Effect of Binder Content and Load History on the One-dimensional Compression of Williams Mine Cemented Paste Backfill

by

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A thesis submitted in conformity with the requirements for the degree of Master of Applied Science

Department of Civil Engineering
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Abstract

Large voids created by underground mining are backfilled to provide regional ground support. This thesis examines using conventional oedometer techniques and electromagnetic (EM) techniques to characterize consolidation and binder hydration in mine backfill so that EM monitoring can be used in the field to provide real-time feedback to operators to optimize the backfilling process.

New techniques are given for interpreting the full range of deformation (initial compression, primary and secondary consolidation). Deformation due to initial compression is non-trivial and may have to be accounted for in numerical back-analyses of field case studies. EM parameters are sensitive to binder content, progress of hydration and loss of water caused by consolidation and binder hydration.

The integrated interpretation of consolidation and EM behaviours has significant potential impact on real-time monitoring of mine backfill operations, and recommendations are made to advance the technique for this purpose.
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I dedicate this work to my brother, Dr. Hassan Jamali.

“Wish You Were Here”
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List of Acronyms

CPB - Cemented Paste Backfill
WMT - Williams Mine Tailings
MT - Mine Tailings
1D NCL - One-dimensional Normal Compression Line
XRF - X-Ray Fluorescence
PC - Portland Cement
FA - Fly Ash
EM - Electromagnetic
Chapter 1. 
Introduction

1.1 Problem statement

The process of mining consists of excavation of valuable mineral(s) from the earth (i.e., ore body). Large amounts of mine waste (e.g., mine tailings) are created during mining operations. The mine tailings may have a harmful effect on the environment; therefore, a concern about how to reduce the amount of mine tailings to be disposed of onto the earth’s surface has always been an important issue in the mining industry. One of the solutions for this challenge is the use of Cemented Paste Backfill (CPB) for filling the underground mine openings (e.g., stopes). CPB is a mixture of mine processing waste (mine tailings, or MT), hydraulic binder (Portland cement (PC), fly ash (FA), ground blast furnace slag (GBFS), etc.) and water. The role of hydraulic binder is to increase the strength of CPB. By using backfilling to fill the underground voids, a greater percentage of ore can be extracted from an ore body as backfilled stopes can replace ore-rich pillars in stabilizing the ground. Additionally, backfilled stopes provide ground stabilization to the surrounding rocks and a secure working environment for mine’s personnel. The water management issue, improved strength due to the use of hydraulic binder, shorter operating time cycle and CPB’s fast delivery rate often make CPB a better solution than other backfills, such as hydraulic backfill or rockfill. This technology permits the optimization of selected mine
operations by providing the underground support, and also by reducing the volume of tailings stored on the surface, thus reducing the environmental impact.

Behaviour and properties of CPB differ from one mine to another mainly because mines typically deal with different types of tailings based on their local chemical, mineralogical and geological characteristics. Moreover, the type of cement and other binding agents (e.g., Fly Ash or Slag), as well as binder content, have an influence on the CPB’s’ properties (Benzaazoua and Belem, 2000; Hassani & Hossein 2000). Additionally, it is suggested that CPB pouring rate (e.g., the rate of filling of large scale underground voids), affects CPB behaviour, such as strength and consolidation parameters (Le Roux, 2004). The recent field study on CPB (Thompson et al., 2012) showed that there is a good correlation between development of stiffness (i.e., onset of effective stress) and hydration progress (as assessed by monitoring the changes in temperature). Given that the CPB strength is essential from mines’ ground stability point of view, the CPB behaviour during curing and loading should be understood.

1.2 Objective

In order to optimize paste backfill system design, the performance of CPB during consolidation and binder hydration must be understood. Thus, the objectives of this study are to:

1. Explore the effects of binder type and content, as well as loading rate, on consolidation of CPB, and

2. Investigate the effect of consolidation on the hydration process and stiffness development in CPB.

1.3 Research Methodology

Two experimental techniques were employed to investigate consolidation and hydration phenomena in CPB in this project:
1. Standard consolidation (Oedometer) test, and

2. Electromagnetic wave-based test.

The consolidation test can be used to assess void ratio and consolidation parameters of cemented and uncemented mine tailings (Le Roux, 2004, Crowder, 2004, Yilmaz et al, 2008). Given that electromagnetic (EM) properties vary during the hydration process; they are a useful tool for monitoring hydration progress in cement-based materials (McCarter and Afshar, 1989, Fam and Santamarina, 1995, 1996 and 1997, Santamarina and Klein, 2001, Simon, 2004, Klein and Simon, 2006). All these tests can provide an insight into the solidification and hardening processes in hydrating CPB. In order to evaluate the effect of binder type and content and loading rate, the following combination of consolidation tests and EM tests are performed on Williams mine’s CPB with a wide range of binder contents (0 %, 3 % or 7 % PC) and curing times, such as freshly-mixed (i.e., 0 day), or 1-day, 3-day or 7 day long curing periods:

- Consolidation and EM tests in which the load increases from 0 kPa to 400 kPa within 2 hours (i.e., 6 loading stages including 10, 25, 50, 100, 200 and 400 kPa at 20 minutes with standard loading rate, \( \Delta \sigma / \sigma = 1 \))

- Consolidation and EM tests in which the load increases from 0 kPa to 400 kPa within 16 hours (i.e., 25 kPa/h loading rate, which typically corresponds to the pouring rate of 1.25 m/h in the stope)

- Consolidation and EM tests in which the load increases from 0 kPa to 400 kPa within 80 hours (i.e., 5 kPa/h loading rate, which typically corresponds to the pouring rate of 0.25 m/h in the stope)

- Consolidation and EM tests in which no normal load was applied (only a preconsolidation load of 5 kPa was applied with no additional load afterwards)
1.4 Thesis Organization

Chapter 2 describes the basic concepts of consolidation and electromagnetic wave based measurement. A review of previous studies on consolidation and electromagnetic properties of CPB are presented in this chapter.

Chapter 3 discusses the experimental set up and the methodology used in consolidation and EM tests. The sample preparation technique and Williams Mine Tailings (WMT) properties are also described in Chapter 3.

Chapter 4 presents the results of consolidation tests conducted in conjunction with EM tests on WMT/CPB with different binder contents and curing times. The effect of loading rate on consolidation response and hydration process of CPB is also investigated in this chapter.

Chapter 5 interprets the results addressed in Chapter 4. Validation of Terzaghi’s one dimensional theory for WMT and CPB is examined in this chapter.

The conclusions and recommended future work are presented in Chapter 6.
Chapter 2.
Literature Review

2.1 Consolidation

2.1.1 Consolidation Review

Consolidation is defined as the reduction in void ratio of a soil matrix due to the loss of water from the soil as a result of increasing effective stress that comes from “instantaneous” application of a constant total stress and subsequent reduction in excess pore water pressure. This loss of water from the soil matrix leads to settlement.

Compression behaviour of a material is governed by the material’s properties, including particle size distribution, hydraulic conductivity and compression characteristics. In most materials, such as undisturbed normally consolidated clays and remolded clays (Terzaghi and Peck, 1962) and in natural well-graded silts with high clay content (Nocilla et al., 2006), compression paths converge to minimum specific volume of unity with a unique one-dimensional (1D) normal compression line (NCL), called the virgin compression curve. However, in some materials, such as silts with low clay content (Nocilla et al., 2006) and some gap-graded materials (Martins et al., 2002), compression paths do not show convergence to a unique 1D NCL, and instead remain parallel even under large pressures (e.g., more than 10,000 kPa). This type of behaviour, called transitional behaviour, is characteristic for materials with no unique NCL. Figure 2.1 shows the
difference in compression paths of a transitional soil with no unique NCL and a typical soil with a unique NCL.

Moreover, there is a difference in consolidation behaviour of undisturbed naturally cemented clays and such clays when remolded. The undisturbed clay samples exhibit higher strength due to natural cementation bond ($\sigma_B$), whereas the remoulded clay samples exhibit only residual strength ($\sigma_R$), as illustrated in Figure 2.2 (Nagaraj et al., 1994, 1995).

Figure 2.1 Schematic illustration of compression of sands and transitional soils (Nocilla et al., 2006)
When subjected to an instantaneously applied total load, a material typically undergoes three different consolidation stages: initial compression, primary consolidation and secondary consolidation, as illustrated in Figure 2.3.
There are several models to assess the consolidation with time during loading, including Terzaghi’s 1D consolidation model (1943) and Gibson models (1958). The most commonly used model is the one-dimensional Terzaghi’s consolidation theory which can only be applied to soils that fulfill a number of conditions, including constant hydraulic permeability and coefficient of compressibility during consolidation.

In general, the one-dimensional consolidation equation is as follows:

![Figure 2.3 Change in displacement with square root of time for saturated clay (Craig, 1983)]
\[ \frac{\partial u_e}{\partial t} = C_v \frac{\partial^2 u_e}{\partial z^2} \quad \text{Eq. 1} \]

Where \( u_e \) is excess pore water pressure, \( t \)=time, \( C_v \)=coefficient of consolidation and \( z \) is the depth.

The degree of consolidation is defined as:

\[ U_z = \frac{(u_i - u_e)}{u_i} \quad \text{Eq. 2} \]

Where \( u_e \)=excess pore water pressure at a particular time during consolidation under the increase in total stress and \( u_i \)=excess pore water pressure immediately after the increase in total stress.

Based on Eq. 1 and Eq. 2, the infinite series formula for degree of consolidation in a double drainage case is as follows (Aysen, 2002):

\[ U_z = 1 - \sum_{m=0}^{\infty} \frac{2}{M} \left( \sin \frac{Mz}{d} \right) \exp(M^2T_v) \quad \text{Eq. 3} \]

Where

\( M=\pi \frac{(2m+1)}{2} \), and

\( T_v \)=time factor

with the following boundary conditions:

a) At \( Z=Z_t \), \( u_e=0 \) at \( t=0 \) (the excess pore water pressure is zero at the top of the compressible layer)

b) At \( Z=Z_t + H \), \( i = \frac{\partial u_e}{\partial z} = 0 \) (the hydraulic gradient is zero at the bottom of compressible layer)
c) At $t=0$, $u_e = \Delta \sigma_z$ (immediately after placement of the load, the applied vertical stress is carried entirely by the excess pore water pressure, is equal to the change in total stress, $\Delta \sigma_z$, and is constant with depth)

The relationship between $U$ and $T_v$ in Eq. 3 can be represented almost by the following "empirical equations" which is called Terzaghi’s simplified method (Terzaghi and Peck, 1962):

\[
\text{for } U < 0.6, \quad T_v = \frac{\pi}{4} U^2 \quad \text{Eq. 4}
\]
\[
\text{for } U > 0.6, \quad T_v = -0.933 \log(1 - U) - 0.085 \quad \text{Eq. 5}
\]

Figure 2.4 shows the range of degree of consolidation as a function of time factor using the Terzaghi’s simplified model.

![Figure 2.4 Range of degree of consolidation vs. time factor for saturated clay (Terzaghi and Peck, 1962)](image)

Terzaghi and Peck (1962) showed that the shape of the experimental time-consolidation curve for saturated clay is very similar to that for spring-piston system up to about 80% of consolidation. After 80% of consolidation, the time-consolidation curve for spring-piston system approaches horizontal asymptotes in infinity, whereas that for clay exhibits a gentle slope due to start of secondary consolidation. As was mentioned in the beginning of this chapter, the last
phase of consolidation is secondary consolidation (i.e., creep). It has been established that secondary consolidation does not need to be explicitly calculated when the ratio of $C/c/(1+e_o)$ is less than 0.25 (Canadian geotechnical society, 2006), and, according to Leroueil, 1996, it is most likely that it occurs simultaneously with primary consolidation.

For certain soils, such as soft soils, pastes and slurries, only a part of their consolidation curve can be interpreted using Terzaghi’s consolidation theory. In order to divide the consolidation curve of these certain soils into several segments and recognize which segment follows the Terzaghi’s consolidation theory, Bo (2008) determined the approximate transition point, which defines the point at which the paste transforms into a Terzaghi’s soil, based on the change of the settlement rate. This is examined in detail in Chapter 5.

### 2.1.2 Consolidation of CPB

The purpose of this section is to provide an overview of the literature that is relevant to the consolidation tests performed in this study. As CPB is utilized to fill the underground mine openings, it is important to determine CPB’s degree of settlement and strength development as they play an important role in stability of the mine. A number of authors, including Le Roux (2004), Yilmaz (2008) and Helinski (2007), have investigated the consolidation behaviour of CPB and other materials, as will be reviewed next.

Le Roux (2004) performed standard oedometer tests on 1 day-cured CPB samples from a gold mine in northern Ontario with different binder contents (0, 0.5, 4 and 6%) to examine the influence of binder content on consolidation behaviour of CPB. Results are shown in Figure 2.5. The same author also carried out oedometer tests with modified loading rate on freshly mixed CPB with binder contents of 0 %, 1 %, 3 % and 5 % to assess the influence of overburden accumulation rate on the consolidation of CPB. Le Roux (2004) used the actual pour rate instead of using a standard loading rate (ASTM-D2435-96, 2000) to resemble the worst-case field loading rate. For this purpose, 19 kPa increment loads were applied every 24 min, 48 min or 2h.
24 min to simulate the accumulation rate of 10 m, 30 m and 60 m in 24 hours, respectively. Figure 2.6 shows void ratio as a function of loading rate and binder content in Golden Giant CPB. Moisture content of all samples used in the study was 37% based on solids weight (i.e., $\frac{w_w}{w_s}$ where $w_w$ is weight of water in sample and $w_s$ is weight of solid in sample).

Figure 2.5 Standard Oedometer Test Results on CPB allowed curing for 24 hours (Le Roux, 2004)
Le Roux (2004) interpreted the results shown in Figure 2.5 and Figure 2.6 respectively, as follows:

1- It was found that by increasing binder content, initial void ratio increased due to effect of finer particles on the structure of the CPB. In other words, for higher binder content, more stiffness developed in CPB due to the cement bonds between particles which form during the hydration process. Moreover, the study (Figure 2.5) showed that the final void ratio was similar for all CPB samples. This indicated that although consolidation curves for higher binder content specimens were flatter than those for lower binder content specimens, once the applied pressure exceeds the strength of CPB, consolidation characteristics of cemented materials revert to the uncemented materials. Hence, for the consolidation stress higher than strength of CPB, change in void ratio is larger for CPBs with higher binder content.

2- The uncemented materials are not sensitive to the rate at which the load is applied. In comparison, in cemented materials, regardless of the binder content, the faster the loading
rate, the steeper the consolidation curve becomes. This is so because consolidation is a time dependent process. Therefore, less cement bonds can be formed between the tailings particles to resist the consolidation stress during fast loading rate.

Yilmaz et al. (2008) carried out 20 consolidation tests on tailings from a mine in Quebec, in order to study the effect of binder content and curing time on CPB structure and consequently consolidation behavior. The material had typical water content of 28.2% (based on total weight) and a wide range of binder contents: 0, 1, 3, 4.5 or 7%. Special cells, called CUAPS or curing under applied pressure system cells, were used in the study (more details can be found in Yilmaz et al., 2008). The results, presented in Figure 2.7, indicate that changes in void ratio, are significantly controlled by binder content and curing time as both Cc and Cr decrease with increasing curing time and/or binder content. This phenomenon was explained by formation of cement bonds during hydration.
Helinski (2007) studied consolidation behavior of CPB through a centrifuge experiment equipped with 620 mm high and 180 mm diameter hollow cylinder. The purpose of using centrifuge test was to resemble the field stress distribution conditions in a small model size in order to investigate the interaction of consolidation, stress distribution (affected by arching) and cement hydration. It was found that the distribution of stress depends on consolidation, while it is mainly independent of cementation. Figure 2.8 displays the experimental results for uncemented tailings and 5% PC CPB with different curing times. According to Figure 2.8, adding minor amount of cement (e.g., 5%) can increase the stiffness significantly, however once the cemented bonds formed between particles are broken, all compression curves tend to be continued with the same compression line.
Helinski (2007) used the concept of incremental yield strength, also suggested by Rotta et al. (2003) to separate the cemented yield stress from uncemented yield stress. Figure 2.9 illustrates the consolidation behaviour of cemented and uncemented materials. It is necessary to note that Rotta et al. (2003) introduced incremental yield strength as a contribution of cementation to the increase in yield stress of material.
2.2 Electromagnetic (EM) Wave Based Measurements

The EM wave-based test is a non-destructive monitoring technique that has no effect on the structure of a material; therefore, it can be used for monitoring the behaviour of the material without disturbance to physical-chemical processes in the material, such as binder hydration. Moreover, EM measurements of cemented mixtures can provide an insight not only on the solidification and hardening process, but also in principle on the physical characteristics such as water content and possibly void ratio.

The primary EM parameters include dielectric permittivity $\varepsilon^*$, electrical conductivity $\sigma$ and magnetic permeability $\mu^*$. This chapter focuses on dielectric permittivity $\varepsilon^*$. Dielectric permittivity is an ability of a material to polarize in response to an applied electric field. In other words, the molecules of a dielectric act as electric dipoles – they orient themselves in regard to an alternating electric field. The ability of dipoles to orient themselves towards an alternating electric field depends on the frequency of the applied electric field. The ratio of the dielectric permittivity of a material to the permittivity of vacuum is relative permittivity $\kappa^*$. Relative
permittivity $\kappa^*$ consists of two parts: a real part, $\kappa'$, and an imaginary part, $\kappa''$. The real part represents the polarizability of a material due to application of an electric field; the imaginary part describes polarization losses. The real relative dielectric permittivity of the mixture is sensitive to water content, as well as the chemistry of the mixture. Therefore, it can be a good indicator of volumetric moisture content (Topp et al. 1980) and progress of certain physicochemical changes, such as binder hydration (Miura et al., 1998, Bois et al., 1998). The imaginary relative permittivity is a good indicator of electrical conductivity and ion mobility and availability of the mixture.

There are a number of studies dealing with EM properties of various cemented mixtures that have shown that EM techniques can be a useful tool in investigating a variety of properties and processes in these materials (Fam and Santamarina, 1995; McCarter, 1996; Klein and Simon, 2006).

Fam and Santamarina (1995) monitored consolidation and EM properties in clay-cement mixtures using a modified oedometer cell in conjunction with dielectric probe, pore pressure transducer and bender element at the bottom of the cell (Figure 2.10) to:

1. Monitor the changes in complex dielectric permittivity
2. Measure pore water pressure
Figure 2.11 represents changes in EM parameters with time during one consolidation stage (from 305 kPa to 610 kPa) at two different frequencies for Kaolinite clay [Fam and Santamarina, 1995]. The same authors found that the real relative permittivity at both low and high frequencies (e.g., 200 MHz and 1.3 GHz) shows a similar trend as water content (and void ratio) changes with time, indicating that consolidation of Kaolinite clay affects only free water. Since the amount of free water decreases during the consolidation stage, the real relative permittivity, being an indicator of free water content, also decreases with consolidation. Moreover, reduction in imaginary permittivity with time at higher frequencies indicates the reduction in free water during consolidation process since it reflects molecular (e.g., water molecules) polarization. However, the imaginary permittivity at lower frequencies (e.g., 200 MHz) shows little change with time, indicating that little change occurs in ionic polarization during this consolidation stage.
Figure 2.11 Complex permittivity: change in real and imaginary permittivity of kaolinite from 305 to 610 kPa vertical effective stress versus time at two different frequencies (Fam and Santamarina, 1995)

Figure 2.12 shows changes in EM parameters with hydration time at three different EM frequencies for a Bentonite-cement mixture that was subjected to 1.5 kPa vertical stress. A decrease in $\kappa'$ at higher frequencies was attributed to: 1. reduction in free water due to consolidation, 2. transformation of free water into bound water due to cement hydration and 3. an increase in ionic concentration and temperature due to cement hydration. An increase in $\kappa'$ at lower frequencies, was attributed to conduction losses caused by the onset of hydration. The changes in imaginary permittivity with time reflects the changes in dc losses due to cement hydration and also the reduction in free water due to consolidation and cement hydration.
Figure 2.12 Change in Complex Permittivity of Bentonite-Cemnet Slurry (B-1-1-23) with Hydration Time, at Three Frequencies: (a) Real; (b) Imaginary (Permittivity Values Are Normalized by Initial Values; Allows Denote Time of Temperature Peaks.), (Fam and Santamarina, 1995)

Klein and Simon (2006) examined the effect of binder content and hydration time on the EM properties of cemented and uncemented gold mine tailings and found that The decrease in $\kappa'$ with frequency in high MHz-low GHz region is due to relaxation caused by water molecule polarization, while the decrease in $\kappa'$ frequency with time is caused by free water loss and transformation of free water to bound water during cement hydration (presented in, Figure 2.13 and Figure 2.14).
Figure 2.13 Frequency spectra of real relative permittivity for pastes with various binder content after 10 minutes of hydration (Klein and Simon, 2006)

Figure 2.14 The variation in real relative permittivity (1 GHz) in various paste with time (Klein and Simon, 2006)

Figure 2.15 shows changes in EC with hydration time in 100% PC-water mixtures and 5% PC CPB that are attributed to Physico-chemical and microstructural changes caused by binder hydration. Thus, an increase in EC with time is associated with PC dissolution, followed by a decrease in EC, which is associated with a major hydration stage (acceleration) when setting and solidification occur.
Figure 2.15 The variation in relative permittivity (1 GHz) and defective conductivity (266 MHz) with time for cemented paste backfill and 100% PC paste (Klein and Simon, 2006)
Chapter 3. 
Experimental Set up

3.1 Material Description and Sample Preparation

Williams Mine Tailings (WMT) mainly consists of silicates, such as quartz, feldspar and plagioclase, with traces of barite. Table 1 shows the chemical composition of CPB ingredients as determined using the X-Ray Fluorescence (XRF) technique, for Mine Tailings (WMT) and Portland Cement (PC). The particle size distribution curve of the Williams mine tailings is shown in Figure 3.1 (Saebimoghaddam, 2010).

WMT were mixed with Portland cement (PC), fly ash (FA) and mine process water using an electric mixer at medium speed for 90 seconds to provide a homogenous paste. The material used in this study had typical water content of 28% based on total weight. Portland cement contents of 3% and 7% PC were chosen as typically used at the mine. 0% cement content was also used for comparison purposes. After mixing, the paste was poured into a confining ring and tapped on the side with a rod in order to remove any large trapped air bubble created during mixing and placement. The top of the sample was trimmed flush with the ring. The mixing and placement procedure lasted approximately 35 minutes for all specimens. The specimens were covered with plastic wrap to prevent water evaporation during curing.
Table 1 Chemical composition of CPB ingredients

<table>
<thead>
<tr>
<th>Mineral</th>
<th>PC (%)</th>
<th>MT (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO₂</td>
<td>16.3</td>
<td>58.3</td>
</tr>
<tr>
<td>Al₂O₃</td>
<td>3.4</td>
<td>11.8</td>
</tr>
<tr>
<td>Fe eq</td>
<td>2.3</td>
<td>2.8</td>
</tr>
<tr>
<td>Ca eq</td>
<td>71.1</td>
<td>5.8</td>
</tr>
<tr>
<td>MgO</td>
<td>3.0</td>
<td>3.7</td>
</tr>
<tr>
<td>Na eq</td>
<td>0.2</td>
<td>3.2</td>
</tr>
<tr>
<td>Ba</td>
<td>-</td>
<td>0.5</td>
</tr>
<tr>
<td>S eq</td>
<td>3.3</td>
<td>1.0</td>
</tr>
<tr>
<td>K eq</td>
<td>0.4</td>
<td>3.4</td>
</tr>
<tr>
<td>Others</td>
<td>0.05</td>
<td>9.5</td>
</tr>
</tbody>
</table>

Figure 3.1 Particle size distribution of the Williams tailings
3.2 Methodology

3.2.1 Consolidation test

In this study, consolidation of Williams mine tailings with a range of binder content (e.g., 0%, 3% and 7%) and curing time (0 day, 3 days and 7 days) is investigated.

CPB samples are subjected to time-dependent loading during oedometer testing. A seating load of 5 kPa is applied at the beginning of the test to provide an appropriate contact between top cap and porous stone. The maximum pressure applied in this study was 400 kPa as it was just more than the maximum pressure observed in field measurements. Two different loading regimes were applied in this study: Standard loading rate and Non-standard loading rate.

In the standard loading rate tests, vertical static loads of 10, 25, 50, 100, 200 and 400 kPa with a load increment ratio of 1.0 ($\frac{\Delta\sigma}{\sigma}$, where $\Delta\sigma=$ increase in pressure and $\sigma=$ pressure before the increase) are applied to all CPB samples tested at the standard loading rate. The unloading is performed using the following steps: 200, 100 and 25 kPa. Since more than 90% of the consolidation of CPB occurs rapidly (i.e., within 20 seconds), the duration of the load increment in this study is reduced to 20 minutes, instead of a standard 24 hours. The coefficient of consolidation $C_v$ can be determined using “Casagrande log time method” and “Taylor root time method”; however, both methods show a certain degree of difficulty due to very short primary consolidation in WMT/CPB samples. Hence, the log time method is used in this study since it yields the less ambiguous values of $C_v$ because this method seems to be less sensitive to the analyst’s bias. Later in Chapter 5 a more objective method for determining $C_v$ is investigated. Compressibility parameters (i.e., compression index $C_c$ and recompression index $C_s$) are obtained from linear portions of the $e$-$\log(\sigma'_v)$ consolidation curve. Preconsolidation pressure ($P'_c$) is determined using Casagrande’s graphical method (Casagrande, 1936) and coefficient of compressibility ($m_v$) is calculated based on the measured data using the following formula:
\[ m_v = \frac{1}{1 + \frac{e_0 - e_1}{\sigma'_1 - \sigma'_0}} \]  

Eq. 6

In the Non-standard loading rate tests 25 kPa/h and 5 kPa/h loading rates, representing the field loading rates, are used to apply the load from 0 kPa to 400 kPa within 16 hours (25 kPa/h) or 80 hours (5 kPa/h). The LDT displacement sensor, connected to the computer, records the displacement of the specimen every 0.1 seconds. The Experimental set up is shown in Figure 3.2.

![Experimental set up for consolidation](image)

**Figure 3.2 Experimental set up for consolidation**

### 3.2.2 EM test

Electromagnetic (EM) measurements were performed using an Agilent 85070 C coaxial termination probe, which was integrated with a network analyzer (Agilent 8712ET RF). The experimental set up is shown in Figure 3.3. A computer is connected to the analyzer to run the measurements and store the data after each reading. The probe operates in the frequency range between 200 MHz and 1.3 GHz.
The analyzer has to be calibrated before each test. In order to obtain reliable data, the position of the connection cable between the probe and the analyser must not be modified after the calibration and is therefore secured to the bench top using tape. Calibration involves measuring an open circuit (air), short circuit (metal) and deionized water. The real relative permittivity of water is approximately 78. If the measured real permittivity is different than 78 for deionized water, the calibration is repeated.
Chapter 4.
Results

All test results are classified in two major groups based on loading rate: standard loading rate and non-standard loading rate.

4.1 Standard loading rate

This section presents the results of oedometer tests and EM tests performed on 0%, 3%, and 7% PC CPB samples cured for 0, 1, 3 and 7 days. Parameters shown here include (i) displacement (settlement) and real relative permittivity during one increment loading stage (e.g., 400 kPa), (ii) incremental settlement, total settlement and variations in real relative permittivity during one increment loading stage and at the end of each increment loading stage, (iii) frequency spectra for all specimens, (iv) Cc, Cs and Cv as a function of curing time.

4.1.1 Consolidation and EM Test for 0% PC CPB sample

Figure 4.1 shows changes in displacement and real permittivity at 1 GHz with time during a 400 kPa increment loading stage. Consolidation in WMT-water mixtures occurs after few seconds, in contrast to pottery clay, which consolidates at a slower rate (see Figure A.1 in the Appendix A.1). The real relative permittivity exhibits a decreasing trend as the specimen consolidates.
Figure 4.1 Change in displacement and real permittivity at 400 kPa loading for a) freshly mixed Williams mine tailings, b) 3-days aged Williams mine tailings
The changes in real relative permittivity, cumulative displacement, delta displacement and electrical conductivity for different loading stages are shown in Figure 4.2. Approximate values of total settlement, difference in real relative permittivity at 1 GHz and compression indices (i.e., Cc and Cs) after the completion of consolidation test, are shown in Table 2.

Figure 4.2 Change in real relative permittivity (1 GHz), cumulative displacement and relative displacement at 10-400 kPa loading for a) freshly mixed Williams mine tailings, b) 3-days aged Williams mine tailings
The specimens that were left unloaded for three days before the loading has been applied exhibit smaller change in settlement and water reduction (as indicated by $\Delta k'$) compared to the specimens that were left unloaded for 0.5 h for the same increase in normal stress. Possible explanation for reduced settlement and water reduction in 3-day-old specimens is that the amount of free water is reduced probably due to evaporation. It can be noted from Figure 4.2 that more than 50% of total change in displacement and real relative permittivity occur during the first 100 kPa of loading. Furthermore, the largest displacement in freshly mixed specimens was observed during the first loading stage (i.e., 10 kPa) indicating that there is little, if any, cohesion between particles. On the other hand, in 3-day-old specimens it seems that the first loading stage of 10 kPa is not enough to cause substantial settlement since no significant deformation was observed in this type of specimens. Figure 4.3 shows the consolidation curves for freshly mixed and 3-days aged WMT.

Table 2: Total settlement and difference in real relative permittivity at 1 GHz for 0% PC CPB samples for different curing time

<table>
<thead>
<tr>
<th>Curing time*</th>
<th>Settlement $\delta$ (mm) 0-400 kPa</th>
<th>Permittivity $\Delta k'$=(k_i' - k_f') 0-400 kPa</th>
<th>Cc</th>
<th>Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 h (fresh)</td>
<td>$\sim$1.8 (9 %)</td>
<td>$\Delta k'$~2.2</td>
<td>0.0926</td>
<td>0.0124</td>
</tr>
<tr>
<td>3 days</td>
<td>$\sim$1.1 (5.5 %)</td>
<td>$\Delta k'$~1</td>
<td>0.0766</td>
<td>0.0153</td>
</tr>
</tbody>
</table>

* as measured prior to loading
The log-time method was used to estimate $C_v$, and the experimental results were used to determine $m_v$ (according to Eq.6), for each load increment. These results are presented in Table 3.
Table 3 Primary consolidation, $C_v$ and $m_v$ at different pressures for a) freshly mixed Williams mine tailings, b) 3-days aged Williams mine tailings

<table>
<thead>
<tr>
<th>Curing time</th>
<th>Stress (kPa)</th>
<th>Primary Consolidation (mm)</th>
<th>$C_v$ (cm$^2$/s)</th>
<th>$m_v$ (cm$^2$/KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 hr</td>
<td>50</td>
<td>0.1760</td>
<td>0.313</td>
<td>4.8228</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.2100</td>
<td>0.240</td>
<td>4.0241</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.2250</td>
<td>0.474</td>
<td>1.6649</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.2300</td>
<td>0.120</td>
<td>0.8357</td>
</tr>
<tr>
<td>3d</td>
<td>50</td>
<td>0.1020</td>
<td>0.625</td>
<td>3.0257</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.1360</td>
<td>0.625</td>
<td>1.9613</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.1600</td>
<td>0.936</td>
<td>1.1805</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.1750</td>
<td>0.936</td>
<td>0.6414</td>
</tr>
</tbody>
</table>

Changes in electrical conductivity are shown in Figure 4.2-a. The electrical conductivity at 456MHz$^2$ remains fairly constant during consolidation indicating that changes in ion mobility and ion availability in WMT-water mixtures are negligible during the consolidation process on specimens used in this study. Figure 4.4 demonstrates changes in real relative permittivity as a function of frequency for different loading stages. With each load increment the water content decreases causing the reduction in real relative permittivity. Moreover, the real relative permittivity is smaller ($k`\sim26-27$) in three-day-old specimens as compared to fresh specimens.

$^1$ Pressures lower than 50 kPa are not shown because of the difficulty to calculate $C_v$ using “Casagrande log time method” Thus, to determine the deformation representing 0% primary consolidation in Casagrande log time method, two points with the time ratio of 1 to 4 need to be selected so that the deformation at later time is less than 50% of the total deformation – in this study, this could only be done in consolidation stages with normal pressures lower than 50 kPa).

$^2$ This lower frequency is chosen to avoid the polarization effect that may be taking place at higher frequencies (Santamarina et al., 2001)
(k~28-30), thus indicating that there is less water and higher ion concentration (Klein and Simon, 2006) in more mature specimens than in the fresh ones.

Figure 4.4 Frequency spectra of real relative permittivity for a) freshly mixed Williams mine tailings at 10-400 kPa loading, b) 3-days aged Williams mine tailings at 10-400 kPa loading
4.1.2 Consolidation and EM test for 3%PC CPB sample

Figure 4.5 shows changes in displacement and real relative permittivity with time at 400 kPa. Real relative permittivity decreases with consolidation as water gets squeezed out from the sample.
Figure 4.5 Change in displacement and real permittivity at 400 kPa loading for a) freshly mixed 3% PC, b) 1-day cured, 3% PC, c) 3-days cured, 3% PC, d) 7-days cured, 3% PC CPB sample
Change in real relative permittivity, cumulative displacement and relative displacement for different loading stages are shown in Figure 4.6. Approximate values of total settlement, difference in real relative permittivity at 1 GHz and compression indices (i.e., Cc and Cs) after the completion of consolidation test, are shown in Table 4.
Figure 4.6 Change in real relative permittivity (1GHz), cumulative displacement and relative displacement at 10-400 kPa loading for a) freshly mixed, 3% PC, b) 1-day cured, 3% PC, c) 3-days cured, 3% PC, d) 7-days cured, 3% PC CPB sample.
Table 4 Total settlement and difference in real relative permittivity at 1 GHz for 3% PC CPB samples for different curing time

<table>
<thead>
<tr>
<th>Curing time* prior to loading</th>
<th>Settlement δ(mm) 0-400 kPa</th>
<th>Permittivity Δk'=(k_i' - k_f') 0-400 kPa</th>
<th>Cc</th>
<th>Cs</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 h (fresh)</td>
<td>~1.90 (9.5 %)</td>
<td>Δk'~2.6</td>
<td>0.1151</td>
<td>0.0131</td>
</tr>
<tr>
<td>1 day</td>
<td>~1.40 (7.0 %)</td>
<td>Δk'~2.2</td>
<td>0.1644</td>
<td>0.0112</td>
</tr>
<tr>
<td>3 days</td>
<td>~0.95 (4.7 %)</td>
<td>Δk'~1.25</td>
<td>0.1545</td>
<td>0.0112</td>
</tr>
<tr>
<td>7 days</td>
<td>~0.65 (3.2 %)</td>
<td>Δk'~1.23</td>
<td>0.1252</td>
<td>0.0100</td>
</tr>
</tbody>
</table>

* as measured prior to loading

Table 4 demonstrates that settlement and change in real relative permittivity decrease with curing time, most likely as a result of hardening process in CPB. However, despite the reduction in settlement, Δk' remains mostly unchanged or slightly increased as a result of increased ion concentration in cement-containing specimens. As shown in Figure 4.6, the main change in displacement and real relative permittivity occurs during the first 100 kPa loading, indicating that most of consolidation occurs during the early stages of the oedometer test (i.e., up to 100 kPa). Figure 4.7 shows the consolidation curves for 3% PC CPB samples with various curing times.
The log-time method was used to estimate $C_v$, and the experimental results were used to determine $m_v$ (according to Eq.6), for each load increment. These results are presented in Table 5.
Table 5 Primary consolidation, $C_v$ and $m_v$ at different pressures for a) freshly mixed, 3% PC, b) 1-day cured, 3% PC c) 3-days cured, 3% PC and d) 7-days cured, 3% PC CPB sample

<table>
<thead>
<tr>
<th>Curing time</th>
<th>Stress (kPa)</th>
<th>Primary Consolidation (mm)</th>
<th>$C_v$ (cm$^2$/s)</th>
<th>$m_v$ (cm$^2$/KN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 hr</td>
<td>50</td>
<td>0.1660</td>
<td>0.284</td>
<td>4.4193</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.2800</td>
<td>0.391</td>
<td>3.4818</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.3200</td>
<td>0.521</td>
<td>2.1118</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.3000</td>
<td>0.521</td>
<td>0.9502</td>
</tr>
<tr>
<td>1d</td>
<td>50</td>
<td>0.0710</td>
<td>1.2021</td>
<td>2.4748</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.2050</td>
<td>0.313</td>
<td>2.6635</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.3850</td>
<td>0.347</td>
<td>2.5897</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.4000</td>
<td>0.391</td>
<td>1.3574</td>
</tr>
<tr>
<td>3d</td>
<td>50</td>
<td>0.0400</td>
<td>1.563</td>
<td>1.5556</td>
</tr>
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<td>0.0680</td>
<td>1.563</td>
<td>1.7543</td>
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<td>200</td>
<td>0.1600</td>
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<td>400</td>
<td>0.3650</td>
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<td></td>
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</tr>
<tr>
<td></td>
<td>200</td>
<td>0.0860</td>
<td>0.977</td>
<td>0.7414</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.2600</td>
<td>0.313</td>
<td>0.9842</td>
</tr>
</tbody>
</table>

Figure 4.8 demonstrates the change in real relative permittivity versus frequency for different loading stages. The loss of water due to consolidation increases with loading causing the reduction in real permittivity. Moreover, the real relative permittivity reduces with curing time (Table 4), indicating that there is less water in more mature specimens than in the fresh ones.
Real Permittivity at 10 - 400 kPa Loading

(a)

(b)
Figure 4.8 Frequency spectra of real relative permittivity at 10-400 kPa loading for a) freshly mixed, 3% PC, b) 1-day cured, 3% PC, c) 3-days cured, 3% PC, d) 7-days cured, 3% PC CPB sample
To further explore the effect of binder type on the consolidation response and EM properties of WMT, Portland cement (PC) was replaced with fly ash (FA). Approximate values of total settlement and difference in real relative permittivity at 1 GHz for freshly mixed 3% FA WMT-water sample are shown in Table 6.

### Table 6 Total settlement and difference in real relative permittivity at 1 GHz for freshly mixed 3% FA WMT sample

<table>
<thead>
<tr>
<th>Curing time prior to loading</th>
<th>Settlement δ (mm) 0-400 kPa</th>
<th>Permittivity $\Delta k = (k_i - k_f)$ 0-400 kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 h (fresh)</td>
<td>~0.9 (4.5 %)</td>
<td>$\Delta k \approx 2$</td>
</tr>
</tbody>
</table>

Adding fly ash to tailings-water mixture caused a change in total settlement and EM data. According to Table 6, the fresh 3% FA WMT-water mixture exhibits less settlement and water reduction compared to 3% PC CPB or WMT-water mixture of equivalent age (see Table 2 and Table 4). This decrease is most likely caused by (i) changes in the structure (i.e., higher particle packing density due to spherical shape and smaller size of FA particles when compared to relatively large and platy mine tailings particles), and (ii) hydraulic properties of FA-containing mixtures, (e.g., hydraulic conductivity). Details from this test can be found in Appendix A.2.
### 4.1.3 Consolidation and EM test for 7% PC CPB sample

Figure 4.9 shows changes in displacement and real relative permittivity with time at 400 kPa. As in 3% PC CPB, real relative permittivity decreases due to water loss during consolidation.
Figure 4.9 Change in displacement and real permittivity at 400 kPa loading for:

- a) freshly mixed, 7% PC,
- b) 1-day cured, 7% PC,
- c) 3-days cured, 7% PC,
- d) 7-days cured, 7% PC CPB sample
Change in real relative permittivity, cumulative displacement and relative displacement for different loading stages are shown in Figure 4.10. Approximate values of total settlement, difference in real relative permittivity at 1 GHz and compression indices (i.e., $C_c$ and $C_s$) after the completion of consolidation test, are shown in Table 7.
Figure 4.10 Change in real relative permittivity (1GHz), cumulative displacement and relative displacement a) and electrical conductivity of freshly mixed, 7% PC, b) of 1-day-cured, 7% PC, c) of 3-day-cured, 7% PC, d) of 7-day-cured, 7% PC CPB sample at 10–400 kPa loading.
As illustrated in Table 7, total settlement and delta k’ have a decreasing trend with curing time, indicating the effect of hardening process on the behaviour of CPB with time. When comparing CPBs with different binder contents, it becomes clear that the effect of the amount of binder on the settlement of CPB is more profound in samples cured for longer time. For instance, the settlement in 7 % CPB is equal to 2.1 % after 3 days of curing, as compared to 4.7 % and 5.5% in 3 % CPB and 0 % CPB specimens, respectively, for the same time period, but it is equal to 8.3 % in freshly-mixed 7 % CPB samples, as compared to ~9 % in freshly-mixed 3 % CPB and 0 % CPB specimens.

As shown in Figure 4.10, the major change in displacement and real relative permittivity occurs during the first 100 kPa loading, indicating that most of the settlement occurs during the early stages of the oedometer test (i.e., up to 100 kPa). Changes in electrical conductivity are shown in
Figure 4.10-a. The electrical conductivity at 456 MHz remains fairly constant during consolidation, indicating that changes in ion mobility and availability are negligible during the consolidation of CPB used in this study. Figure 4.11 shows the consolidation curves for 7% PC CPB samples with various curing times.

![Consolidation Curves](image)

**Figure 4.11 Normalized consolidation curves of 7% PC CPB samples for various curing times**

The log-time method was used to estimate $C_v$, and the experimental results were used to determine $m_v$ (according to Eq.6), for each load increment. These results are presented in Table 8.
Table 8 Primary consolidation, $C_v$ and $m_v$ at different pressures for a) freshly mixed, 7% PC, b) 1-day cured, 7% PC, c) 3-days cured, 7% PC, d) 7-days cured, 7% PC CPB sample

<table>
<thead>
<tr>
<th>Curing time</th>
<th>Stress (kPa)</th>
<th>Primary Consolidation (mm)</th>
<th>$C_v$ (cm$^2$/s)</th>
<th>$m_v$ (cm$^2$/kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.5 hr</td>
<td>50</td>
<td>0.1480</td>
<td>0.260</td>
<td>2.3625</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.2200</td>
<td>0.391</td>
<td>1.8569</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.2700</td>
<td>0.601</td>
<td>1.1721</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.2350</td>
<td>0.601</td>
<td>0.5272</td>
</tr>
<tr>
<td>1d</td>
<td>50</td>
<td>0.0290</td>
<td>1.042</td>
<td>1.3520</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.0700</td>
<td>0.893</td>
<td>1.1301</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.1080</td>
<td>1.042</td>
<td>0.9873</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.2400</td>
<td>0.391</td>
<td>0.9687</td>
</tr>
<tr>
<td>3d</td>
<td>50</td>
<td>0.0135</td>
<td>2.233</td>
<td>0.7368</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.0340</td>
<td>1.563</td>
<td>0.8070</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.0920</td>
<td>0.977</td>
<td>0.6148</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.1120</td>
<td>0.854</td>
<td>0.4096</td>
</tr>
<tr>
<td>7d</td>
<td>50</td>
<td>0.0156</td>
<td>1.736</td>
<td>0.6643</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.0240</td>
<td>1.042</td>
<td>0.4241</td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.0600</td>
<td>1.116</td>
<td>0.5250</td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.0960</td>
<td>1.042</td>
<td>0.3644</td>
</tr>
</tbody>
</table>

Figure 4.12 demonstrates the change in real permittivity as a function of measurement frequency for different loading stages. As incremental load increases, the amount of free water lost during consolidation also increases, causing the real relative permittivity at 1 GHz to decrease.
Figure 4.12: Frequency spectra of real relative permittivity at 10-400 kPa loading for a) freshly mixed, 7% PC, b) 1-day cured, 7% PC, c) 3-days cured, 7% PC, d) 7-days cured, 7% PC CPB sample.
4.2 Non-standard loading rate

This section presents the results of oedometer and EM tests on 3 % and 7 % PC CPB samples loaded at 25 kPa/h, 5 kPa/h and 0 kPa/h. Variations in displacement and real relative permittivity with time during the last increment loading stage (i.e., 400 kPa), as well as the total settlement and real relative permittivity at the end of each standard increment loading stage (i.e., 10, 25, 50, 100, 200 and 400 kPa) are presented in this section. The real relative permittivity is monitored at 1 GHz to estimate changes in water content in CPB during consolidation. The effective electrical conductivity at lower MHz frequencies (e.g., 456 MHz), which reflects the changes in the availability and mobility of ions, is also presented for various CPB.

4.2.1 Consolidation and EM properties of CPB at 25 kPa/h field loading rate

Figure 4.13 shows changes in displacement and real relative permittivity with time at 400 kPa for 3 % PC and 7 % PC CPB samples. Decrease in real relative permittivity after applying the load during the consolidation reflects a decrease in free water content in CPB samples.
Figure 4.13 Change in displacement and real permittivity of a) 3% PC CPB sample loaded at 25 kPa/h at 400 kPa loading, b) 7% PC CPB sample loaded at 25 kPa/h at 400 kPa loading

Changes in real relative permittivity, cumulative displacement and relative displacement for different loading stages are shown in Figure 4.14.
Figure 4.14 Change in real relative permittivity (1GHz), cumulative displacement and relative displacement of a) 3 % PC CPB sample loaded at 25 kPa/h within 10-400 kPa loading, b) 7 % PC CPB sample loaded at 25 kPa/h within 10-400 kPa loading

Figure 4.15 presents the evolution of the effective electrical conductivity at 456 MHz for CPB samples with different binder contents (i.e., 3% PC and 7% PC).
Figure 4.15 Variation in EC in a) 3% PC Williams CPB loaded at 25 kPa/h, b) 7% PC Williams CPB loaded at 25 kPa/h

Approximate values of total settlement and delta k for 3% and 7% PC CPB specimens loaded up to 400 kPa in 16 hours (i.e., 25 kPa/h field loading rate) are shown in Table 9.
Table 9: Total settlement and difference in real relative permittivity at 1 GHz for 3% and 7% PC CPB sample loaded at 25 kPa/h

<table>
<thead>
<tr>
<th>Specimen composition</th>
<th>Curing time prior to loading</th>
<th>Settlement $\delta$ (mm)</th>
<th>Permittivity $\Delta k' = k'_i - k'_f$</th>
<th>EC peaks first/second (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% CPB</td>
<td>0.5 h</td>
<td>~0.65 (3.25%)</td>
<td>$\Delta k' \approx 1.5$</td>
<td>411/773</td>
</tr>
<tr>
<td>7% CPB</td>
<td>0.5 h</td>
<td>~0.52 (2.6%)</td>
<td>$\Delta k' \approx 2.5$</td>
<td>150/496</td>
</tr>
</tbody>
</table>

As previously observed in the standard loading test, the amount of settlement in 7% PC CPB is smaller compared to 3% PC CPB as a result of stronger particle bonding caused by a higher amount of hydrated products in CPBs with higher binder content. According to Figure 4.14, the most significant change in displacement occurs during the first loading stage (e.g., the first 25 kPa loading), indicating that the settlement mostly occurs during the early stages of the oedometer test (e.g., the first several loading stages). An abrupt decrease in the real relative permittivity occurs in the next several loading stages, during which an increase in bound water and a decrease in free water occur. In addition, data shown in Table 9 suggest that $\Delta k'$ increases with further addition of binder, most likely as a result of higher ion concentration and increased amount of bound water in CPB specimens. The effect of bound water becomes more pronounced as the duration of the test increases from, for example, 2 hours, as in the standard loading test, to 16 hours, as in the field loading test, as more free water is being transformed into bound (adsorbed) water during hydration. Other changes that take place in hydrating CPB with time include the changes in the occurrence of EC peaks. There is a difference in the times when EC peaks occur in CPBs with different binder contents. The first and second EC peaks for 3% PC
CPB occur at \(~410\) and \(~770\) minutes, respectively, and for 7 \% CPB at \(~150\) and \(~500\) minutes, respectively, indicating that hydration process commences sooner in CPB with higher PC content. The good correlation between EC and hydration was also observed by (Simon, 2004).

Figure 4.16 demonstrates the change in real relative permittivity with frequency for different loading stages. By increasing the applied load, free water continues to be squeezed out from the pores, reducing the amount of water remaining in the sample. Free water is further reduced with increasing load because of hydration process. Thus, it takes 16 hours to apply 400 kPa, and only 1 hour to apply the first 25 kPa; therefore, more free water was transformed into bound water during hydration after 16 hours than after 1 hour, causing the reduction in real relative permittivity.
Figure 4.16 Frequency spectra of real relative permittivity of a) 3% PC CPB sample loaded at 25 kPa/h at 10-400 kPa loading, b) 7% PC CPB sample loaded at 25 kPa/h at 10-400 kPa loading
4.2.2 Consolidation and EM properties of CPB at 5 kPa/h field loading rate

Figure 4.17 shows changes in displacement and real relative permittivity with time at 400 kPa for 3 % PC CPB sample. Decrease in real relative permittivity after applying the load during the consolidation reflects a decrease in free water content in CPB sample.

![Figure 4.17 Change in displacement and real permittivity of 3 % PC CPB sample loaded at 5 kPa/h at 400 kPa loading](image-url)
Change in real relative permittivity, cumulative displacement and relative displacement for different loading stages are shown in Figure 4.18.

![Graph showing change in real relative permittivity, cumulative displacement and relative displacement](image)

*Figure 4.18* Change in real relative permittivity (1GHz), cumulative displacement and relative displacement of 3% PC CPB sample loaded at 5 kPa/h within 10-400 kPa loading
Figure 4.19 presents the evolution of the effective electrical conductivity at 456 MHz for 3% PC CPB sample.

Approximate values of total settlement and difference in real relative permittivity at 1 GHz after the completion of consolidation test for 3% PC CPB specimen loaded at 400 kPa in 80 hours (i.e., 5 kPa/h field loading rate) is shown in Table 10.

**Table 10** total settlement and difference in real relative permittivity at 1 GHz for 3% PC CPB sample loaded at 5 kPa/h

<table>
<thead>
<tr>
<th>Specimen composition</th>
<th>Curing time prior to loading</th>
<th>Settlement $\delta$ (mm)</th>
<th>Permittivity $\Delta k = k_i^' - k_f^'$</th>
<th>EC peak first/second (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% CPB</td>
<td>0.5 h</td>
<td>~0.4 (2%)</td>
<td>$\Delta k \sim 1.7$</td>
<td>393/760</td>
</tr>
</tbody>
</table>
Figure 4.20 demonstrates the change in real permittivity with frequency for different loading stages. By increasing the applied load, more water is being displaced from the specimen, reducing the amount of water remaining in the sample, as previously observed in oedemeter tests with 25 kPa/h loading rate. Part of free water is further reduced due to binder hydration process that takes place during consolidation test. Thus, it takes 80 hours to complete the application of 400 kPa and only 5 hours to apply the first 25 kPa. So, more free water can be transformed into bound water, causing the reduction in real relative permittivity, during hydration process after 80 hours (i.e., at the end of 400 kPa loading stage) than after 5 hours (at the end of 25 kPa loading stage).

![Figure 4.20 Frequency spectra of real relative permittivity of 3% PC CPB sample loaded at 5 kPa/h at 10-400 kPa loading](image)

*Figure 4.20 Frequency spectra of real relative permittivity of 3% PC CPB sample loaded at 5 kPa/h at 10-400 kPa loading*
4.2.3 Consolidation and EM properties of CPB at 0 kPa/h

Figure 4.21 shows changes in real relative permittivity for 3 % and 7 % PC CPB samples. The variations in real relative permittivity when no normal stress is applied to the samples are due to self-weight consolidation and hydration process with time.

Figure 4.21 Change in real relative permittivity (1GHz) for a) 3% PC CPB sample loaded at 0kPa/h within 16 hours, b) 7% PC CPB sample loaded at 0kPa/h within 16 hours
Figure 4.22 presents the evolution of the effective electrical conductivity at 456 MHz for 3 % and 7 % PC CPB samples.

Figure 4.22 Variation in EC at 0 kPa/h for a) 3 % PC CPB, b) 7 % PC CPB
Table 11 shows the approximate values of displacement and EM parameters for 3% and 7% PC CPB during 16 hours, when no normal stress is applied on top of the sample.

Table 11 Total settlement, difference in real relative permittivity at 1 GHz and EC peaks at 456 MHz for 3% and 7% PC CPB sample loaded at 0 kPa/h

<table>
<thead>
<tr>
<th>Specimen composition</th>
<th>Curing time prior to loading</th>
<th>Settlement $\delta$ (mm)</th>
<th>Permittivity $\Delta k' = k_i' - k_f'$</th>
<th>EC peak first/second (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% CPB</td>
<td>0.5 h</td>
<td>~0.024 (0.12%)</td>
<td>$\Delta k' \approx 0.69$</td>
<td>361/ 604</td>
</tr>
<tr>
<td>7% CPB</td>
<td>0.5 h</td>
<td>~0.026 (0.13%)</td>
<td>$\Delta k' \approx 1.46$</td>
<td>152/ 480</td>
</tr>
</tbody>
</table>

As expected, the settlement in unloaded specimens is negligible in comparison to consolidated samples with the same binder content and test duration. Thus, the settlement of only 0.026 mm was measured in unloaded 7% CPB specimens as compared to 0.52 mm in consolidated 7% CPB specimen (see Table 7). This small settlement value in unloaded specimens is in good agreement with small water loss that was observed and assessed by EM measurements: $\Delta k' \approx 1.46$ in unloaded 7% CPB as compared to $\Delta k' \approx 2.95$ in consolidated 7% CPB. Table 11 also indicates that settlement, regardless of the binder content, does not change dramatically with time if normal stress is not applied. However, $\Delta k'$ increases by further addition of binder as a result of higher ion concentration and increased amount of bound water. In addition, there is a difference in the times when EC peaks occur in CPBs with different binder contents. The first and second EC peaks for 3% PC CPB occur at ~361 and ~604 minutes, respectively, and for 7% CPB at
~152 and ~480 minutes, respectively, indicating that hydration process commences sooner in CPB with higher PC content (Simon, 2004).
Chapter 5.
Discussion

In this section, test results are analyzed to better understand the impact of binder (content and type), curing time and loading rate on the consolidation behaviour and hydration processes in CPB using the oedometer test and electromagnetic measurements.

5.1 Investigation of Terzaghi’s model for WMT-water mixtures and CPB

The comparison between experimental and theoretical consolidation curves is considered in this section. Figure 5.1 shows a typical square root time-settlement relationship for saturated clay (Craig, 1983). The initial compression segment in saturated clay is very steep compared to the linear part of the primary consolidation segment. This is due to immediate load application on top of the sample in a very short period of time and the compression of entrapped air (Lamb, 1951). The Terzaghi’s one dimensional theory does not include the initial compression segment (Lambe, 1951) and so the initial compression data is often omitted in compression graphs. Figure 5.2 shows a typical square root time-settlement relationship for freshly mixed WMT and 7%PC/7d CPB at 50 kPa. Similarly to clay, WMT and CPB exhibit initial compression behaviour that lasts for about a second, but in contrast to clay, it is non-linear. In order to
separate the initial compression segment from primary consolidation segment, a transition point is determined at the end of initial compression, as suggested in Bo (2008). The approximate transition point which defines the point at which the paste begins to ‘behave’ as a Terzaghi’s soil, is based on the change of the settlement rate. In Figure 5.2, points “a” and “b” represent transition points that mark the end of the initial compression for the freshly mixed WMT and 7%PC/7d CPB, respectively, as the initial compression segments of freshly mixed WMT-water mixture and 7%PC/7d CPB exhibit different settlement rates (have different slopes) compared to the linear portion of the primary consolidation segment. This trend was observed in all CPB samples regardless of binder content and curing time. The difference between the initial compression behaviour of WMT-water mixtures and CPBs in comparison with clay is most likely due to the difference in structure/structural bonds in these materials (Lambe, 1951). Further investigation may be required to confirm this explanation. Moreover, the rate of settlement in WMT/CPB samples changes considerably at the end of primary consolidation right before the secondary consolidation starts. The second transition points of “c” and “d” in Figure 5.2 are defined at the end of primary consolidation of freshly mixed WMT and 7%PC/7d CPB, respectively. In WMT/CPB specimens the rate of settlement increases after the first transition point (i.e., end of initial compression) followed by the reduction after the second transition point (i.e., end of primary consolidation). However, in clay the rate of settlement decreases after the initial compression segment (i.e., first transition point) followed with the reduction after the primary consolidation (i.e., second transition point).
The next step is to investigate whether the consolidation curves for WMT and CPB are in agreement with Terzaghi’s consolidation theory model. Thus, the time-consolidation curves for selected samples were compared with those obtained using Terzaghi’s simplified model by adjusting the Cv as a free variable (statistically fitted Terzaghi’s model).

The fitting technique was carried out by using the following Terzaghi’s equation (for \( U < 0.6 \), \( T_v = \frac{\pi}{4} U^2 \) and for \( U > 0.6 \), \( T_v = -0.933 \log(1 - U) - 0.085 \)) in terms of \( U(t) = f(C_v) \) so that \( C_v \) is the free variable. The least squares error method was used to minimize the difference between the time-consolidation curves obtained from the original data and the best-fit Terzaghi line that would give the optimal value for \( C_v \). The consolidation graphs for the remaining WMT-water mixtures and CPB samples with different binder contents and curing times are shown in Appendix A.3. Table 12 compares the values of \( C_v \) determined based on Casagrande log-time method and statistically fitted Terzaghi’s model.
Figure 5.3 Variation of time with percentage of consolidation U for a) freshly mixed WMT, b) 7%/7d CP sample
Table 12 Cv determined based on Casagrande log-time method and statistically fitted Terzaghi’s model

<table>
<thead>
<tr>
<th>Cement content</th>
<th>curing time</th>
<th>Stress</th>
<th>Cv (cm²/s) based on original data</th>
<th>Cv (cm²/s) based on the best fit</th>
</tr>
</thead>
<tbody>
<tr>
<td>0% fresh</td>
<td>50</td>
<td>0.3125</td>
<td>0.1326</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.2404</td>
<td>0.2645</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.4736</td>
<td>0.4839</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.1202</td>
<td>0.1657</td>
<td></td>
</tr>
<tr>
<td>3d fresh</td>
<td>50</td>
<td>0.6251</td>
<td>0.5951</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.6251</td>
<td>0.7670</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.9358</td>
<td>0.9363</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.9358</td>
<td>0.9723</td>
<td></td>
</tr>
<tr>
<td>1d fresh</td>
<td>50</td>
<td>0.2841</td>
<td>0.1341</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.3907</td>
<td>0.2307</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.5209</td>
<td>0.3709</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.5209</td>
<td>0.5351</td>
<td></td>
</tr>
<tr>
<td>3d 7%</td>
<td>50</td>
<td>1.5628</td>
<td>1.8343</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>1.5628</td>
<td>2.0838</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.8930</td>
<td>1.0074</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.3473</td>
<td>0.2773</td>
<td></td>
</tr>
<tr>
<td>7d 7%</td>
<td>50</td>
<td>0.9767</td>
<td>1.4232</td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>0.9767</td>
<td>1.1672</td>
<td></td>
</tr>
<tr>
<td></td>
<td>200</td>
<td>0.3126</td>
<td>0.2626</td>
<td></td>
</tr>
<tr>
<td></td>
<td>400</td>
<td>0.3126</td>
<td>1.2231</td>
<td></td>
</tr>
</tbody>
</table>

As shown in Figure 5.3, parts of time-consolidation curves for both freshly-mixed WMT and 7%/7d CPB lie above the best fit Terzaghi line while some parts lie below the Terzaghi line during primary consolidation; nevertheless, the difference between the original data and the best fit Terzaghi line is negligible. Similar trend was also observed in the remaining samples (See
Appendix A.3). Moreover, it seems that there is no significant difference between $C_v$ determined from original data and the one calculated from statistically fitted Terzaghi’s model. It should be stressed that $C_v$ in original data was determined using the “Casagrande log time method” which is a graphical method and may be subject to bias in determination of $t_{50}$. As a result, it can be concluded that primary consolidation of WMT/CPB is well represented by Terzaghi’s model and is best fit when a least squares method is used to objectively determine $C_v$.

### 5.2 The effect of binder type and content

#### 5.2.1 Consolidation response in freshly mixed CPB samples

The initial void ratios of freshly mixed CPBs depend on the binder content. As shown in Figure 5.4, the higher the binder content, the higher the initial void ratio in CPB. This is probably due to the increased amount of fine particles (e.g., PC particles) that cause changes in the CPB’s structure (i.e., increased porosity and surface area in CPBs with higher fines content). Furthermore, an increase in binder content tends to reduce the compressibility (i.e., $\Delta e$) during consolidation, as shown in Figure 5.5.\(^3\) The reduction in $\Delta e$ is only related to a small extent to the hydration process of PC as CPB has only been hydrated for less than 1 hour and initial set is expected to be around 4 hours. Instead, the reduction in $\Delta e$ is related to a larger extent to changes in the structure, such as finer pore structure and greater tortuosity, that are found in CPB with higher binder content (e.g., it is harder to squeeze the water out from finer pores than from larger pores). This finding was verified by testing the WMT-water mixtures with fly ash (without

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\(^3\) The discrepancy observed in freshly mixed 3% PC is most likely due to experimental error margin.
Portland cement). Thus, fly ash-WMT mixture exhibits reduced $\Delta e$ that can be attributed mainly to finer pore structure and only to a smaller extent to the hydration process of fly ash since no Portland cement was present to activate fly ash particles. It can be concluded that the initial resistance to consolidation in CPB samples increases with addition of fine particles, including Portland cement and/or fly ash.

**Figure 5.4** Consolidation curves of freshly mixed CPB samples with various binders (type and content)

**Figure 5.5** Normalized consolidation curves of freshly mixed CPB samples with various binders (type and content)
5.2.2 EM measurement

The effect of Portland cement and fly ash on dielectric permittivity is addressed in this section. Figure 5.6 represents a spectral response of real relative permittivity at frequencies ranging between 0.2 GHz and 1.3 GHz for WMT mixed with different amounts of PC (0 %, 3 % or 7 %) and FA. Water content is approximately 28% (based on total mass, i.e., mass of water/total mass) for all specimens. Based on Figure 5.6, EM measurements are sensitive to changes in binder composition: PC-containing CPB has higher real relative permittivity than WMT-water mixtures or WMT-FA-water mixtures. This is probably due to increased ion concentration caused by a release of dissolved ions at early stages of the hydration process (Santamarina et al., 2001) in PC-containing CPB. The presence of FA causes little change in real relative permittivity most likely due to hindered hydration of its particles, which are unlikely to react with water in the absence of PC (Neville, 1995).

![Figure 5.6 Frequency spectra of real relative permittivity for freshly mixed CPB samples with various binders (type and content)](image-url)
5.3 The effect of curing time and binder content

5.3.1 Consolidation response

Figure 5.7 and Figure 5.8 show the consolidation behaviour of 3 % PC and 7 % PC CPBs, respectively, as a function of curing time. The differences between compression paths for various specimens are due to (i) variations in tortuosity and hydraulic conductivity as a result of higher content of fine particles in fresh samples, and (ii) variations in structure caused by cementation in longer-cured samples. Figure 5.7 and Figure 5.8 suggest that curing time significantly influences the void ratio during oedometer test. Decrease in void ratio reduces with curing time so that the longer the curing time, the higher the initial resistance to consolidation. This increase in resistance is caused by formation of cemented bonds which improve CPB’s strength to resist the applied consolidation stress while maintaining higher void ratio as compared to less hydrated samples. Since the hydration process is time-dependent, more cemented bonds develop within the CPB with curing time. Further addition of binder has similar effect on CPB: the increased number of cemented bonds will enhance the resistance to consolidation of CPB. As a consequence, the consolidation curve remains horizontal (or close to horizontal) in CPBs with higher binder content and longer curing time. This phenomenon where consolidation curve remains horizontal with development of cemented bonds between particles has also been observed by Nagaraj et al. (1994) and (1995). According to Nagaraj et al. (1994) and (1995), in freshly-mixed samples the applied stress is carried by soil particles per se, presented as $\sigma_R$ since there are not enough cemented bonds to carry the load. In contrast, in longer-cured CPB samples that are subjected to consolidation, there are enough cemented bonds that can resist the applied stress (i.e., $\sigma_B$) until the yield stress is achieved. Once the yield stress is achieved, some cemented bonds will begin to break down leading to a progressive decrease in void ratio. As the loading continues, more cemented bonds will be broken until minimum specific volume of unity is achieved. As a consequence, once the consolidation stress exceeds the strength of CPB (i.e.,
yield stress), the consolidation curve becomes steeper. Similar observation was noted by le Roux (2004) and Yilmaz et al. (2008).

Figure 5.7 Normalized consolidation curves of 3% cement CPB samples for various curing time

Figure 5.8 Normalized consolidation curves of 7% cement CPB samples for various curing time
The following consolidation parameters are analyzed next: preconsolidation stress, compression indices (i.e., Cc and Cr), coefficient of consolidation (Cv), coefficient of volume compressibility (Mv) and primary settlement.

Figure 5.9 shows variation of preconsolidation stress ($P'_c$) for 3% PC and 7% PC with curing time. It is most likely that preconsolidation stress in this study is representative of yield stress only, since laboratory-prepared samples did not experience any vertical stress prior to oedometer test. Figure 5.9, implies that curing time and amount of binder content significantly affect the preconsolidation stress. In general, the preconsolidation stress increases with curing time and binder content. This increase in preconsolidation stress is most likely due to hydration process, i.e., formation of cemented bonds between solid tailings particles. Since no unique 1D normal compression line was obtained in this study, the preconsolidation stress values for CPB with higher binder content are somewhat underestimated, resulting in lower values when compared to specimens with lower binder content.

![Figure 5.9 Change in preconsolidation stress for various binder contents and curing time](image)
The compression indices of WMT-water mixtures and CPB samples with various binder content and curing times are needed to calculate the magnitude of settlement for a given stress. Based on the properties of the material used in this study, which includes a well-graded silt ($D_{50} \approx 18 \mu m$, Simon and Grabinsky, 2012) mixed with 3% or 7% Portland cement ($D_{50} \approx 4\mu m$), a transitional mode of behaviour is expected during consolidation of CPB samples (Nocilla et al., 2006). However, this type of behavior was not observed in CPB samples; instead, compression paths were not parallel to each other (Figure 5.7 and Figure 5.8) and showed the tendency to converge, which might not be obvious for pressures up to 400 kPa used in this study, but was shown by Le Roux (2004) on CPB with similar composition loaded up to 3,200 kPa (Figure 2.6).

Variations in compression index and recompression index for 3 % PC and 7 % PC CPBs with curing time are shown in Figure 5.10 and Figure 5.11, respectively. The compression index has an incremental trend at the beginning (at early times of curing), followed by a decrease at later times. The variations in compression index for CPB samples with different binder content and curing times are due to changes in microstructure in hydrating CPB and also due to relatively low pressures (up to 400 kPa) which might not be enough to obtain 1D NCL in these samples. In other words, compression index should rise with time, therefore, reduction in $C_c$ after 1 day is probably due to lack of vertical stress to break all of the cemented bonds. Figure 5.11 shows that recompression index decreases with increasing curing time and binder content; therefore, stiffness increases when more cemented bonds form between particles.
It is well known for clays that the coefficient of consolidation, $C_v$, depends on both mechanical variables, such as flexibility and surface friction of particles, and physico-chemical variables, such as surface charge density and distribution (Robinson and Allam, 1998). Thus, $C_v$ increases with consolidation pressure if mechanical factors control the consolidation behaviour, but it
decreases with pressure if physico-chemical factors control the consolidation behaviour. Similar behaviour is found in WMT/CPB samples.

Table 13 shows the value of $C_v$ at different consolidation pressure for WMT-water mixture and CPB samples with different binder contents and curing time. In general, $C_v$ has a decreasing trend with consolidation pressure in longer-cured CPB samples, but it increases with consolidation pressure in WMT water mixtures and freshly-mixed CPB samples. This inconsistency is probably due to materials’ properties since WMT-water mixture and fresh CPB samples are soft and flexible and so their response to pressure increase is governed by mechanical factors (Robinson and Allam, 1998). However, in longer-cured CPB samples the ion concentration increases with time (and consequently with pressure), and so it is more likely that physico-chemical factors control the dependency of $C_v$ on pressure. In addition, since 3%/1d CPB is still soft as a result of low binder content and short curing time, it behaves similar to 3%PC/fresh sample. (e.g., $C_v$ has an incremental trend).

Table 13 $C_v$ value for WMT-water mixture and CPB samples with different binder contents and curing times

<table>
<thead>
<tr>
<th>PC content</th>
<th>Curing time</th>
<th>$C_v$ (cm$^2$/s)</th>
<th>50kPa</th>
<th>100kPa</th>
<th>200kPa</th>
<th>400kPa</th>
</tr>
</thead>
<tbody>
<tr>
<td>0%</td>
<td>0.5 hr</td>
<td>0.3126</td>
<td>0.2404</td>
<td>0.4736</td>
<td>0.1202</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3d</td>
<td>0.6251</td>
<td>0.6251</td>
<td>0.9358</td>
<td>0.9358</td>
<td></td>
</tr>
<tr>
<td>3%</td>
<td>0.5 hr</td>
<td>0.2841</td>
<td>0.3907</td>
<td>0.5209</td>
<td>0.5209</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1d</td>
<td>0.3126</td>
<td>0.3473</td>
<td>0.3907</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3d</td>
<td>1.5628</td>
<td>1.5628</td>
<td>0.8930</td>
<td>0.3473</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7d</td>
<td>1.5628</td>
<td>0.9767</td>
<td>0.9767</td>
<td>0.3126</td>
<td></td>
</tr>
<tr>
<td>7%</td>
<td>0.5 hr</td>
<td>0.2605</td>
<td>0.3907</td>
<td>0.6011</td>
<td>0.6011</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1d</td>
<td>1.0419</td>
<td>0.8930</td>
<td>1.0419</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>3d</td>
<td>2.2325</td>
<td>1.5628</td>
<td>0.9767</td>
<td>0.8540</td>
<td></td>
</tr>
<tr>
<td></td>
<td>7d</td>
<td>1.7364</td>
<td>1.0419</td>
<td>1.1163</td>
<td>1.0419</td>
<td></td>
</tr>
</tbody>
</table>

Table 14 shows the change in displacement during primary consolidation for WMT-water mixture and CPB samples with different binder contents and curing times. As shown in Table 14,
primary settlement decreases with curing time, which is in agreement with hydration progress that produces sufficient strength and stiffness for CPB to carry higher loading pressures. Hence, the longer the curing time, the stronger the CPB becomes as a result of formation of cemented bonds between particles, and so less settlement occurs in samples with longer curing time. In uncemented mixtures, it is density that increases with curing time due to self-weight consolidation and so it causes less settlement in time during application of the same amount of loading pressure.

Table 14 Change in displacement during primary consolidation for WMT-water mixture and CPB samples with different binder contents and curing times

<table>
<thead>
<tr>
<th>PC content</th>
<th>Curing time</th>
<th>Loading pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>50kPa</td>
</tr>
<tr>
<td>0%</td>
<td>0.5 hr</td>
<td>0.176</td>
</tr>
<tr>
<td></td>
<td>3d</td>
<td>0.102</td>
</tr>
<tr>
<td>3%</td>
<td>0.5 hr</td>
<td>0.166</td>
</tr>
<tr>
<td></td>
<td>1d</td>
<td>0.071</td>
</tr>
<tr>
<td></td>
<td>3d</td>
<td>0.040</td>
</tr>
<tr>
<td></td>
<td>7d</td>
<td>0.031</td>
</tr>
<tr>
<td>7%</td>
<td>0.5 hr</td>
<td>0.148</td>
</tr>
<tr>
<td></td>
<td>1d</td>
<td>0.029</td>
</tr>
<tr>
<td></td>
<td>3d</td>
<td>0.014</td>
</tr>
<tr>
<td></td>
<td>7d</td>
<td>0.016</td>
</tr>
</tbody>
</table>

5.3.2 EM measurements

Figure 5.12 and Figure 5.13 describe the changes in the real relative permittivity at different curing times of 3% PC and 7% PC CPB samples, respectively, at the end of 400 kPa consolidation stage. All specimens exhibit relaxation in real relative permittivity with frequency, as measured by $\Delta \kappa'$, which increases with curing time. The real relative permittivity at 1 GHz decreases with curing time as a result of hydration process, during which water becomes partially consumed/adsorbed by newly formed hydration products. Since hydration process is time-dependent, the free water continues to be consumed during the hydration (and with time). As a
result, the real relative permittivity continues to decrease in hydrating CPB samples; however, the rate of reduction in real relative permittivity seems to slow down after 3 days of curing for 3% and 7% PC CPB samples (as shown in Figure 5.12 and Figure 5.13). This can be attributed to the fact that the majority of hydration reactions (that facilitate the formation of cemented bonds, e.g., hydration products) slows down after the first several days (Bishop et al, 2003).

![Figure 5.12 Normalized frequency spectra of real relative permittivity for 3% cement CPB samples with various curing time](image)
Figure 5.13 Normalized frequency spectra of real relative permittivity for 7% cement CPB samples with various curing time

Figure 5.14 implies that the higher the binder content, the larger the relaxation of the real relative permittivity. By increasing the binder content, for the same curing time, more cemented bonds are created between the tailings particles and the cement particles during hydration process, and since hydration process is water consuming, the real relative permittivity decreases with increasing binder content.
Figure 5.14 Comparison between change in real permittivity of 3% and 7% cement CPB samples with various curing time

Figure 5.15 demonstrates the change in electrical conductivity of freshly mixed 0 % PC and 7 % PC CPBs at 456 MHz. According to Figure 5.15, there is a little change in electrical conductivity in all specimens during the standard loading test, indicating little change in ion mobility and availability during standard consolidation test. This was shown for kaolinite-water mixtures by Fam and Santamarina (1995). Adding binder has an effect on the magnitude of electrical conductivity: the higher the cement content, the higher the magnitude of electrical conductivity. This is most likely due to an increase in ion concentration and mobility caused by increasing binder content.
5.4 The Effect of Loading Rate on Consolidation Response

5.4.1 Consolidation response

The effect of application of stress during curing period on consolidation and consequently stiffness development in 3% and 7% CPB are shown in Table 15 and Table 16, respectively. According to Table 15 and Table 16, the stiffness of CPB is sensitive to loading rate. For all freshly-mixed specimens, the smaller the loading rate, the smaller the settlement, thereby indicating that smaller loading rate may allow CPB to rearrange its particles and becomes stiffer (Le Roux, 2004). In addition, change in void ratio is significantly smaller in specimens cured during small loading rate compared to specimens cured in the absence of loading for the same period of time before being subjected to a fast loading rate. Thus, applying the normal stress at early stages of hydration may contribute to the stiffness development in CPB (Fahey et al, 2011).
Table 15 Comparison of stiffness development in 3% CPB at different loading rate

<table>
<thead>
<tr>
<th>Specimen composition</th>
<th>Loading rate</th>
<th>Settlement, ( \delta ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3% PC CPB</td>
<td>0-400 kPa within 2 h (CPB cured for 16 hours before the load was applied)</td>
<td>( \sim 1.40 ) (7.0 %)</td>
</tr>
<tr>
<td>3% PC CPB</td>
<td>Continuous load rate of 25 kPa/h (0-400 kPa within 16 h)</td>
<td>( \sim 0.65 ) (3.25 %)</td>
</tr>
<tr>
<td>3% PC CPB</td>
<td>Continuous load rate of 5 kPa/h (0-400 kPa within 80 h)</td>
<td>( \sim 0.40 ) (2%)</td>
</tr>
<tr>
<td>3% PC CPB</td>
<td>No normal stress applied during 16 hours test duration</td>
<td>( \sim 0.02 ) (0.12%)</td>
</tr>
</tbody>
</table>

Table 16 Comparison of stiffness development in 7% CPB at different loading rate

<table>
<thead>
<tr>
<th>Specimen composition</th>
<th>Loading rate</th>
<th>Settlement, ( \delta ) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>7% PC CPB</td>
<td>0-400 kPa within 2 h (CPB cured for 16 hours before the load was applied)</td>
<td>( \sim 0.80 ) (4.0 %)</td>
</tr>
<tr>
<td>7% PC CPB</td>
<td>Continuous load rate of 25 kPa/h (0-400 kPa within 16 h)</td>
<td>( \sim 0.52 ) (2.6%)</td>
</tr>
<tr>
<td>7% PC CPB</td>
<td>No normal stress applied during 16 hours test duration</td>
<td>( \sim 0.03 ) (0.13%)</td>
</tr>
</tbody>
</table>
5.4.2 EM measurements

Figure 5.16 shows the EC measurements for 3% and 7% PC CPB subjected to the normal load of 0-400 kPa at different loading rates. According to the EC data presented in section 4.2 and also Figure 5.16, loading rate does not affect the hydration process in CPB because EC peaks occur at the same time for the same amount of binder regardless of loading rate. Therefore, normal stress has little effect on the onset of the hydration process (even in cases in which no normal stress was applied) in CPB analyzed in this study. This indicates that the structural changes in CPB caused by consolidation may not be sufficient to affect the progress of binder hydration. Electrical conductivity of CPB is sensitive to changes in binder content. EC increases with increasing binder content as more ions are released and become available during cement dissolution. The data in Figure 5.17 suggests that the higher the binder content the earlier the onset of hydration progress takes place as particle bonds form at faster rate in higher binder content-containing CPBs (Simon, 2004).
Figure 5.16 Evolution of electrical conductivity with different loading rates for a) 3% PC CPB sample, b) 7% PC CPB samples

Figure 5.17 Variation in EC in 3% and 7% PC Williams CPB loaded at 25kPa/h
Chapter 6. Conclusions and future work

6.1 Conclusions

The effect of binder content, curing time and load history on consolidation behaviour of Williams mine tailings-water and CPB have been investigated. Evolution of various changes in tailings-water mixtures and CPB was monitored using (i) an oedometer in conjunction with automatic displacement measurements and (ii) a network analyzer to measure real relative permittivity and imaginary permittivity. Both oedometer test and EM measurements provided useful information about physicochemical changes in Williams mine CPB. The main conclusions obtained from this study are as follows:

1- Improved bonding between particles causes less reduction in void ratio during consolidation, thereby increasing the stiffness of CPB, as shown in Table 2 and Figure 3.1. Stiffness of WMT-water mixtures and CPB samples varies with binder content and curing time. Higher binder contents and longer curing times improve the bonding between particles which leads to less reduction in void ratio during consolidation. As a result, all specimens exhibited increase in stiffness with binder content and curing time resulting in flatter consolidation curves. However, consolidation curve becomes steeper once the applied stress on a specimen exceeded the yield stress of CPB. Looking at the effect of different binder contents, it is necessary to note that, although the addition of 3 % PC caused little change to the stiffness of CPB, further addition of
PC increases the resistance to consolidation in both fresh and matured specimens significantly.

2- The real relative permittivity is a good indicator of water content in hydrating CPB exposed to various levels of loading. Higher binder content and longer curing time cause more relaxation in real relative permittivity during oedometer test. This water relaxation (i.e. reduction in free water) is due to consolidation and cement hydration.

3- EC Imaginary permittivity, being representative of ion mobility and availability, does not significantly change during the quick standard consolidation process shown in this study. However, imaginary permittivity increases in higher binder content as more ions are released during cement dissolution.

4- EC of CPB varies with binder content and curing time. EC increases with increasing binder content as more ions are released during cement dissolution.

5- The higher the binder content the earlier the onset of hydration progress takes place as particle hydration bonds form faster in higher binder content CPBs.

6- According to the EC data, loading rate does not affect the hydration process in CPB. In other words, the EC peaks occur at the same time for the same amount of binder regardless of loading rate (even in cases in which no normal stress was applied). This indicates that the structural changes in CPB caused by consolidation may not be sufficient to affect the progress of binder hydration. Results showed that the stiffness of CPB is sensitive to loading rate. For all fresh specimens, the slower the loading rate, the smaller the change in void ratio. This finding indicates that slower loading rate may allow CPB to rearrange its particles and become stiffer. Based on the laboratory tests, change in void ratio is less in specimens cured under slow loading rate compared to specimens that were cured unloaded for the same amount of time before subjected to quick loading.
In summary, the laboratory data demonstrate that the stiffness development in CPB, envisioned in this study as the resistance to settlement/consolidation, is caused by changes in structure due to consolidation and hydration process. Consolidation has a significant role in improving the stiffness in non-cemented and low-cement-content pastes, whereas hydration plays a determining role in stiffness development in higher cement content pastes. At early times of hydration, changes in CPB structure due to consolidation of up to 400 kPa do not have a significant effect on the progress of hydration. This implies that essential characteristics (including water content and ion concentration) of consolidated CPB are sufficient to maintain the hydration progress observed in non-consolidated CPB.

6.2 Future work

Suggestions for future work are to investigate the effect of additional factors on consolidation process in hydrating CPB from the Williams Mine, including:

1- Effect of other binder types (e.g., various Portland Cements and blends of PC&FA)

2- One way drainage vs. two way drainage (to simulate the drainage pattern found in the stope)

3- Incorporating the initial compression and secondary consolidation in numerical models
References


Appendix

A.1. Summary of consolidation test on Pottery Clay

![Pottery Clay Consolidation Test](image)

**Figure A. 1** Change in displacement and real permittivity at 50 kPa loading
A.2. Summary of consolidation test on 3% freshly mixed FA

Figure A. 2 Change in displacement and real permittivity of freshly mixed, 3% Fa WMT sample at 400 kPa loading

Figure A. 3 Change in real relative permittivity (1GHz), cumulative displacement and relative displacement of freshly mixed, 3% Fa WMT sample 10-400 kPa loading
Figure A. 4 Frequency spectra of real relative permittivity at of freshly mixed, 3% Fa WMT sample at 10-400 kPa loading
A.3. Summary of Validation of Terzaghi’s model for WMT-water mixtures and CPB

0 % PC:

![Uncemented/fresh-100 kPa](image1)

![Uncemented/3d-100 kPa](image2)

**Figure A. 5 Variation of time with percentage of consolidation U for a) freshly mixed WMT, b) 3-days aged freshly mixed WMT**
Figure A.6 Variation of time with percentage of consolidation U for a) freshly mixed 3% PC, b) 1-day cured, 3% PC, c) 3-days cured, 3% PC, d) 7-days cured, 3% PC CPB sample
7% PC:

Figure A. 7 Variation of time factor $T_v$ with percentage of consolidation $U$ for a) freshly mixed 7% PC, b) 1-day cured, 7% PC, c) 3-days cured, 7% PC, d) 7-days cured, 7% PC CPB sample