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Seismic induced liquefaction of cemented paste backfill: Effect of mixing water

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ABSTRACT: Cemented paste backfilling (CPB) is a mixture of tailings, water and cement that is used as tailings disposal method to minimize geotechnical and environmental risks associated with mine waste management. Fresh CPB placed into a stope can fail due to liquefaction during earthquakes, causing injuries/fatalities and significant financial consequences for mines. CPB behavior could be affected by the chemistry of pore water which often contains sulphate ions. This study aims to assess the effect of the chemistry (sulphate content) of the pore water on the earthquake-induced liquefaction of fresh CPB. Shaking table tests (0.13 g of peak ground acceleration) are performed on fresh CPB materials with and without sulphate ions in the pore water. The obtained results show that the presence of sulphate in the mixing water increases the susceptibility of CPB to liquefaction. The findings in this research will contribute to more cost-effective design of CPB structures.

1 INTRODUCTION

Mining is one of the most important industries around world. This industry greatly contributes to the economy and the employment market. However, the extraction of ore during mining activities may negatively impact public health and the environment as the task generates substantial quantities of potentially harmful waste, otherwise known as tailings. Improper disposal of these tailings can produce an environmentally hazardous material or fluid, such as toxic leachate. Also, mining activities may create large underground openings that are known as stopes, which might be susceptible to several kinds of geotechnical engineering problems, such as ground subsidence. (Jamali 2012, Farkish & Fall 2013).

In order to minimize the risks associated with mining activities and traditional means of mining waste management, a novel method of tailings management has been developed by mixing tailings with water and binder materials. The mixture which contains these three components is called cemented paste backfill (CPB). Typically, a CPB mixture is composed of 70% - 85% tailings, fresh or mine processed water, and often 3% - 7% (by total weight of solid) hydraulic binder (usually cement) (Aldhafeeri & Fall 2016, Haiqiang et al. 2016). Using CPB as backfill material for mine stopes can increase the stability of the stopes and will allow large volumes of mined tailings to be returned back to the extracted stopes (Thompson et al. 2009).

However, fresh CPB placed into mine stopes can be susceptible to liquefaction under dynamic loadings (such as seismic activities). Liquefaction-induced failure of CPB structures may cause injuries of workers and/or fatalities in the mine and the surrounding public areas, have negative impacts on the environment, and also lead to significant economic repercussions (Abdelaal 2011, Ghirian & Fall 2013).

Several historical seismic events have been recorded in Canadian mining areas with different magnitudes. For example, north-eastern Ontario recorded five earthquakes with a magnitude of 3.5 or more between 1985 and 2016. Also, the Saguenay earthquake in 1988 in Quebec had a magnitude of 5.9 (Saebimoghaddam 2010).

There is general consensus that seismic-induced liquefaction is significantly affected by the value of each seismic parameter, such as the peak horizontal ground acceleration and duration of the shaking (number of loading cycles) (Carter 1988). Soil liquefaction might occur if the peak ground acceleration is reduced to 0.05 g (James et al. 2003). Furthermore, the duration of the shaking greatly affects the liquefaction resistance of CPB at the early ages (or freshly placed CPB) (Saebimoghaddam 2010, Sassa & Yamazaki 2017).

Previous studies have found that CPB may contain sulphate ions. These ions originate from different sources including: (i) the oxidation of sulphate in tailings; (ii) the mine processing water used as the mixing water in CPB preparation; (iii) additives (such as gypsum) which are used to control the setting of cement; and (iv) sulphur dioxide and air method which is done in some mines (such as gold mines) to remediate cyanide. The initial content of sulphate has been found to be one of the most common factors that could chemically affect the mechanical behavior of CPB (Ercikdi et al. 2009, Pokharel & Fall 2013).

Several previous studies (Bairrao & Vaz 2000, James et al. 2003, Pépin et al. 2009, Özgen et al. 2011, Mohamed 2014) have addressed the liquefaction of natural soils or tailings (without cement) under seismic loadings with the use of a shaking table, while other studies (Aldhafeeri & Fall 2016, Li & Fall 2016) have been carried out to determine the effect of the initial content of sulphate on the strength of CPB. However, only a few studies have examined the behavior of CPB under dynamic loading by applying cyclic loading on CPB with the common triaxial test (Saebimoghaddam 2010). Nevertheless, there are no studies to date that have evaluated the effect of sulphate on the seismic response of CPB by using a shaking table. Accordingly, this study aims to evaluate the effect of the chemistry of the mixing water (sulphate content) on the liquefaction response of CPB during seismic loading by using a shaking table.

2 MATERIALS AND PROCEDURES

2.1 *Materials*

Artificial tailings (manufactured by U.S. Silica Co.) which are made of ground silica and commonly known as silica tailings (ST) are used in this study as the main component of the CPB mixture. The grain size distribution of ST is illustrated in (Fig.1). The mineral composition of ST is essentially quartz, which is a predominant mineral in Canadian tailings from hard rock mines. The high percentage of silica (99.8% silicon dioxide ($SiO2$)) makes ST a chemically inert material. Therefore, ST is used in this study to reduce the uncertainties related to the use of natural tailings by minimizing/controlling the potential chemical interactions of the tailings with other ingredients (e.g., cement, water) in the CPB mixture (Aldhafeeri & Fall 2016, Haiqiang et al. 2016).

2.2 *CPB preparation*

The CPB samples were prepared by mixing ST with Portland cement type I (PCI; 4.5 wt%) and water for a water-to-cement ratio (w/c ratio) of 7.6. The backfill was mixed by using a 0.1 m^3 mixer (1/3 Hp electric cement mixer) for 10 min to obtain homogeneity. The slump of the

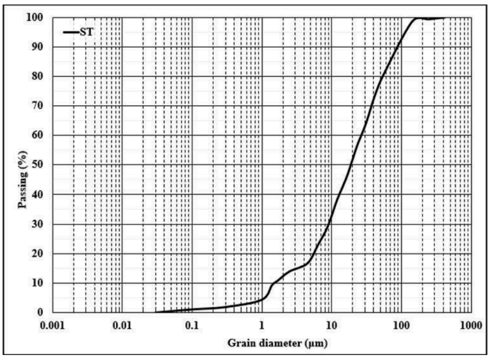

Figure 1. Grain Size distribution of the silica tailings (ST).

prepared backfill mixture was 18 cm. The slump test procedure of (ASTM C143/C143M-15a 2015) was followed. Afterwards, the CPB mixture was poured into a laminar shear box. To avoid evaporation, the laminar shear box with the CPB mixture was sealed and kept at a constant temperature or room temperature of 25° C for curing until the tested ages in accordance with the testing program described below. In order to determine the effect of the chemistry of the mixing water, 5000 ppm of sulphate in the form of sulphate salt ($FeSO_4$ $7H_2O$) was added to the mixing water as the initial amount of chemical additive.

2.3 *Shaking table*

In this study, dynamic loading is simulated by subjecting the samples to a series of 1-D (longitudinal) cyclic motions by using a computer controlled shaking table at the University of Ottawa (Fig. 2). This table moves back and forth to represent the movement of CPB during an earthquake, which provides lateral displacement with a one degree of freedom. This shaking table consists of a rigid steel base and platform with dimensions of ~1200 mm × ~1060 mm, with steel C-channels between them.

The shaking ranges from 1 to 17 Hz and is driven by a hydraulic actuator which is digitally controlled in order to simulate ground vibration and sinusoidal and/or earthquake shaking. The digital control module allows calculating the harmonic spectrum, pre-storing earthquake records, and reproducing other types of time-dependent dynamic displacement. In order to drive the shaking table, low voltage signals that are generated by the digital control module are amplified by using an amplifier. The maximum base shear capacity and displacement limit of the shaking table are 27 kN and 120 mm, respectively (Mohamed 2014).

2.4 *Setup and instrumentation*

In order to examine the seismic response of CPB by using a shaking table, a flexible laminar shear box (FLSB) (Fig. 3) was designed and constructed at the University of Ottawa. The FLSB consists of 30 horizontal laminas made of aluminum alloy sections with dimensions of 31.7 mm × 31.7 mm. The inner dimension of each lamina is 750 mm × 750 mm, and the clearance spacing between the lamina was arranged to be 2 mm to ensure the independent movement of each lamina. The total capacity of the assembled FLSB is 750 mm × 750 mm × 1000 mm (W × L × H).

A flexible plastic bag was placed inside the FLSB to contain/hold the CPB mixture. This bag has no or negligible effect on the movement of the FLSB as it has a maximum thickness of 0.5 mm, aside from its high flexibility. The FLSB and the flexible plastic bag were then bolted to the platform of the shaking table. The prepared CPB mixture was poured into the FLSB. During pouring, an electric vibrator with a small diameter was placed into the FLSB to vibrate the poured mixture at high frequencies to eliminate air voids that might have accumulated in the mixture. The final dimensions of the CPB samples for testing are 750 mm × 750 mm × 700 mm.

Omega PX309 pressure transducers with a range of -15 to +15 PSI and ±0.25% accuracy were placed at different levels on the CPB samples to monitor the changes in pore water pressure

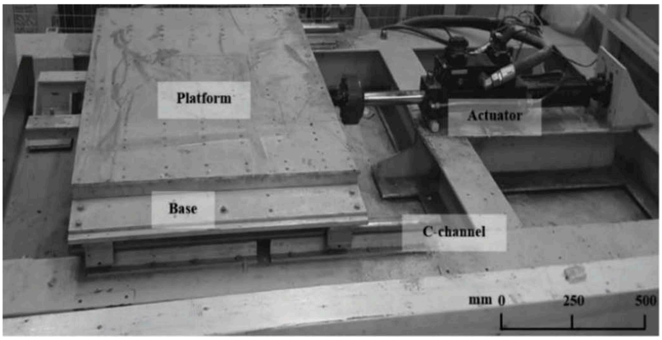

Figure 2. Shaking table used in this study.

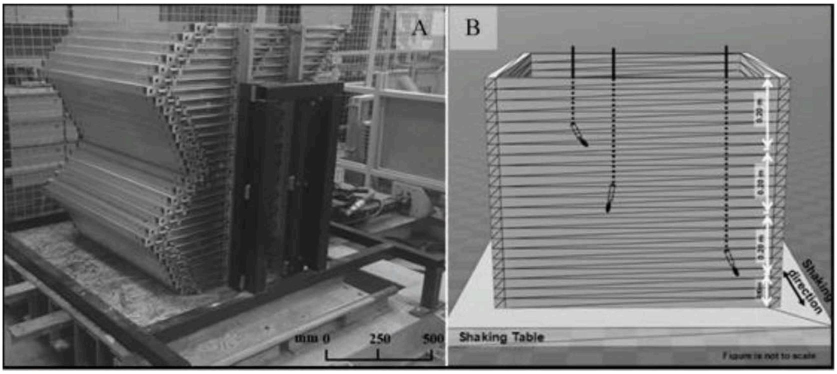

Figure 3. Flexible laminar shear box, (A) General view (B). Schematic view and location of instruments.

(PWP) during shaking (Fig. 3B). To record the data during shaking, the pressure transducers were connected to a signal conditioning and data acquisition system which was connected to a computer. The data were recorded at approximately (1 s) time intervals. Furthermore, a digital camera was used to record each step of the testing (mixing, installing and shaking).

2.5 *Experimental test*

The main goal of the testing was to evaluate the influence of the presence of sulphate on the seismic response of fresh CPB. In this regard, two types of CPB samples were prepared: (1) CPB which did not have sulphate salt added to the mixing water, and (2) CPB prepared with mixing water that contained 5000 ppm of sulphate. Both samples were cured for 4 h.

In order to simulate the ground shaking conditions, the related seismic parameters were determined prior to conducting the tests. These parameters include the sinusoidal loading frequency (SLF), shaking peak horizontal acceleration (SPHA), horizontal displacement amplitude (HDA), and duration of the shaking (SD). Table 1 summarizes the experimental test conditions.

As shown in Table 1, the shaking tests are performed in this study by using a sinusoidal loading frequency of 1 Hz to accommodate the sensitivity/limitations of the monitoring instruments. Although the typical frequency range of many recorded earthquakes in North America is relatively higher (Nuttli 1973), it has been found that the magnitude of the loading frequency applied in laboratory seismic tests has a slight influence on the response of the tested materials (Sriskandakumar 2004).

Although recorded earthquakes do not last very long, a time scaling of ground motion (with respect to the size difference between the real mine and the laboratory model) was necessary to be applied in this study. Accordingly, the seismic loading (shaking) in this study is carried out for 30 minutes (1800 s) as shown in Table 1. The duration of the dynamic loading in this study is not meant to be representative of the actual duration of earthquakes. A duration of 30 minutes was used to allow good observation of the dynamic behaviour of the CPB samples and relative comparisons of their response, which is important for the future development

Table 1. Summary of experimental test conditions.

Test	CPB Material	Sulphate (ppm)	HDA (mm)	SLF (Hz)	SPHA	SD (min)	CT (h)
1	CPB without Sulphate	0	32	1	0.13g	30	4
2	CPB with Sulphate	5000	32	1	0.13g	30	4

HDA: Horizontal displacement amplitude ; SLF: Sinusoidal loading frequency; SPHA: Shaking peak horizontal acceleration; SD: Duration of shaking; CT: Curing time of CPB of a constitutive model to describe the dynamic response of soils undergoing cementation and subjected to chemical attacks. Moreover, similar durations have been often used in previous studies on liquefaction (eg. James et al. 2003; Pépin et al. 2012). Also, James et al. (2003) found that a duration of shaking of (1000 s) is suitable to reach the cyclic peak of the liquefaction of tailings without waste rock inclusion.

Many studies in the extant literature have indicated that tailings may liquefy when they are exposed to ground motion with a peak ground acceleration that exceeds 0.05 g (Carter 1988, James et al. 2003). Therefore, the peak ground acceleration in this study is 0.13 g, which is equal to the ground acceleration of the Saguenay earthquake in 1988 in Québec.

The maximum displacement of the simulator (deformation amplitude) in this study is 32 mm. This is based on the values of the loading frequency and peak ground acceleration by using the basic dynamic equations in (Douglas 2003, Chopra 2005).

3 REPRESENTATIVE TEST RESULTS

In this study, different tests have been conducted, which have resulted in a large quantity of data. Therefore, only representative results from the testing are presented in this section. These results are related to shaking induced changes in the PWP and a liquefaction analysis with respect to the presence of sulphate. The parameters were evaluated at the depths of 20 cm and 60 cm from top of the sample cured for 4 h.

3.1 *Change in pore-water pressure*

Taking in consideration the role of cement in the PWP of the CPB material, and to study the response of the CPB under seismic conditions, it is important to determine the initial conditions (hydrostatic conditions) of the CPB material prior to conducting shaking by recording the PWP at each depth of the CPB sample before applying seismic loading.

The changes in PWP at the depths of 20 cm and 60 cm within the CPB models that were prepared with and without adding sulphate to the mixing water are illustrated in (Fig. 4).

Before shaking (Fig. 4A) there was a decrease in PWP till the start of shaking events. The decrease in PWP is related to the water consumption due the progress of cement hydration (Scrivener et al. 2015). This was confirmed by determining the degree of saturation of each sample. It was noted that the degree of saturation of both samples decreased from 100% (immediately after casting) to around 96% before shaking (after 4 hours of curing) in both CPB samples.

When the shaking began, there was a significant increase in the PWP (development of excess of PWP) in the CPB with sulphate, while there was less excess of PWP in the CPB

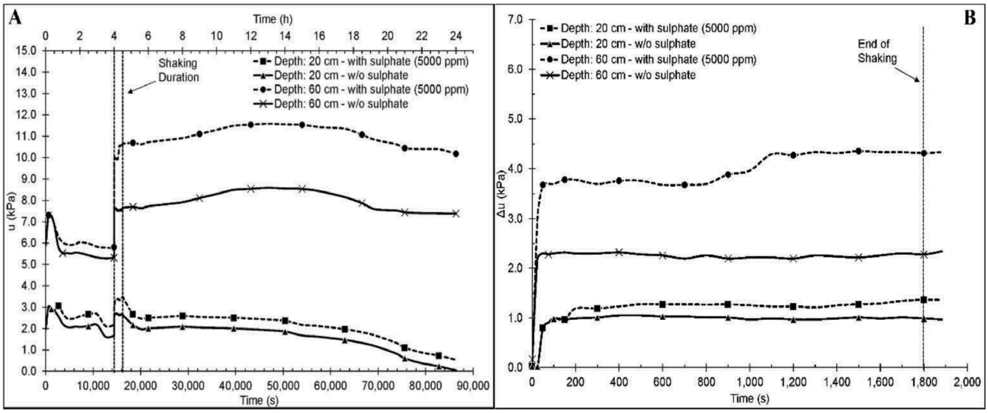

Figure 4. Seismic response of CPB prepared with and without sulphate: (A) Change in PWP at different depths of both samples before, during and after shaking, (B) Excess PWP developed during shaking.

without sulphate; see (Fig. 4B). The maximum excess of PWP developed at depths 20 cm and 60 cm within the CPB sample without sulphate and subjected to shaking for 50 s are 0.9 kPa and 2.3 kPa, respectively. On the other hand, the maximum excess of PWP developed at the same depths within the CPB sample with sulphate and also subjected to 50 s of shaking are 1.1 kPa and 3.8 kPa, respectively. The maximum excess of PWP developed at the depths of 20 cm and 60 cm within the CPB sample that contains sulphate after being subjected to shaking for 1250 s are 1.3 kPa and 4.3 kPa, respectively. While that of the CPB sample without sulphate remained constant until the end of the shaking.

After the end of shaking, the PWP continued to increase in both samples. It was noted that the rate of PWP increase (after shaking) was higher in the CPB sample with sulphate than that in the CPB sample without sulphate. Also, the degree of saturation increased to 99% and 98% in the CPB samples with and without sulphate, respectively. This phenomena can be attributed to the contraction of CPB particles due to the termination of the cyclic loading, which created additional PWP (Pépin et al. 2009). Subsequently, the PWP at each depth was relatively stable in all samples for a certain period of time. This is followed by the start of PWP dissipation in some depths within each sample (Fig. 4A).

3.2 *Liquefaction analysis*

There are several criteria of laboratory assessment of liquefaction, such as PWP-based criteria, strength-based criteria, and strain/deformation-based criteria. The PWP-based criteria is considered as the basic and popular laboratory criterion as it depends on the essential element of liquefaction mechanisms, which is the change in PWP (Jiaer et al. 2004). Accordingly, this study uses this criterion.

The excess of PWP ratio (R_u), which is the ratio of the change in PWP (Δu) and the initial effective stress (σ'_o), has been used as an evaluation factor of susceptibility to liquefaction. Liquefaction can be defined if R_u1, and if $R_u < 1$, there is no liquefaction (Jiaer et al. 2004).

In this study, the PWP ratio (R_u) is determined for each tested CPB sample by using the following equation (Jiaer et al. 2004):

$$R_u = \Delta u / \left(\sigma'_o\right) \tag{1}$$

As shown in (Fig. 5), the CPB sample with sulphate is susceptible to liquefaction under the applied seismic loading conditions (R_u1), while the CPB sample without sulphate resists to

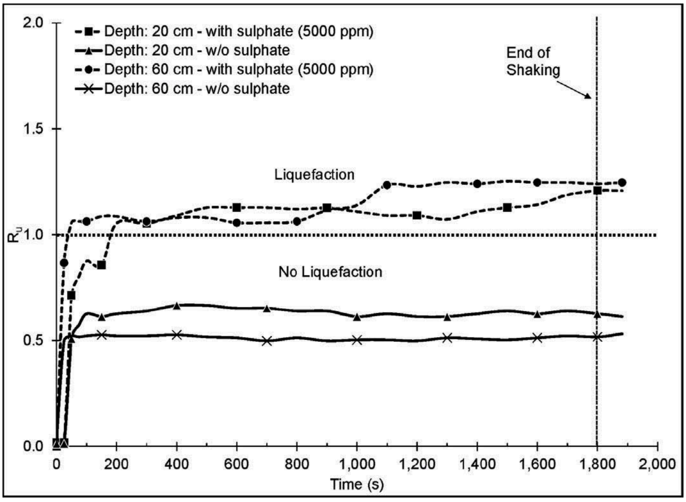

Figure 5. PWP ratio during shaking.

liquefaction ($R_u < 1$). In other words, the presence of sulphate in CPB mixing water increases the susceptibility of CPB to liquefaction under the studied seismic conditions.

4 DISCUSSIONS AND CONCLUSIONS

The difference in the behavior or liquefaction potential of the CPB samples with sulphate and without sulphate can be attributed to the effect of two competing factors: (i) the positive effect of the curing time on cement hydration, and (ii) the negative effect of sulphate on the cement hydration as discussed below.

There is general consensus that the primary goal of using cement as the binder material in CPB mixtures is to bind the tailings particles, which increases the strength of the mixture (Jamali 2012). It is also common knowledge that cement hydration progresses with time (Bullard et al. 2011).

As the cement hydration advances more cement hydration products, such as C-S-H, CH, will be precipitated within the CPB pores. These hydration products will progressively bond the CPB particles together (generation of cohesion), reduce the pore space between these particles and reduce the amount of water (water content) within the CPB through self-desiccation (cement hydration leads to a net reduction of the total volume of water and solids, thereby decreasing the PWP or moisture content inside cementitious materials (Li & Fall 2016). These factors gradually increase the liquefaction resistance of a soil undergoing cementation with time; they explain why the CPB without sulphate cured for 4 h did not liquefy during shaking.

However, it is well documented that sulphate ions slow down the cement hydration (Fall & Pokharel 2010). This negative effect of sulphate on the cement hydration is attributed to the inhibition of cement hydration by sulphate ions. This inhibition is usually due to the reaction of the sulphate anions in the liquid with the C_3A grains of the cement forming ettringite. The ettringite forms a thin coating of anhydrated cement particles, which prevents the C_3A from quickly reacting with the water (Li & Fall 2016). This inhibition decreases the liquefaction resistance of the sulphated CPB due to the combined effects of the following mechanism: (i) the sulphate induced decrease of the cement hydration rate leads to a less intense self-desiccation within the CPB with sulphate, as demonstrated in many previous studies (e.g. Li & Fall 2016). This is obviously associated with less dissipation of PWP within the CPB with sulphate, in other words, this results in lower effective stress in the sulphated CPB. As a result of the sulphate-induced lower effective stress, the liquefaction susceptibility of the CPB with sulphate increases; (ii) the inhibition leads to the formation of less cement hydration products (C-S-H, CH) within the CPB with sulphate (Li & Fall 2016). Fewer hydration products are understandably associated with less and weaker cementation between the tailings particles of the sulphated CPB.

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