Shaking Table Investigation of Cemented Paste Backfill Liquefaction Potential under Cyclic Loading

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Abstract
The liquefaction potential of cemented paste backfill (CPB) masses under cyclic loading at early ages is a concern in underground mine backfilling operations. As underground mines face gradual depletion of shallow ore reserves in various regions worldwide, mining operations are increasingly moving to greater depths with larger volumes, leading to more severe and frequent cyclic loading events. This research utilizes the shaking table technique to assess the liquefaction potential of hydrating CPB during cyclic loading at early ages. A series of shaking table tests were conducted on large, fresh CPB samples cast in a specially designed flexible laminar shear box. Some of these tests were carried out at different curing ages (2.5, 4.0, and 10.0 hrs) to investigate the influence of cement hydration progress on CPB's liquefaction potential.

Additionally, another set of tests explored the impact of pore-water or mixing water chemistry, specifically sulphate content, on the seismic response of fresh CPB by subjecting CPB models to seismic loads with varying sulphate ion concentrations. Various parameters, such as pore water pressure, horizontal and vertical displacement, acceleration, temperature, and electrical conductivity, were continuously monitored before, during, and after shaking. The results revealed distinct cyclic behavior and performance of CPB under different conditions. Specifically, the progress of cement hydration (longer curing time) enhanced the liquefaction resistance of CPB, while the presence of sulphate ions diminished it. Furthermore, the study demonstrated that the acceleration, horizontal and vertical displacement, and excess pore water pressure of CPB under cyclic loading were greatly influenced by the curing time, depth within the CPB, and the chemistry of the mixing water.

These findings contribute to a deeper understanding of the cyclic behavior and liquefaction potential of CPB at early ages, providing valuable insights for liquefaction assessment of CPB structures.

Key words: paste backfill, tailings, mine, dynamic loadings, pore water pressure, sulphate

Introduction
In recent decades, CPB has been widely employed for filling underground mine voids to support the ground and manage tailings. Consequently, CPB plays a crucial role in ensuring a safe work environment, supporting mine productivity, and facilitating sustainable mine waste management. Nevertheless, the young CPB mass, once deposited in underground mine cavities (stopes), can be prone to various geotechnical challenges. These include mechanical instability under static loads, and liquefaction when subjected to dynamic or cyclic loads. CPB failure within mine stopes poses risks of injury or fatality to miners and damage to equipment, with significant economic repercussions for the mine and its operations (Belem et al., 2006; Poulos et al., 1985, Orejarena and Fall, 2008, Wu et al., 2014). Consequently, understanding the geotechnical and liquefaction response of CPB under cyclic loading is a crucial consideration in mine backfill design.

CPB structures in stopes may face seismic loads originating from natural earthquakes or mining-induced seismic events. These events encompass various sources such as fault slip, rockburst, bump, pillar burst, outburst, pillar punching, disruption from active longwall mining, overburden strata failure, and coal bursts. The frequency and severity of mining-induced seismic events tend to escalate with increased volume extraction and mining depth (Hasegawa et al., 2009). As underground mining operations increasingly occur at greater depths and volumes due to diminishing shallow ore reserves worldwide, CPB structures may encounter more frequent and severe seismic events, potentially heightening the risk of liquefaction.

While earlier studies on the mechanical stability of young CPB focused on static loading conditions (Li and Aubertin, 2012; Cui and Fall, 2018), there is a scarcity of research on the geotechnical and liquefaction response under cyclic loading conditions. Limited studies have experimentally explored the behavior and liquefaction potential of early-aged CPBs under cyclic loading, but they primarily utilized small-size samples in common small cyclic triaxial or direct shear test apparatus (Saebimoghaddam, 2010; Suazo et al., 2017). Because of the associated high costs and challenges in reproducing in-situ stress conditions, shaking tables have been frequently used for assessing the cyclic response of geo-materials and engineering structures. However, there is a paucity of studies employing shaking table testing techniques despite their potential benefits.

This study aims to use shaking table techniques to investigate the impact of curing time and chemical composition, especially presence of sulphate ions in mixing water, on the cyclic response and liquefaction potential of hydrating CPB during cyclic loadings. By doing so, the research seeks to enhance our understanding of the time-dependent response of CPB to cyclic loading, CPB liquefaction potential, and how the chemical composition of CPB pore water influences these responses. Ultimately, this information will contribute to the design of more efficient and cost-effective CPB structures.

Experimental program

Materials and CPB preparation

This study utilized a combination of synthetic silica tailings (ST), hydraulic binder, and water as key components for the CPB material. The ST comprises predominantly quartz, mirroring the grain size distribution typical of nine mine tailings sourced from various mines in Canada. The ST material consists of silt-size particles of approx 75% of its composition. The ST material can be classified as medium-sized tailings (35–60 wt% of < 20 μm particles) (Landriault, 2001). The specific size distribution of ST is characterized by values of 1.9 μm for D_{10}, 9.0 μm for D_{30}, and 31.5 μm for D_{60}. Unlike natural tailings, ST lacks reactive minerals that might introduce uncertainties through chemical interactions within the CPB mixture, ensuring stability in the interpretation of results. With a silica content of 99.8% SiO_2, ST proves chemically inert in CPB systems. Portland cement type I (PCI), the prevalent choice in backfill operations, served as the hydraulic binder. Tap water free of sulphate ions functioned as the mixing water for sulphate-free CPB. To assess the impact of mixing water chemistry, tap water was modified with sulphate salt ($FeSO_4 \cdot 7H_2O$) to achieve a sulphate content of 5000 ppm, a concentration commonly found in CPB systems (Fall and Benzaazoua, 2005). Sulphate ions in CPB systems can originate from various sources (Fall and Benzaazoua, 2005), including:

- oxidation of sulphide minerals in the tailings
- utilization of the sulfur dioxide/air method to remove cyanides in gold mining
- incorporation of gypsum ($CaSO_4 \cdot 2H_2O$) or anhydrite ($CaSO_4$) in the clinker to regulate cement setting, and
- use of mine processing waters as mixing water for CPB preparation.

ST, PCI, and mixing water (with or without sulphate ions) underwent a 10 min homogenization process. The cement proportion was set at 4.5%, maintaining a consistent water-to-cement ratio (w/c) of 7.6 across all mixtures in this study (Fall et al., 2004; Wang et al., 2016).

The water saturation degree of the prepared CPB was uniformly determined to be 100%. The slump, (ASTM C143/C143M-15a), yielded a value of 18 cm for the freshly prepared CPB material.

Subsequently, these CPB mixtures were poured into a specially designed laminar shear box (Figure 1) with final dimensions of 75 cm long × 75 cm wide × 70 cm high. To prevent alterations in water content due to evaporation, the laminar shear box containing CPB mixtures was sealed and allowed to cure at room temperature (approx 20° C) until it reached the desired testing age.

Experimental configuration and measurement instruments

The testing program utilized the Flexible Laminar Shear Box (FLSB), which was specifically developed and manufactured at the Faculty of Engineering, University of Ottawa. To emulate the behavior of CPB samples under cyclic loads, the FLSB was securely affixed to the shaking table platform (Figure 1). The shaking table dimensions are 120 cm × 106 cm, and it operates through a digitally controlled hydraulic actuator with a shaking range spanning 1–17 Hz. The shaking table has a maximum base displacement of 12 cm and a shear capacity limit of 27 kN. Constructed with 30 horizontal aluminum laminas, the FLSB has inner dimensions of 75 cm × 75 cm. To ensure independent movement, a clearance spacing of 0.2 cm was implemented between each lamina, resulting in a total assembled FLSB capacity of 75 cm × 75 cm × 100 cm. For containment during tests, a 0.5 mm thick highly flexible polyethylene membrane was positioned within the FLSB before pouring CPB mixtures (Figure 2). The membrane's flexibility minimally impacts the FLSB's movement.

Various instruments and sensors were strategically placed at different depths within the FLSB to observe CPB sample properties and responses before, during, and after shaking, as illustrated in Figure 2. These instruments include pressure transducers to track changes in pore-water pressure before testing, accelerometers for measuring shaking acceleration, MPS6 suction sensors to monitor suction potential throughout CPB curing, and ECH2-5TE sensors to record changes in electrical conductivity (EC), volumetric water content (VWC), and temperature (°C). The variations in EC signify the rate of ion movement resulting from chemical reactions between cement and water.

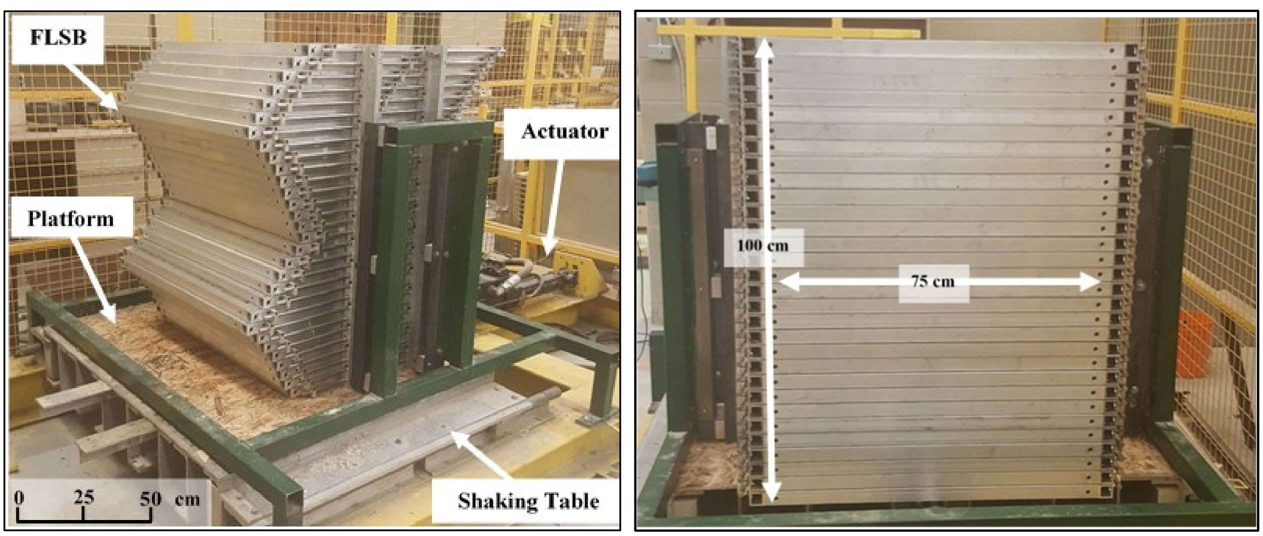

Figure 1. Shaking table and flexible laminar shear box (FLSB) employed in this research.

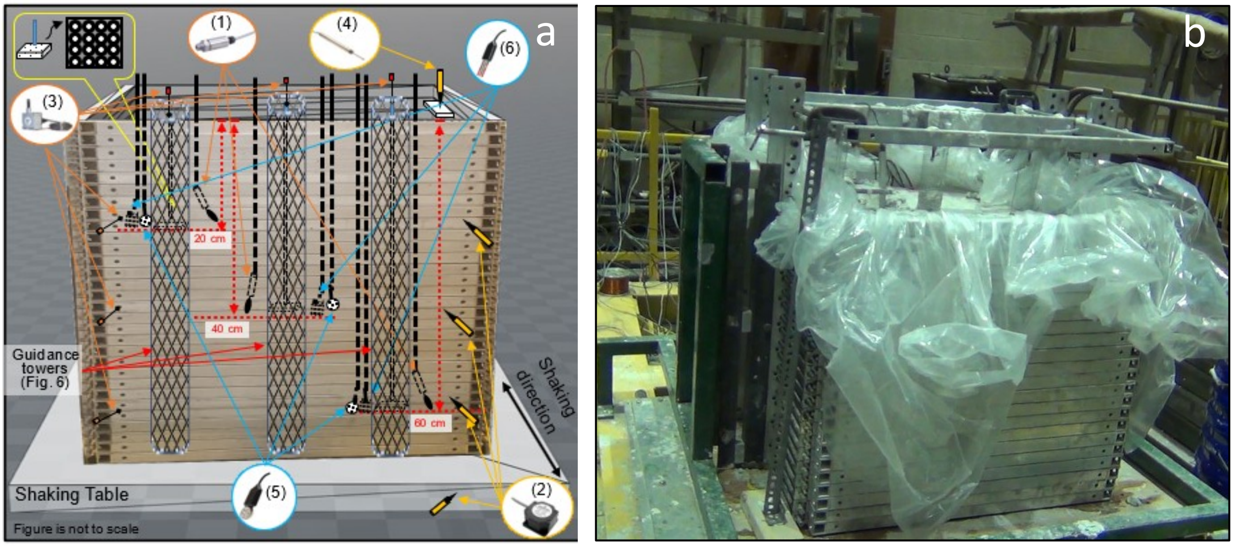

Figure 2. FLSB with sensors and CPB: (a) Instrumented FLSB with: (1) Pressure transducers, (2) Accelerometers, (3) Cable transducers, (4) LVDT, (5) MPS6 sensors, and (6) 5TE sensors; (b) FLSB containing CPB.

Testing program and procedure

The testing program on the shaking table and its conditions (Table 1), involved the application of a one-dimensional signal with a uniform amplitude, a constant frequency of 1 Hz, and a peak horizontal acceleration of 0.13 g on the CPB sample. Additionally, the CPB underwent shaking for up to approximately 1800 seconds. It is essential to emphasize that the loading conditions in this study were not intended to mimic those occurring in a natural or real earthquake. Unlike natural earthquakes, which do not exhibit a one-dimensional signal, uniform amplitude, constant frequency, and prolonged duration, the applied conditions here featured a distinct one-dimensional signal, uniform amplitude, constant frequency, and a lengthy duration. In natural earthquakes, the number of cycles varies with earthquake magnitude (typically 5–20 cycles), and motion amplitudes experience gradual increments and decrements. The chosen frequency of 1 Hz for sinusoidal loading was based on prior liquefaction studies (Ishihara, 1996; Pépin et al., 2012; Geremew and Yanful, 2012) and aligned with the monitoring capabilities of the employed sensors and the shaking table capacity. The selected peak horizontal acceleration of 0.13 g corresponded to the peak ground acceleration recorded during the 1988 Saguenay earthquake in Quebec; note that only the peak acceleration aligned with the Saguenay Earthquake, not the entire time series.

Previous investigations (Carter, 1988, Pépin et al., 2012) suggested that tailings may undergo liquefaction under ground shaking with a peak horizontal ground acceleration of 0.05 g or higher. The cyclic loading in this study persisted for up to 1800 seconds, exceeding the duration of recorded earthquakes (Natural Resources Canada, 2019). This extended shaking period facilitated thorough observation of dynamic behavior for CPB samples, and enabled response comparisons aiding in the development of future constitutive models. Similar durations have been employed in prior studies on the dynamic behavior of tailings materials (Pépin et al., 2012). It has been reported that the cyclic peak liquefaction of tailings without inclusions or cement can occur within 1000 seconds of shaking (James et al., 2003). Given the cementing nature of the CPB mix in this study, shaking durations ranged from 1–30 mins (60–1800 cycles) depending on material response, with post-loading monitoring continuing for an additional 24 hrs as required.

Microscopic examination was also performed on selected samples of CPB. This analysis allowed the evaluation of alterations in the microstructure of the CPB material induced by curing time and exposure to sulphates, potentially influencing its behavior under cyclic loads. The study encompassed a thorough microstructural analysis, incorporating thermal examination techniques such as differential thermogravimetry (DTG) and thermal gravimetry (TG). The TGA Q 5000 IR equipment from TA Instruments was employed for these analyses. Prior to initiating the tests, the test samples underwent an initial drying process at 45°C in a vacuum oven until reaching mass stabilization. Subsequently, the various dried samples (approx 20 mg) underwent heating in an inert nitrogen atmosphere at a rate of 10°C/min, reaching a temperature of 1000°C.

Table 1. Overview of the testing program

Tes t	Material	Age (hrs)	Sulphate* content	HDA (mm)	SLF (Hz)	SPHA	PLMD (hrs)
1	CPB	2.5	0 ppm	32	1	0.13g	24
2	CPB	4	0 ppm	32	1	0.13g	24
3	CPB	4	5,000 ppm	32	1	0.13g	24
3	CPB	10	0 ppm	32	1	0.13g	24

HDA : Horizontal Displacement Amplitude
SPHA : Shaking Peak Horizontal Acceleration
PLMD : Post Loading Monitoring Duration
SLF: Sinusoidal Loading Frequency
*Sulphate content of the mixing water

Liquefaction susceptibility and assessment criteria used

Diverse criteria have been proposed and employed to characterize or identify soil liquefaction, encompassing strength-based, strain/deformation-based, energy-based, and (excess) pore ratio-based criteria. Each of these approaches has its advantages and limitations, described in prior studies (Wu et al., 2004). Furthermore, past shaking table tests (Turan et al., 2009) have involved assessing liquefaction based on the examination of the stress-strain relationship, which can be inferred from accelerometer measurements. Conversely, excess pore-water pressure ratio criteria have been widely utilized in appraising the liquefaction potential of soils or tailings, particularly in shaking table tests. In this investigation, the excess pore-water pressure ratio served as the factor for evaluating CPB liquefaction susceptibility. The excess pore-water pressure ratio (R_u) represents the ratio between the excess PWP (Δu) and the initial effective stress ($\sigma_o^{'}\sigma_o'$). Liquefaction is generally defined if $R_u \geq 1 R_u \geq 1$. However, if $R_u < 1$, there is no liquefaction (Wu et al., 2004).

Results and Discussion

Multiple effects of cyclic loading on the geotechnical behavior and liquefaction response of CPB with different curing times and sulphate contents were obtained, and selected results and data, in particular those relating to excess pore water pressure ratio and susceptibility to liquefaction, are presented and discussed in this section. A full and detailed presentation and discussion of the results related to all investigated geotechnical parameters (eg, pore water pressure, effective stresses, lateral deformation, settlement, peak acceleration) is available elsewhere (Alainachi and Fal, 2021, 2022, 2023).

Effect of curing time on the liquefaction response of CPB under cyclic loadings

Similar to any cementitious material, the engineering characteristics of CPB, including mechanical properties, are impacted by the advancement of cement hydration. As time elapses, improved mechanical performance is anticipated in these materials. Understanding and knowing when the backfill mass reaches its design mechanical properties, such as resistance to liquefaction, is essential to ensure a safe working environment and to schedule the opening of barricades or mining cycles, which has a large impact on mine productivity. Thus, an exploration into the impact of cement hydration progress (curing time) on the liquefaction potential of freshly prepared CPB under cyclic loads was conducted. This was accomplished through shaking table tests on three CPB specimens poured into FLSB and subjected to varying curing times. All CPB samples were uniformly placed inside the FLSB in a single layer (continuous filling), and the three CPB samples underwent curing at a consistent room temperature of 20°C for 2.5, 4, and 10 hrs. The findings reveal that the acceleration, horizontal and vertical displacements, excess pore water pressure and liquefaction susceptibility of CPB under cyclic loading are notably influenced by curing time or the extent of cement hydration and the depth within the CPB, as detailed in Alainachi and Fall (2021, 2022). For example, Figure 3(a-c) illustrates the pore-water pressure ratios determined during the shaking of CPB samples subjected to curing periods of 2.5, 4, and 10 hrs. Observably, CPB samples cured for 2.5 hrs exhibit susceptibility to liquefaction ($R_u \geq 1$) under the cyclic loading conditions applied. Conversely, samples subjected to shaking after 4.0 and 10.0 hrs of curing display resistance to liquefaction ($R_u < 1$). Simply put, the longer the curing time allowed for cement action, the lower the susceptibility of CPB to cyclic-induced liquefaction. The heightened liquefaction resistance of CPB with increasing curing time is attributable to the combined impact of the following two factors:

1. Generation of more cement hydration products within CPB pores due to the progression of cement hydration, enhances cementation or cohesion between tailings particles, thereby increasing the shear strength of the CPB material. This leads to an escalation in CPB liquefaction resistance. Experimental evidence supports the increased formation of cement hydration products with prolonged curing times, as revealed by microstructural analyses, specifically thermal analysis (TG/DTG analyses) conducted on cement pastes of CPBs cured for 1 hr and 4 hrs (Figure 4). A comparison of the TG/DTG diagrams for CPBs cured at 1.0 hr and 4.0 hrs distinctly shows higher first and second peaks or weight changes in the latter case. This observation implies that the quantity of hydration products, such as calcium hydroxide (CH) and calcium silicate hydrate (C-S-H), increases greatly with extended curing periods.

2. Water consumption resulting from cement hydration (self-desiccation), leads to a reduction in pore water pressure or excess pore pressure within the backfill. This reduction is evidently linked to an elevation in effective stress within the CPB, consequently increasing the liquefaction resistance of the cementing backfill.

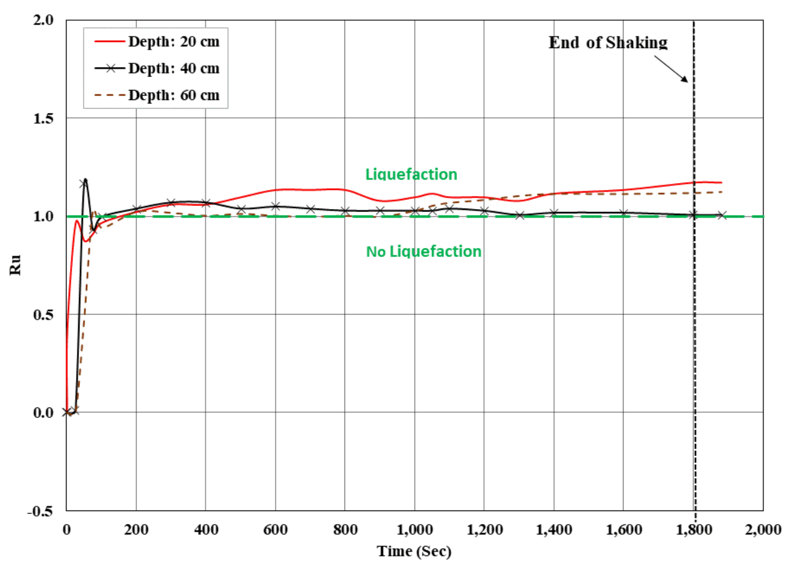

Figure 3a. Excess pore water pressure (Δu) at depths vs times for CPB samples cured to 2.5 hrs.

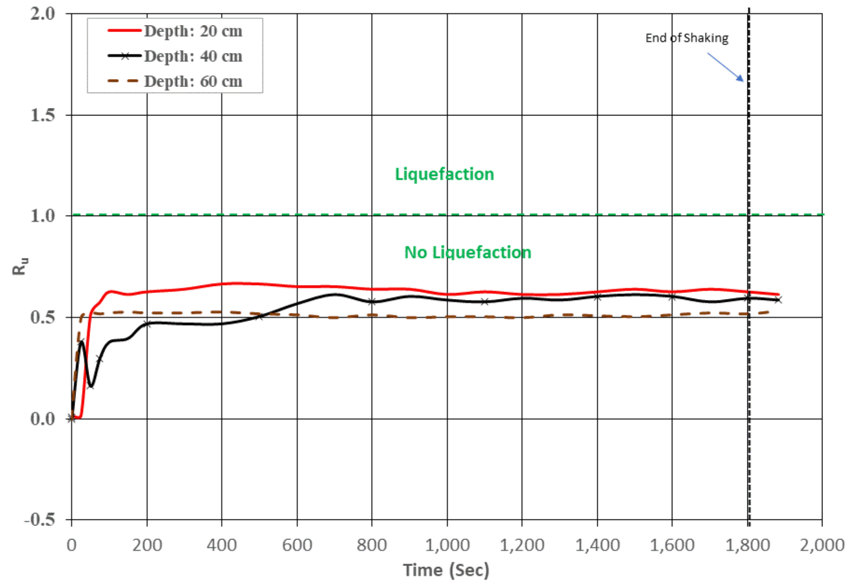

Figure 3b. Excess pore water pressure (Δu) at depths vs times for CPB samples cured to 4 hrs.

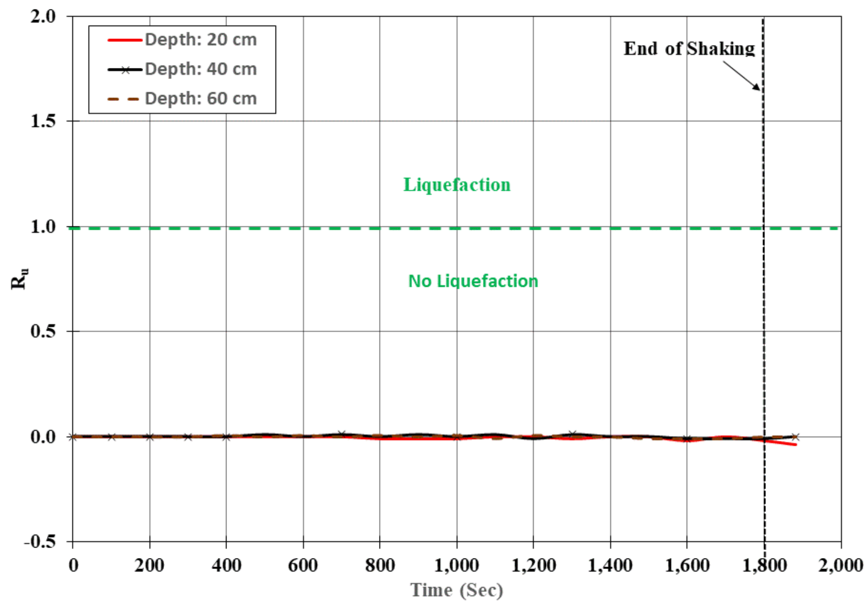

Figure 3c. Excess pore water pressure (Δu) at depths vs times for CPB samples cured to 10 hrs.

In addition to aforementioned findings, it is viable to broaden the implications of results from this investigation in the context of backfill practices. This can be achieved by establishing a correlation between the liquefaction susceptibility of early age CPB material and the uniaxial compressive strength (UCS) values of freshly deposited CPB material within mine stopes. Several scholars have adopted this methodology, linking the cyclical failure or liquefaction of CPB to the minimum required strength values (UCS_{min}). Le Roux (2004) proposed a rule of thumb suggesting that the UCS of CPB material should be at least 100 kPa to be considered resistant to liquefaction. Conversely, Belem and Mbonimpa (2016) determined that the UCS_{min} of non-liquefiable CPB was 32 kPa.

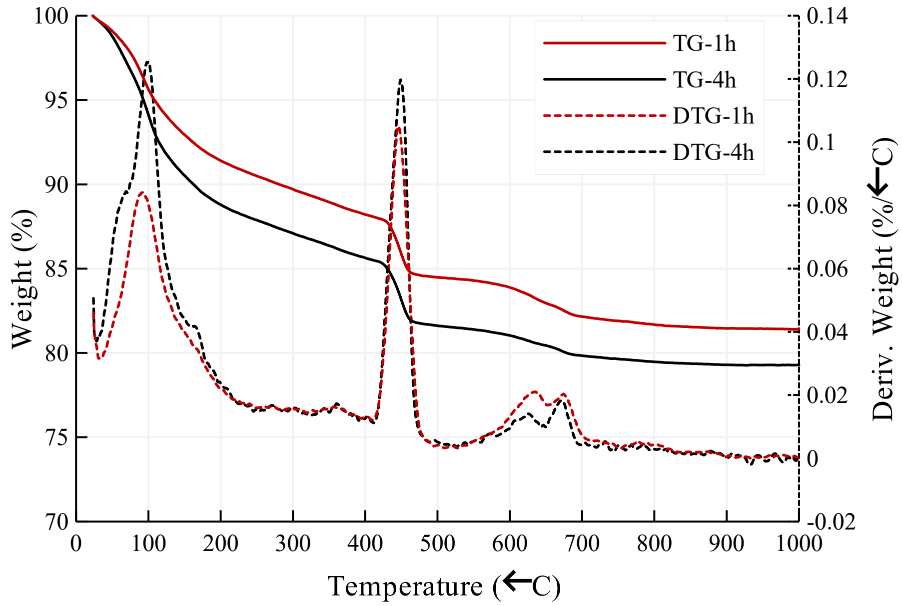

Figure 4. Effect of curing time on TG/DTG diagrams for CPB cured to 1.0 hr and 4.0 hrs

However, it is crucial to note that none of these recommendations or values was grounded in the cyclic response of CPB as observed in shaking table tests. Consequently, it is valuable to scrutinize the outcomes of the current study in relation to the UCS values of CPB as ascertained by Alainachi (2020), where UCS values of CPB were tested at 2.5, 4, and 10 hrs of curing time at 2.0, 10, and 40 kPa, respectively. The shaking table test results reveal that under cyclic loading-induced stresses caused by ground acceleration of 0.13 g, the risk of liquefaction failure becomes negligible when the UCS value reaches 10 kPa (ie, after 4 hrs of curing). Based on these estimations, it can be argued that the aforementioned rule of thumb for this condition may be overly conservative.

Effect of sulphate ions on the cyclic behaviour and liquefaction response of CPB

In practice, CPBs may exhibit varying concentrations of sulphate ions deriving from diverse sources, both internal and external. Internally, these sulphate ions may originate from the oxidation of sulphide minerals like pyrite commonly found in hard rock tailings, and from mine processing water utilized as the mixing water in CPB preparation, which could contain sulphate ions. External sources encompass the use of sulfur dioxide and air methods in remediating cyanide in gold mines, along with chemical additives like gypsum and anhydrite, often added to the clinker for controlling cement setting.

Consequently, a study was conducted to examine the impact of the chemistry of the mixing water (initial sulphate content) on the liquefaction potential of 4 hrs aged CPB under cyclic loadings. Shaking table tests were carried out on two CPB samples prepared with different sulphate contents: 0 ppm and 5000 ppm. Both samples were prepared and cured under a stable room temperature of 20°C for 4 hrs and poured into the FLSB in a single layer (continuous filling). Figure 5 illustrates the pore-water pressure ratios determined during shaking of the sulphate-free CPB sample and sulphate-rich CPB sample. It is evident that the CPB sample containing sulphate is prone to liquefaction when subjected to cyclic loading, whereas the sulphate-free CPB sample resisted shaking-induced liquefaction.

The reduced liquefaction resistance of sulphate-containing CPB can be attributed to two factors:

- a decrease in the intensity of cement hydration and subsequent self-desiccation, weakening the effective stress of CPB with sulphate; and,
- inhibition of the cement hydration process due to sulphate presence, resulting in a reduction of cement hydration products and weakening the bonds between CPB particles. This, in turn, increases the liquefaction susceptibility of sulphate-rich CPB under seismic conditions.

The negative impact of sulphate ions on the cement hydration rate is linked to the reaction of sulphate anions in the CPB pore-liquid with the C_3A grains of the cement, forming ettringite. Ettringite creates a thin coating on unhydrated cement particles, hindering the rapid C_3A-water reaction (Aldhafeeri and Fall, 2017). This diminishes the intensity of cement self-desiccation within CPB particles, crucial for material strength during cementation. Experimental support for the production of fewer cement hydration products in the 4 hr CPB with sulphate, compared to the sample without sulphate, is provided by TG/DTG (Figure 6). The CPB with sulphate exhibits lower weight loss (TG) and peaks (DTG) in the 400–500°C temperature range, indicating a lesser amount of hydration products in the CPB sample due to sulphate (Wang et al., 2016). Additional findings (Figure 7) illustrate the outcomes of monitoring the development over time of cement hydration at various depths within both CPBs. This figure reveals that the rate of cement hydration progress, or the quantity of formed cement hydrations in the CPB, remains relatively consistent across all depths of each CPB specimen. However, the introduction of sulphate has had an impact on these rates. Specifically, in the CPB without sulphate (Figure 7a), the EC reaches its peak value faster compared to the CPB with sulphate (Figure 7b). Additionally, it was observed that the EC peak value for the CPB with sulphate is lower than that of the CPB without sulphate. According to the operational principles of EC sensors, the initial rise in EC corresponds to an increase in ion concentration in the CPB pore water solution due to cement particle dissolution. Therefore, the delay in EC reaching its peak value in the presence of sulphate indicates a retardation in the cement hydration process, while lower EC values signify a decrease in cement hydration intensity (Aldhafeeri and Fall, 2017).

Based on our findings, it can be inferred that the decline in the liquefaction resistance of CPB, attributed to the presence of sulphate ions, may have practical implications for the mining cycle and overall productivity. The reduction in CPB liquefaction resistance resulting from the inhibition of cement hydration by sulphates will impede the filling cycles. This means that more time will be necessary for each fill of CPB material to attain the minimum required strength before permitting additional backfilling. Consequently, mine productivity will experience a downturn. However, there are various solutions to address this issue. Indeed, the utilization of binders, such as Portland cement type V and blast furnace slag, known for their resistance to sulphate attack, can enhance the strength and rate of strength gain of CPB, thereby improving its liquefaction resistance. Furthermore, implementing proper drainage conditions during the backfilling process will contribute to mitigating the seismic-induced development of excess pore-water pressure.

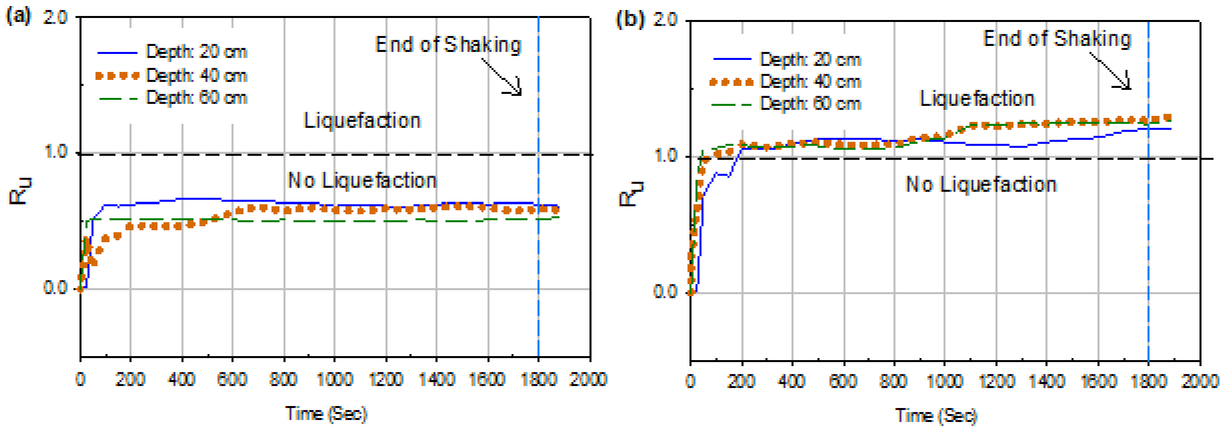

Figure 5. Pore-water pressure ratios determined at different depths vs times for CPB samples prepared: a) without sulphate, and b) with sulphate.

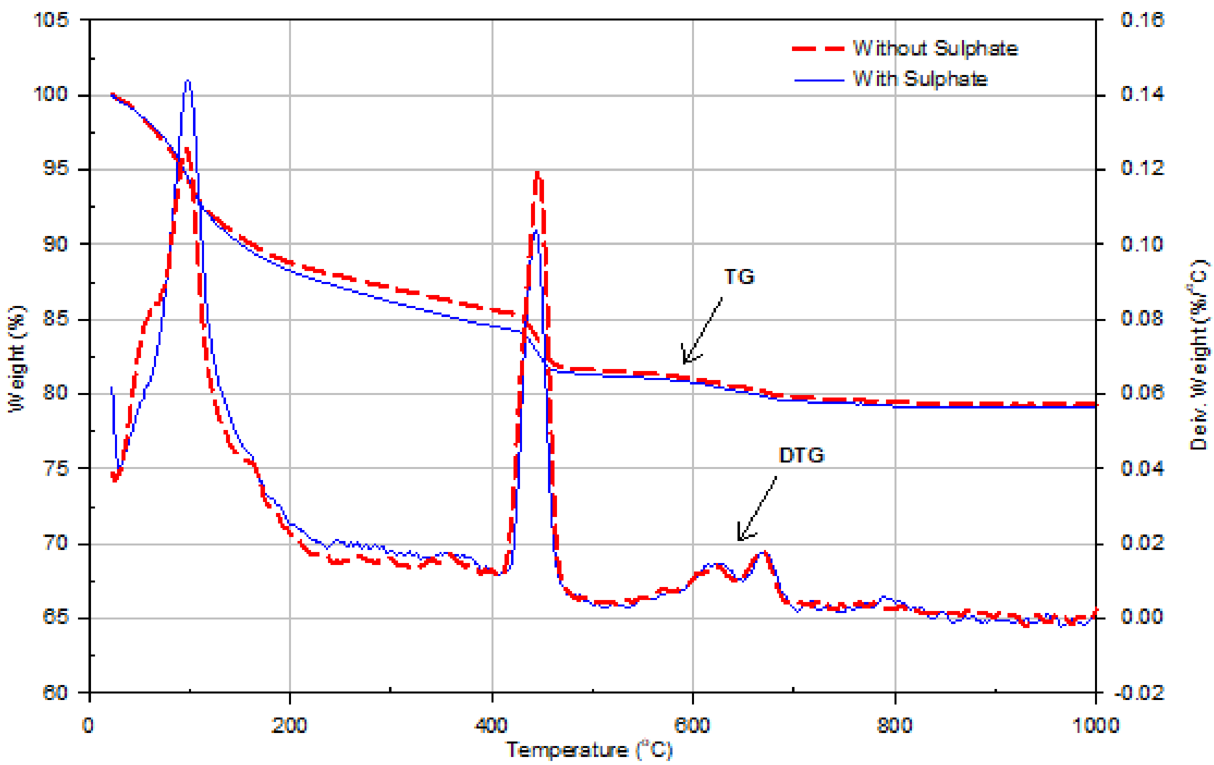

Figure 6. Effect of sulphate content on TG/DTG diagrams for 4 hr CPB samples prepared: a) without sulphate, and b) with sulphate.

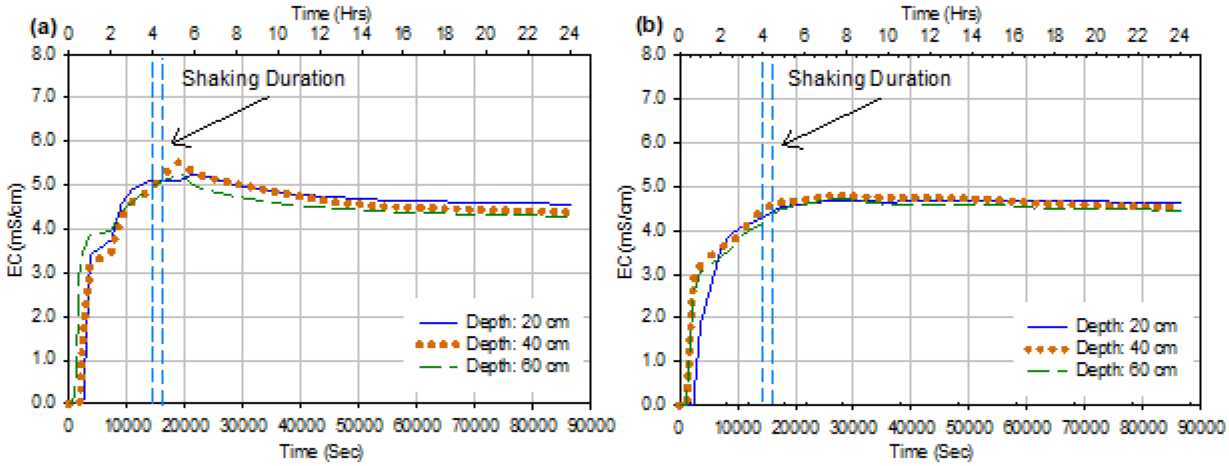

Figure 7. Electrical conductivity at different depths of 4 hr CPB samples prepared: a) without sulphate, and b) with sulphate.

Summary and Conclusion

In this investigation, a sequence of experiments using a shaking table was carried out on freshly prepared large CPB specimens. These specimens were mixed and poured into a specially designed flexible laminar shear box created for this research, aiming to evaluate their behavior under cyclic conditions and susceptibility to liquefaction. Various tests were conducted at different maturation stages (2.5, 4, and 10 hrs) to explore the impact of the progression of cement hydration on the liquefaction potential of CPB. Additionally, another series of tests were performed to examine the influence of pore-water chemistry, specifically the sulphate content, on the cyclic response of fresh CPB. This involved subjecting CPB models with varying concentrations of sulphate ions (0.0 and 5000 ppm) to cyclic loads. The conclusions drawn from the study are:

1. Results reveal distinct cyclic behaviors and performances of CPB under the specified conditions.
2. Progression of the cement hydration process over time greatly affects the cyclic behavior of CPB. Young CPB material (2.5 hrs old) exhibited susceptibility to liquefaction under cyclic loading, while older materials (cured for 4 or 10 hrs) demonstrated resistance. Cyclic loading had minimal impact on CPB materials cured for 10 hrs. The increased liquefaction resistance with curing time is attributed to enhanced shear resistance resulting from improved cementation between soil particles, along with reduced pore-water pressure (PWP) and the development of suction within the backfill due to cement self-desiccation, consequently elevating effective stress in the CPB and enhancing liquefaction resistance under seismic conditions.
3. Sulphate presence has a notable effect on the cyclic behavior of CPB. CPB materials aged 4 hrs with sulphate were susceptible to liquefaction, while sulphate-free counterparts were resistant. The reduced liquefaction resistance in sulphate-rich CPB is linked to the decrease in cement hydration intensity, leading to reduced self-desiccation and weakened effective stress. Additionally, the inhibition of cement hydration due to sulphate presence hinders the production of cement hydration products, weakening bonds between CPB particles and increasing liquefaction susceptibility under seismic conditions.

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