high delivery rate and tight characteristics. When deposited in the stope, initially CPB behaves like a dense fluid with close to zero shear strength. Therefore, CPB must be held at the bottom of the stope, using a retaining structure called barricade to prevent its flow to the access tunnels. Barricades must be designed to withstand the normal stress that are applied to them through the CPB mass. Barricade failures have been previously reported and must be prevented (e.g. Sivakugan, 2008; Revel and Sainsbury, 2007).

The forces applied to the barricade are lateral stresses developed within CPB. These lateral stresses are dependent on the effective vertical stresses and pore water pressures that are developed within CPB during and after deposition due to self-weight consolidation and cement hydration (Thompson et. al, 2012; and Helinski et al., 2007). The coupled nature of the problem makes it difficult to accurately predict the lateral stresses using numerical tools and hence more experiments that are compatible with in-situ loading and curing conditions, must be performed to have a better understanding of the stress distribution within backfilled stopes.

The problem of consolidation of CPB has been previously studied numerically (e.g. Shahsavari and Grabinsky, 2015 and 2016; Doherty, 2015; and Fahey et al. 2010). Fahey et al (2010) applied Gibson's (1958) solution to the problem of consolidation of an accreting soil layer to the consolidation of CPB. However, Fahey et al. (2010) did not consider the effect of cement hydration in their analysis and obtained the upper and lower bound solutions to the problem. Other attempts have been made to include the role of cement hydration in the self-weight consolidation analysis of CPB (e.g. Doherty, 2015). While these numerical analyses are valuable and very useful in predicting the stresses that are being applied to the barricade, they are still not completely capable of perfectly simulating the coupled in-situ chemo-hydro-mechanical interactions. Hence, it is necessary to go back and revisit the whole process of consolidation and hydration through laboratory and in-situ measurements.

Yilmaz et al. (2015) performed oedometer tests on CPB samples that were both fresh and cured up to a week. Their results showed a significant decrease in compressibility of CPB with curing time. This is an important design implication that with time less excess pore pressures would be developed with an increase in CPB stiffness. However, the in-situ self-weight consolidation and strength gain is very dependent on the deposition rate (Shahsavari and Grabinsky, 2016; and Fahey et al., 2010). Hence, the way the normal oedometer tests are performed on CPB does not necessarily replicate the in-situ loading condition. The CPB might be under consolidated or undergone creep deformation before the application of the next load step in the field, while in a conventional oedometer test (even with reduced time steps), the sample is always consolidated before the application of the next load step.

Le Roux (2004) tried to replicate the in-situ consolidation process by applying load at the same rate as that happens in the field using an oedometer test. Le Roux (2004) samples were all fresh prior to load application and aged as they were being consolidated at different loading rates. However, the effect of in-situ loading rate on cured samples were not studied. Le Roux (2004) applied load increments every 24 min, 48 min, and 2 hours 24 min to replicate the backfilling rates of 10 m, 30 m, and 60 m in a period of 24 hours. The in-situ backfilling, on the other hand, is continuous and these values are just an average of the overall backfilling rate. Therefore, if the laboratory consolidation loading is not performed in a continuous way while controlling the loading rate, then it may not fully replicate the in-situ loading conditions.

In this paper, a series of oedometer tests have been performed on CPB samples that are fresh or cured to different ages up to 48 hours. The loading is performed at different rates to replicate backfilling rates. CPB samples were loaded at 5 kPa/hr, 10 kPa/hr, and 20 kPa/hr corresponding to backfilling rates of 25 cm/hr, 50 cm/hr, and 100 cm/hr, respectively, given a unit weight of 20 kPa/m^3.These values of loading rates were selected to represent the most common backfilling rates. The loading was applied continuously to fully capture the coupled chemo-hydro-mechanical behavior of CPB. The fresh samples represent a continues backfilling scenario while cured samples are a representative of a backfilling scenario where first a plug layer is backfilled and cured before the rest of the stope is being backfilled.

In the following sections, first the experimental set-up is explained, then the tailings and cement details and sample preparation technique will be discussed. Finally, the results are presented and comments on the effect of backfilling (i.e. loading) rate on the consolidation characteristics of fresh and cured CPB sample are made.

2 EXPERIMENTAL WORK

A series of consolidation tests on CPB samples are performed to better understand the in-situ behaviour and deformation characteristics of CPB. To simulate the in-situ stress path, the samples are being loaded using loading rates that are representative of in-situ loading conditions. These loading rates are 5 kPa/hr, 10 kPa/hr, and 20 kPa/hr to represent backfilling rates of 25 cm/hr, 50 cm.hr, and 100 cm/hr, respectively. The loading has been performed continuously using an automatic, electromechanical system.

Fresh and cured samples are being tested in this study. Fresh samples were cured for 4 hours just to get to the point where cement hydration starts (Saebimoghaddam, 2010). The aged samples were cured under water for 12, 24, and 48 hours prior to loading. These cured samples represent samples in the plug body that are being cured for a certain period prior to backfilling of the rest of the stope.

The material properties details, cement properties, and testing set-up are explained in detail in the following sections.

2.1 Oedometer testing set-up

The one-dimensional consolidation apparatus from Wille Geotechnik was used in this study. The one-dimensional consolidation test set-up is shown in Figure 1. The testing machine is an electromechanical, microprocessor-controlled apparatus that enables fully automatic performance of continues loading. The microprocessor-controlled system is very useful in these tests where loading does not follow the conventional loading paths and a continues variable load must be maintained.

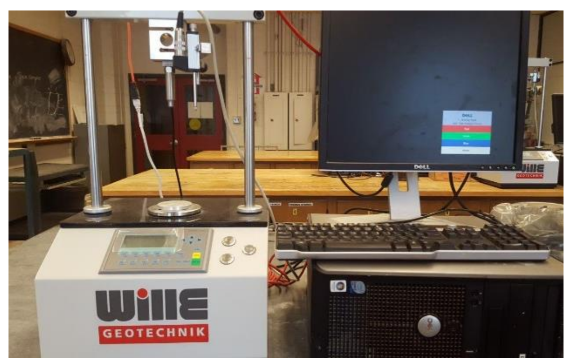

Figure1. Wille Geotechnik one-dimensional consolidation testing apparatus

The device is equipped with a Linear Variable Displacement Transducer (LVDT) with a precision of better than 0.002 mm to record vertical deformations. An "S"-Beam load cell with a precision of better than 0.01 N and capacity of 10 kN was used to measure the applied vertical load.

Cylindrical samples of 50 mm in dimeter with a height of 25 mm were used to be consistent with ASTM D2435 recommendations. Porous stones of 50 mm in dimeter were placed at the top and bottom of the sample to provide a two-way drainage situation. This two-way drainage for a cured sample might not be 100% true of what happens in the field. However, it facilities the consolidation process and we would expect to read higher deformations compared to the in-situ ones and hence be on the conservative side.

Samples were initially subjected to 5 kPa stress to establish contact with the loading ram prior to the initiation of the test. The deformations during this initial phase were recorded and the void ratios were normalized to this void ratio prior to loading. Fresh samples had the most void ratio change of 1% during the set-up loading.

2.2 Material tested

In this study, oedometer tests were performed on cemented mine tailings. The tailings were obtained from Williams mine in northern Ontario. Mine tailings are silt sized particles that are consisted of silicates, such as quartz, feldspar and plagioclase, with traces of barite. Figure 2 shows the grain size distribution of mine tailings. The grain size distribution is determined based on ASTM C136-06 and ASTM D422-63 using both sieve and hydrometer analyses. A deflocculating agent needed to be used in the hydrometer test. Table 1 shows the mine tailings' chemical composition based on the sequential X-ray fluorescent (XRF) analyzer results (Klein and Simon 2006).

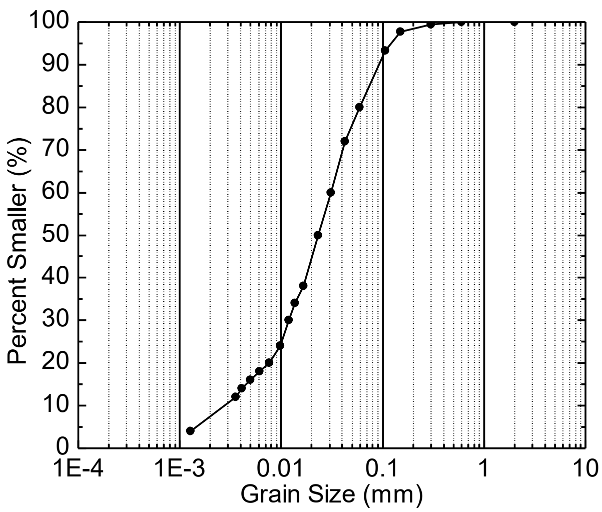

Figure 2. Grain size distribution of William mine tailings

The Canadian Standards Association (CSA) Type 10 Portland cement from Lafarge was used in this study as it is also being used in the field. The mineralogical and chemical compositions of the cement are shown in Table 2 and 3, respectively (Klein and Simon 2006).

2.3 Sample preparation

Reconstituted samples must closely represent the in-situ composition and fabric of the CPB. There are a variety of techniques that can be used to prepare samples (e.g. Jafari et al., 2017 and Le Roux, 2004). Mine tailings and cement particles have different particle sizes and hence during sample preparation segregation and deposition of larger particles must be avoided. On the other hand, samples must be uniform and have the same initial void ratios throughout the height even after hydration. Le Roux (204) showed that large occluded air bubbles can be created during sample preparation and must be avoided by rodding the sample after it is being poured in the mold. Jafari et al. (2017) considered the mentioned factors and suggested a sample preparation technique that yields uniform, consistent samples at an initial void ratio of 1.0±0.01. It is important to have an initial void ratio of 1 as the field initial void ratio is also 1 (Grabinsky et al., 2013) and lower void ratios can yield to a stronger response.

Table 1. Chemical composition of Mine Tailings (Klein and Simon 2006)

Compound	Content (%)
SiO_2	59.30
Al_2O_3	13.50
S	5.90
Ba	5.20
Fe	4.30
K	3.60
Ca	2.00
Mg	1.75
Na	1.50
Others	3.00

Based on Jafari et al. (2007) method, the mine tailings were first mixed with the process water for about 15 minutes in a bucket using a mixer. Then the bucket water content was measured and based on that and targeted gravimetric water content of 38% extra water was added to the mix. The cement content in this study is a fraction of the total solid weights. Therefore, for samples with 5% cement in this study, first the total solid weight based on water content and unit weight of the saturated material is determined and then the amount of cement is calculated. The cement, water, and mine tailings were then mixed for 10 minutes in a bowl using a hand mixer prior to being poured into the mold. It was made sure that during mixing no segregation and large air bubbles are occurred. After mixing, the water content was measured to make sure the targeted water content (38%) has reached.

The mixed CPB was then poured into solid stainless-steel molds shown in Figure 3. The solid molds were specifically prepared for this study following Jafari et al. (2017) recommendations about sample preparations. The mold has a diameter of 50 mm and height of 30 mm. The extra height is given so that the sample and mold would fit on top of the 50 mm diameter porous stone at the bottom of the sample. CPB was then poured into the mold, in 3 layers of equivalent height. Each layer was then rodded 20 times with a 5 mm thick rod to remove any entrapped air bubbles. The top cap was then placed, and it was made sure that there is no air on top of the sample. The top cap holes were sealed, and samples were cured under water for 12, 24, and 48 hours. The fresh samples, however, were made slightly different. The top cap was not placed and instead the samples' bottom was sealed using rubber membranes. The fresh samples were put in a chamber with high humidity for 4 hours. Prior to testing, the samples' surfaces were polished to ensure the surface smoothness and flatness. All samples had an initial void ratio of 1.0±0.01 that was determined based on control samples to measure void ratio using Archimedes principles.

To prevent formation of bonds between CPB and the body of the mold, the molds were lubricated with silicon oil prior to sample preparation and hence the shear stresses along the mold and CPB interface were minimized.

Table 2. Mineralogy (%) of CSA type 10 Portland cement (Klein and Simon 2006)

Mineral	
Tricalcium silicate or alite (C_3S)	63
Dicalcium silicate or belite (C_2S)	11
Tricalcium aluminate (C_3A)	9
Tetracalcium aluminoferrite (C_4AF)	7

Table 3. Chemical composition of CSA type 10 Portland cement used in this study (Klein and Simon 2006)

Compound	Content (%)
SiO_2	18.060
Al_2O_3	3.510
SO_3	4.540
Na_2O	0.086
MgO	3.156
K_2O	0.530
CaO	61.580
Fe_2O_3	2.558

3 TEST RESULTS AND DISCUSSION

After the samples were prepared and cured (if necessary) they were loaded under 3 different loading rates. Figure 4 shows the variation of normalized void ratio with time for a fresh sample loaded at loading rates of 5 kPa/hr, 10 kPa/hr, and 20 kPa/hr to a targeted vertical stress level of 400 kPa. It must be noted that the stresses mentioned in this study are total stresses and unlike the conventional consolidation tests, the excess pore pressure might have not been dissipated unless for the last loading step.

Slower loading rate lead to less deformations even though the samples had the same age. This difference in behaviour is due to the fact that the sample that was loaded at 5 kPa/hr had 80 hours of curing time under stress before reaching the final load. This extra curing has contributed to the sample strength gain and hence lead to less deformations. It might be expected that the samples that are loaded faster would gain more strength (Fahey et al., 2011). However, these results show that the combined effect of variable loading and drainage play a bigger role in strength gain.

Lower loading rate would lead to less excess pore pressure generations and hence less consolidation. The excess pore water pressure in the sample that was being loaded more slowly, would have more time to dissipate during each loading step. In addition, the strength gain would prevent the generation of much pressure and this would lead to less deformations with time. All these factors would lead to less deformations when the loading rate (i.e. backfilling rate) is slow. The fresh sample's final void ratio shows great agreement with the in-situ void ratios measured by Grabinsky et al. (2013).

Figure 3. Consolidation test molds and sample preparation

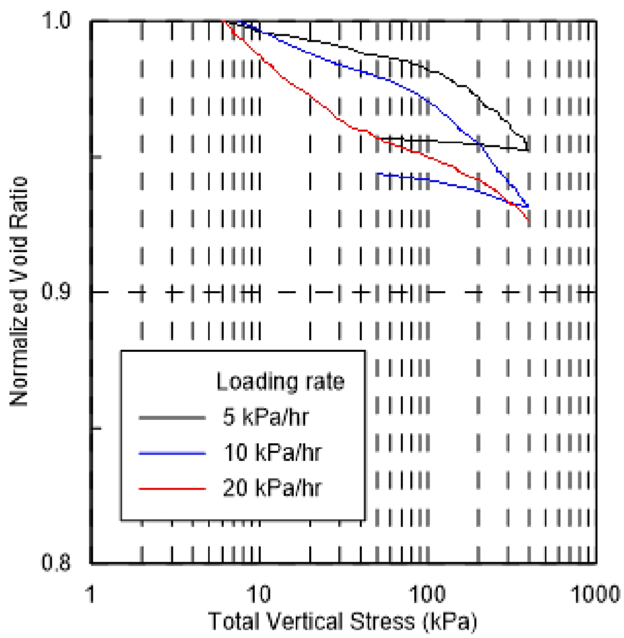

Figure 4. Normalized void ratio variation with vertical stress for fresh CPB samples with 5% binder content

Figures 5, 6, and 7 show the normalized void ratio-total vertical stress relationship of the samples that were cured for 12, 24, and 48 hours prior to loading. It is clear from the figures that the longer the samples are cured prior to loading, the final void ratios are less dependent on loading rate. The practical implication of these figures is that, after the plug is cured for a day or two, the backfilling rate would have less effect on void ratio changes within the plug. However, if the water phase is connected and drainage is lowered due to a decrease in permeability of the plug, pore pressures would still build up, but they would build up at a lower rate since material is less contractive due to the stiffness gain.

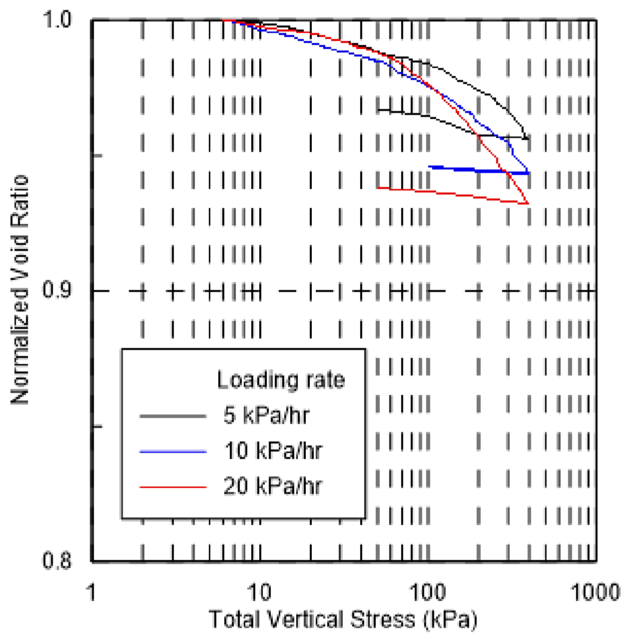

Figure 5. Normalized void ratio variations with vertical stress for 12-hour old CPB samples with 5% binder content

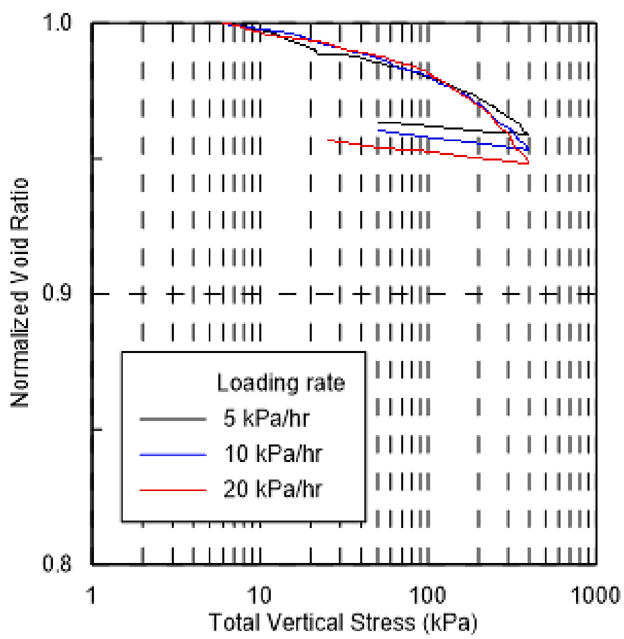

Figure 6. Normalized void ratio with vertical stress for 24-hour old CPB samples with 5% binder content

To have a better understanding of the combined effect of loading rate and curing time, the void ratio variation with the vertical stresses for samples loaded at 10 kPa/hr but with different curing times prior to loading are shown in Figure 8. The fresh sample consolidates at much faster rate. As the curing time increases, the difference between the final void ratios of samples becomes less. The fresh sample recovers more deformations upon unloading compared to the cured sample. This observation is counterintuitive; however, it must be noted that the samples are being cured as they are loaded during these tests and the combined effect of drainage, consolidation, and curing under stress might cause the anomaly. Cured samples show similar unloading behaviour and the rebounding index is very close between these samples. This last observation is consistent with the Yilmaz et al. (2015) and Le Roux (2004) observations from conventional consolidation tests on CPB.

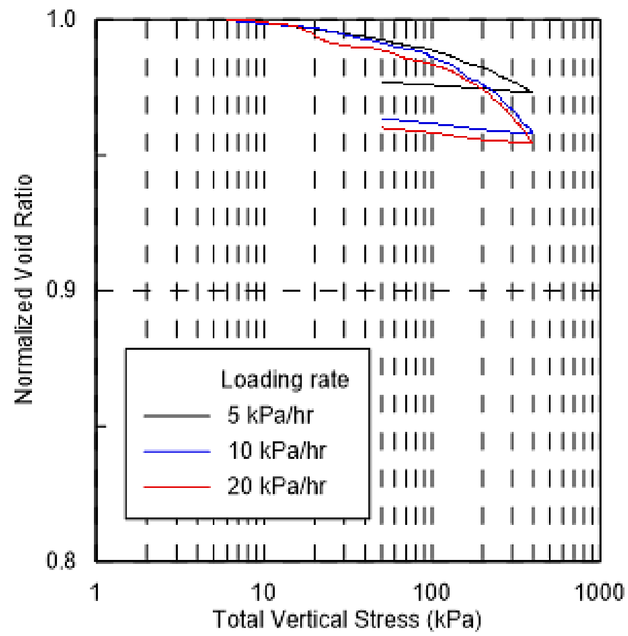

Figure 7. Normalized void ratio variation with vertical stress for 48-hour old CPB samples with 5% binder content

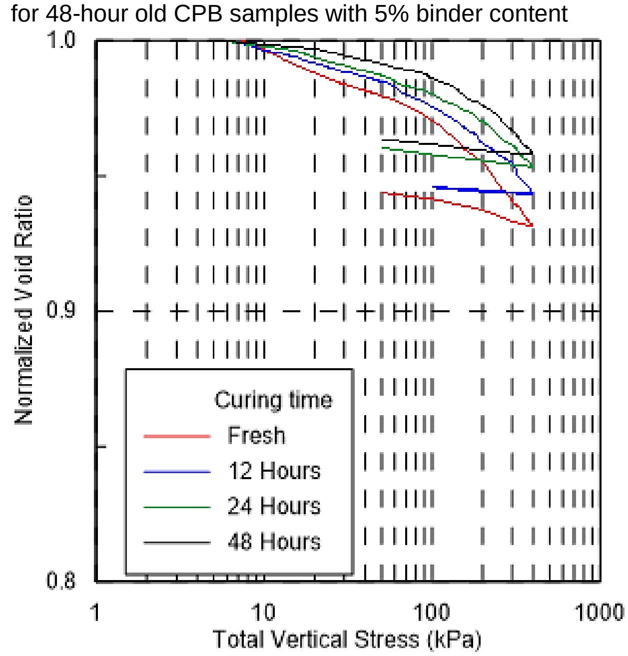

Figure 8. Normalized void ratio variation with vertical stress of CPB samples loaded at 10 kPa/hr but aged differently prior to loading

4 CONCLUDING REMARKS

A series of consolidation tests were performed on cemented paste backfill samples with 5% cement content by solid weight. The load increments were applied to replicate the in-situ stress path. Samples were loaded at rates of 5 kPa/hr, 10 kPa/hr, and 20 kPa/hr to represent backfilling rates of 25 cm/hr, 50 cm/hr, and 100 cm/hr, respectively.

It was shown that loading rate can influence the deformation characteristics of CPB. With a reduced backfilling rate CPB has more time to cure under stress and hence less deformations would occur. On the other hand, a slow backfilling rate is usually not desirable as it would cause delays in the mining operation. These experiments can help the backfill engineer to make proper decisions about choosing a safe and yet economical backfilling rate based on the cement content and curing time.

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