

**Coupled Thermo-Hydro-Mechanical-Chemical (THMC)  
Processes in Cemented Tailings Backfill Structures and  
Implications for their Engineering Design**

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**To my wife SARA  
and my daughter ELINA**

# ABSTRACT

The main result of underground mining extraction is creating of large underground voids (mine stopes). These empty openings are typically backfilled with an engineering cementitious material called cemented paste backfill (CPB). The main purpose of CPB application in underground mining is to provide stability and ensure the safety of underground openings, maximize ore recovery, and also provide an environmental-friendly means of underground disposal of potential acid generating tailings. CPB is a mixture of mine tailings, cement binder and water.

CPB has a complex geotechnical behaviour when poured into mine voids. This is because of the different thermal (T), hydraulic (H), mechanical (M) and chemical coupled processes and interactions that take place in CPB soon after placement. In addition to these THMC behaviours, various external factors, such as stope geometry, drainage condition and arching effects add more complexity to its behaviour. In order to acquire a full understanding of CPB behaviour, there is a need to consider all of these THMC factors and processes together. So far, there has not been any study that addresses this research need. Indeed, fundamental knowledge of the THMC behaviour of CPB provides a key means for designing safe and cost-effective backfill structures, as well as optimizing mining cycles and productivity of mines.

Innovative experimental tools and CPB testing methods have been developed and adopted in this research to fulfill the objectives of this research. In the first phase of the study, experiments with high columns are developed to study the THMC behaviour of CPB from early to advanced ages with respect to height of the column and curing time. The column experiments simulate the mine stope and filling sequence and provide an opportunity to study external factors, such as evaporation, on the THMC behaviour of CPB. However, an important factor is the overburden pressure from the stress due to self-weight that cannot be simulated through column experiments. Therefore, in the second phase of this study, a novel THMC curing under stress apparatus is developed to study the THMC behaviour of CPB under various pressures due to the self-weight of the CPB, drainage conditions, and filling rate and sequence. Comprehensive instrumentation and geotechnical testing are carried out to obtain fundamental knowledge on the THMC behaviour of CPB in different curing conditions from early to advanced ages.

The results of these studies show that the THMC properties of CPB are coupled. Important parameters, such as curing stress, self-desiccation due to cement hydration, temperature, pore water chemistry, and mineralogical and chemical properties of the tailings, have significant influence on the shear strength and compressive strength development of CPB. Factors such as evaporation and drying

shrinkage can also affect the hydro-mechanical properties of CPB. The curing conditions (such as curing stress, drainage and filling rate) also has significant impact on CPB behaviour and performance. The THMC interactions and the degree of influence of each factor should be included in designing backfill structures and planning mining cycles. This innovative curing under stress technique can be replaced the conventional curing of CPB (curing under zero stress and no THMC loadings), in order to optimize CPB mechanical strength assessment, increase mine safety and enhance the productivity.

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## List of Symbols and Abbreviations

| <b>Symbols</b> | <b>Definition</b>                  |
|----------------|------------------------------------|
| $C_c$          | Coefficient of Curvature           |
| $C_u$          | Coefficient of Uniformity          |
| $C_v$          | Solid content by volume            |
| $C_w$          | Solid content by mass              |
| $G_s$          | Specific Gravity                   |
| $k_{sat}$      | Saturated hydraulic conductivity   |
| $k_{unsat}$    | Unsaturated hydraulic conductivity |
| $S_r$          | Degree of saturation               |
| $e'$           | Effective Void ratio               |
| $\gamma_{dry}$ | Dry Density                        |
| $\gamma_{wet}$ | Wet Density                        |
| $e$            | Void ratio                         |
| $\gamma$       | Bulk Density                       |
| $\sigma$       | Total Stress                       |
| $\sigma'$      | Effective Stress                   |
| $\omega$       | Water content                      |
| $C$            | Cohesion                           |
| $k$            | Thermal Conductivity               |
| $\varphi$      | Angle of Internal Friction         |
| $u$            | Pore Pressure                      |
| $\alpha$       | Angle of sliding wedge             |

| <b>Acronym</b>    | <b>Definition</b>                                       |
|-------------------|---------------------------------------------------------|
| $d_{cr}$          | Critical Diameter                                       |
| $d_{th}$          | Threshold Diameter                                      |
| AE                | Actual Evaporation                                      |
| AEV               | Air Entry Value                                         |
| AMD               | Acid Mine Drainage                                      |
| ASTM              | American Society for Testing and Materials              |
| C <sub>2</sub> S  | Dicalcium Silicate or Belite                            |
| C <sub>3</sub> A  | Tricalcium Aluminate                                    |
| C <sub>3</sub> S  | Tricalcium Silicate or Alite                            |
| C <sub>4</sub> AF | Tetracalcium Alumina Ferrite                            |
| CD                | Consolidation Drained                                   |
| CH                | Calcium Hydroxide                                       |
| CPB               | Cemented Paste Backfill                                 |
| CPR               | Cumulative Pore Pressure Reduction                      |
| CRF               | Cemented Rock Fill                                      |
| C-S-H             | Calcium Silicate Hydrate                                |
| CTB               | Cemented Tailings Backfill                              |
| CU                | Consolidated Undrained                                  |
| CUS               | Curing Under Stress                                     |
| EC                | Electrical Conductivity                                 |
| ER                | Evaporation Rate                                        |
| FA                | Fly Ash                                                 |
| FS                | Factor of Safety                                        |
| ICP-AES           | Inductively Coupled Plasma Atomic Emission Spectroscopy |
| LVDT              | Linear Variable Differential Transformer                |
| MIP               | Mercury Intrusion Porosimetry                           |
| OPC               | Ordinary Portland cement                                |
| PE                | Potential Evaporation                                   |

|      |                                    |
|------|------------------------------------|
| PFA  | Pulverized Fly Ash                 |
| PSD  | Pore Size Distribution             |
| PWP  | Pore Water Pressure                |
| RH   | Relative Humidity                  |
| SEM  | Scanning Electron Microscope       |
| ST   | Silica Tailings                    |
| SWCC | Soil Water Characteristic Curve    |
| TGA  | Thermo Gravimetric Analysis        |
| THMC | Thermo Hydro Mechanical Chemical   |
| TP   | Total Pressure                     |
| UCS  | Unconfined Compressive Strength    |
| URF  | Uncemented Rock Fill               |
| USCS | Unified Soil Classification System |
| W/C  | Water to Cement ratio              |
| WRC  | Water Retention Curve              |
| wt%  | Percentage by weight               |
| XRD  | X-Ray Diffraction                  |
| ZnT  | Zinc Tailings                      |

## **Chapter 1: General introduction**

### **1.1. Introduction**

The main processes of mining operations include blasting, crushing, milling ore rock and metal extraction. They produce a large amount of crushed rocks and tailings on the surface which are called mine waste (Ritcey, 2005). The actual worldwide volume of mine waste is difficult to estimate, but for the sake of illustration, a single mine itself can produce over one billion tons of waste during 50 years of operation (Blight, 2010). These mine wastes are problematic because they may contain various dangerous substances, such as heavy/toxic metals, radioactive elements, etc. or generate Acid Mine Drainage (AMD), which can cause serious human health and environmental problems (Lottermoser, 2010).

The mine waste management techniques used on the surface can be classified into tailing dams, densified tailings methods (e.g. thickened tailings disposal, surface paste tailings) and co-disposal technique (mixing of tailings and waste rock). All of these surface disposal methods have their own geotechnical and geo-environmental issues. The most important geotechnical problems associated with the aforementioned methods are tailings dam instability, liquefaction problems of thickened tailings, etc. (Landriault et al., 1997). In addition to the geotechnical problems related to surface deposits, geo-environmental issues such as AMD is still a great concern (Akcil and Koldas, 2006; Coussy et al., 2012).

In this case, recycling of such mine waste has become popular in the mining industries. One approach is to use the mine waste to backfill the underground mined-out void created during extraction processes, which is known as mine stoping. Different materials are used to prepare the backfill recipe, such as hydraulic fills, rockfills and cemented paste backfills (CPB) (Hassani and Archibald, 1998). However, among all of these materials, CPB, which is also called cemented tailings backfill (CTB), a relatively new technology, has been extensively used in several mines around the world, especially in Canada (Fall et al., 2009).

CPB is a mix of milled tailings with a solid percentage between 75% and 85%, binder and water. A binder or a blend of different binders, such as Ordinary Portland cement (OPC), fly ash (FA), or blast furnace slag is used with a percentage (often) between 3 and 7 (wt%). Water (fresh or mine processed) is then added to the mix in order to attain the paste for the required transportability or flow ability (Fall et al., 2005). The main reason for adding binder is to provide the required mechanical strength to the backfill (Kesimal et al., 2005; Fall and Benzaazoua, 2005). The use of CPB technology enables a reduction in the amount of mine waste (tailings) that needs to be stored on

the surface and therefore reduces the associated geo-environmental hazards, such as tailing dam failures and AMD pollution. Moreover, by placing CPB into a mine stope, the CPB acts as ground support for the adjacent pillars to assure the stability and safety of the underground excavation, and maximize mining cycles and productivity. Also, CPB serves as a mucking (trafficked) floor to support the weight of loading equipment (Benzaazoua et al., 2004; Rankin and Sivakugan, 2007; Belem and Benzaazoua, 2008; Simms and Grabinsky, 2009).

## **1.2. Problem statement**

Once placed into an underground mine stope, a CPB structure is simultaneously subjected to thermal (e.g., mine temperature, heat generated by binder hydration), hydraulic (e.g., drained/partial drained/undrained conditions, pore water pressure, suction), mechanical (e.g., rock and overburden stresses, arching effect, filling rate), and chemical (e.g., mixing water made of chemically aggressive mine processing waters, cement reactions, sulphate attacks) coupled processes. These coupled processes will affect the performance properties of CPB, and thus its design. An understanding of these coupled thermo-chemo-hydraulic-mechanical (TCHM) processes and their impacts on CPB performance is crucial for reliably assessing the performance of backfill structures, as well as for their cost-effective design. Knowledge of these THMC coupled processes in backfill material is still very limited. To date, there is no study that addresses these issues.

## **1.3. Objectives of the research**

The main objectives of this research are to develop novel experimental methods and conduct experimental investigations to provide fundamental and advanced knowledge on the THMC processes that occur in CPB and their effects on CPB behaviour and performance properties. This will contribute to significantly improve the understanding of the behaviour of CPB and a better engineering design of CPB structures. The specific objectives of the research are summarized below.

- \* To provide background information on CPB and their performance properties, binder hydration and THMC coupled processes in porous media;**

- \* To develop an advanced column experimental setup and methods to study the THMC coupled processes in CPB and their effects on the properties of CPB from early to advanced ages;**

- \* To develop a novel THMC pressure cell apparatus, which enables the curing of CPB samples under different conditions that are close to those encountered in the field (e.g., stress due to the self-weight of CPB, filling rate, drainage, tailings types, mixing water chemistry,**

etc.), as well as to monitor the THMC behaviour of CPB under these various loading conditions;

- \* To study the THMC behaviour of CPB at early ages by using the developed THMC pressure cell apparatus;

- \* To elucidate the THMC behaviour of CPB at advanced ages by using the THMC pressure cell apparatus; and

- \* To provide recommendations for a better geotechnical design of CPB structures.

#### **1.4. Research approach and methods**

The THMC properties and behaviour of CPB have been experimentally studied to achieve the objectives of this study. Two types of approaches are used to investigate the THMC coupled processes: (i) studying the THMC behaviour and properties of CPB in column experiments, and (ii) studying the THMC behaviour and properties of CPB by using a THMC pressure cell apparatus, especially developed for this purpose (Figure 1.1).

Two types of experimental setups are engineered and manufactured for these purposes including an experiment with high columns and a THMC curing pressure cell. In the first phase of the study with the column experiments, the THMC coupled processes were investigated as a function of curing time and height of the column. In the second phase of the study, the THMC coupled processes were studied with respect to curing stress and time, filling rate and sequence, and drainage conditions.

In the column experiments, five high columns are built, which include one column for monitoring purposes and four columns for curing the CPB test samples at different curing times of 7, 28, 90 and 150 days. The samples are taken from different heights of the columns and then subjected to different testing, including thermal (T), such as to determine the thermal conductivity; hydraulic (H), such as to determine the saturated hydraulic conductivity and water retention; mechanical (M), such as to determine unconfined compressive strength and shear strength properties; and chemical (C), such as to determine pore fluid chemistry. All of the experiments are conducted in accordance with the latest version of the ASTM (American Society for Testing and Materials) standards.

In the THMC studies which use the THMC pressure cell apparatus, all of the above mentioned THMC laboratory testing are conducted on samples that have been cured at early ages (i.e., 1, 3 and 7 days of curing), as well as at advanced ages (up to 150 days), under different curing conditions. Furthermore, the THMC evolution of the CPB samples is monitored up to 150 days. The obtained experimental results allow fundamental knowledge to be gained about the THMC behaviour of CPB, as well as a better understanding of the impact of the THMC processes on CPB performance.

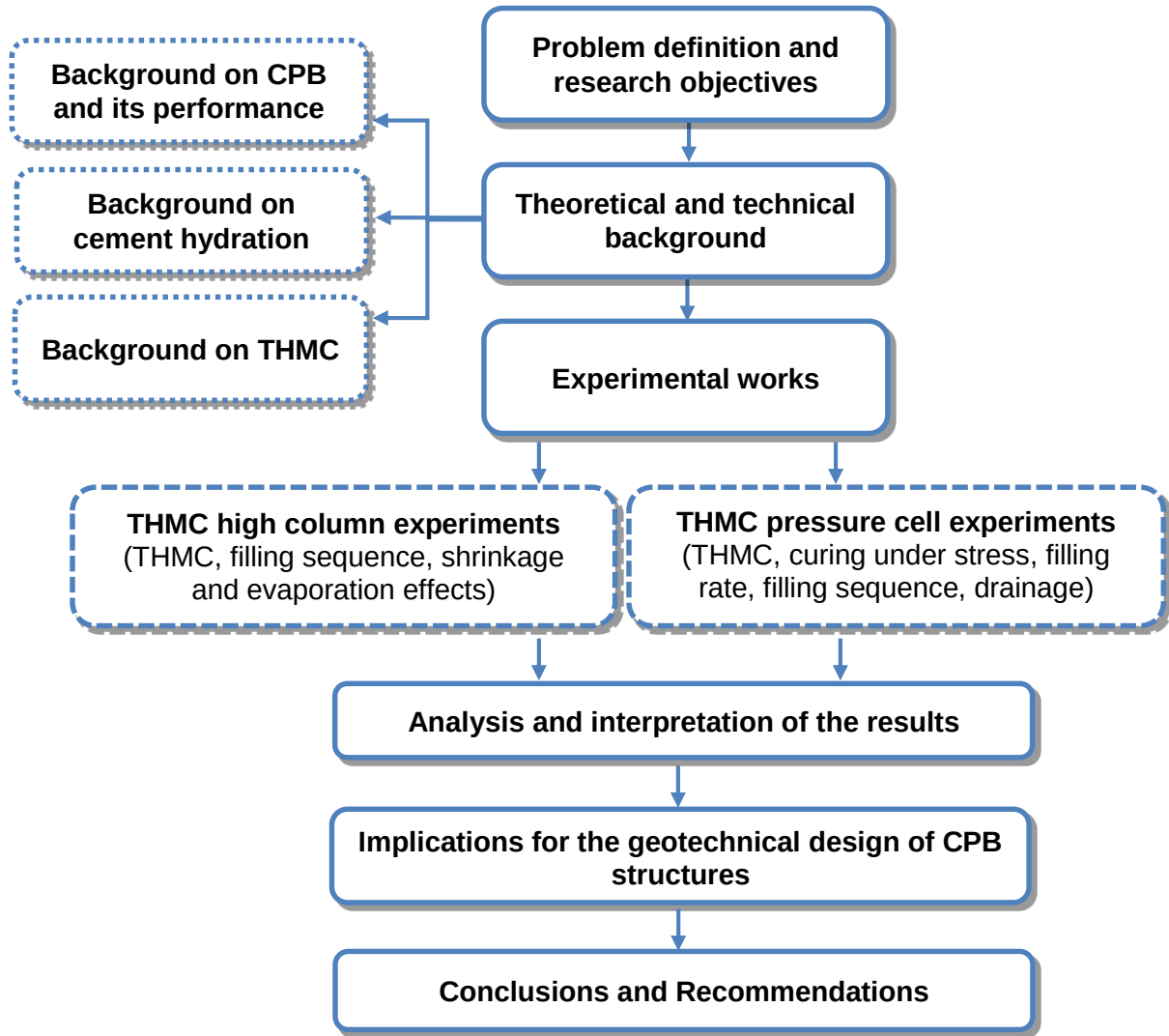


Figure 1.1. Research and study approach

## 1.5. Tasks and organization of the thesis

The thesis is organized into seven chapters that contain discussions of the different tasks and objectives of the current PhD research. Figure 1.2 presents the structure of the main tasks that have been carried out. **Chapter One** is a general introduction, which contains problem statements, objectives, and research methods employed in this research. **Chapter Two** is structured to provide a comprehensive literature review and/or background information on CPB technique and performance, binder hydration and THMC coupled processes in porous media. Chapters **Three to Five** are structured into a manuscript based thesis format, which comprises five technical manuscript; therefore, each technical paper includes an introduction, sections on the material and methods,

experimental results and discussion, and a conclusion. It should be noted that because the main results of the chapters are presented as technical manuscript, some information is repeated in the papers. This is because each paper is independently written (i.e., without taking into account the content of the other papers or the rest of the document) and in accordance with the manuscript preparation instructions of the corresponding publication medium. **Chapter Three includes two research manuscripts (Technical Papers I and II).** The chapter deals with the long term THMC coupled processes in CPB through experiments with high columns in terms of curing time and height of the columns. Also, the effect of the filling sequence and surface evaporation on the THMC performance of backfill materials is assessed.

**Chapter Four contains two research manuscripts (Technical Papers III and IV)** in which the THMC coupled processes in CPB material at early ages are studied by using a developed THMC cell pressure. In Technical Paper III, the THMC behaviour of CPB cured in a pressure cell under different applied stresses is investigated to address the effect of pressure due to the self-weight of backfill on its THMC behaviour and properties. The work provides information to improve the current backfill design approach which is mostly based on mechanical strength measurements. The mechanical properties of CPB are obtained by conducting unconfined compressive strength (UCS) testing on CPB samples prepared by a conventional curing method (by using plastic moulds). In this study, CPB samples are cured under controlled stress to simulate underground curing conditions which can be a rational assessment of the in-situ conditions. Furthermore, the research work provides comprehensive knowledge on the THMC behaviour of CPB materials that help practitioners to deliver cost-effective and site-specific mine stope designs. In Technical Paper IV, by using a THMC cell apparatus, different filling rates and sequences, and drainage conditions are employed to assess the effect of these factors on strength evolution and deformation behaviour of CPB at early ages.

**In Chapter Five,** the long term THMC coupled processes that occur in CPB cured in a THMC cell is examined (**Technical Paper V**). **Chapter Six** contains a section that provides the implications of the conducted THMC studies on the geotechnical design of CPB structures. **Chapter Seven** presents the summary, conclusions and directions for future research.

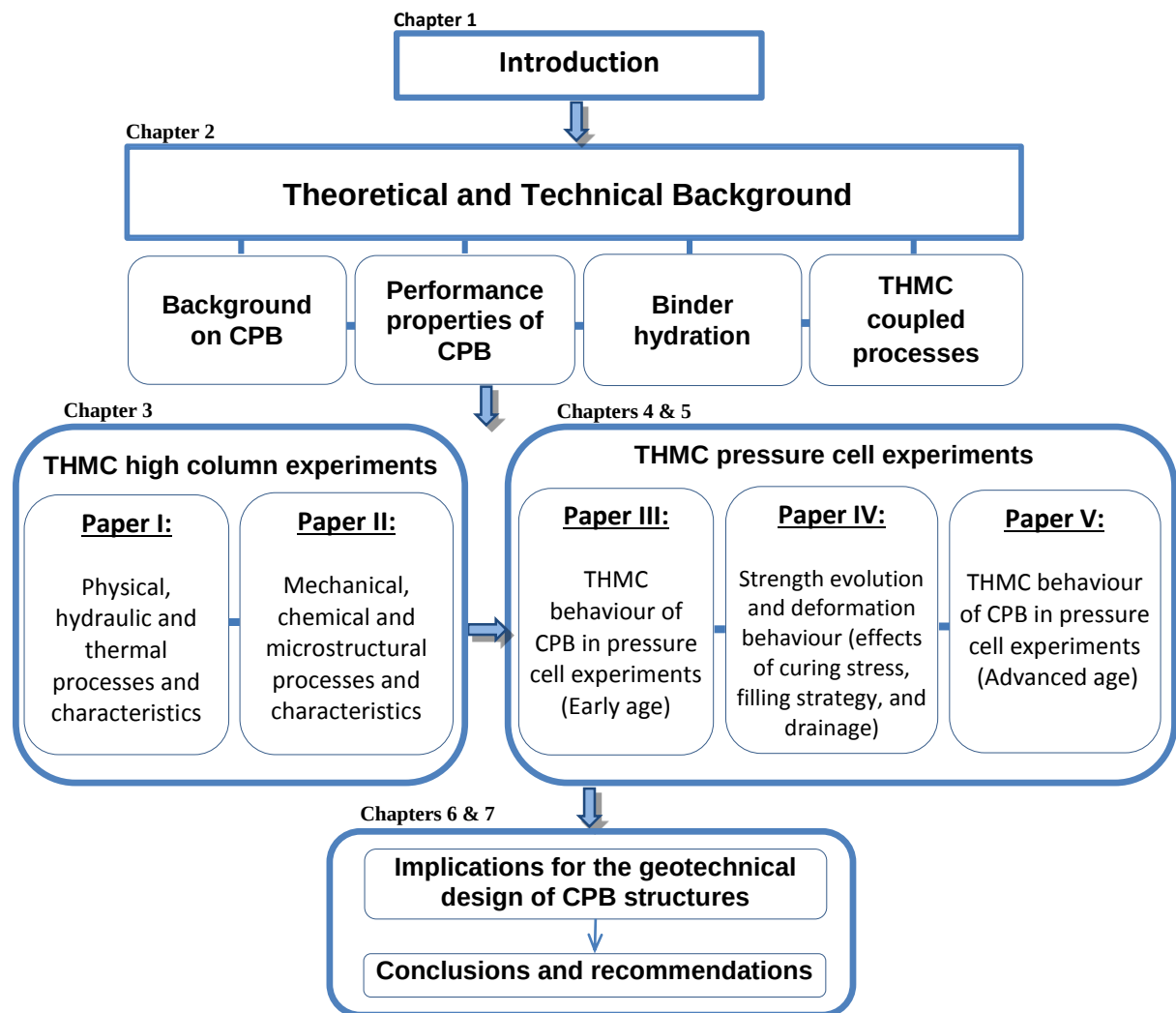


**Figure 1.2. Tasks and organization of the thesis**

## 1.6. Statement of Authorship

| Title of Papers                                                                                                                                                                                | Publication Status | Publication Details                                                                                                                                   |
|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|--------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------|
| Technical Paper I: Coupled Thermo-Hydro-Mechanical-Chemical Behaviour of Cemented Paste Backfill in Column Experiments. Part I: Physical, hydraulic and thermal processes and characteristics  | Published          | Engineering Geology (2013), 164: 195–207                                                                                                              |
| Technical Paper II: Coupled Thermo-Hydro-Mechanical-Chemical Behaviour of Cemented Paste Backfill in Column Experiments. Part II: Mechanical and Microstructural Processes and Characteristics | Published          | Engineering Geology (2014), 170: 11-23                                                                                                                |
| Technical Paper III: Coupled Behaviour of Cemented Paste Backfill at Early Ages                                                                                                                | Published          | Geotechnical and Geological Engineering (2015), 33(5): 1141-1166                                                                                      |
| Technical Paper VI: Strength Evolution and Deformation Behaviour of Cemented Paste Backfill at Early Ages: Effect of Curing Stress, Filling Strategy and Drainage                              | In Press           | International Journal of Mining Science and Technology                                                                                                |
| Technical Paper V: Long-term Coupled Behaviour of Cemented Paste Backfill in Load Cell Experiments                                                                                             | Published          | Geomechanics and Geoengineering (2016), <a href="http://dx.doi.org/10.1080/17486025.2016.1145256">http://dx.doi.org/10.1080/17486025.2016.1145256</a> |

## Author Contributions

In this Statement of Authorship, author's contribution to the aforementioned publications is specified, as well as the permission is granted for the publications to be included in the candidate's PhD thesis.

|                              |                                                                                                                                           |
|------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------|
| Name of the principal Author | Alireza Ghirian                                                                                                                           |
| Contribution to the paper    | Developed testing equipment, Performed required tests on the samples; analysed and interpreted data; wrote first draft of the manuscript. |

|                           |                                                                                                                                                                          |
|---------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Name of Co-Author         | Mamadou Fall                                                                                                                                                             |
| Contribution to the paper | Supervised development of the research; provided significant help in data analysis and interpretation, manuscript writing and evaluation; acted as corresponding author. |

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## **Chapter 2: Theoretical and Technical Background**

### **2.1. Introduction**

In this chapter, a review of the fundamental theoretical and technical background information on mine backfill is provided. This information is required for a better understanding of the investigations performed on CPB. Following the introduction in Section One, background information on mine backfill materials and technology is provided in Section Two.

In the third Section, the current knowledge on the main properties of CPB materials is reviewed and discussed. These properties include thermal, hydraulic, mechanical and chemical properties of backfill materials and the factors that can affect them. In the fourth Section, a general review on cement hydration is provided. In CPB, a certain amount of binder should be added to provide mechanical strength. Binder hydration is one of the important factors that can significantly control the behaviour of CPB. Therefore, knowledge on the binder hydration is required to better understand the THMC coupled processes in CPB and the results of this research. Finally, in Section five, background information on THMC coupled processes in porous media is provided. This will help to provide a better understanding of the results presented in this research.

### **2.2. Background information on mine backfills**

The main consequence of underground mining activities is the production of large amounts of waste on the surface. Also, underground mining activities can result in the creation of huge underground space known as “stopes”, which can lead to mining area instability. Only a small amount of mined-out materials that contain valuable minerals, are suitable for use and therefore, the remaining materials on the surface are mine waste (Nasir and Fall, 2009). Several mining extraction methods can be employed, such as cut-and-filling, drift-and-filling, and undercut-and-filling. The primary-secondary stope-pillar sequence is one of the most economical extraction sequence. It can be used in conjunction with mass blasting techniques and cemented backfill. As illustrated in Figure 2.1, ore bodies are mined from primary stopes by a series of carefully controlled production blasts. Then, extracted materials are removed from drawpoints, located at the bottom of the stopes, until all of the ore is mined. Then, mining of the secondary stopes commence in a similar way, while primary mined-out stopes are backfilled (Villaescusa, 2003). Before backfill is poured into the stope through pipelines or boreholes, a barricade (also named as bulkhead) must be constructed at the end of the drawpoint. Barricades are a retaining wall (or a barrier), which can be made of bricks, rocks, masonry, shotcrete or concrete (Rankine et al., 2006). The role of barricades is to maintain fresh CPB

in the mine stope, and they must be stable during and after the operations (Li et al., 2009) (see Figure 2.1).

Mine backfills can be used as (1) a mine waste disposal method, (2) a ground support technique, (3) a mucking floor to support heavy equipment, and (4) a construction material. The primary source of material for mine backfills is provided from mill tailings and waste rock from underground or open pit mining. However, supplementary sources such as alluvial deposits and quarried rock can be considered as well (Belem and Banzaazoua, 2008). The application of mine backfill in underground mining has significantly increased. This has resulted in a reduction of the use of conventional surface mine waste disposal techniques (e.g., tailings ponds and other types of surface impoundments), which have significant negative impacts on the environment in terms of surface water and groundwater contamination, and acid generated from tailings/waste (AMD) (Landriault, 2001).

Underground backfill was introduced in the mining industry in the early 1930s, when Noranda's Home Mine in Canada mixed furnace slag with tailings to consolidate the backfills poured into mine stopes (Patton, 1952). Later in the late 1940s, slurry fills were applied in many North American mines as unconsolidated backfill; however, low drainage and difficulties in mining the pillars between the old filled stopes remained a problem. In the early 1960s, some of the mines started to add a small amount of cement to tailings to improve the backfill performance, while using new mining methods such as cut-and-filling and undercut-and-filling to speed up the mining cycles. These innovations allowed the application of new forms of fills, such as cemented rock-fill, and the use of slag and fly ash in addition to cement (Landriault, 2001).

In the early 1980s, CPB, which is currently used in many mining operations around the world, was developed in Preiessage's Bad Grund Mine in Germany. This material allowed high solid content paste to be transported through boreholes/pipelines into mine stopes. CPB has a lower binder content and water/cement ( $w/c$ ) ratio compared to other types of backfills. However, it cannot be commonly placed underground without a binder which is same as classified tailings, or rock-fill that can be placed with or without a binder (Landriault, 2001).

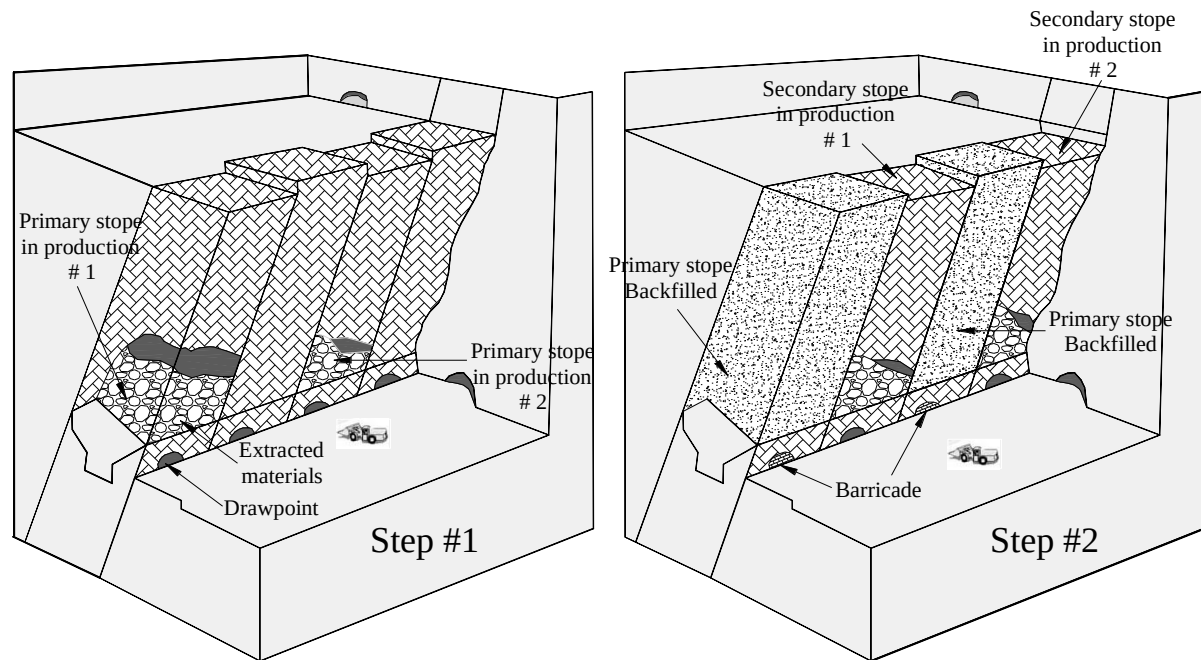


**Figure 2.1. Primary-secondary mining sequence (source: Hamrin, 2001)**

### **2.2.1 Background information on different types of mine backfills**

Mine backfills are typically classified into three main types: rock fill, hydraulic fill (slurry backfill) and paste fill (or paste backfill). The selection among these three types depends on several factors, including geometry/depth/orientation/grade of the ore bodies, mining method, stope sequence and size, available filling materials, and operational costs (Landriault, 2001). The average grain size distribution of the three main types of backfills is presented in Figure 2.2.

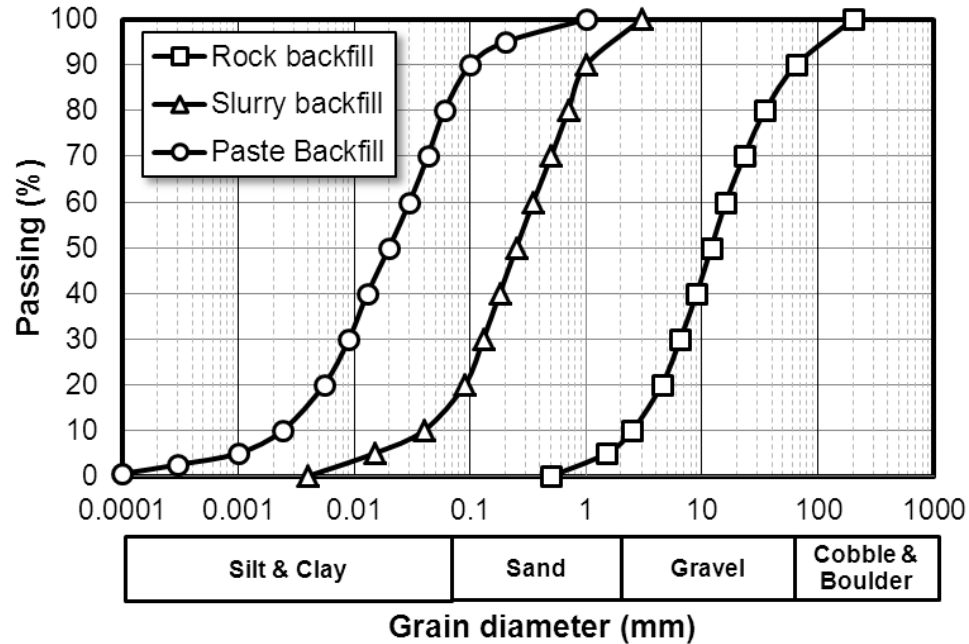


**Figure 2.2. Average grain size distribution of three types of backfills (source: Landriault, 2001)**

#### **2.2.1.1. Rock Backfill**

Rock fill is a mixture of waste rock, tailings/or unclassified sand. The main requirement of rock backfilling is the availability of waste rock at mine sites. Therefore, it is a good method for managing mine wastes in underground mining. Also, simple preparation, high strength and no stope dewatering are the main advantages of this type of backfilling. Rock fill can be used as cemented (CRF) or uncemented (URF) material. Typically 4% to 8% cement is added to strengthen rock fill. Cement paste can be added through pipelines and mixed with waste rock before placement. The required strength ranges from 0.2 to 4.0 MPa and it is a function of stope size, mining technique and stope recovery time (Hassani and Archibald, 1998; Stone, 2007). It is difficult to control the segregation and achieve a good quality control (Belem and Benzaazoua, 2008; Hassani and Archibald, 1998). Factors such as grain size distribution, binder content, rock type, placement method, segregation, and water to cement ratio control the CRF strength (Henderson et al., 1998; Chen et al., 2004). Also, rock crushing, transportation and the need for fine materials to be used as filler in rock backfilling result in high costs when using this method. The employing of a proper placement method and control of moisture content can reduce the segregation potential (Landriault et al., 1997; 2001).

#### **2.2.1.2. Hydraulic Backfill**

Slurry backfill or hydraulic backfill is a material that is highly permeable and has low solid density. It normally includes tailings, sand and/or rock materials that can be mixed with a small percentage of cement and water. Hydraulic backfill can be prepared on the surface or underground and transported through borehole/pipeline distribution systems through the hydraulic head generated by gravity. To facilitate the removal of excess water, perforated drainage pipes are installed in mine stopes. The main advantages of this backfilling method are simplicity of installation and operation, ease in supervision, ease of quality control, availability of solid parts as mine waste and reduction in surface waste disposal (Hassani and Archibald, 1998). Disadvantages of this backfilling method are the high amount of excess water, segregation of cement from the solid phase and cement washout (Landriault et al., 1997; Hassani and Archibald, 1998; Landriault, 2001).

#### **2.2.1.3. Paste Backfill**

Paste backfill, which is also known as CPB, is an uniform and low permeability mixture which has high solid density (commonly between 75% and 85% by weight) compared to other backfill types. The solids are typically milled tailings. The binding agent and water are added in a CPB plant located at the surface of the mine or underground. The fresh CPB is transported to the underground stope through pipelines. Paste backfill particles do not separate into two different phases (water and tailings) at static conditions because colloidal electrical charges can retain all of the water between the particles. Therefore, at least 15% of the particles are required to be finer than 20 microns in the backfill preparation (Grice, 2001; Landriault, 2001). Chemical content and mineralogical composition of the tailings also affect the colloidal properties. This unique requirement reduces the water needed for transportation. After placement, the excess water is often consumed by cement hydration reactions and therefore dewatering is mostly not required (Landriault, 2001).

Short stope cycles due to earlier development of mechanical strength, optimization of ore recovery, and increase in the safety of mine workers are the main advantages in the use of this material. The disadvantages are high-pressure pipeline systems needed to deliver the materials, need for supervision and high quality control (Hassani and Archibald, 1998; Landriault, 2001).

### **2.2.2. Cemented Paste Backfill Technology**

#### **2.2.2.1. Mix design**

The optimization of CPB mix designs is important to minimize cement consumption and achieve the required strength. Furthermore, the most important factors that can affect the CPB

performance in terms of cost and transportability (slump) include cement content, tailings fineness,  $W/C$  ratio, and tailings density (Fall et al., 2008). Of the total mine operating costs, 10% to 20% consist of backfill costs, with cement itself making up 80% of the backfill costs. This means an increase in cement content can considerably increase the cost of CPB (Grice, 1998).

Ordinary Portland cement (OPC) and blast furnace slag are two principal binding agents that are commonly used in the Canadian mining industry. Other types of binders, such as pozzolans, non-ferrous slag and fly ash (FA) may also be used. However, OPC is a popular choice at most mine sites due to its high availability (Landriault et al., 1997). Water is required for cement hydration reactions, as well as to provide the required consistency to transport the backfill to underground (Benzaazoua et al., 2004). If chemicals are found in water, such as zinc, lead, sulphate, or other factors, such as a low pH, these can considerably alter the short-term and long-term backfill strength (depending on the available concentration). Therefore, water chemistry analysis is needed prior to usage (Benzaazoua et al., 2002).

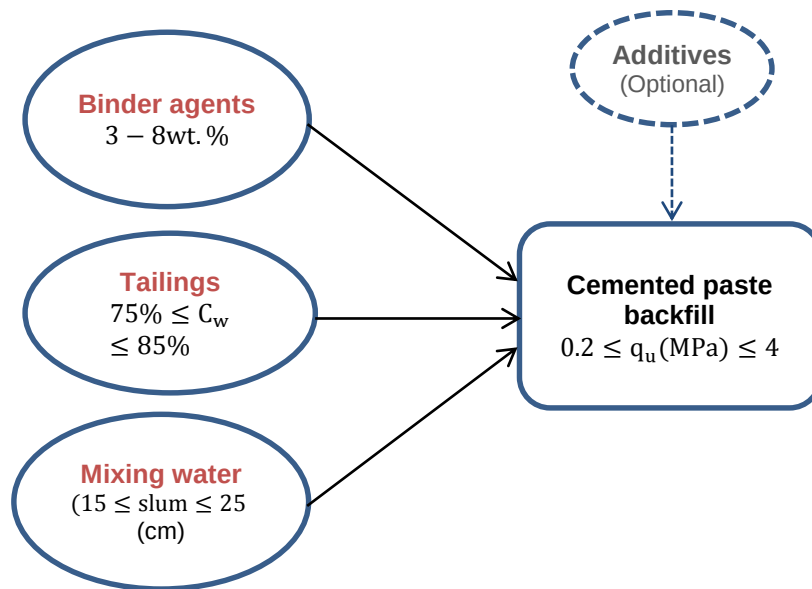


**Figure 2.3. Schematic diagram of various paste backfill components with typical portions**

#### 2.2.2.2. Backfill preparation

Mine tailings obtained from milling processes have a solid concentration, which varies between 35% and 60%. In order to use mine tailings in CPB preparation, the tailings are required to be dewatered to increase the solid percentage to more than 75%. The tailings pass through different processes (equipment and materials), including high-capacity thickeners, disk filters, and gravity settling tanks in order to densify mill tailings into filter cakes. Then, the filter cakes are sent to a spiral (or screw) mixer, where binder and water are added to the mixture to produce CPB with a

particular consistency (slump). Once the CPB is prepared, it is transported (by gravity or through pumping) into the stope through an underground distribution system (Landriault et al., 1997). A typical layout of cemented paste backfill system is shown in Figure 2.4.

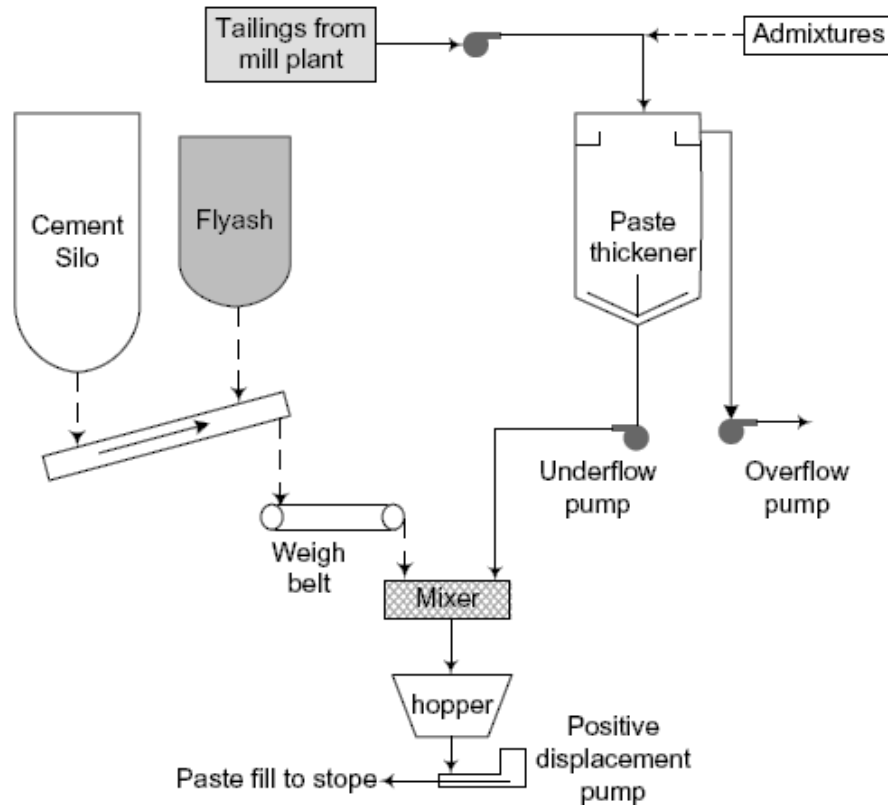


**Figure 2.4. Typical layout of cemented paste backfill plant (Slotte, 2004)**

### 2.2.2.3. Transportation and delivery system

The transportation of paste backfill through a delivery system depends on its rheological behaviour. CPB is a non-Newtonian fluid and therefore to commence the flow through a pipeline system, the applied stress should be greater than the yield stress. In order to determine the rheological properties of fresh CPB, both shear yield stress and viscosity should be measured. A simple way which is commonly practiced in the mining industry is to determine CPB consistency by using slump tests. Then, the slump value should be correlated to the yield stress and viscosity (rheological parameters) in order to calculate the applied pressure gradient. It should be noted that different factors can affect the slump value such as cement content, binder type, temperature and elapsed time after preparation (Wu et al., 2013). Based on the mine's distribution system (e.g., gravity, pumping, etc.), paste flow-loop tests are required to estimate the friction head loss in order to calculate the maximum horizontal distance for gravity driven paste flow (Belem and Benzaazoua, 2008). However,

several intrinsic factors can also influence the rheological properties of paste backfill, such as tailings grain size distribution, fine particle content, and chemical and mineralogical compositions. Furthermore, to optimize the delivery systems, there needs to be a balance among the velocity, relative density and pipe diameter (Landriault et al., 1997).

#### **2.2.2.4. Rate of Backfilling**

The rate of backfilling is the rate at which the backfill materials are poured into the stope. This rate can be different from one mine to another or one stope to another (Nasir and Fall, 2010). The filling rate can be expressed by the volume ( $\text{m}^3/\text{h}$ ), or height of the stope ( $\text{m}/\text{h}$ ). It is mostly determined based on several factors such as allowable barricade pressure, backfill setting time (hydration processes), binder content and arching effect. Fast filling rates can increase the mining cycles which in turn can increase production. However, fast backfilling rates and low binder content can result in high barricade pressure which can increase the risk of the barricade failure (Thompson et al., 2012). A practical method to control the pressure on barricades is the application of staged pouring. In this method, backfill is poured in two stages. Plug pour (typically with high binder content) is poured to partially fill the stope in order to plug the barricade, and this is followed by a curing period (break period) between 1 and 7 days depending on the hardening of the backfill. Afterwards, the main pour (typically with low binder content) is continually backfilled into the stope (Abdul-Hussain and Fall, 2012). In-situ monitoring shows that staged backfilling can considerably reduce the barricade pressure (Yumlu, 2008).

#### **2.2.2.5. Geotechnical design of CPB structures**

The hardening process and strength gain in CPB structures can commence when it transforms from a hydraulic paste to a solid state (hardened backfill). CPB can gain strength through a combination of different factors, such as cement hydration, self-desiccation (suction), consolidation as a result of the pressure due to self-weight and the influence of ambient relative humidity (RH) (Galaa et al., 2011). Due to differences in stiffness and yielding characteristics between the backfill and surrounding rock mass, part of the stress inside the backfill is transferred to the adjacent rock walls, which is known as the arching effect (Figure 2.5). The result is that the vertical stress below the arching area becomes smaller than the backfill overburden pressure ( $\sigma_v < \gamma h$ ) (Li et al., 2003).

To maintain the resultant field stresses, backfill should satisfy certain static and dynamic design requirements depending on the intended function (Rankine and Sivakugan, 2007). Some important static stability requirements include that CPB must (1) be free-standing when vertical faces are exposed; (2) support the load of equipment when used as working platform; (3) support the

surrounding rock walls against failure and sloughing; (4) remain stable during undercut mining; (5) remain stable during development of openings; and (6) gain early age mechanical strength. The main dynamic design requirement is to be stable against liquefaction and other failure modes in the event of blasting and seismic loadings (Grice and Bloss, 2001). The main design criterion of backfill is to meet a specified unconfined compressive strength value. In general, the required UCS in a typical mine stope is commonly lower than 5 MPa which ranges from 0.2 to 4 MPa (e.g., Grice 1998; Revell 2000). The conventional design approach is to examine the backfill against possible failure modes, such as bending failure, block sliding, and rotational failure at the hangingwall contact, and sloughing of the wall rock (Landriault et al., 2001). Furthermore, the following factors should be taken into consideration for mine stope design:

- Barricade design: type of structure, design loads, structure dimensions;
- Filling strategy: necessity of initial plug in order to protect the barricade against hydrostatic pressures, curing time of plug, and rate of filling to minimize the barricade failure; and
- Backfill curing time: to ensure that fill does not fail under blasting forces, or the liquefaction potential of CPB (Grabinsky and Bawden, 2007).

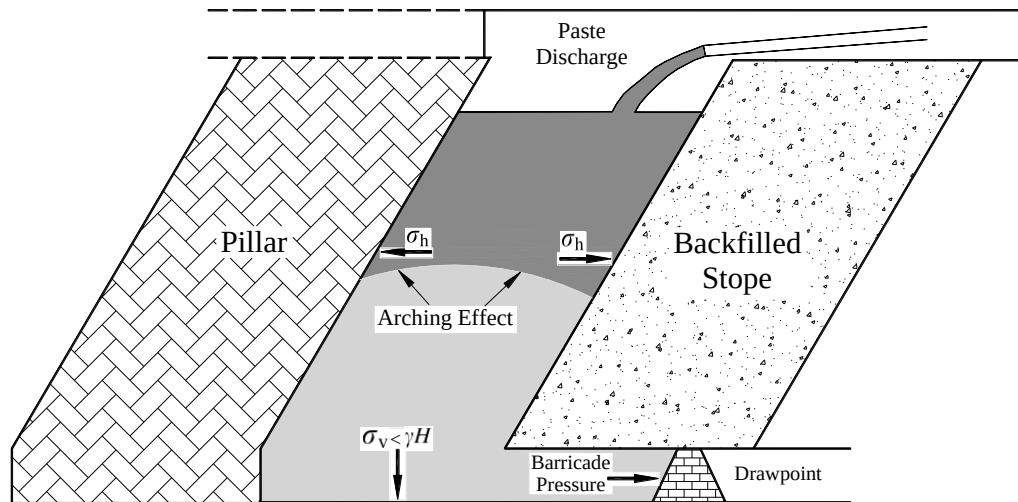


**Figure 2.5. Schematic diagram of backfilled and stress distribution (source: Belem & Benzaazoua, 2008)**

### **2.3. Properties of CPB**

In this section, a comprehensive literature review on the current knowledge of the thermal, hydraulic, mechanical and chemical properties of CPB and factors that affect them is provided.

### **2.3.1. Physical properties of CPB**

The strength and performance of CPB are influenced by its physical properties, such as porosity (or void ratio), unit weight, water content and degree of saturation. There is a need to study the physical properties of CPB in order to understand the main THMC processes that take place during its hardening process. The physical properties of CPB have been reported by previous authors based on laboratory and field investigations. However, the in-situ physical properties of CPB have been rarely reported in the literature, and available data are mostly related to laboratory tests. This is mainly due to the difficulties related to in-situ sampling and testing such as lack of access to backfilled stopes and safety issues (le Roux et al., 2002).

Field results obtained by le Roux et al. (2005) (including a summary of the results obtained by Pierce (1997) showed that there are variations in the physical properties inside a mine backfill, mostly due to reasons such as preparation and placement techniques, stress regime, tailings and cement properties, etc. They reported that at 90 days of curing, the void ratio ranges between 1.10 and 1.40, unit weight from 18.40 to 20.10 kN/m<sup>2</sup>, and degree of saturation between 79% and 100%. Also, they compared field and laboratory results obtained from tests conducted on the same CPB mix. They found that the in-situ void ratio and degree of saturation had values that are on average 20% higher and 10% lower respectively, compared to the laboratory results.

Laboratory investigations carried out by Belem et al. (2006) who used column experiments on 91 day CPB samples showed that the void ratio ranges between 0.85 and 0.97 and degree of saturation between 83% and 94% in the undrained condition. In the drained column, the void ratio ranges from 0.77 to 0.91 and degree of saturation varies between 75% and 93% depending on the location in the height of the column.

Yilmaz et al. (2009) investigated the variation of physical properties with respect to binder content (3, 4.5, 7 and 10%), for unconsolidated and consolidated 28 day CPB samples. They reported that for unconsolidated samples prepared with OPC, the porosity range from 0.42 to 0.47, degree of saturation ranges between 90% and 97% and gravimetric water content varies from 38% to 46%. For consolidated samples (cured under pressure) the porosity ranges from 0.41 to 0.45, degree of saturation ranges between 80% and 94% and gravimetric water content differs from 33% to 42%. The review in this research showed that the physical properties (porosity, void ratio, degree of saturation, unit weight) of CPB decreases as cement content increases due to the effect of desaturation as a result of cement hydration (in unconsolidated samples). Also, a comparison between the unconsolidated and consolidated tests showed that the drainage due to consolidation reduces the values of the physical properties. Recently Yilmaz et al. (2014) studied the physical properties of CPB samples prepared with a blend of Slag-Portland cement (3, 4.5 and 7%) with respect to curing times of 7, 14

and 28 days and different drainage conditions (drained, undrained and consolidated). They found that the gravimetric water content of these samples varies from 13% to 25%, degree of saturation differs from 67% to 98% and void ratio varies between 0.59 and 0.8. A comparison of the above findings showed that factors such as curing time, drainage and consolidation affect the physical properties of CPB at the laboratory scale. The obtained results from both field and laboratory testing showed that the physical properties of CPB are widely different from one mine to another. Also, they are variable with respect to the height of the backfill. These variations can be due to tailings types, field conditions and placement or the THMC processes that occur in CPB and to which the CPB is subjected in field curing conditions. The conducted literature review showed that despite the significant contributions of these studies to better understand the physical properties of CPB, none of the previous studies have investigated the impact of THMC processes on the physical properties of CPB and their evolution. Also, the early and advanced age evolution of the physical properties have not been addressed in the previous literature. Furthermore, there is limited knowledge on the relationship between physical properties and hydro-mechanical behaviour of CPB, such as mechanical strength and hydraulic properties.

### **2.3.2. Mechanical properties of CPB and factors that can affect them**

Mechanical stability is one of the most important design criteria for hardened cemented paste backfill (Fall et al., 2007). The most common and direct method to determine the mechanical strength of backfill materials is to measure its UCS (Belem et al., 2002). Other methods such direct shear test (e.g., Fall and Nasir, 2010), and triaxial test are also used to determine the shear strength properties and stress-strain behaviour of backfill (e.g., le Roux et al., 2005; Rankine and Sivakugan, 2007; Simms and Grabinsky, 2009). In addition, different indirect methods have been recently used to assess the CPB mechanical strength, such as ultrasonic wave measurements, thermal profiling and shear wave velocity (e.g., Mozaffaridana, 2011; Klein and Simon, 2013; Ercikdi et al., 2014). This information is required to perform stability analysis on CPB structures, especially backfilled stopes with an exposed (unsupported) face (Mitchell et al., 1982; Li and Aubertin, 2012; Li, 2014).

Previous investigations (i.e., le Roux et al., 2005; Rankine and Sivakugan, 2007; Veenstra 2013) on the shear strength parameters of backfill showed different values of the friction angle ( $\phi$ ) with respect to curing time. For example, Rankine and Sivakugan (2007) conducted triaxial consolidated drained (CD) tests and reported that the friction angle is slightly reduced from  $38^\circ$  at 14 days to  $37.9^\circ$  at 28 days and from  $35.7^\circ$  at 14 days to  $32.7^\circ$  at 28 days for CPB samples with 2% and 6% binder, respectively. Pierce (1997) reported that cohesion significantly increases when binder content and curing time increase. On the other hand, the  $\phi$  decreases when curing time increases. le

Roux et al. (2005) conducted triaxial tests and reported that the friction angle ranges between 32° and 37° for an undisturbed block of CPB sample at 90 days. Recent studies conducted by Veenstra (2013) showed that the friction angle is reduced when curing time is increased. Different tailings grain size (from clayey silt to fine sand) and different binder content were tested. The typical obtained values ranged on average from 38° to 43° at 1 day, and from 23° to 36° at 7 days of curing.

A review of the previous literatures shows that there is a slight decrease in the friction angle with curing time. This reason is not well understood, but most likely can be attributed to different mechanisms, such as chemical processes related to cement hydration reactions, oxidation of mine backfill (weathering), self-desiccation, drainage, in-situ stress and presence of air voids in the backfill (Rankine, 2004; Rankine and Sivakugan, 2007).

However, cohesion ( $c$ ) is a time dependent factor and can reach up to 1500 kPa at advanced ages, depending on the binder type and content, solid content and curing time (Belem et al., 2000). Veenstra (2013) reported that  $c$  increases when cement content is increased. He found that  $c$  ranges from 40 to 130 kPa at 7 days and from 240 to 680 kPa at 21 days for the studied materials.

Previous studies on CPB mechanical strength showed that UCS values mostly vary between 0.2 and 4 MPa (Klein and Simon, 2006; Belem and Benzaazoua, 2008; Pokharel and Fall, 2011; Peyronnard and Benzaazoua, 2011; Cihangir et al. 2012; Ercikdi et al., 2014). Short-term and long-term mechanical strength can be significantly affected by variation of several factors. Tailings characteristics, including mineralogy, chemical content (e.g., sulphide-rich tailings), fineness and density can affect strength development (Fall et al., 2005; Kesimal et al., 2005). The presence of sulphide minerals, as well as soluble sulphates has a harmful effect on the CPB strength due to sulphate attacks (Benzaazoua et al., 2002; Kesimal et al., 2004). Fall et al. (2005) reported that increasing tailings fineness (particles  $< 20 \mu m$ ) to more than approximately 55% can reduce the UCS due to deleterious effects on porosity and pore size distribution. Also, higher tailings density can lead to higher binder consumption which generally provides a higher strength to the CPB (Fall et al., 2004). Yilmaz et al. (2009) reported that curing stress has a significant impact on the UCS of CPB.

Binder properties, such as binder type and content, and the chemical characteristics of binders (e.g., soluble sulphate concentration) are one of the most important factors that can influence CPB strength. Higher binder content generally produces higher strength (Benzaazoua et al., 2004). Furthermore, binder type (i.e., ordinary Portland cement (OPC), Slag, Fly ash (FA) or their combination) can deliver different strength to CPB. Benzaazoua et al. (2002) found that OPC and FA/OPC mixture are appropriate for high sulphate-rich tailings in terms of compressive strength.

Mixing water properties and contents including chemical concentration (e.g., sulphate content) and water to binder ratio can affect the strength acquisition process. Water chemistry can alter the

cement chemistry and hydration processes. It can affect the formation of the primary and secondary cement hydration products which are responsible for backfill strengthening (Benzaazoua et al., 2002). Furthermore, increase in the  $w/c$  ratio as the main factor in mixing can considerably decrease the strength values.

Previous studies (e.g., Fall and Samb, 2006; Fall et al., 2007; Fall et al., 2010) have revealed that the curing temperature significantly influences the short-term and long-term mechanical strength and pore structure of CPB materials. The coupled effect of curing temperature and sulphate significantly affects the strength of CPB. This effect can be positive (strength increase) or negative (strength decrease) depending on the initial amount of sulphate content, the curing temperature, and type of binder (Fall and Pokharel, 2010). Furthermore, increase in curing temperature up to a certain value (e.g., 50°C) can increase the compressive and tensile strength, as well as the elastic modulus, and affects the stress–strain behaviour (Fall and Samb, 2008). It can also reduce fluid transportability (Fall et al., 2009). However, the magnitude of the effects depends on the binder content and curing time (Orejarena and Fall, 2008).

The literature review presented above shows that the majority of the previous research work are conducted on the mechanical behaviour of backfill and the factors that can affect such behaviour. However, most of them have only focused on the isolated effect of one influencing factor (e.g., temperature, water chemistry, tailings, binder) on the mechanical properties (particularly, UCS) of CPB. Moreover, deformation behaviour (settlement, shrinkage, stress-strain behaviour, etc.) of CPB is mostly ignored. To date, no studies on the impact of the THMC processes that occur in CPB in terms of its mechanical properties and behaviour have been reported. Also, there are no previous studies (except for the preliminary work of Simms and Grabinsky, 2009) that have investigated the effect of the unsaturated state (i.e., suction development due to self-desiccation, desaturation, etc.) on the mechanical and shear strength properties of CPB. Finally, there is a lack of knowledge of the evolution of the shear strength properties (especially friction angle) with curing time. Therefore, there is a need to address these issues for the cost-effective design of CPB.

### **2.3.3. Hydraulic properties of CPB and factors that can affect them**

The main hydraulic properties or behaviour of CPB include pore water pressure (positive or negative) and hydraulic conductivity (saturated and unsaturated). An understanding of the development and evolution of positive and negative (suction) pore water pressure in CPB is essential for the assessment of the mechanical behaviour and stability of CPB at early and advanced ages, liquefaction potential of CPB, stability of barricades, as well as to quantify the deformation behaviour and stress distribution within the CPB. Pore water pressures that develop within CPB influence the

magnitude of the effective stresses. The principle of effective stress is one of the most important concepts of soil mechanics. This effective stress has a considerable impact on the behaviour of porous media, such as soil, CPB and rocks.

Experimental measurements of the evolution of pore water pressure in CPB have been rarely addressed in previous literature. Helinski (2007) conducted centrifuge experiments to investigate the interaction of consolidation, pore pressure change (due to cement hydration) and total stress. Despite that the apparatus monitored the stress and pore pressure changes in backfill; the apparatus can not fully couple the studied parameters. Simms and Grabinsky (2009) modified a triaxial cell with a miniature tensiometer to measure the evolution of negative pore pressure (suction) during consolidated undrained (CU) triaxial tests. CPB samples cured at 2 days were subjected to triaxial shear testing, and stress-strain and suction were monitored during shearing. However, the evolution of suction with curing time and its relationship to mechanical strength (and effective stress) were not studied.

Despite a very limited number of experimental studies on pore pressure measurements, the field instrumentation of backfill has increasingly received more attention among researchers (e.g., Belem et al., 2004; Yumlu, 2008; Thompson et al., 2009; Grabinsky, 2010; Veenstra et al., 2011; Thompson et al., 2012). The field monitoring was conducted by installing different sensors, such as piezometers and pressure cells, in different locations of mine stopes (different stope heights and proximity to barricades). Different parameters, such as pore water pressure, and vertical and horizontal total stresses were measured up to 150 days of curing. Also, the filling sequence (effect of plug) and filling rate were addressed in this literature. The major contribution of such studies is to provide an understanding of the fundamental behaviour of CPB with regard to the evolution of pore pressure, effective stress, cement hydration reaction, self-desiccation and hardening process in the field stopes. Recently, El Mkadmi et al. (2014) studied the effect of drainage and sequential filling on the behaviour of mine backfill by using SIGMA/W numerical model.

A review of the previous literatures shows that there is still limited information of the effects of THMC factors on pore pressure and stress state. Also, external factors, such as drainage conditions, arching effects, curing temperature, and chemical composition of CPB components have not been controlled and therefore their effects on the studied parameters are not well understood.

The hydraulic conductivity of CPB can be expressed in both saturated and unsaturated conditions. There are some authors in the literature who have studied the saturated and unsaturated hydraulic conductivities of CPB (e.g., Godbout and Bussière, 2007; Fall et al., 2009; Witteman and Simms, 2011; Abdul-Hussain and Fall, 2012; Pokharel and Fall, 2013). Saturated hydraulic conductivity ( $k_{sat}$ ) is required to study consolidation behaviour (Helinski et al., 2010), as well as

assess the fluid transportability of backfill, which can be used to investigate the environmental performance of CPB, the ground water flow within the backfill and/or between the CPB and surrounding rock, after mine flooding. Also, it is required to estimate the drainage ability and leakage potential of metal ions from the backfill into the groundwater (Levens et al., 1996). Furthermore, CPB can experience unsaturated conditions. In this case, knowledge of water retention capacity and unsaturated hydraulic conductivity ( $k_{unsat}$ ) is needed to study the fluid transportability of backfill (Abdul-Hussain and Fall, 2012).

Several factors can affect the saturated hydraulic conductivity of CPB. The  $k_{sat}$  value decreases as the curing time increases. Also, the  $k_{sat}$  value decreases when curing temperature is increased. It can be also affected by the mix components (Pokharel and Fall, 2013). The permeability decreases as the binder content increases or the w/c ratio decreases. Tailings with finer particles produce lower permeability. The sulphate can have two opposite impacts on the  $k_{sat}$  value. Sulphate content can reduce the  $k_{sat}$  value at early ages (< 28 days). However, high sulphate content at an advanced age (90 days) can increase the  $k_{sat}$  due to the secondary formation of cement products and development of micro-cracks (Fall et al., 2009; Pokharel and Fall, 2013). Furthermore, mechanical damage induced by high levels of applied stress (more than 80% of the UCS) can increase the hydraulic conductivity, mainly due to the formation of micro-cracks in the CPB matrix under high external stress (Fall et al., 2009). In unsaturated backfill, factors including degree of saturation, suction and air entry value, control the unsaturated hydraulic conductivity (Abdul-Hussain and Fall, 2012).

A review of the previous literature on the hydraulic properties of CPB shows that in spite of the comprehensive knowledge on the saturated hydraulic properties of CPB, our understanding on the evolution of the unsaturated behaviour of CPB is still very limited. Further, there is paucity in research regarding suction development due to self-desiccation, pore pressure changes, and unsaturated properties. Finally, the effect of THMC loads and factors on the hydraulic properties of CPB has not been studied in the previous literature. Therefore, it is important to address these issues.

#### **2.3.4. Thermal properties and temperature development within CPB and the factors that can affect them**

The thermal characteristics of CPB can be classified into: (1) intrinsic properties such as thermal conductivity, and (2) external thermal factors such as curing temperature, initial CPB temperature and heat of binder hydration. Both properties and factors are required to understand the thermal behaviour of backfill, and also the THMC behaviour of CPB. Knowledge of thermal conductivity is required for thermal analysis of CPB and heat transfer between the CPB and

surrounding environment (rock, mine atmosphere, etc.). However, there is a paucity of studies and information on the thermal conductivity of CPB.

Several factors can affect the thermal conductivity of CPB, such as tailings mineralogy and fineness, curing temperature, porosity and degree of saturation (Celestin and Fall, 2009). Tailings with higher conductive minerals (e.g., quartz) have higher thermal conductivity (Cote and Konrad, 2005). Also, the thermal conductivity of CPB increases as the fineness of the tailings increases. This is mainly due to the fact that increasing the tailings fineness reduces the packing density of the tailings, which in turn, contribute to increasing the overall porosity of the hardened cement matrix (Celestin and Fall, 2009). However, some factors, such as  $w/c$  ratio, cement type, binder content (at constant slump), curing time and sulphate content have a minor influence on the thermal conductivity (Celestin and Fall, 2009).

There are various sources of temperature (or thermal loads) in mine backfill operations. They comprise heat generated by the binder hydration, host rock and deep mine temperatures, self-heating of sulfidic rock (and tailings), initial temperatures of the CPB mix components, and heat generated by blasting and mine fires. The rock temperature (i.e., hot rock temperature in deep mines and cold rock temperature in permafrost mines) mostly depends on the rock type, mine depth and geographical location (Fall and Samb, 2006). The self-heating of rocks/tailings is dependent on the type and quantity of sulphide and pyrrhotite minerals, as well as accessibility to oxygen and water for oxidation (Bernier and Li, 2003). Among the different sources of temperature in mine backfills, the heat produced by binder hydration is the most significant source. Since CPB structures are very large, the temperature increase due to binder hydration can reach up to 50°C (Fall et al., 2010; Thompson et al., 2012). The amount of heat generated in the backfill depends on factors such as the  $w/c$  ratio, mixing water chemistry, binder type and quantity. It can also be affected by external factors such as the stope size, binder content, filling rate and placing temperature (Nasir and Fall, 2009).

The literature review presented above shows that most of the previous studies performed on the thermal properties or behaviour of CPB have focussed on the isolated influence of the mix components of CPB on its thermal conductivity (e.g., Celestin and Fall, 2009) and the monitoring (Yumlu, 2008; Thompson et al., 2012) or prediction (e.g., Nasir and Fall, 2009) of the heat generated by the hydration of the binder of CPB. Our understanding of the evolution of the thermal properties or behaviour of CPB under coupled THMC loading conditions, as well as the impact of the CPB temperature on its THMC behaviour, is still limited. This needs to be addressed in this research.

### **2.3.5. Chemical properties of CPB and factors that can affect them**

The chemical properties or factors of CPB depend on the chemical and mineralogical characteristics of its constituents, including mixing water, tailings chemistry and mineralogy, and binder chemical compositions and reactions. These chemical factors can significantly influence the short and long-term strength of CPB (Benzaazoua et al., 2002). Two chemical mechanisms can take place to alter the mechanical strength of the backfill. These can be either direct or indirect. In the former, CPB prepared with sulphide rich tailings (e.g., pyrite) can be oxidized in the presence of oxygen (also called weathering). The degree of oxidation is mainly a function of pyrite percentage and degree of saturation. The weathering causes release of metal ions and acid mine drainage into the environment (Ouellet et al., 2003). In the latter, the initial chemical compositions (e.g., sulphides, sulphate) in the CPB ingredients (i.e., tailings, binder and mixing water) can negatively affect the CPB strength development due to sulphate attacks (Benzaazoua et al., 2004). For example, sulphate in the initial CPB matrix can inhibit cement hydration reactions at early ages and therefore reduce the strength (Fall and Benzaazoua, 2005; Pokharel and Fall, 2011). In advanced ages, the formation of secondary expansive minerals in the backfill pores, such as ettringite and gypsum, can cause internal cracks and eventually lead to strength deterioration (Fall and Benzaazoua, 2005). However, usage of sulphate resistance binders can help to maintain a long-term strength so as to compensate for strength deterioration (Ercikdi et al., 2009).

In the tailings chemical or mineralogical composition, the presence of sulphide minerals (e.g., pyrite) and sulphate ions, as well as the chemical characteristics of mixing water, which may have the presence of soluble sulphates, can affect the strength acquisition of backfill (Kesimal et al., 2005).

Benzaazoua et al. (2004) used different types of binders (OPC, blast furnace slag and FA) with different chemical compositions, 5 types of tailings with different percentages of pyrite and sulphur, and mixing water with different percentages of soluble sulphate to prepare CPB samples. They found that the chemical properties of the three main components of the CPB are interrelated and play an important role in mechanical strength acquisition. Also, chemical composition and the concentration of dissolved ions in the pore water are the main factors that influence the hardening process in cemented materials (Benzaazoua et al., 2004).

Most of the previous studies which examined the effect of chemical factors (e.g., pore water chemistry) on the properties of cemented material were conducted on concrete samples (e.g., Rothstein et al., 2002; Ramlochan et al., 2004; Lothenbach et al., 2007; Chen and Brouwers, 2010). Thus, since CPB is different from concrete, those results cannot be directly applied or transferred to CPB. Furthermore, there are no studies on the evolution of the pore water chemistry of CPB and the

influence of chemical factors on the behaviour or properties of CPB subjected to THMC coupled loading conditions. These issues are addressed in this study.

## **2.4. Background information on binder hydration and some of the characteristics of binder**

### **2.4.1. Introduction**

Different types of binding agents can be added to mine tailings and water mixture to create bonding between tailings particles and build up strength. The most common binder is ordinary Portland cement [OPC] (called Type I in ASTM standard; and General Use [GU] in Canada CSA standard). Also, sulphate resistance Portland cement (Type V in ASTM standard; and HS in CSA standard) sometimes is used in CPB to add sulphate resistance to the mix. Pozzolanic materials are often used, alone or blended with OPC, to increase the final strength and reduce the binder cost. The most frequently used pozzolans in backfills are pulverized fly ash (PFA) and blast furnace slag (Kesimal et al., 2005; Bellem and Benzaazoua, 2004 & 2008). Besides the economic advantage, the application of Slag and Fly Ash in cement based materials can enhance the durability, deliver denser C-S-H and produce finer pore structures (Langan et al., 2002; Chindaprasirt et al., 2004). The detailed information on Slag and Fly Ash can be obtained from, Mehta and Gjorv (1982), Wesche (2005) and Gambhir (2013). The main characteristics of OPC and their effects on CPB behaviour are discussed in the following subsections.

### **2.4.2. Portland cement hydration**

The main constituents of anhydrous Portland cement clinkers are:

- Silicates: tricalcium silicate or alite ( $C_3S$ , 26% to 53%); and dicalcium silicate or belite (16% to 54%  $C_2S$ ), and
- Aluminates: tricalcium aluminate ( $C_3A$ , 3% to 15%); and tetracalcium alumina ferrite ( $C_4AF$ , 8% to 12%) (Hansen et al., 1973). Figure 2.6 shows the cement grain compounds and cement hydration products. Cement hydration reactions produce three main types of cement hydration products, including calcium silicate hydrate (C-S-H), calcium hydroxide ( $Ca(OH)_2$  or CH), and calcium sulphoaluminate known as ettringite ( $3CaO \cdot Al_2O_3 \cdot 3CaSO_4 \cdot 31H_2O$ ). C-S-H is formed by the hydration of  $C_3S$  and  $C_2S$  at different rates. It occupies approximately 60% (by volume) of the total cement hydration products in hardened cement. Its structure ranges from poorly crystalline to amorphous (Mehta and Monteiro, 1993). The nanostructure of C-S-H was elucidated by Beaudoin et

al. (2011) and Alizadeh (2009). CH is a by-product of the hydration of calcium silicates and takes up to 20% of the cement hydration products. CH has crystals that are thin to large hexagonal prisms (Double, 1983). Ettringite is the product of the hydration of the aluminate phases and gypsum. It has a needle-like morphology (Double, 1983). The anhydrous constituents in cement clinkers and cement hydration reactions are illustrated in Figures 2.6 and 2.7.

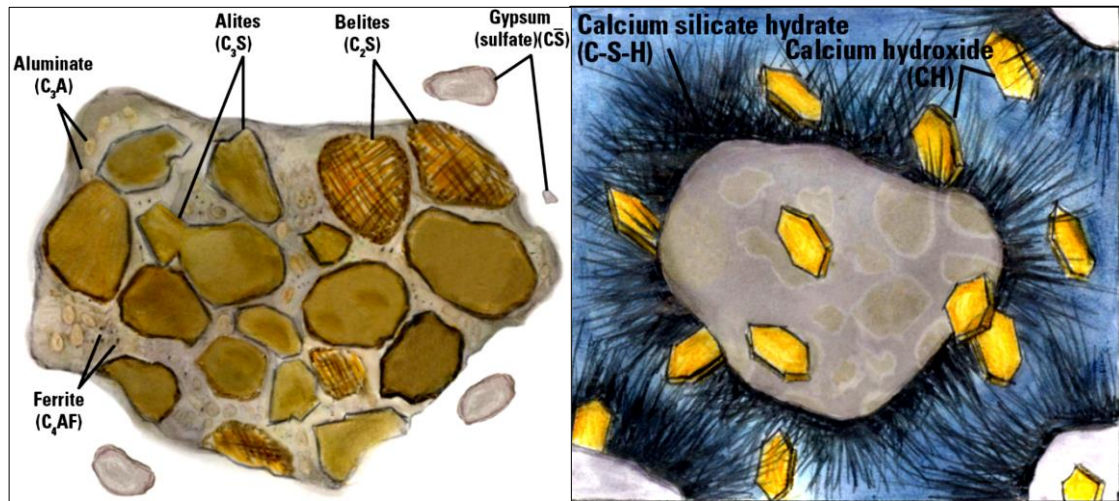


**Figure 2.6. Cement grain compounds (left); main cement hydration products (right) (National Concrete Pavement Technology Centre, 2007)**

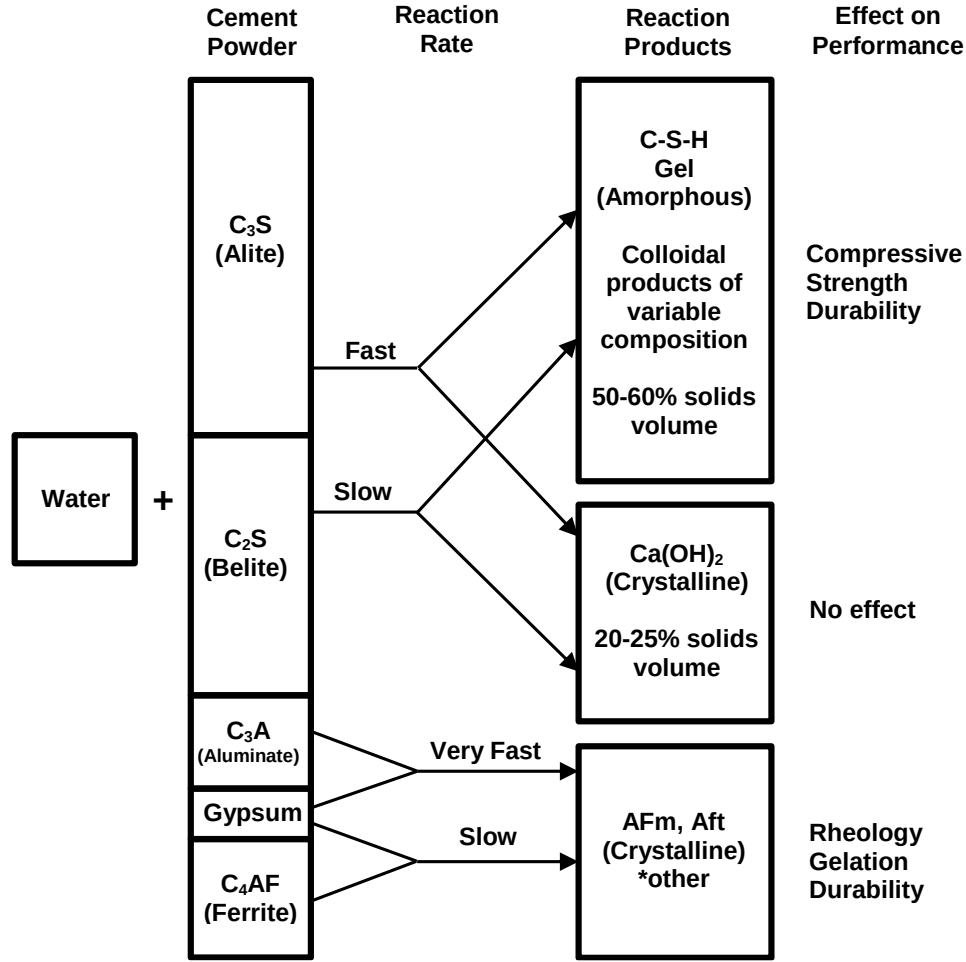


Figure 2.7. Schematic diagram of cement hydration processes (size of the box corresponds to the volume) (Double, 1983)

#### 2.4.3. Setting/hardening/heat of hydration processes

Cement hydration can be defined as the chemical reactions between solid compounds (clinkers) and the liquid phase (Chen and Brouwers, 2010). Cement hydration is an exothermic chemical process, which produces significant amounts of heat. The heat of cement hydration can be calculated as the summation of the heat of hydration of each cement compound as follows:

$$Q_{sum} = Q_{C_3S} + Q_{C_2S} + Q_{C_3A} + Q_{C_4AF} \quad (\text{Eq. 2.1})$$

Typical values of specific heat of hydration of cement clinker compounds are: C<sub>3</sub>A (1340 kJ/kg), C<sub>3</sub>S (502 kJ/kg), C<sub>4</sub>AF (419 kJ/kg) and C<sub>2</sub>S (260 kJ/kg) (Swaddiwudhipong et al., 2002).

The hydration process of OPC and generated heat of hydration typically take place in five distinct stages, including: initial, induction, acceleration (or setting), deceleration (or hardening) and densification (Figure 2.8) (Mehta and Monteiro, 1993). The summary of the different stages is

presented according to Soroka (1980), Neville (1995), Swaddiwudhipong et al. (2002), SPE (2007), Bullard et al. (2011), and Winter (2012):

(1) Initial reaction (0 to 30 min.): almost immediately after water is added during the mixing period, the rapid dissolution of aluminates and gypsum takes place, which results in the release of significant amounts of heat as well as Na, K, Ca, OH and  $\text{SO}_4$  ions into the pore solution;

(2) Induction (dormant period, 30 min to 3 hrs): reaction of calcium silicates ( $\text{C}_3\text{S}$  and  $\text{C}_2\text{S}$ ) which result in the initial formation of C-S-H gel and a supersaturated solution of Ca and OH in the pore solution. Also, reactions between gypsum and  $\text{C}_3\text{A}$  result in the formation of ettringite. The formation of C-S-H and ettringite around the  $\text{C}_3\text{S}$  and  $\text{C}_3\text{A}$  particles separates them from the pore solution, which in turn, retards the further rapid migration of the ions into the pore solution. During this time, the paste is plastic and does not generate heat,

(3) Acceleration (setting period, 3 to 17 hrs): at the end of the dormant period, a preventive coating formed around the cement grains is ruptured as a result of excess pressure. A significant amount of heat is generated due to the reaction of the  $\text{C}_3\text{A}$  and gypsum, and later on,  $\text{C}_3\text{A}$  and ettringite, which leads to a specific heat of 1495 kJ/kg. C-S-H and CH are formed as a result of the hydration of alites and belites. In this period of hydration, the porosity decreases and strength increases, thus resulting in the setting of the paste,

(4) Deceleration (hardening period, 17 to 48 hrs): the C-S-H and CH continue to grow at a slower rate, which limits the access of water to undissolved cement grains. The sulphate ions are also depleted and the remaining aluminate reacts with C-S-H. Less stable ettringite converts into more stable monosulphate. The heat of hydration reaches its peak value and then starts to drop. The hydration products gradually fill the pores, thus resulting in further pore refinement at a slower rate; and,

(5) Densification (48 hrs to several months/years): belites and alites dissolve at very slow rates, which form a solid mass of C-S-H and CH products. High strength, very low porosity and low hydraulic conductivity evolve in this stage and may take up to several years.

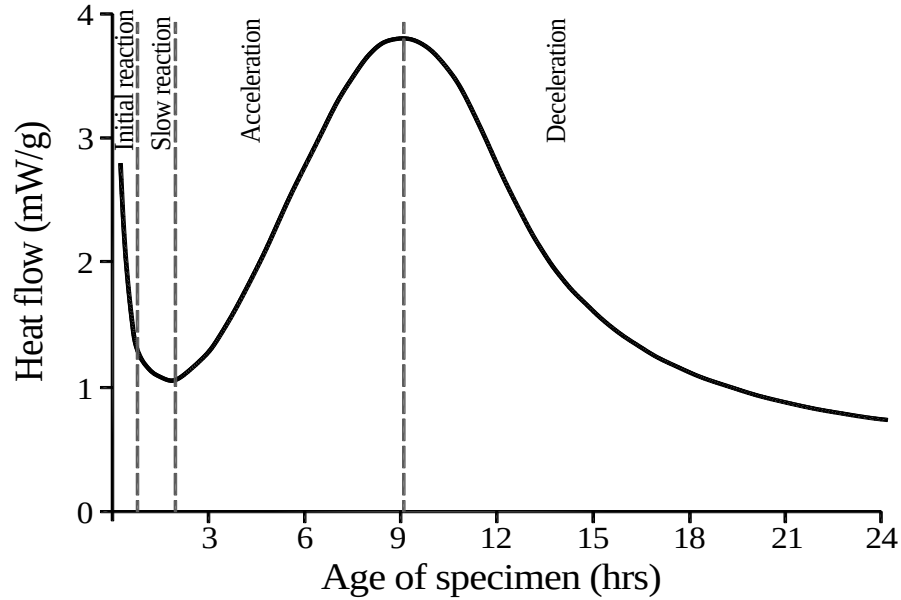


**Figure 2.8. Rate of hydration with curing time (Bullard et al., 2011)**

#### **2.4.4. Factors that affect cement hydration**

Cement hydration can be affected by several factors, such as w/c ratio, fineness of cement, and curing temperature (Lin and Meyer, 2009).

##### **Cement fineness**

Cement fineness can affect the final degree of hydration and the hydration rate. Cement with finer particles has a higher surface area. This can result in greater surface contact with water and higher hydration rate. Also, finer cement particles have cement hydration products with less thickness, which in turn, increase the final degree of hydration. Therefore, finer cement particles reduce the setting time, accelerate the hardening process and increase the mechanical strength (Ginebra et al., 2004; Bentz et al., 2008; Lin and Meyer, 2009) (Figure 2.9a).

##### **Water-cement ratio**

A lower w/c ratio can increase the rate of hydration, which in turn, increases the heat of hydration. Furthermore, a decrease in the w/c ratio can reduce the porosity (decrease the hydraulic conductivity) and increase the mechanical strength (Goto and Roy, 1981; Bentz et al., 2009) (Figure 2.9b).

**Curing temperature**

Curing temperature can accelerate the rate of cement hydration reaction. Also, it increases the density of cement hydration products and short-term compressive strength. However, high curing temperatures (e.g., above 85°C) can reduce the mechanical strength at advanced ages. This can be attributed to higher porosity, less uniform microstructure and coarser pore structure which can lead to decreases in mechanical strength (Kjellsen et al., 1990; Maltais and Marchand, 1997; Elkhadiri et al., 2009) (Figure 2.9c).

**Curing pressure**

Curing under high pressure can increase the rate of hydration. For example, experimental studies have shown that the hydration of  $C_3S$  increases under pressure. Also, precipitation of cement hydration products (C-S-H and CH) is faster under the application of pressure (Bresson et al., 2002). The time of the application of pressure can also affect the rate of hydration, and it is more effective during the first 48 hrs of curing under pressure. The applied pressure can increase the accessibility of cement grains to water required for hydration which can lead to hydration of the unreacted cement particles, which in turn, increases the degree of hydration (Zhou and Beaudoin, 2003). Furthermore, curing pressure can increase the compressive strength through the formation of denser cement gel around the unhydrated cement particles, as well as decrease the porosity (Roy et al., 1972) (Figure 2.9d).

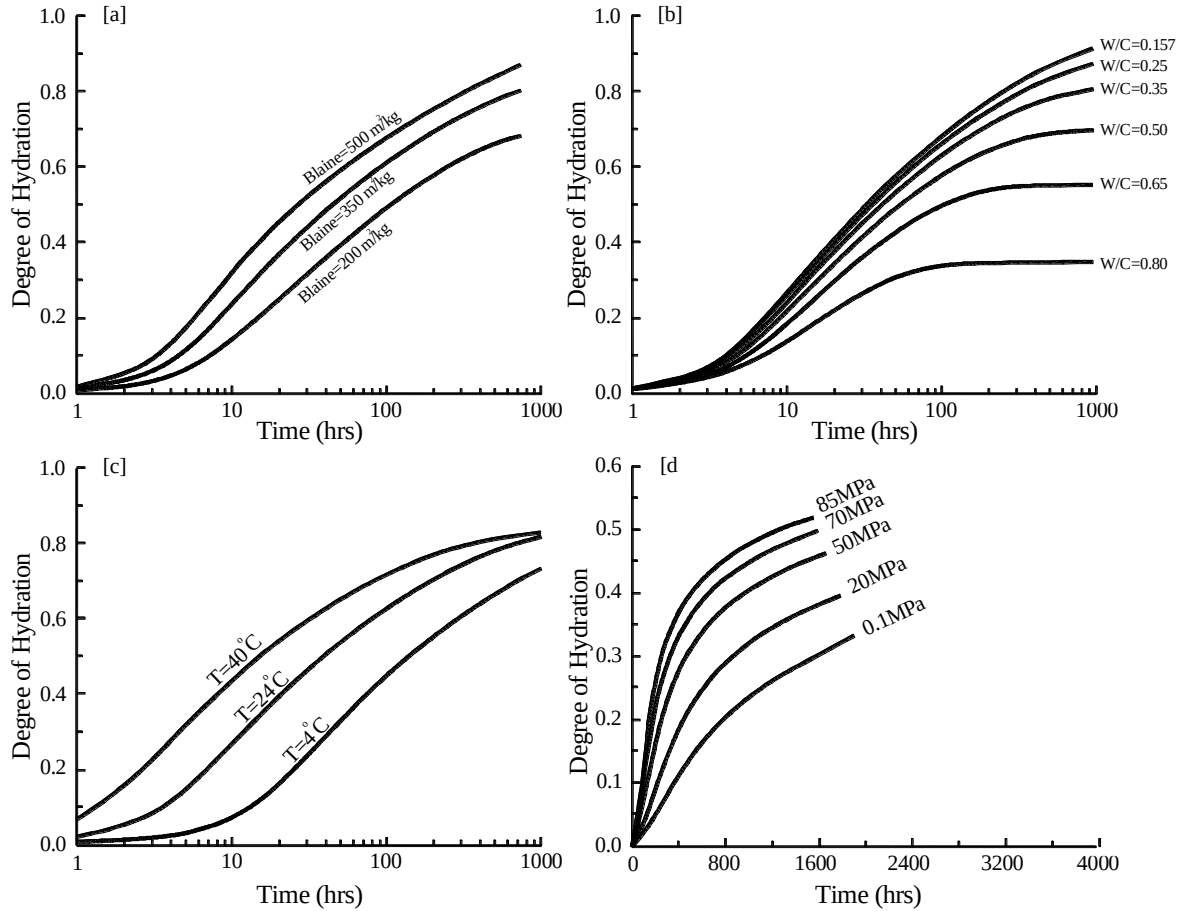


**Figure 2.9. Typical example of effect of [a] cement fineness; [b] w/c ratio; [c] curing temperature; and [d] curing stress on degree of hydration (source: Lin and Keyer, 2009)**

## 2.5. Thermo-hydro-mechanical-chemical coupled processes in porous media

### 2.5.1. Introduction

THMC processes in porous media are one of the most important phenomena in geotechnical and environmental engineering. The main objective of this section is to provide a concise explanation of the governing interactions of THMC processes in porous media. THMC coupled processes are applicable for a wide range of geo-system analyses, such as nuclear waste disposal, carbon dioxide storage, oil reservoirs, etc. (Kolditz et al., 2012). Rocks and soils, and cementitious materials such as concrete and similar materials, can be considered as a porous material. A porous material contains pores or voids. The pores are typically filled with a fluid such as air, water, oil, etc. or a mixture of some fluids. A porous media must be permeable to a fluid. In other words, a fluid should be able to penetrate one face of the material and exit from the other side (Dullien, 1992).

## 2.5.2. Coupled THMC processes

Coupled THMC processes in a media (e.g., geologic systems, porous media, cement based materials, etc.) are the various processes that continuously take place at different rates, based on the nature and strength of the sources (Noorishad and Tsang, 1996).

In a coupled system, individual processes affect the initiation and progress of the others (Jing and Feng, 2003). In other words, the whole process cannot be predicted by independently considering individual processes which may result in misunderstanding of the studied phenomena (Chan et al., 1996). For THMC coupled studies, two-way interactions between individual processes are to be studied. Table 2.1 presents the main interactions between coupled processes. In each process, there are “agents” and “objects” (Jing and Feng, 2003). The agent affects or initiates a process in the object. For instance, in TM coupled processes, the T (thermal factor) is an agent and may affect the M or mechanical factor [ $M = f_m(T)$ ]. However, in the MT process, the mechanical factor may affect the thermal factor in different process rates or strength [ $T = f_t(M)$ ] (Jing and Feng, 2003).

**Table 2.1. Effect of interaction between coupling processes**

| Agent<br>Object | T            | H            | M            | C            |
|-----------------|--------------|--------------|--------------|--------------|
| T               | o            | $T = f_t(H)$ | $T = f_t(M)$ | $T = f_t(C)$ |
| H               | $H = f_h(T)$ | o            | $H = f_h(M)$ | $H = f_h(C)$ |
| M               | $M = f_m(T)$ | $M = f_m(H)$ | o            | $M = f_m(C)$ |
| C               | $C = f_c(T)$ | $C = f_c(H)$ | $C = f_c(M)$ | o            |

(T: thermal, H: hydraulic, M: mechanical, C: chemical)

To study THMC coupled processes, it is necessary to completely understand each factor and then establish the governing coupled processes between them. However, to simplify a THMC problem, only the important processes are considered in the solution.

Some of the more important processes in porous media are: M-mechanical factors, such as stress, deformability, strength, damage of soil/rock matrix; H-hydraulic factors, such as fluid pressure, saturation, unsaturated condition, density, viscosity, porosity, permeability, fracture aperture; T-thermal factors, such as temperature; thermal properties; and C-chemical factors, such as

solute transport property, chemical reactions and reaction rate (Jing and Feng, 2003). A summary of the main THMC coupled processes is given in Table 2.2.

**Table 2.2. THMC coupled processes and factors (general application) (Adopted from Tsang and Stephansson, 1996; Jing and Feng, 2003; Chen et al., 2009)**

|                                                                                                                                        |                                                                                                                                                                                                                 |                                                                                                                                                                                                           |                                                                                                                                                                                                                                                                         |
|----------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| <u>Mechanical (M) factor:</u><br>Stress, deformation, damage, strength, shrinkage/ source: in-situ stress, gravity, excavation         | <u>M→H coupling:</u><br>Stress, deformation and damage induced change in porosity, transmissivity and pores connectivity (i.e. consolidation)                                                                   | <u>M→T coupling:</u><br>Mechanical works induced heat (mechanical energy conversion)                                                                                                                      | <u>M→C coupling:</u><br>Mechanical induced chemical process                                                                                                                                                                                                             |
| <u>H→M coupling:</u><br>Fluid pressure induced change in effective stress, aperture/pressure/stiffness function of fracture properties | <u>Hydraulic (H) factor:</u><br>Darcian or non-Darcian fluid flow in fractures, liquid pressure/Source: water infiltration, groundwater gradient, oil and gas flow in reservoir                                 | <u>H→T coupling:</u><br>Fluid velocity induced heat convection                                                                                                                                            | <u>H→C coupling:</u><br>Change in fluid pressure, velocity and saturation induced solid/gas solution, precipitation and solute transport                                                                                                                                |
| <u>T→M coupling:</u><br>Thermal stress and expansion induced damage or irreversible deformation in matrix                              | <u>T→H coupling:</u><br>effects of temperature on the dynamic viscosity; effects of heat flow on water potential gradient; fluid phase change (water to vapor: evaporation); thermal diffusion of moisture flow | <u>Thermal (T) factor:</u><br>Heat conduction, convection, radiation/ Source: Radioactive wastes, geothermal gradient, cement hydration, hot-cool water injection, freezing-thawing effect in permafrost. | <u>T→C coupling:</u><br>Temperature induced changes in reaction rate and chemical stability of minerals/elements                                                                                                                                                        |
| <u>C→M coupling:</u><br>Chemical reactions induced strength and deformation alteration                                                 | <u>C→H coupling:</u><br>Chemical reactions (e.g., solid dissolution and precipitation) induced hydraulic properties changes                                                                                     | <u>C→T coupling:</u><br>Chemical reactions induced heat release or consumption                                                                                                                            | <u>Chemical (C) factor:</u><br>Fluid-rock interaction, cement chemical reactions/ Source: Contamination migration, solid dissolution and precipitation, gas solution-exsolution, salt water intrusion, oxygen-rich surface, water infiltration, and material corrosion. |

Note: some processes may not be included in this table.

### 2.5.3. Typical example of the application of coupled processes

For the formulation of a THMC coupled process involved in a natural or human-made media, the major processes that are normally taken into consideration are mostly dependent on the nature of the problem. Some typical examples of the application of coupled processes are shown in Table 2.3.

**Table 2.3. Applications of typically coupled processes (Adopted from Chan et al., 1996; Jing and Feng, 2003; Wang and Wang, 2003; Kolditz et al., 2012)**

| Coupled processes | Application                                                                                                              |
|-------------------|--------------------------------------------------------------------------------------------------------------------------|
| H-M               | Oil reservoirs; consolidation; unsaturated porous media                                                                  |
| T-H-M             | Flow and mechanics of fractures; permafrost and freezing soil; tunnelling; geothermal oil sand extraction; thermal piles |
| H-M-C             | Ground pollution; underground water modelling                                                                            |
| T-H-M-C           | Mine paste backfill; nuclear waste repositories; CO <sub>2</sub> storage; glacial loading/unloading                      |

## 2.6. Conclusion

The conducted literature review on the existing body of knowledge on the CPB behaviour has revealed the knowledge gaps and the main areas that need to be studied more in depth. This shows that not only that each individual THMC property of CPB is still required to be investigated in more depth, but the interactions between them and how each individual THMC factor can affect or initiate different processes in CPB also need to be addressed. In addition, these THMC coupled processes need to be studied in more realistic stress states and curing conditions akin to field conditions. Therefore, the current experimental apparatus and CPB testing methods have been developed and applied in this research to address the objectives of this PhD study.

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## Chapter 3: High Column Experiments

### ABSTRACT

Once CPB structure is placed in a mine stope, it is subjected to strong coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes. Comprehensive series of experiments by means of insulated-undrained high columns were carried out to understand these THMC processes and factors.

CPB mixture was loaded into two columns and instrumented with various sensors to monitor the evolution of temperature (thermal factor), pore water pressure and suction (hydraulic factor), vertical deformation and drying shrinkage (mechanical factor) for a period of 150 days. In addition, four CPB columns were cured at 7, 28, 90 and 150 days. Then, extensive THMC experimental tests were performed on the extracted CPB samples from these columns with regards to their various THMC properties. The tests included unconfined compressive strength (UCS) and shear strength parameters (mechanical factor), thermal conductivity (thermal factor), saturated hydraulic conductivity and water retention properties (hydraulic factor), and pore fluid chemistry (chemical factor). Physical and microstructural properties of all samples also were measured. Moreover, the rate of evaporation was monitored in a cylindrical CPB sample for the entire period of study.

The results show that strongly coupled THMC processes control CPB behaviour. Mechanical properties are coupled to chemical reactions due to cement hydration and temperature changes inside the columns. Also, suction development due to self-desiccation can significantly increase the uniaxial compressive strength values with time. Chemical analysis including ion concentration changes with time revealed that change in pore fluid chemistry affects the pores structure (microstructural evolution), and thereby results in change in hydro-mechanical performance. It also influences the physical properties of the backfill. Further, according to the results a higher temperature causes faster cement hydration reactions and hence enhances the pore refinement. This process results in lower fluid transportability. Reduction in the degree of saturation decreases thermal conductivity. The hydraulic properties are strongly coupled to chemical and mechanical factors.

THMC properties of CPB are strongly coupled due to several internal mechanisms, such as heat of hydration, self-desiccation, suction development and rate of cement hydration reactions. External environmental loading, such as surface evaporation and drying shrinkage can affect the durability performance of CPB structures. The results show that there was degradation of strength following surface shrinkage as well as an increase in saturated hydraulic conductivity due to existence of micro-cracks.

The findings of this study can contribute to a better understanding of the behaviour of CPB and thus towards the designing of more cost-effective and durable CPB structures.

### **3.1. Introduction**

In Chapter three coupled Thermo-Hydro-Mechanical-Chemical behaviour of cemented paste backfill in high column experiments from early to advanced ages is studied. The obtained experimental results are presented in two research manuscripts (technical papers I and II). In the technical paper I the physical, hydraulic and thermal processes and characteristics are discussed. In the second technical paper, the results of mechanical and chemical processes are presented.

### **3.2. Technical Paper I: Coupled Thermo-Hydro-Mechanical-Chemical Behaviour of Cemented Paste Backfill in Column Experiments. Part I: Physical, hydraulic and thermal processes and characteristics<sup>1</sup>**

#### **3.2.1. Introduction**

Over the past few decades, cemented paste backfill (CPB) technology has been extensively used in mining operations as an effective means of underground mine support and/or tailings disposal (e.g., Rankine et al., 2001; Yilmaz et al., 2003; Fall and Benzaazoua, 2005; Cihangir et al., 2012). CPB is a mixture of dewatered tailings from the milling or processing operations of the mine, water and hydraulic binders (Kesimal et al., 2003, 2005; Benzaazoua et al., 2004; Klein and Simon, 2006; Orejarena and Fall, 2008). It has become one of the most commonly used ways in mine backfilling around the world. This technology helps to reduce the volume of surface tailing deposits and therefore minimizes the associated geoenvironmental problems (Archibald et al., 2000; Fall et al., 2004; Yilmaz et al., 2004; Sivakugan et al., 2005; Huang et al., 2011).

The mechanical behaviour, stability of barricades, durability and environmental performance are important design criteria of CPB structures. The critical challenge is to estimate the loads exerted on the barricades and manage their opening time. These two issues are strongly influenced by the pore water pressure (PWP) that develops behind the barricade, and suction development due to cement hydration. The latter results in the dissipation of excess pore pressure and increase in

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<sup>1</sup> Published in Engineering Geology (2013), 164: 195–207; Alireza Ghirian and Mamadou Fall

effective stress (i.e., strength gain) concurrent with transitioning from the paste phase to the hardening stage. Hydraulic factors, such as saturated hydraulic conductivity, pore water pressure, water retention capacity and suction development due to “self-desiccation” control the hydraulic performance of CPB, which also has significant influence on its mechanical stability, durability and environmental performance (Rankine et al., 2001; Helinski et al., 2006; Fall et al., 2008). Self-desiccation is a mechanism caused by binder hydration. Binder hydration leads to a net reduction in the total volume of water and solids, thereby decreasing the pore water pressure or leading to suction development inside cementitious materials. However, our understanding of the hydraulic performance of CPB has been limited to a few works of research (e.g., Godbout, 2005; Fall et al., 2009; Abdul-Hussain and Fall, 2011). Furthermore, there is a paucity of technical information on the coupled effects of mechanical, thermal and chemical (e.g., binder hydration) processes in the hydraulic performance of CPB structures. A deeper understanding and accurate prediction of these couplings are important for the design of barricades and management of the stope filling sequence.

Thermal factors can also affect the behaviour (mechanical, hydraulic, etc.) of CPB structures (Fall et al., 2010). They include the different sources of internal (e.g., heat generated by the binder hydration, Williams et al., 2001; Nasir and Fall, 2009); and external temperature (e.g., climatic temperature, self-heating of the sulfidic rock mass) loads applied onto a CPB structure as well as the intrinsic thermal characteristics or properties (such as specific heat capacity and thermal conductivity) of the CPB materials. In terms of intrinsic thermal properties, thermal conductivity is the most important property which is required to predict the heat flux inside a CPB structure. The knowledge of the thermal conductivity of CPB is needed when heat transfer analysis should be conducted in a CPB structure (Fall et al., 2010). So, there is a need to understand the evolution of thermal conductivity with curing time. In order to consider the various internal and external thermal loads on the CPB structural design, the temperature inside a CPB structure should be determined (Celestin and Fall, 2009). Knowledge of the thermal conductivity of CPB materials is also required for such calculations.

In recent years, the application of coupling processes in porous media has become important to solve complex engineering problems in the geotechnical field. The term “coupled processes” means that one process provokes and then develops other processes (Jing and Feng, 2003). In the field of underground mining, the backfilling of an underground mine stope by using CPB technology is a complex geotechnical process. Once prepared and placed, the CPB structure, which is a geotechnical system, is subjected to strong coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) (THMC) processes or factors. The strong interplays between THMC processes demand a comprehensive study of the fully coupled THMC behaviour of CPB structures which is crucial for a

reliable and cost-effective design. Figure 3.1 shows the main internal and external THMC factors that can affect a CPB structure. It should be noted that field investigation of such THMC behaviour or processes is not commonly feasible and is extremely difficult and costly due to several obstacles, such as (1) the need to stop mining operations for instrumentation and sampling, (2) the difficulties, time consuming aspect and high expenses of instrumentation and in-situ testing, and (3) underground mine work safety issues. To overcome the problems, CPB column experiments with controlled filling and curing conditions can be conducted to better understand the coupled THMC behaviour of CPB structures. To date, a limited number of studies have addressed the coupling processes in CPB material: thermo-mechanical–chemical, T-M-C (e.g., Orejarena and Fall, 2011; Pokharel and Fall, 2011); thermo-mechanical, T-M (e.g., Fall and Samb, 2006, 2009; Fall et al., 2010; Nasir and Fall, 2010); hydro-mechanical, H-M (e.g., Helinski et al., 2006; Li and Aubertin, 2009), and thermo-hydro-mechanical, T-H-M (Abdul-Hussain and Fall, 2012). The understanding of these THMC processes is critical for the proper assessment and understanding of the field behaviour of CPB and thus for the design of cost-effective, safe and durable CPB structures. However, no studies have tackled the THMC processes or behaviour of CPB. Thus, the objective of the present study is to determine the THMC processes and behaviour of CPB by conducting experiments with high columns. The results obtained on the THMC behaviour of CPB will be presented in this section, in which the results related to the hydraulic, thermal and physical factors are provided, whereas the results related to the mechanical, chemical and microstructural processes will be discussed in section 3.3.

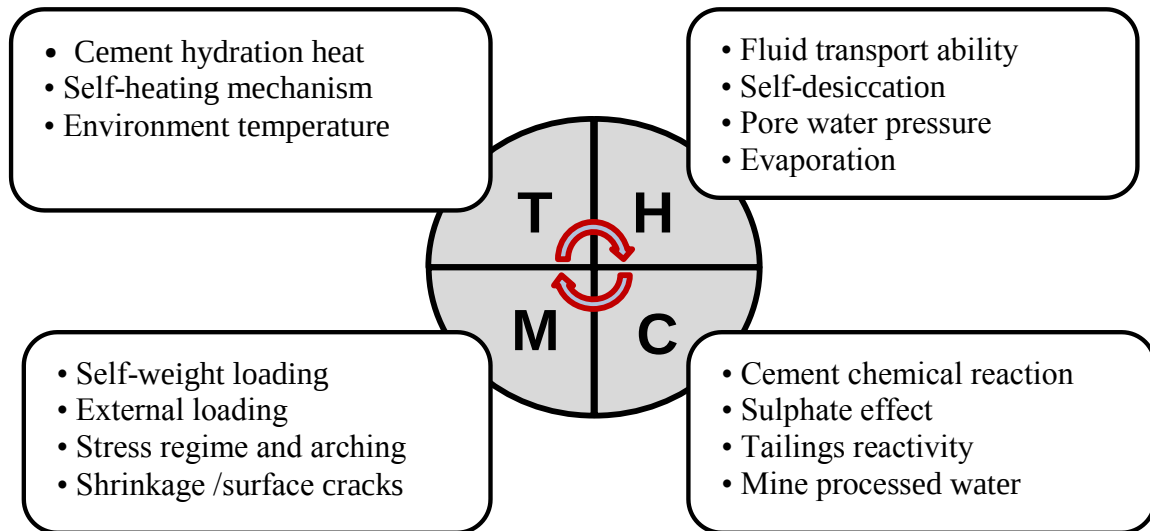


**Figure 3.1. Primary coupled THMC factors that affect the behaviour of CPB structures**

### 3.2.2. Materials, methods and experimental program

#### 3.2.2.1. Materials

The materials used include binder, tailings, and water.

##### - Cement and water

The most popular cement used in backfill operations is ordinary Portland cement type I (OPC) which is also used in this study. The characteristics of the OPC used are listed in Table 3.1. Tap water was used to prepare the CPB.

##### - Tailings

Silica tailings were used to prepare the fresh CPB. These tailings are made from ground silica which contains 99.8% silicon dioxide ( $\text{SiO}_2$ ). The grain size distribution of the silica tailings is very close to the average of nine Canadian hard rock metal mine tailings. The physical properties of the silica tailings are presented in Table 3.2. The main benefit of choosing silica tailings is to accurately control the chemical and mineralogical compositions of the tailings. Natural tailings can contain several reactive chemical elements, and often, sulphide minerals. These sulphide minerals can interact with cement, and thus, affect the interpretation of the results. Furthermore, the use of silica tailings (non-reactive or evolutive tailings) ensures that the tailings used in all of the columns have the same geochemical compositions or properties. Indeed, since the CPB columns have to be filled at different time intervals, the geochemical compositions of the natural tailings may be modified by the reactions of certain minerals contained in the tailings. This will result in a significant increase in the uncertainty of the results. Therefore, silica tailings are used to minimize the uncertainty induced by the factors mentioned above. As reported by Orejarena and Fall (2011) silica tailings have about 41–45 *wt.*% fine particles (<20 mm) which can be classified as medium tailings. Furthermore, according to the Unified Soil Classification System (USCS), the tailings used in this study can be classified as sandy silt with low plasticity in the ML group. The ML group comprises tailings from hard rock mines as also measured by Vick (1990).

**Table 3.1. Characteristic of Portland cement type I.**

| Type of binder | MgO (%) | CaO (%) | SiO <sub>2</sub> (%) | Al <sub>2</sub> O <sub>3</sub> (%) | Fe <sub>2</sub> O <sub>3</sub> (%) | SO <sub>3</sub> (%) | Relative density | Specific surface (m <sup>2</sup> /g) |
|----------------|---------|---------|----------------------|------------------------------------|------------------------------------|---------------------|------------------|--------------------------------------|
| PCI            | 2.65    | 62.82   | 18.03                | 4.53                               | 2.70                               | 3.82                | 3.10             | 1.30                                 |

**Table 3.2. Physical properties of the silica tailings**

| Element | $G_s$ | $D_{10}$<br>( $\mu\text{m}$ ) | $D_{30}$<br>( $\mu\text{m}$ ) | $D_{50}$<br>( $\mu\text{m}$ ) | $D_{60}$<br>( $\mu\text{m}$ ) | $C_u$ | $C_c$ |
|---------|-------|-------------------------------|-------------------------------|-------------------------------|-------------------------------|-------|-------|
| Tailing | 2.7   | 1.9                           | 9.0                           | 22.5                          | 31.5                          | 16.6  | 1.3   |

### 3.2.2.2. Specimen preparation and mix proportions

The CPB mix adopted for this study includes 4.5 wt% PCI and a water to cement ratio ( $w/c$ ) equal to 7.6. Tailings material, cement and water were mixed and homogenized in a concrete mixer for about 10 minutes. In all of the mixes, the  $w/c$  ratio and cement proportions were kept constant. The slump or the consistency of the paste mixtures, measured by a slump test in accordance with ASTM C143 (2010), was equal to 18 cm, which is the most frequently used slump value in CPB operations. The average initial physical characteristics of the fresh CPB are tabulated in Table 3.3. After CPB mixtures were produced, it was lifted up with small bucket to the top of the column and then poured gradually in 5 minutes. The column loading was completed in 3 layers that were 50 cm each in height for three consecutive days in order to understand the effect of several factors, such as filling rate on CPB, formation of a plug and backfilling interruption on CPB behaviour. To fill stopes, many mines use a strategy in which backfilling is carried out in two stages which include a plug pour and final pour in order to reduce the pressures on the barricade. The curing period for a plug pour is often between 3-7 days which is a conservative approach. This delay will lead to CPB strength gain and thus protect the backfill barricade when the final pour is backfilled. The reducing of the curing time to 1-2 days or application of continuous filling will reduce the stope cycle time and thus result in financial benefits (Abdul-Hussain and Fall, 2012). The filling strategy adopted for this study, which is three stages of filling and 24 hours of curing time (or delay) between each lift, allows the understanding of the effects of different backfill placement strategies or even unexpected interruptions during fillings (e.g., CPB plant breakdown) on the coupled THMC behaviour of CPB structures.

**Table 3.3. The mean physical characteristics of CPB used in the column experiments**

|                                |       |
|--------------------------------|-------|
| Void ratio, $e$                | 1.0   |
| Degree of saturation, $S_r$    | 100%  |
| Percent solid by mass, $C_w$   | 75%   |
| Water content, $\omega$        | 33.1% |
| Percent solid by volume, $C_v$ | 60%   |
| Water to solid ratio ( $w/s$ ) | 0.25  |
| Slump                          | 18cm  |

### **3.2.2.3. Column experiment setup**

Figure 3.2 presents a schematic diagram of the developed experimental set-up of columns. In total, six columns were manufactured including two columns for instrumentation and four columns for sampling at different curing times. Studies show that undrained backfill exhibits weaker mechanical properties in comparison to drained backfill (i.e., Belem et al., 2002). Therefore, in consideration of the worst case scenario, the undrained condition is chosen for this study. To manufacture the columns, two tubes with an external diameter of 30 cm, inner diameter of 20 cm, and height of 150 cm were used as the framework. Expansive insulating foam sealant was used to fill the gaps between the tubes to prevent any thermal interactions of the CPB mixture with the surrounding environment. An impermeable cap was placed at the bottom of the column to maintain an undrained condition. Columns were placed on a steel frame that was designed for this purpose. The top of the columns remained open in consideration of environmental factors, such as moisture and air on the THMC behaviour of CPB. The reason was to simulate underground mine stope conditions such that the surface of the backfill is exposed to the environment, while the sides and the bottom are surrounded by the adjacent rocks. Then, four of the columns were filled with fresh CPB and cured in a laboratory room for 7, 28, 90 and 150 days. A temperature and humidity sensor was used to monitor the room temperature and humidity during the curing time. Once the desired curing time was reached, each column was dismantled over a period of 3 days and then CPB samples were taken out from different heights of the columns: 10, 25, 40, 60, 75, 90, 110, 125, 140 and 145 cm for the experimental testing program.

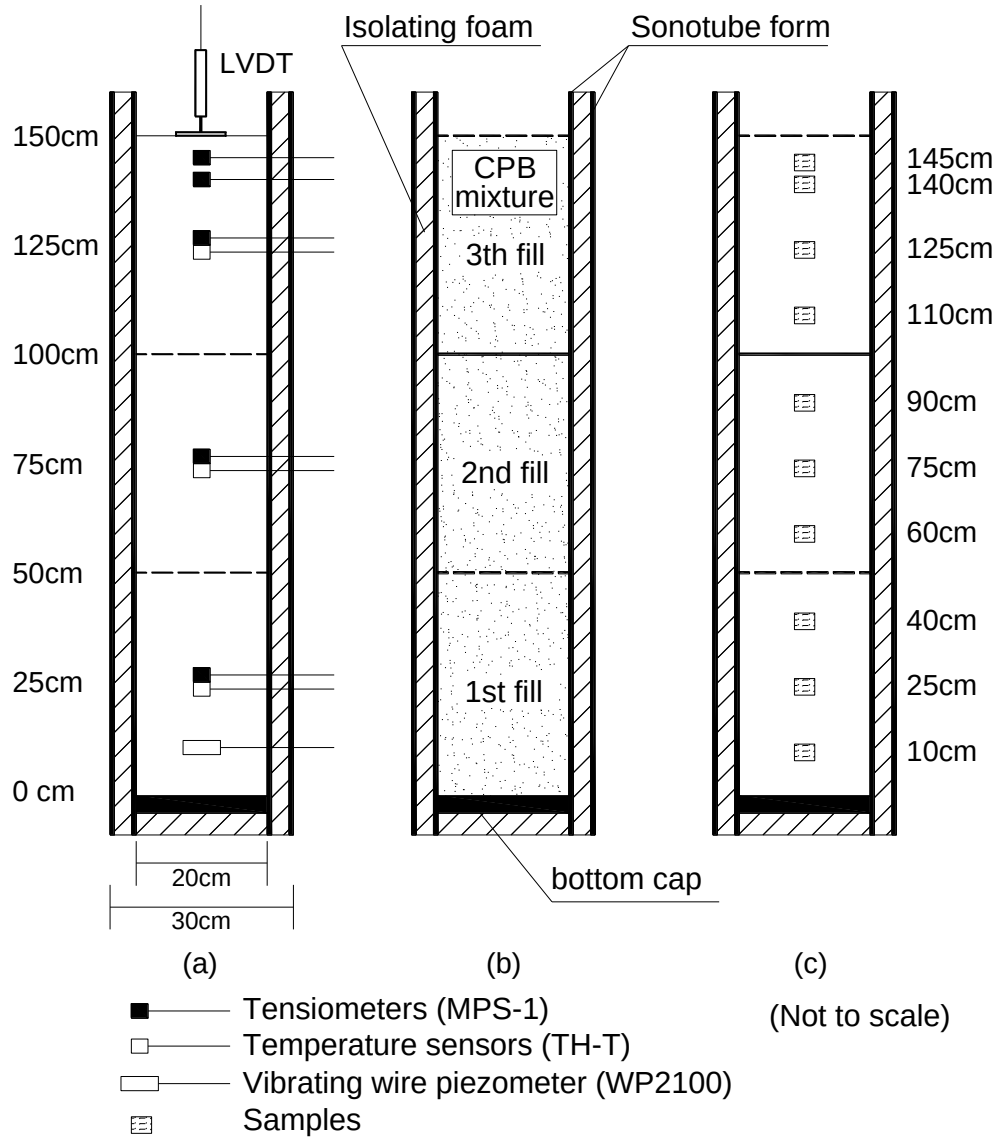


**Figure 3.2. Schematic diagram of the experimental set-up: (a) arrangement of sensors, (b) filling sequence and (c) sampling locations (total number of columns = 6).**

#### 3.2.2.4. Column instrumentation and monitoring

Two of the six columns were equipped with various sensors, including temperature sensors, a vibrating wire piezometer and tensiometers at different heights of the columns, with a linear variable differential transformer (LVDT) at the top. A summary of all of the instrumentation programs is presented in Figure 3.2. The columns were continuously monitored in terms of heat of cement hydration, pore water pressure, evolution of the suction and settlement for a minimum period of 150 days after column filling. To measure the self-weight settlement as well as drying shrinkage due to

evaporation, an LVDT was installed at the top immediately after casting the third layer into the column. The tip of the LVDT was connected to a small circular plastic plate that was located on the top of the fresh CPB. This plate is heavy enough not to float on the bleed water of the CPB, yet light enough not to sink farther into the fresh CPB. The sensor was connected to a data logger to record settlements with time. The monitoring results of the settlement and drying shrinkage are described in section 3.3. The monitoring of suction development with time was conducted by using a dielectric water potential sensor, model MPS-1. This sensor is capable of measuring the soil water potential between -10 and -500 kPa with an accuracy of  $\pm 5$  kPa. In order to understand the temperature evolution due to cement hydration at various heights of the column, TH-T temperature sensors with an accuracy of  $\pm 0.5\%$  were employed. Three temperature sensors were calibrated by thermometers before installation. The temperature sensors and tensiometers were installed in the middle of each layer at heights of 25, 75 and 125 cm from the bottom to measure the suction and temperature profiles within the column. Two tensiometers were also placed close to the column surface (5 and 10 cm below the surface) to monitor the evolution of the suction due to water loss by evaporation and self-desiccation. The evolution of the pore water pressure (PWP) is critical in the designing of barricades in mine stopes. The applied hydrostatic pressure (PWP) normally reaches the highest value at the bottom of the stope. A vibrating wire piezometer was employed in order to understand the evolution of the PWP with time especially after placing fresh CPB in the column as well as monitor the consequences of sequential filling on PWP. For this purpose, a WP2100 piezometer with  $\pm 70$  kPa pressure range and  $\pm 0.1\%$  accuracy equipped with a low air entry value ceramic filter was calibrated and installed at a height of 15 cm from the bottom of the column. The piezometer was connected to a data logger and readings were collected for each minute up to 5 days after CPB placement. The design locations of the sensors, filling sequence and location of obtained samples are shown in Figure 3.2. In addition to the monitoring of the internal THMC mechanisms, the moisture losses of a cylinder mould filled with CPB from column casting were measured with an electrical balance. Both column instrumentation monitoring and evaporation testing were simultaneously carried and in the same temperature controlled room. The CPB samples were cast in a cylinder plastic mould that was 30 cm in height with a diameter of 10 cm. The weight loss of the samples showed a corresponding amount of water that was evaporating from the CPB surface.

#### **3.2.2.5. Experimental test program**

In addition to the column monitoring procedure described above, an extensive laboratory test was conducted on CPB samples taken from different heights and columns to understand the THMC behaviour of the CPB material, as summarized in Figure 3.3. All sampled CPBs were tested in terms

of their thermal properties (thermal conductivity), hydraulic properties (hydraulic conductivity, water retention capacity (WRC) and evaporation test), mechanical properties (uniaxial compressive strength (UCS), shear strength parameters, modulus of elasticity, settlement and surface shrinkage) and chemical properties (pore fluid chemistry). In addition, extensive physical testing and observation of the microstructural properties were conducted to understand the evolution of the index properties and pore structure of the CPB from early to advanced ages. Gravimetric water content ( $\omega\%$ ), volumetric water content ( $\theta\%$ ), degree of saturation ( $S_r\%$ ), void ratio ( $e$ ), porosity ( $n$ ) and wet/dry density ( $\gamma$ ) were determined for the entire columns. The tests carried out to determine the physical, hydraulic and thermal properties of the CPB will be described in the coming sections, whereas the mechanical and microstructural tests, and chemical analyses performed are discussed in Part II (section 3.3).

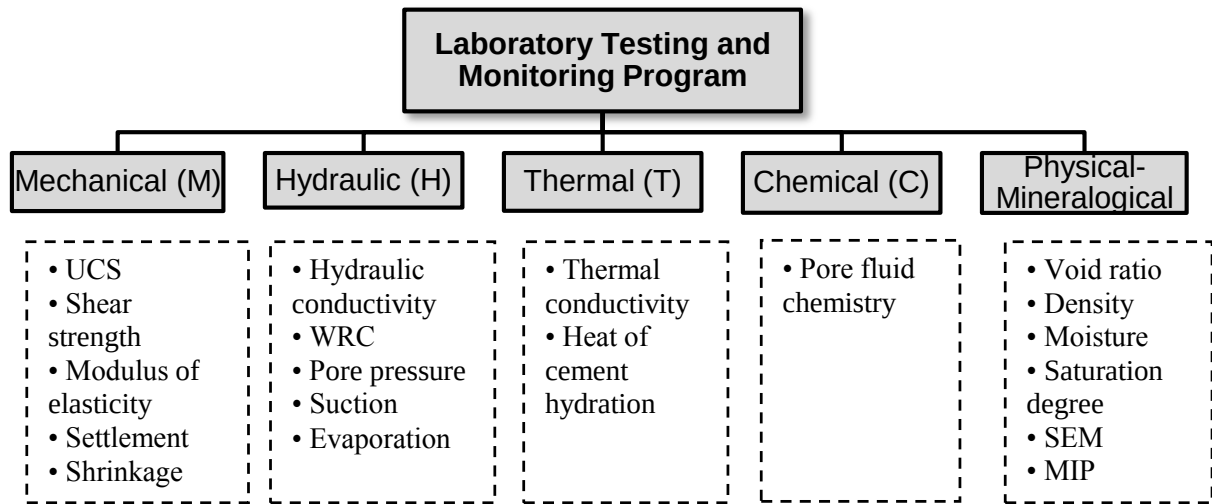


**Figure 3.3. Summary of laboratory experimental testing and monitoring program**

#### **- Tests to determine hydraulic properties**

Saturated hydraulic conductivity tests were performed by using TRI-FLEX II on the CPB specimens for each curing time and at different heights. The flexible wall technique was used to determine the hydraulic conductivity of the CPB. The procedure for this method is described in ASTM D5084 (2010) and was conducted in a constant head mode equal to 10 kPa. Two samples were tested and at least 3 readings were done, and the average value was the saturated hydraulic conductivity of the samples tested.

A WP4-T dewpoint potentiometer device was used to measure the water potential of the CPB samples. The WP4-T was adopted in order to obtain all results of the samples from each layer on the same day to avoid any significant changes in the microstructure of the CPB as hydration proceeded. This device is capable of measuring the suction from 0 to 60 MPa with an accuracy of  $\pm 0.1$  MPa

from 0 to 10 MPa and  $\pm 1\%$  from 10 to 60 MPa. The WP4-T was placed into a temperature and humidity controlled room. The CPB samples were cut and trimmed with a spatula into a diameter close to 37.80 mm and less than 5.5 mm in height, and then placed into the WP4-T to measure their water potential. In order to construct the WRC, the CPB samples were air dried at room temperature for about 15-20 minutes and then the next reading was carried out. To accelerate moisture loss in the samples, a small fan was installed above to increase the evaporation rate (*ER*). Eventually, the CPB samples were oven dried, and the solid mass and gravimetric water content were calculated during each drying step.

#### **- Determination of the thermal conductivity**

A KD2 thermal conductivity probe (see Appendix) was utilized to measure the thermal conductivity of the CPB samples obtained from various heights of the column. The device computes the values of thermal conductivity by monitoring the dissipation in heat from a line source given a known voltage. To carry out the thermal conductivity measurement, a hole with 2.80 mm diameter was first drilled into the centre of the CPB sample and then the thermal probe was inserted. Special care was taken to fill the gaps between the needle probe and walls of the hole so that proper contact should be made during the readings. For this purpose, a high thermal conductivity silver polysynthetic compound ( $k=8 \text{ w/m.k}$ ) was used. Each test was repeated at least three times to verify the repeatability of the results.

### **3.2.3. Results and discussion**

#### **3.2.3.1. Evolution of physical properties**

The strength and performance of CPB materials can be influenced by their physical properties, such as void ratio ( $e$ ), density ( $\gamma$ ), water content and degree of saturation ( $S_r$ ) (Belem et al., 2006). Therefore, the evolution of these properties with column height and time has been investigated. Figure 3.4a illustrates the variation of the void ratio within the columns for different curing times. The void ratio of the CPB materials generally decreased with longer curing times. This is due to an increase in binder hydration which generates larger amounts of binder hydration products. In terms of variation of void ratio with the height of the column, two different behaviours can be observed depending on the locations in the columns: (I) middle and bottom layers; (II) top layer and near the surface. At the bottom of the columns and for each different curing time, the void ratios were relatively high, which ranged from 1.01 for 7 days to 0.92 for 150 days. In the middle part, the void ratio appreciably decreased to 0.91 for 7 days and 0.87 for 90 days. The overall trend showed a

decrease in the void ratio from the bottom to the middle for almost all of the curing times. However, in the top layer, almost all of the void ratio values for different curing times started to increase, from heights of 75 cm to 125 cm. Near the surface, the void ratio increased to 1.02 in 7 days; however, the void ratio dropped to very low values for 28, 90 and 150 days, which ranged from 0.87 to 0.92 at a height of 140 cm.

To explain the observed behaviours, it should first be emphasized that in cementitious materials, changes in the void ratio can be related to two different mechanisms that include: (1) a decrease in the void ratio as a result of cement hydration progress; and (2) the result of water content variations. In the column experiments, the latter can explain the void ratio changes with height, while the former explains the void ratio changes with time. Indeed, a higher void ratio in the bottom layer can be attributed to the variations in water content inside the columns. The flow of water from the middle to the bottom layer at a very early age of curing resulted in an increase in the  $w/c$  ratio in the bottom layer and a decrease in the  $w/c$  ratio in the middle. Thus, CPB with a higher  $w/c$  ratio (i.e., higher water content) will have more void volume filled with water and therefore a higher void ratio (Fall et al., 2008). This higher void ratio would decrease the degree of saturation. However, near the surface, variations in the void ratio depend more on the shrinkage effect. A high evaporation rate at the surface can develop shrinkage and associated volume changes. Very low values of degree of saturation in the 90 and 150 day samples support this argument. A high reduction in the void ratio at the shrinkage limit can be observed in Figure 3.4d.

Figure 3.4b presents the variations in both the wet and dry densities in the columns for different curing times. The variations of wet density were not uniform, neither in the height of the column nor with time. The overall trend showed that the wet density ( $\gamma_{wet}$ ) decreased with curing time. A great reduction in the  $\gamma_{wet}$  value can be observed for 150 days of curing. This can be attributed to the fact that as the curing time increases, (i.e., the binder hydration progresses) more water will be consumed by cement hydration. The variation in the wet density is not regular within the columns. In almost all of the cured columns, the wet density increased from the bottom (ranged from 1.67 to 1.74 g/cm<sup>3</sup>) to the middle (varied from 1.71 to 1.83 g/cm<sup>3</sup>) of the columns and then decreased to the lowest value near the surface as a result of evaporation. The wet density near the surface was 1.70 g/cm<sup>3</sup> for 7 days of curing and 1.42 g/cm<sup>3</sup> for 150 days of curing. On the contrary, the dry density ( $\gamma_{dry}$ ) at 90 and 150 days showed a higher value in comparison to that at 7 days. This can be due to the refinement of the pore structure and reduction of the void ratio as the pore voids are filled with cement hydration products in the cemented matrix, which eventually produce a CPB material with a higher dry density. This behaviour can be supported by comparison of surface area analysis of 7 and 150 days samples obtained from MIP test which is presented in Figure 3.5. This

figure compares the cumulative pore volume intruded as a function of pore diameter for the 7 and 150 days samples. It can be seen that 150 days samples has much more higher cumulative pore volume meaning very finer pore size distribution compared with 7 days sample. Variation in the dry density seemed to be uniform for column height for almost all of the curing times.

Figure 3.4c shows the variations in degree of saturation against column height. The degree of saturation of the CPB material was around 100% after preparation and remained high (i.e. 85% to 95%) in the part of the column (height of 100 cm) that was not influenced by the evaporation for about 3 months after column filling. The degrees of saturation of the columns cured at 7, 28 and 90 days were almost the same (around 90%) up to 100 cm with respect to the height of the columns. However, this parameter showed a significant decrease after 150 days and reached 62.3% to 69.7% in the majority of the column height. The variations in degree of saturation in the columns showed a slight increase in the middle layer and then a significant reduction towards the surface of the column. The significant reduction in the degree of saturation towards the surface can be mainly attributed to the loss of water due to the combined effects of cement hydration and evaporation. It is also interesting to note that around 30% of the column height (45 cm), particularly after 90 days of curing, was affected by evaporation. This can be important for CPB structures prepared with high sulphate rich mine tailings (e.g., pyrite) that may be susceptible to sulphate attacks due to the reactivity of the tailings. However, it is necessary to stress that high desaturation would be limited to the first few meters of a field CPB which is only a small part of the mine stope compared to its large size. This needs to be investigated by long term observation of field CPB.

Figure 3.4d presents the change in void ratio with respect to the water content multiplied by specific gravity ( $\omega G_s$ ). It can be observed that there is a direct relationship between water content and void ratio for degrees of saturation above 80%. The void ratio decreased with water content until shrinkage limit was reached. In CPB materials, the main factor responsible for volume changes is the refinement of pores through filling with hydration products. For degrees of saturation that were less than 80%, shrinkage due to evaporation took place close to the surface and caused a distinguished behaviour. Thus, any further decrease in degree of saturation had no effect on void ratio reduction and reached a constant value ( $e=0.9$ ). The highly dried samples shown in Figure 3.4d present this behaviour.

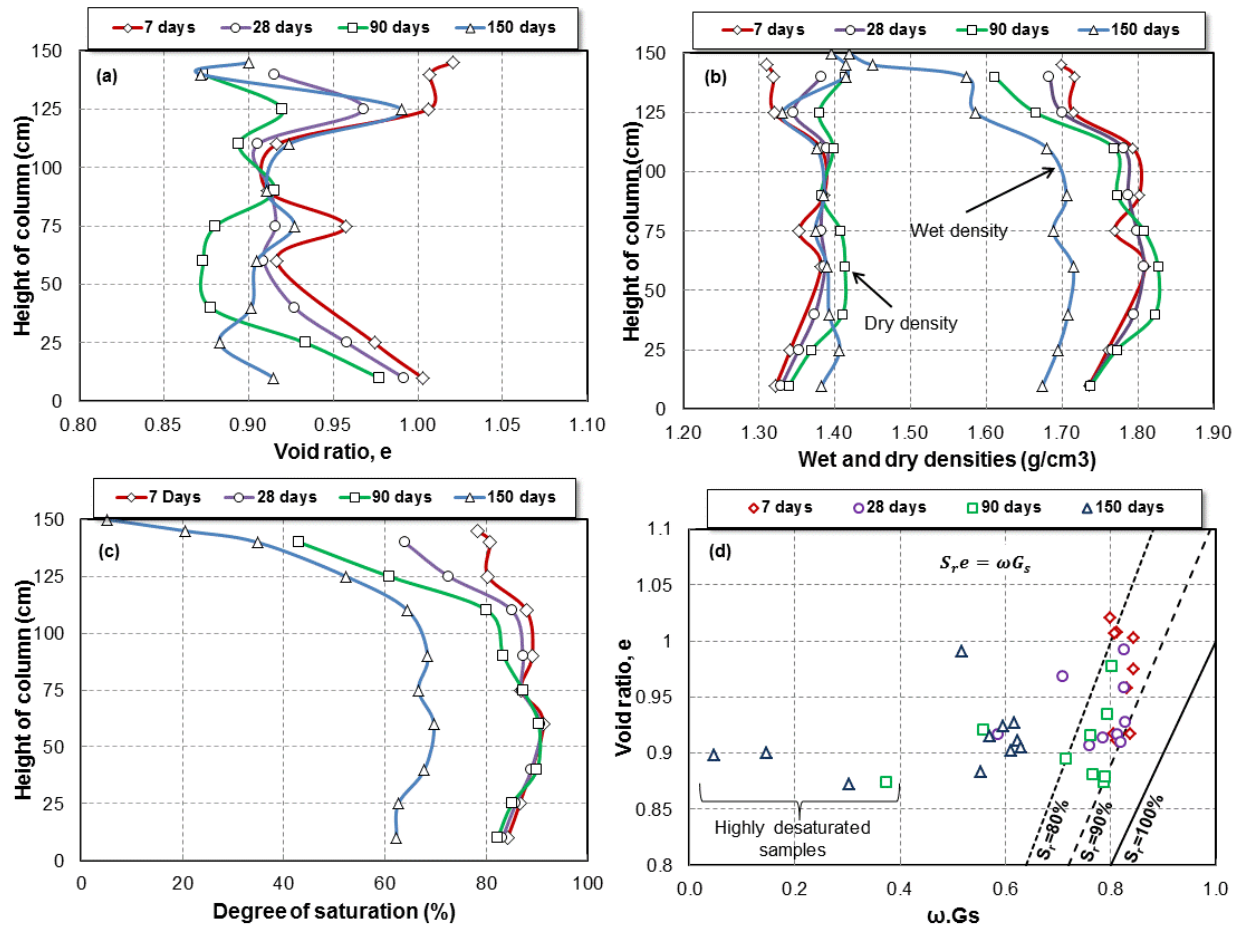


Figure 3.4. Evolution of the physical properties within columns cured at different ages, (a) void ratio, (b) wet and dry densities, (c) degree of saturation, and (d) void ratio versus  $\omega.G_s$

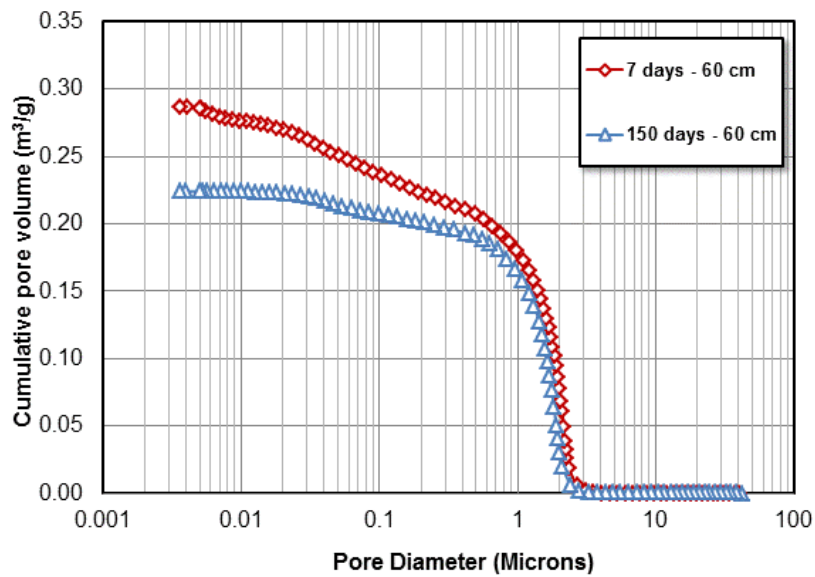


Figure 3.5. MIP test results for 7 and 150 days samples at height of 60cm

### 3.2.3.2. Evolution of hydraulic (H) properties

#### - Hydraulic conductivity

The evolution of saturated hydraulic conductivity ( $k_{sat}$ ) with column height and curing time is shown in Figure 3.6. Moreover, Figure 3.7 demonstrates the evolution of the mean values of the hydraulic conductivity in different parts of the columns with time. From these figures, it can be seen that the values of  $k_{sat}$  decreased with time, except for 150 days at the top of the columns. This decrease in hydraulic conductivity can be attributed to the refinement of pores as a result of the cement hydration process (will be discussed later). However, the variation of the obtained results was not uniform within the height of the columns. For the 7 and 28 days columns, there was a slight increase in  $k_{sat}$  values in the middle of the columns. For 90 and 150 days, the values of  $k_{sat}$  were approximately the same from the bottom to the middle of the columns, and then started to increase near the surface at 150 days. This observed increase in  $k_{sat}$  near the CPB surface is mainly attributed to the development of surface crack networks due to drying shrinkage which can change the microstructure. The presence of shrinkage crack networks led to a preferential path flow; thereby increases in  $k_{sat}$  values close to the surface of the columns. The scanning electron microscopy (SEM) images obtained from 150 days samples supports the developed micro cracks on the surface of the column, which are demonstrated in Figure 3.8.

Figure 3.9 presents the variation of saturated hydraulic conductivity with effective void ratio. The concept of effective void ratio was originally adopted from Jongpradist et al. (2011) and rewritten into a new format for this study. They explained that with a wide range of water content and unsaturated conditions, both void ratio and water content values should be considered to describe volume changes:

$$e' = \omega \times \ln(e/c) \quad (\text{Eq. 3.1})$$

where  $e'$  is the effective void ratio,  $\omega$  is the gravimetric water content,  $e$  is the void ratio for specific cured samples and  $c$  is the cement content. From Figure 3.9, it can be concluded that the effective void ratio has a significant influence on  $k_{sat}$ , since a decrease in the effective void ratio caused a decrease in the  $k_{sat}$  values. Any decrease in pore size or refinement of pores due to cement hydration processes can lead to lower values of void ratio and porosity. A reduction in the capillary porosity during hydration along with a denser cemented matrix eventually reduced the fluid transportability of the CPB. However, it should be noted that the  $k_{sat}$  was not only controlled by the effective void ratio, but other factors as well, since there was not a perfect fit between the regression line and obtained data ( $R^2=0.55$ ). These factors may be pore size distribution, tortuosity and surface shrinkage, and associated micro-cracks. Factors such as drainage of water from the upper to the lower

part of the columns (see Section 3.3.1) and variation in water content especially at the early times of hydration, heat of cement hydration, and trapping of air bubbles in CPB material during preparation can considerably influence pore size distribution, which results in variation of the  $k_{sat}$  values. To predict the evolution of the  $k_{sat}$  values at any curing time, the applicability of the model proposed by Fall et al. (2009) which is based on the evolution of  $k_{sat}$  as a function in the binder hydration degree index ( $\alpha$ ) is investigated here:

$$k_{sat} = A \cdot k_T \cdot \alpha^B \quad \text{and} \quad \alpha = \frac{UCS_t}{UCS_{max}} \quad (\text{Eq. 3.2})$$

where  $k_T$  (cm/s) is the saturated hydraulic conductivity of the tailings used,  $UCS_t$  (kPa) is the uniaxial compressive strength of the CPB for a given time,  $UCS_{max}$  (kPa) is the maximal UCS of the CPB (considered as the UCS of the 150 day old CPB in this study), and  $A$  and  $B$  are dimensionless fitting parameters to be determined for each CPB mix. The  $k_r$  value can be determined by running saturated hydraulic conductivity tests on the tailings used for the CPB preparation or estimated from a suitable empirical model to predict the saturated hydraulic conductivity of fine soils and/or tailings (e.g., Aubertin et al. 1996; Chapuis and Aubertin 2003). It should be emphasized that the proposed model is only applicable for the part of the column not exposed to evaporation effects, since drying shrinkage and micro-cracks may affect the  $k_{sat}$  values (Figure 3.7). From Figure 3.7, it can be noted that there is good agreement between the predicted and measured values.

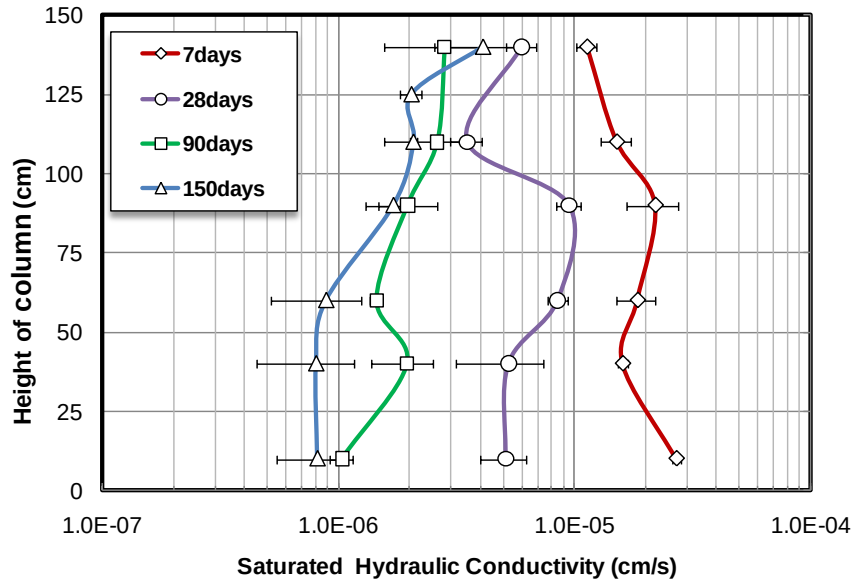


**Figure 3.6. Evolution of saturated hydraulic conductivity in the column cured at different ages**

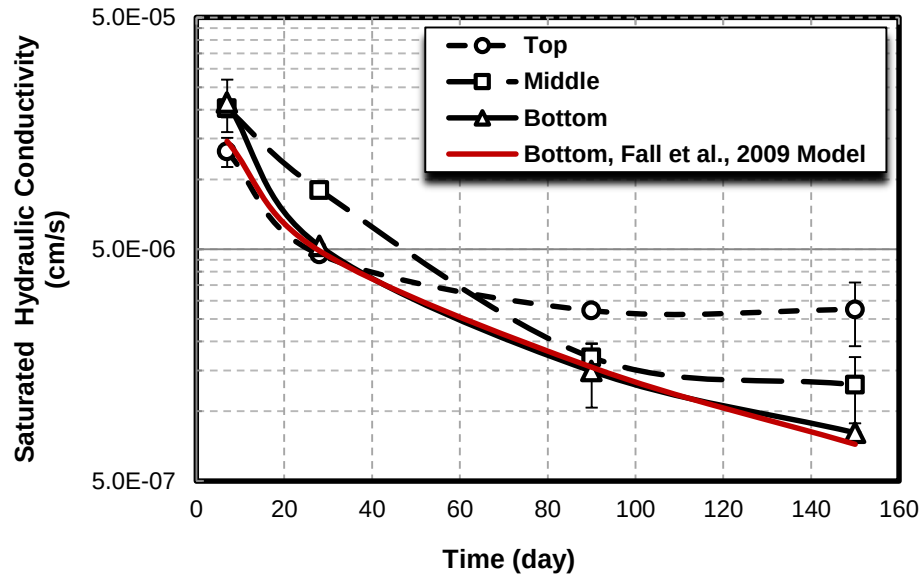


Figure 3.7. Evolution of saturated hydraulic conductivity with time

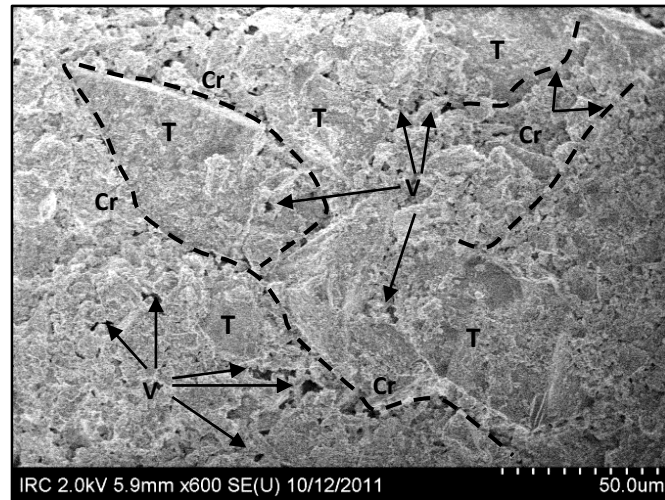


Figure 3.8. SEM image shows the developed micro cracks (150 days from surface of the column); V: air voids; Cr: crack; T: tailings particle

#### - Pore water pressure response

The design of barricades can be influenced by the magnitude of stress and stress distribution within mine stopes. Two terms of physical factors, including effective stress ( $\sigma'$ ) and pore water pressure ( $u$ ), play significant roles in the stability analysis of CPB fill mass and barricade design. At early ages of backfilling, the existing PWP at the bottom of the stope can be significant. An understanding of PWP evolution and the stress regime in backfills help to better plan mining

extraction sequences, especially when the stability of a stope is vital. Therefore, the evolution of PWP and suction within the columns has been studied. The obtained results for young CPB are shown in Figure 3.10. The results from both the vibrating wire piezometer (for  $+PWP$ ) and suction meter (for  $-PWP$ ) installed at the bottom of the column (15 and 25 cm from the bottom) were combined to produce the curve. Also, this graph presents the variation of PWP and suction for a period of 16 hrs and 6 days, respectively, after loading. Right after the placement of the first layer of CPB, the PWP increased up to 9.6 kPa, which is considerably high. The results showed a significant development of PWP at the bottom of the column. The ratio of pore pressure ( $u$ ) to effective stress ( $\sigma'_v$ ) was about 2.7 right after loading. This means that there is a significant reduction in effective stress at the time of the placement and existing high PWP. However, due to self-desiccation as a result of cement hydration, the PWP dropped to a zero value after about 2.8 hours. Then, considerably rapid development of negative PWP (suction) started with time. As expected, after placement of the second layer, water drained into the sub-layer and then the PWP started to increase, but lower than the value which was experienced before. This finding supports the drainage of the middle part of the column into the lower parts.

In addition, the slope of the first part of the PWP curve up to the casting of the second layer clearly demonstrates the rapid evolution of self-desiccation due to cement hydration processes. This evolution of the cement hydration illustrated in the Figure 3.10 will be discussed later. Also, it can be noticed that the development of suction was affected by the sequence of CPB filling. This finding is important for the early age stability of the barricade and CPB. Indeed, it is well documented that the decrease in suction will decrease the strength value for cemented backfill structures (e.g., Abdul-Hussain, 2010). The obtained results help to understand the importance of infiltration of water from the top to the lower part of a mine stope due to drainage behaviour. This needs to be considered in the evaluation of the stability of the barricades and CPB at early ages.

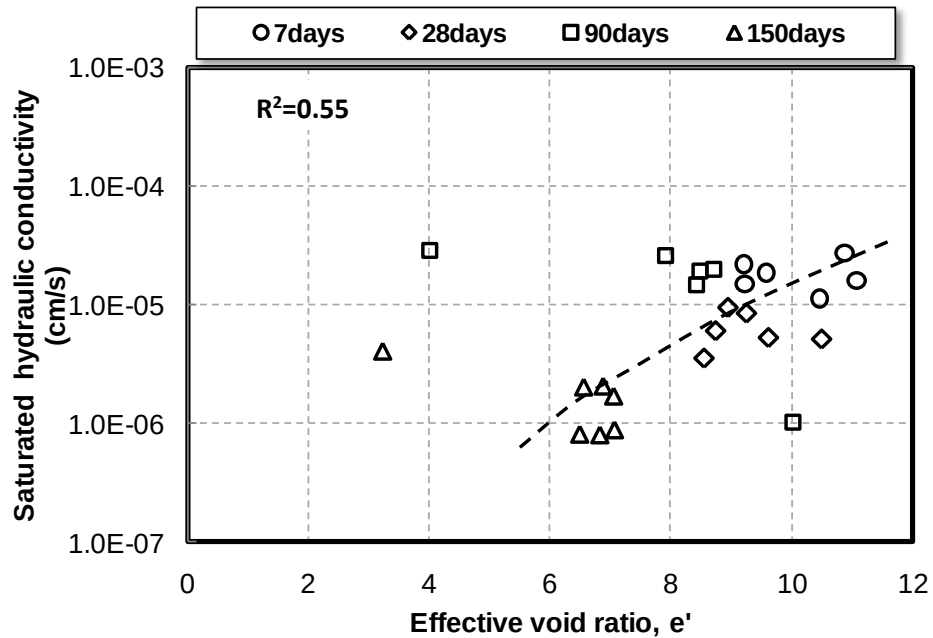


Figure 3.9. Variation in saturated hydraulic conductivity against effective void ratio

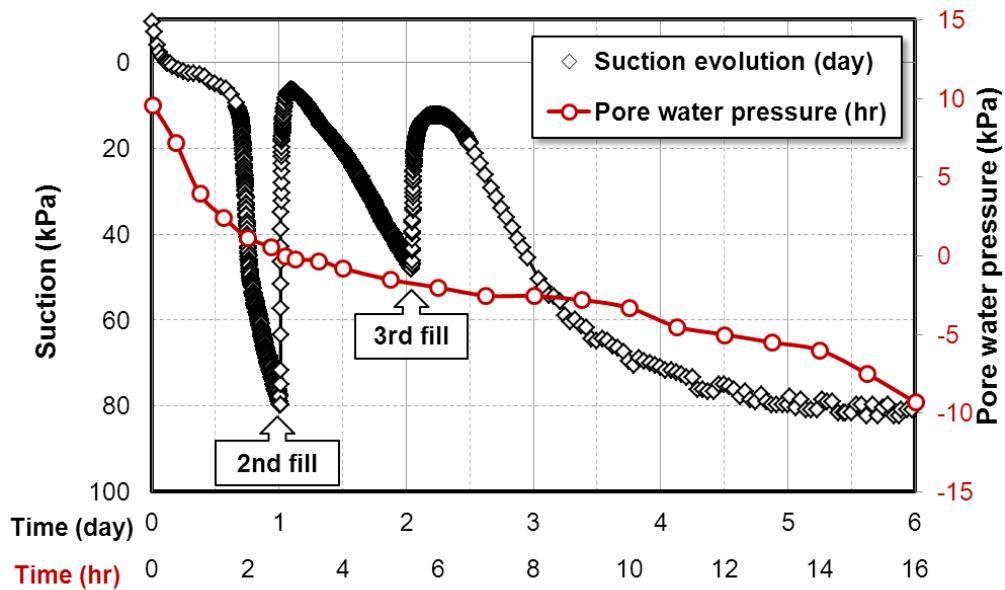


Figure 3.10. Evolution of suction and pore water pressure with time (early age)

#### - Suction

Figure 3.11a demonstrates the variation in suction within the column for a period of 150 days after commencing the filling. The first reading for the suction sensor at 25 cm was 76.7 kPa. This point of measurement is important since it was located the closest to the bottom of the column and may provide valuable information regarding the evolution of suction near the barricade at the bottom

of a mine stope. By loading the second layer after 24 hrs, the suction drops to a lower value of 44.9 kPa due to the combined effects of the increase in effective stress as a result of mechanical loading, and the drainage of water from the middle to the lower part of the column (dominating influencing factor). This is consistent with the observations made by Abdul-Hussain and Fall (2011) on similar column experiments. The authors demonstrated that high amount of water can be drained out just in the first hour after loading. However, from Fig. 3.11a, it can be seen, that by adding the third layer in the next day, the effect of drained water from the upper to the lower layer is not significant due to a longer flow distance and higher degree of cement hydration which results in more refinement of the pore structure and thus lower hydraulic conductivity as discussed later.

Only the suction readings at the column height of 75 cm are selected for further discussion. This height can be a representative point, since the middle part of the column can be drained to the lower part as well as be far enough from environmental effects (e.g., surface evaporation). By looking at the suction profiles inside the column for different curing times, a large gap was noticeable between 3 and 7 days. Just 2 days after filling the second layer, the suction reached to 68 kPa (equivalent to 42% of the final suction at 150 days). Afterward, the suction increment was about 57 kPa after 7 days of commencing the first filling; which was equal to 125 kPa around 80% of the final developed suction within 150 days. The observed behaviour is mainly attributed to the effect of heat of cement hydration on suction development. The heat accelerated cement hydration processes and therefore more water was consumed due to self-desiccation (Fall et al., 2010). This can lead to more rapid development of suction inside the CPB. Moreover, it is interesting to note that variation in suction values was not uniform inside the column. In other words, for each curing time, the suction increased from the bottom to the top of the column. It can be attributed to the drainage of water to the lower part of the column and therefore produced greater suction upwards. Upon approaching the surface, the effect of evaporation on desaturation of the pores also can contribute in self-desiccation and thus the highest magnitude of suction was achieved near the surface of the column.

In Figure 3.11b, the evolution of temperature at 75 cm is presented. It can be seen that within 2 days of casting the second layer, the temperature peaked to its maximum value. It showed the high contribution of heat of hydration in self-desiccation. However, between 2 and 7 days of curing the heat of hydration started to gradually decrease. In this period, the contribution of chemical reactions was much stronger than the temperature. This phenomenon can be supported from the pore fluid analysis which is presented in Figure 3.12. The evolution of Ca and SO<sub>4</sub> (as representative ions) showed that there was rapid reduction in their concentrations from 2 to 7 days of curing, arguing that the chemical reactions were the main source of self-desiccation. After 7 days, the very slow rate of

cement reactions such as precipitation of calcium silicate hydrate (C-S-H) and calcium hydroxide (CH) can generate self-desiccation and pore refinement in terms of long term suction development.

Figure 3.13 presents the evolution of negative PWP (suction) with time for the early hours of column filling and long term evolution. In the graph on the right hand side, the suction evolution for a period of 120 hrs is presented. The obtained results from suction sensors placed at different heights of the column showed that the rate of suction development reduced after 75 to 81 hrs of loading. By examining the evolution of suction for each layer with respect to its own filling time (i.e., excluding the filling sequence), after 27 to 33 hrs, the suction development started to slow down. In terms of the long term evolution, the suction meter installed at 25 cm showed the lowest suction value. At 75 cm, which corresponds to the middle part of the column suction development showed the average values compared to the bottom and top of the column. During the 150 days of curing the suction in the middle of the column was around 40 kPa higher than that at the bottom. This clearly showed that an increase in water content due to the drainage of water from the upper to the lower part can significantly reduce suction and thus strength gain inside the materials.

In field CPB, excess water can originate from water seepage from the surrounding media into the mine stope or/and gravity drainage of water from the upper parts to the lower parts of the stope. In such cases, the slow evolution of suction, especially close to the bottom of the stope, will result in the slow development of effective stress and thus increase the curing time to achieve the required CPB strength. This can prolong the opening of a barricade and affect the barricade design.

In terms of suction development at the heights of 125, 140 and 145 cm, a noticeable phenomenon was observed. Immediately after column loading, the highest suction value was evident at 140 cm up to 100 days. However, at 145 cm (which is close to the surface), a significant decrease in suction to values close to those observed at 140 cm after only 40 days was evident. This is because suction development at the surface was influenced by the balance between the supplied and consumed water. The accumulation of bleeding water at the surface of the column during the early ages of curing and moisture gradients from the lower part of the column toward the surface were the main sources of water (or moisture). In this case, higher water content available for evaporation caused greater differences in relative humidity ( $RH$ ) between the surface and ambient air (Abdul-Hussain and Fall, 2012). This means a higher evaporation rate ( $ER$ ) at the top of the column. The obtained results from the evaporation tests which is presented in Figure 3.16 supports this argument. From this figure, it can be seen that there was a high  $ER$  up to about 40 days. However, there was more supplied water due to moisture gradients than consumed water as a result of internal self-desiccation and surface evaporation. This can lead to lower rates of suction development at the surface up to 40 days as illustrated in Figure 3.11a. Afterwards, a decrease in the  $ER$  (between 40 to

150 days) caused a reverse in the water balance in which more water is consumed, and hence higher rates of suction development. This can be observed by the suction increase from 140 to 220 kPa between 40 to 150 days.

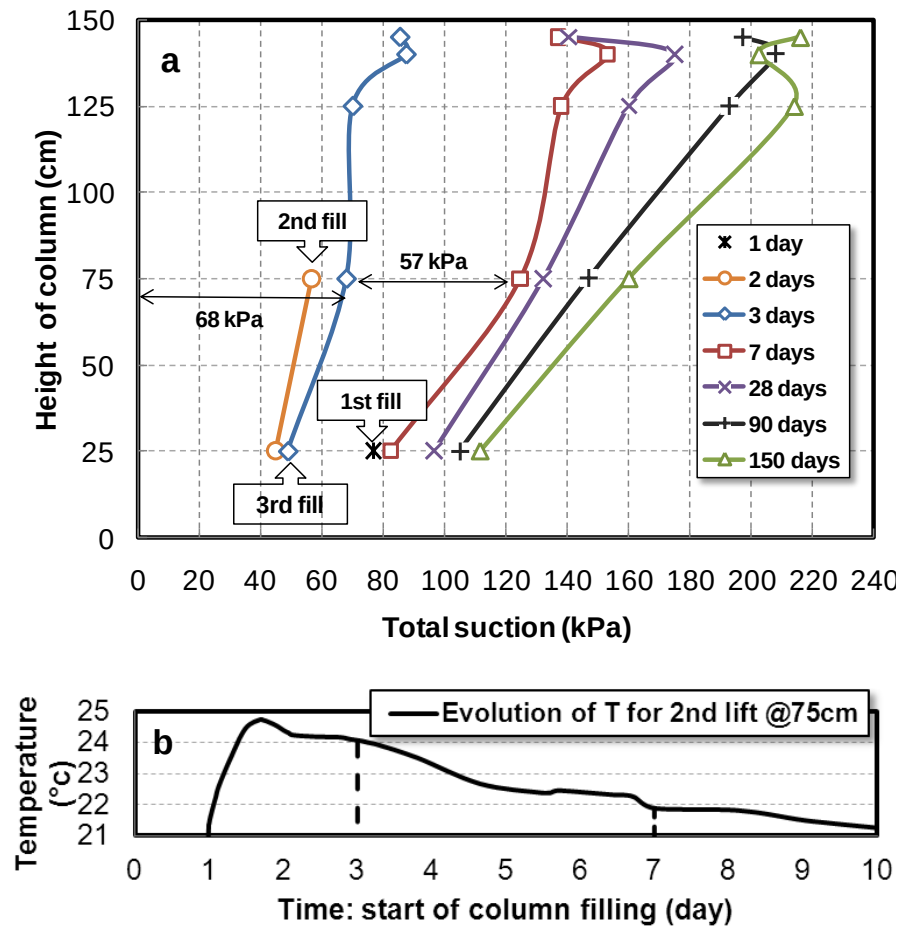


Figure 3.11. (a) Evolution of total suction in the column, (b) Evolution of temperature at depth of 75 cm

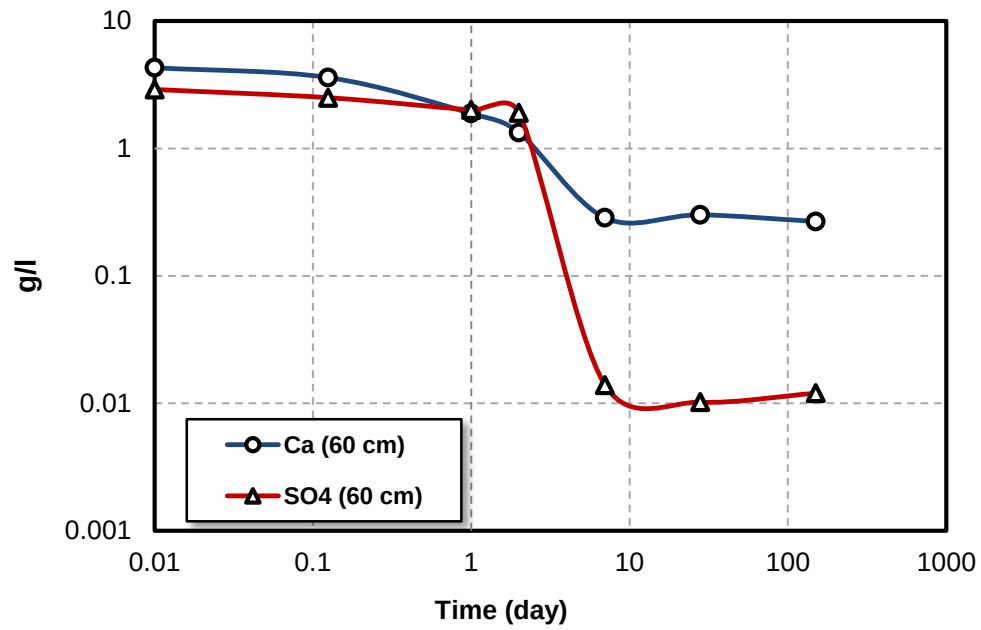


Figure 3.12. Evolution of pore fluid chemistry at depth of 60 cm

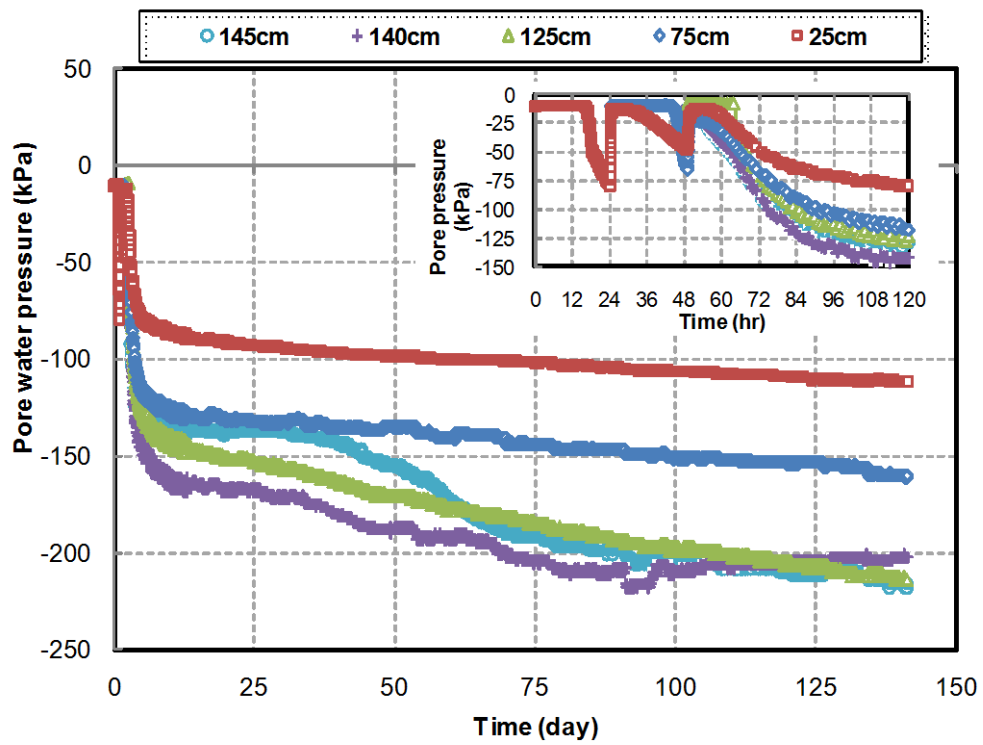


Figure 3.13. Evolution of total suction with time

### - Water retention curve (*WRC*)

The evolution of suction in CPB material by monitoring the PWP inside the experimental column showed that a few hours after column filling, the capillary pores started to desaturate due to self-desiccation. This means a change from the slurry phase to a hardening stage, and an unsaturated condition will dominate the behaviour of CPB structures. In this case, it is more rational to use unsaturated properties to describe the behaviour of CPB. For instance, if the effect of suction on hydraulic conductivity is taken into consideration, this may lead to a more realistic and appropriate understanding of CPB behaviour in unsaturated conditions. However, the measurement of unsaturated geotechnical properties of any material (e.g., soils and CPB) demands extensive laboratory work. The ability to remove water from an unsaturated porous medium can be carried out by varying the water content with suction, which is translated into a water retention curve (*WRC*). It has been proven in *WRCs* that there is a relationship between a specific soil or porous medium and unsaturated engineering properties (e.g., Fredlund and Rahardjo 1993). For example, there are several empirical approaches to predict unsaturated properties, such as hydraulic conductivity and shear strength based on the *WRC*. Figure 3.14a illustrates the *WRC* of CPB material that was cured for 7 days with respect to height. The empirical model by van Genuchten (1980) was employed to fit the best curve to the experimental data. Abdul-Hussain and Fall (2011) showed that among the numerous empirical equations to simulate *WRCs*, the model by van Genuchten (1980) was more applicable for CPB materials. It can be seen from Figure 3.14a, no significant changes in water retention behaviour with respect to height of the column can be observed for 7 days column. This showed that the variation in pore size distribution versus the height of the column did not need to be taken into consideration at 7 days of curing. Figure 3.14b shows the evolution of the *WRC* for samples cured for 7, 28 and 150 days. With increases in curing age, the *WRC* illustrates a higher range of suction. Samples cured for 150 days had higher suction than those cured for 7 and 28 days. This observed behaviour can be explained by the fact that as cement hydration proceeds, the pore size decreases as a result of an increase in hydration products. This change in pore size reduces the porosity and refines the pore structure, and thus changes the water retention properties of CPB material. This refinement of the pore structure due to the progress of cement hydration or advancement of the curing time is demonstrated by Figure 3.5 as previously discussed. Figure 3.14c illustrates the evolution of air entry value (*AEV*) with time. The *AEV* is described as the matric suction when air starts to enter the largest pores in the porous medium (Fredlund and Xing, 1994). It can be seen that the *AEVs* increased with curing time. From 3 to 7 days of curing, there was considerable increase in the *AEVs*, due to the coupling effects of the cement hydration process and heat of hydration on the refinement of pore structure and porosity reduction, where cement hydration products (Fall et al., 2009) had filled the

pores in the cement matrix of the CPB. It should be noted that still there was a considerable increase in *AEVs* between 28 and 150 days. However, with reference to the curve on suction development with time (Figure 3.13), the rate of evolution of suction inside the materials slows down before a curing time of 7 days. This suggests that the refinement of pores in the advanced ages are mainly due to increases in cement hydration products such as C-S-H, CH and ettringite with time as observed from the SEM images presented in Figure 3.15.

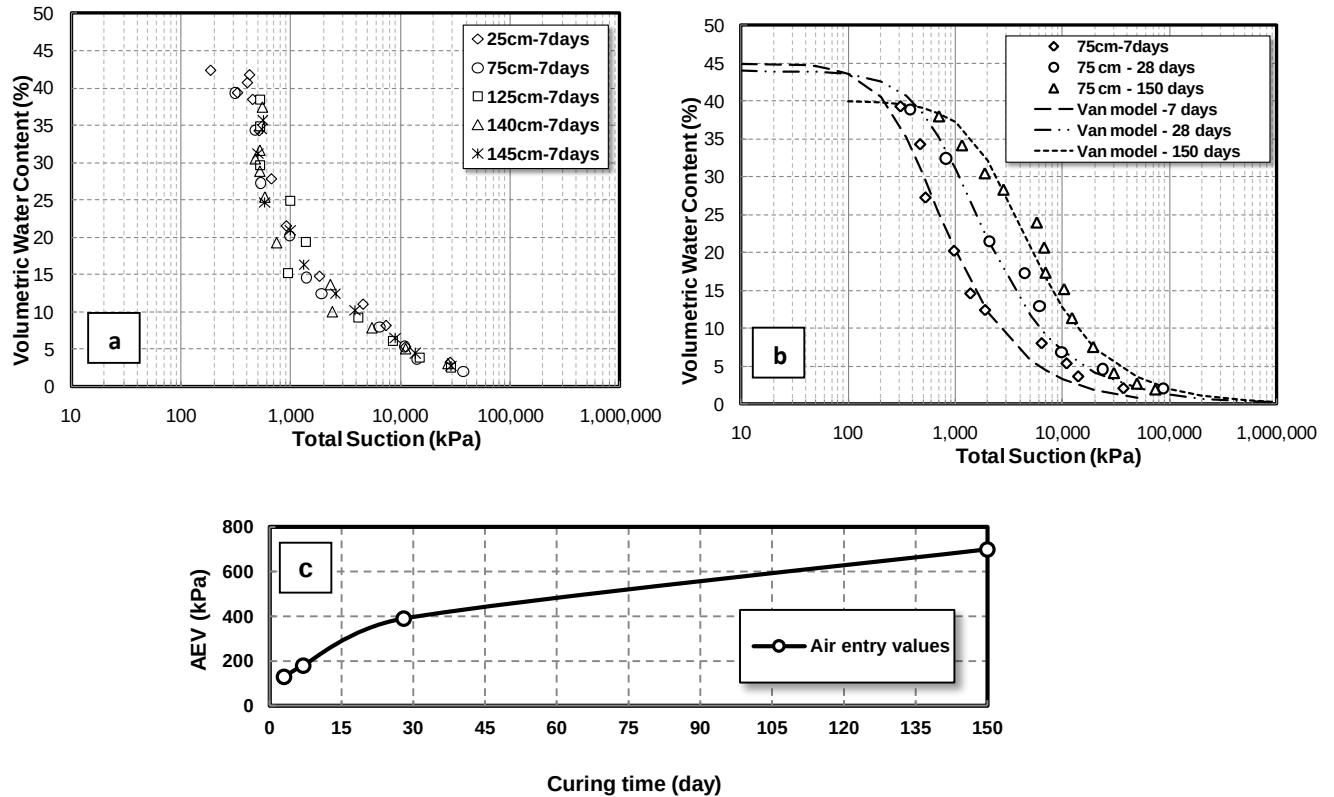


**Figure 3.14. Water retention properties of CPB materials: (a) 7 days; (b) Evolution of *WRC* at height of 75 cm; (c) Evolution of *AEV* with time**

### - Evaporation

Understanding of evaporation in CPB materials is essential to predict surface shrinkage and associated development of cracks in CPB structures that are exposed to the atmosphere. A series of experiments were conducted to determine the rate of evaporation from free water surface (potential evaporation (*PE*)) compared to that from CPB surface (actual evaporation (*AE*)). Therefore, the moisture loss from a CPB cylinder sample and a similar cylinder filled with water was measured and the results, which include the rate of evaporation and accumulative water loss, are plotted in Figure 3.16a for a period of 150 days. The average ambient temperature and relative humidity (*RH*) in the

laboratory during the test period were 20.91°C and 34.09%, respectively. The evaporation rate (*ER*) of the CPB cylinder was approximately 10.53 kg/m<sup>2</sup>day immediately after casting. The *ER* rapidly decreased during the first 48 hrs. After 10 days, the *ER* became very low and almost stable. Again, from this point up to about 40 days, the rate of evaporation gradually decreased and finally reached a relatively stable condition at 150 days. Cumulative water loss rapidly increased prior to 10 days and then gradually up to 150 days. For soil materials, evaporation is defined as a function of the vapour pressure gradient and *RH* between the soil surface and the ambient atmosphere (Wilson et al., 1997). The evaporation process depends on the material properties and climatic conditions. Evaporation in fresh CPB material has a somewhat similar behaviour to that in soil. This means that as long as CPB is in a saturated condition, evaporation can be predicted based on free water evaporation or *PE*. However, it is important to note that a reduction in the moisture due to evaporation means that CPB starts to de-saturate at the surface and hence suction starts to develop. Figure 3-16b shows the variation in the *AE/PE* with time. The *AE/PE* ratio was close to one for 12 days of curing. After that, the moisture loss from the CPB surface compared to that from free water reduced up to 40 days. From the figure, the CPB lost moisture and decreased to 50% of the free water *ER* after approximately 40 days. Then, the *AE/PE* ratio slowly decreased from 0.5 to 0.36 between 40 and 150 days. It can be seen that the rate of evaporation from an unsaturated CPB surface was less than that from saturated CPB or water. This can be attributed to the fact that under similar humidity and temperature conditions, there was less moisture transfer from unsaturated CPB surfaces with high values of suction than from saturated surfaces (Wilson et al. 1997). Reduction in availability of unbounded water at the surface and at the same time development of suction as a result of evaporation can be responsible for the *AE/PE* reduction between 12 and 40 days.

It should be emphasized that the rate of evaporation observed in this study cannot be directly implemented into field CPB without taking into consideration the variable humidity and temperature conditions in underground mines. In many underground mines, the *RH* of ambient air is relatively high. In this case, the rate of evaporation will be lower due to a low vapor pressure gradient and thus evaporation can be limited to the first few meters of a CPB structure which are generally quite large. However, when an underground mine is located in an area with ambient air that has a lower *RH*, a high rate of evaporation can indicate a high potential for surface shrinkage and crack propagation in CPB materials, which should be considered as potential mechanical and environmental performance degradation, and weakening potential in CPB materials. This issue should be studied and carefully monitored in such cases to record any surface shrinkage and cracking. As explained before, the surface cracks can act as water and air paths into a CPB structure and thus make the CPB susceptible to *AMD* and associated geoenvironmental problems.

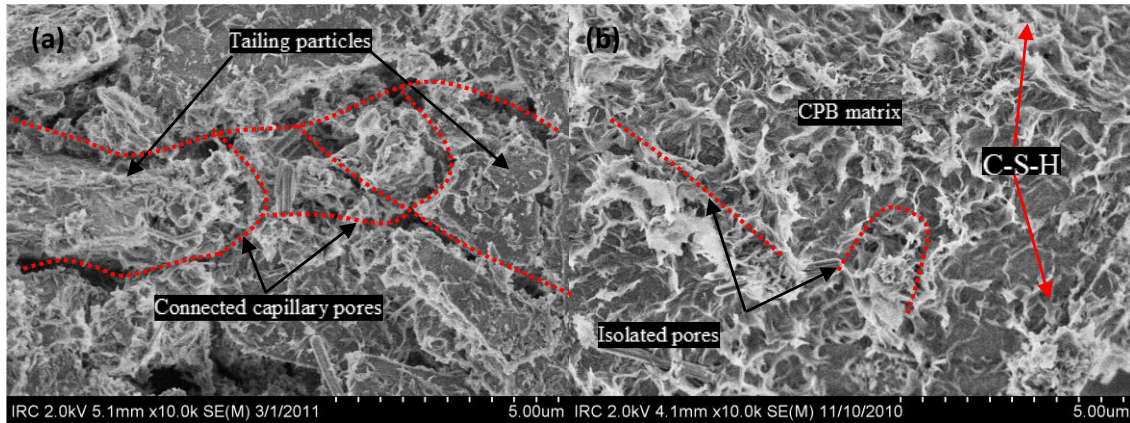


Figure 3.15. SEM images show CPB microstructure at (a) 7 days and (b) 90 days of curing

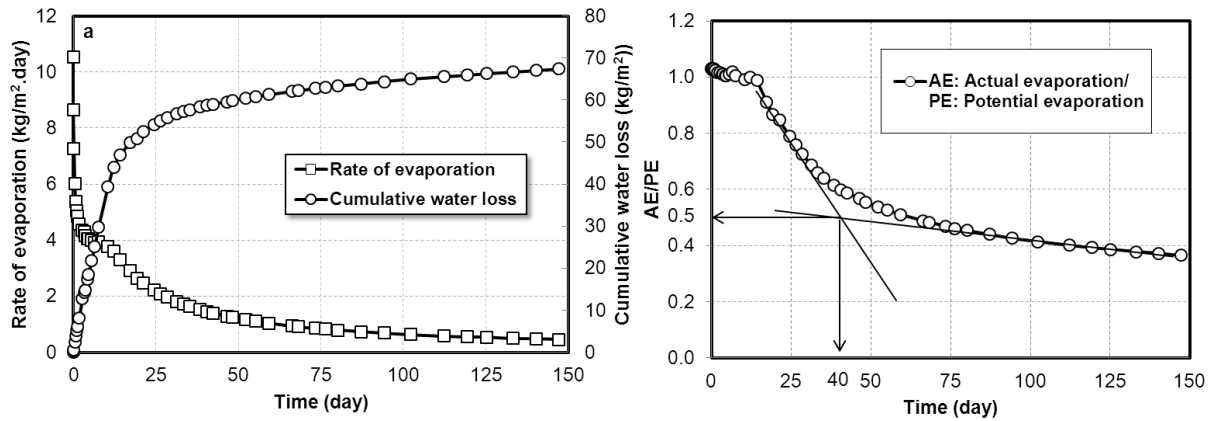


Figure 3.16. (a) Rate of evaporation and cumulative water loss with time; (b) AE/PE versus time

### 3.2.3.3. Evolution of thermal (T) properties and heat development

#### - Thermal conductivity properties

The variations in thermal conductivity for different curing times inside the column are demonstrated in Figure 3.17. As the curing time increased from 7 to 150 days, the  $k$  values decreased, which can be mainly attributed to the decrease in the degree of saturation as the result of self-desiccation (except at the top of the column). Near the surface, the  $k$  values started to significantly decrease inside the column. The variations in the  $k$  values with time and height for the samples located at the top of the column can be mainly attributed to a strong relationship between the thermal conductivity and the variations in degree of saturation induced by the combined effect of self-desiccation and evaporation. It should be mentioned that studies on concrete materials and small samples of CPB revealed that the curing time or degree of binder hydration does not have a

considerable effect on the evolution of thermal conductivity; however, the degree of saturation has a significant effect on thermal conductivity (Celestin and Fall, 2009). This is in agreement with the results of thermal conductivity versus degree of saturation, which are presented in Figure 3.18a. This is because air has a lower thermal conductivity than water; therefore, desaturation as a result of evaporation and self-desiccation followed by an increase in air voids reduces the thermal conductivity of CPB materials. So, similar to concrete material as reported by Khan (2002), the thermal conductivity of CPB increased with increase in the degree of saturation.

To predict the evolution of thermal conductivity with degree of saturation, a simple model is proposed here. A literature review conducted on the available empirical models for the thermal conductivity of soils and cement based materials (i.e., Khan, 2002; Kim et al., 2003; Côté and Konrad, 2005; Lu et al., 2007) showed that the most important parameters that can be included in a model were degree of saturation, porosity, effect of mineral content and grain size distribution for soils, and in terms of cement based materials (such as concrete, mortar and cement paste), factors such as aggregate volume fraction, moisture condition,  $w/c$  ratio and types of admixtures play important roles in their thermal properties. Celestin and Fall (2009) studies on thermal conductivity of CPB revealed that the mix parameters of CPB (e.g.,  $w/c$  ratio and binder content and binder type) have a minor effect on thermal conductivity, while the tailings physical properties (e.g., presence of quartz minerals and percentage of fine grains) have a greater contribution. Therefore, parameters include degree of saturation, porosity, and mineral composition were considered and introduced into the model. The model for predicting the thermal conductivity of CPB materials can be written as follows, which the simplified form of the equation is originally proposed by Côté and Konrad (2005):

$$k = k_{sat}S_r + k_{dry} \quad (\text{Eq. 3.3})$$

where  $k$  is the predicted thermal conductivity of the studied CPB ( $W/m^\circ C$ );  $k_{sat}$  is the thermal conductivity of CPB in saturated conditions;  $S_r$  is the degree of saturation ( $0 < S_r < 1$ ); and  $k_{dry}$  is the thermal conductivity of CPB in dry conditions.  $k_{sat}$  can be calculated from the equation proposed by Côté and Konrad (2005) as follows:

$$k_{sat} = k_s^{1-n} k_w^n \quad (\text{Eq. 3.4})$$

where  $k_s$  is the mean value of the thermal conductivity of minerals available in the tailings;  $k_w$  is the thermal conductivity of water ( $W/m^\circ C$ ); and  $n$  is the porosity of the CPB at any curing time or can be obtained from Abdul-Hussain and Fall (2011) as:

$$n(\alpha) = G\alpha + n_0 \quad (\text{Eq. 3.5})$$

where  $n(\alpha)$  is the porosity; ( $\alpha$ ) is the degree of hydration;  $G$  is an empirical material parameter that should be experimentally determined; and  $n_0$  is the initial porosity after setting has accrued. It should be noted that  $k_{dry}$  should be measured for each studied CPB material. This value for the

current study ranges between  $0.7 - 0.8 \text{ (W/m } ^\circ\text{C)}$ . The outcomes of the predicted versus measured values are presented in Figure 3.18b. It can be noticed that there is a relatively good agreement between the predicted and experimental values.

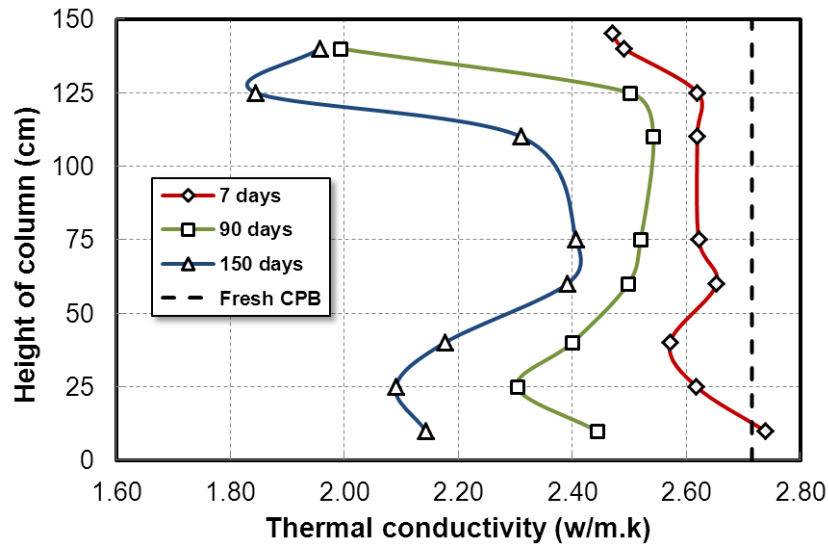


Figure 3.17. Evolution of thermal conductivity in the column and for different curing times

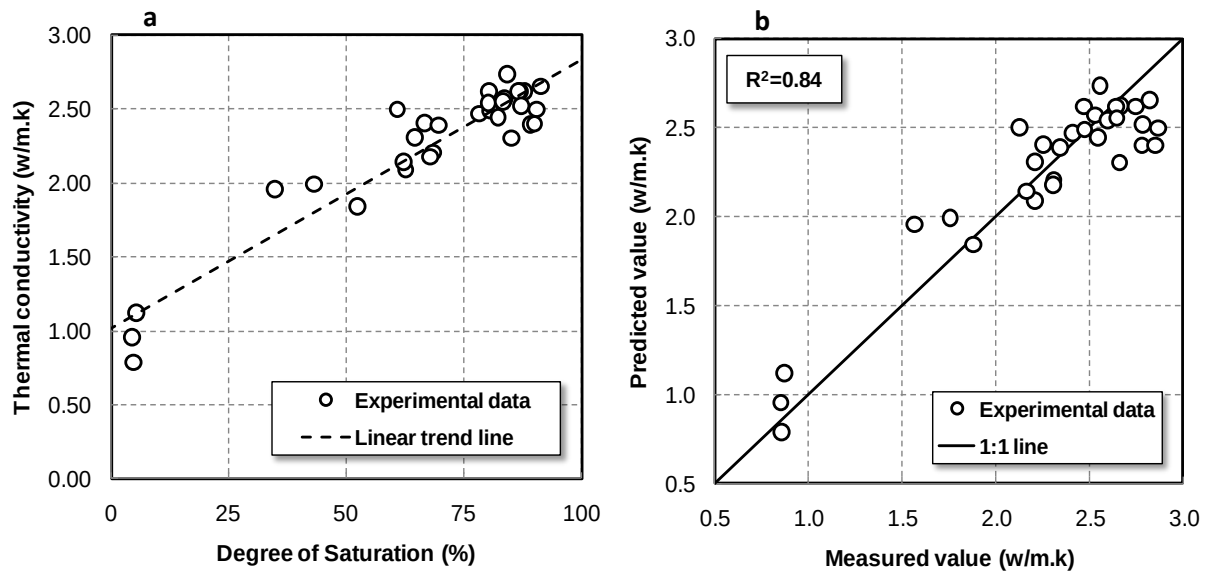


Figure 3.18. (a) Variations in thermal conductivity against degree of saturation; (b) Predicted values against measured values of thermal conductivity

### **- Heat of cement hydration**

Figure 3.19 shows the evolution of the heat of cement hydration at different column heights with time. In almost all three different layers, the heat of hydration rapidly reached the highest value around 20 hrs after CPB casting. From this point up to 72 hrs, the heat of hydration did not dissipate and therefore accelerated the cement hydration process and associated suction development. From this point up to 7 days, the CPB started to gradually cool down, but the contribution of heat of hydration is still remarkable in the evolution of the geotechnical properties of the CPB.

As discussed before in Figure 3.13, the evolution of the suction for each layer with respect to its own filling time has the highest rate of increase during the first 27 to 33 hrs after casting. As evident from both curves of suction (Figure 3.13) and temperature evolution (Figure 3.19), there is strong thermo-hydro coupled process in the CPB material. The maximum rate of suction development happened at the utmost temperature. The setting time of the CPB materials and change from a paste form to a hardening state takes place in this period of time. It is important to note that the heat of cement hydration plays a substantial role in the evolution of geotechnical properties (e.g., strength, suction) of CPB especially at very early ages. This phenomenon is more important in practice since CPB structures are often very large and the temperature of cement hydration can significantly increase (sometimes up to 50°C) inside the CPB structures depending on the binder content (Celestin and Fall, 2009; Nasir and Fall, 2009). From the Figure 3.19, it can be seen that the temperature sensor close to surface of the column showed a lower temperature compared to the middle and bottom of the column. During the evaporation process at the column surface, a large amount of heat is normally absorbed which is known as the latent heat of evaporation. As a result, there was a considerable decline in temperature at the surface up to about 65 days. Eventually, after decrease in the rate of evaporation and reaching to a thermal equilibrium, the temperature at the surface evolved into an ambient temperature. This is attributed to the close relationship of the surface temperature of the CPB with evaporation and moisture. As water loss from the CPB at the top of the column consumed some of the heat at the surface, a lower temperature at the surface can therefore be expected.

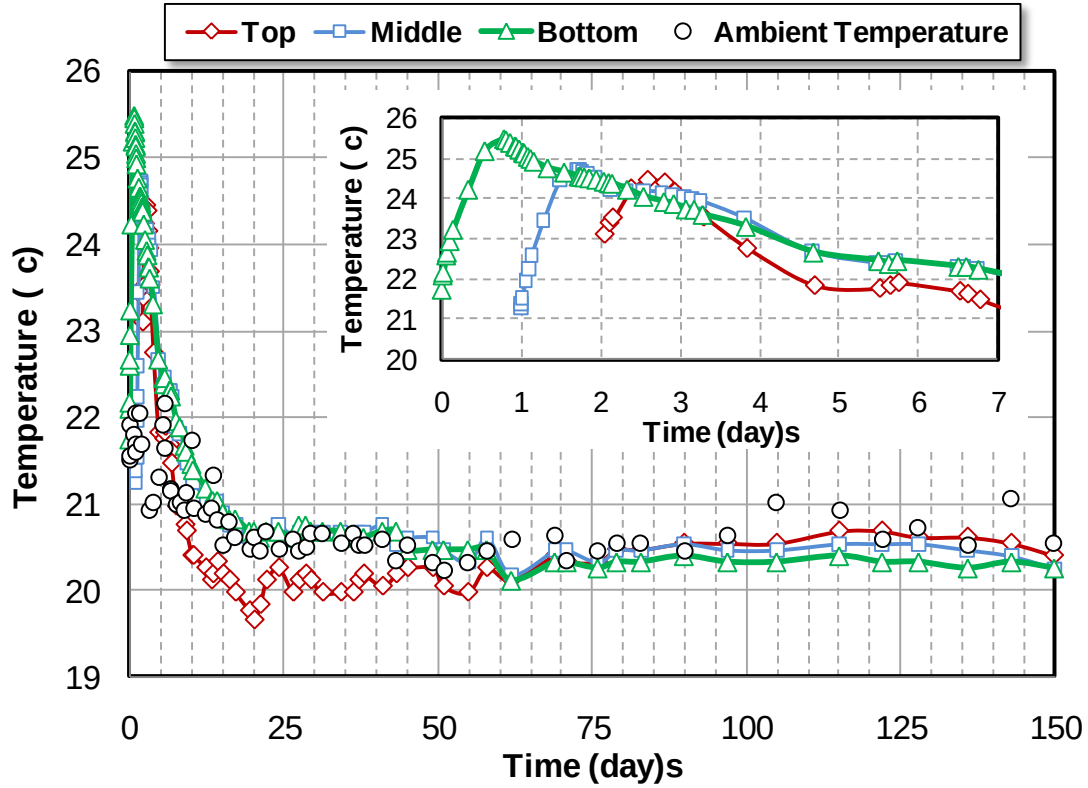


Figure 3.19. Evolution of heat of cement hydration at different heights in the column

### 3.2.4. Summary and conclusion

This chapter has presented and discussed the first part of the results obtained from investigations on the evolution of coupled THMC processes in CPB material by means of a column experiment. It focused on the coupled physical, hydraulic and thermal processes that occur in CPB. The obtained results showed that the physical properties of CPB, such as void ratio (porosity), water content and degree of saturation, are highly variable with time and height of the columns. The evolution of these properties can influence CPB performance. For example, a decrease in the void ratio can lead to a decrease in saturated hydraulic conductivity. Also, porosity and degree of saturation are two factors that control the evolution of thermal conductivity in CPB materials. Furthermore, the obtained results showed that filling sequence can affect some of the CPB behaviours or properties, such as hydraulic conductivity and evolution of suction. Drainage of water from the upper part to the lower part of the column influenced the pore pressure and suction development.

In terms of hydraulic factors, excess pore pressure was generated at the bottom of the column right after placement. A high  $w/c$  ratio in fresh CPB reduced the contact between tailings particles and therefore most of the self-weight pressure carried by unabsorbed water resulted in excess PWP at

the bottom. Suction development due to self-desiccation can be considered as a significant factor in the evolution of CPB mechanical properties. Suction started to develop 3 hrs after the loading of CPB into the column and the rate of suction development decreased after 27 to 33 hrs. Different values for suction were obtained, which range from 110 to 220 kPa from the bottom to the top of the column for 150 days of curing. It should be mentioned that the lower range of suction referred here is the result of self-desiccation due to cement hydration. A higher range ( $\geq 300$  kPa) of suction can be generated due to desaturation as the result of evaporation. A high range of suction cannot be measured by tensiometers due to limitations and the mechanism used in these sensors. The WRCs are needed to acquire a high range of suction due to evaporation.

Surface evaporation can influence the hydro-mechanical and physical performances of CPB structures. In the column experiment, this has led to the development of tensile stress and hence drying shrinkage at the surface of the CPB. In turn, drying shrinkage develops into micro-cracks. The results showed that microcracks caused increase in the saturated hydraulic conductivity at advanced ages. Also, this is an important issue with regard to AMD generation in a sulphide-rich CPB where the mine stope is exposed to environmental effects, such as evaporation.

The thermal factors of CPB play an important role in the performance of CPB structures. The heat of cement hydration (and also curing temperature) can accelerate the cement chemical reactions and hence lead to faster strength development. It can also increase the rate of suction development and decrease the setting time of CPB. This should be considered as a positive factor in backfilling strategies to reduce the stope cycle time and increase mine productivity. In terms of thermal conductivity, an equation has been proposed to obtain the thermal conductivity of CPB as a function of the degree of saturation, porosity and mineralogy of tailings.

Strength development at the early ages is a function of effective stress increase and suction development in CPB materials. In addition, a higher hydration temperature can lead to faster strength gain. The findings showed that considering the effect of drainage of mine stopes, and suction development on early age strength gain, can lead to the earlier openings of barricades and hence improve mining efficiency and production. However, it should be emphasized that the pressure generated onto barricades is very intricate and relies on several other field conditions, such as the arching effects, stope geometry, the tailings physical properties, overburden pressure, etc., which should be taken into consideration for each specific mine site. The findings of this study can be used to better understand coupled THMC behaviour in CPB materials and help to design safe, economic and durable CPB structures.

### **3.3. Technical Paper II: Coupled Thermo-Hydro-Mechanical-Chemical Behaviour of Cemented Paste Backfill in Column Experiments. Part II: Mechanical and Microstructural Processes and Characteristics<sup>2</sup>**

#### **3.3.1. Introduction**

Extraction of ore bodies from the ground creates large underground voids (stopes) which are backfilled by using appropriate materials and backfilling methods to provide ground support, dispose the tailings in a safe manner and reduce the risk of surface subsidence. Among the different methods of backfilling, cemented paste backfill (CPB) technology has become increasingly popular around the world (e.g., Kesimal et al., 2003; Sivakugan et al., 2005; Orejarena and Fall, 2008 & 2011). CPB is an engineering mixture of dewatered tailings generated during mineral processing, hydraulic binder (e.g., cement) and water. Once CPB is placed into a mine stope, cement hydration contributes to the development of mechanical stability within the CPB structure so that it remains self-supporting during the recovery of the adjacent stopes to guarantee the safety of mine workers (Yilmaz et al., 2003). Mechanical properties are considered a key factor for a safe and efficient design of CPB structures, such as unconfined compressive strength (UCS) and stress–strain behaviour (Archibald et al. 2000; Klein and Simon, 2006; Fall et al., 2007; Fall and Samb, 2009; Huang et al., 2011). These properties are significantly affected by several coupled THMC factors, such as heat of cement hydration (T), hydraulic factors (H) (e.g., suction, pore water pressure [PWP]), chemical reactions (C) (e.g., pore fluid chemistry) and mechanical (M) load (e.g., self-weight load). For instance, temperature rise due to the hydration process (or also higher curing temperature) affects the rate of UCS gain in backfills (Fall et al., 2010). Also, hydraulic factors such as suction development as a result of self-desiccation significantly influence the mechanical performance (e.g., Helinski et al., 2006; Abdul-Hussain and Fall, 2012). In addition, the physical properties (e.g., void ratio and degree of saturation) as well as CPB mix design proportion can significantly affect the mechanical behaviour of CPB (Fall et al., 2004 & 2008). There is therefore a need to understand these coupled THMC processes during the curing time of a CPB structure.

Furthermore, susceptibility to Acid Mine Drainage (AMD), which results from the oxidation of sulphide-bearing tailings, is one of the most important environmental and durability issues of backfill

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<sup>2</sup> Published in Engineering Geology (2014), 170: 11-23; Alireza Ghirian and Mamadou Fall

structures. In the case where sulphide minerals are present in the tailings used in CPB preparation, there would be a potential of reactivity of these minerals with water and oxygen which can produce contaminants such as acidic leachate and toxic heavy metals. The contaminants can be transported into the surrounding environment, where water can flow through the backfill structure (Ouellet et al., 2006; Fall et al., 2009). For CPB structures exposed to the atmosphere, drying shrinkage due to surface evaporation can lead to micro-cracks development. This in turn can create preferential water and air paths in de-saturated backfill structure exposed to the atmosphere (Holt and Leivo, 2004). It is an environmental issue when a durable CPB structure is needed to minimize susceptibility to AMD generation (MEND report, 2006). Furthermore, this is important in terms of mechanical strength degradation and fluid transport ability (Pokharel and Fall, 2011). Although the relationship between shrinkage cracks and strength loss is well documented in the concrete literature (i.e., Huo and Wong, 2006), yet to date, the effect of surface drying shrinkage and associated micro-crack development on CPB materials has not been addressed and there is the need to understand its effect on the coupled hydro-mechanical performance of CPB structures.

Chemical reactions due to the cement hydration process are one of the crucial factors in coupled THMC processes in CPB material. This hydration results in precipitation of cement hydration products into the pores, which in turn can lead to pore refinement and porosity reduction (Fall et al., 2009). This microstructural evolution contributes to the improvement of mechanical properties (e.g., strength, setting and hardening) and hydraulic properties (e.g., reduction in saturated hydraulic conductivity). There is therefore the need to understand the effects of chemical factors on coupled THMC processes in CPB materials.

The objectives of the present study are to investigate the evolution of the coupled effects of mechanical, chemical and microstructural processes on CPB behaviour, and understand the interactions of hydraulic, thermal (which are presented in section 3.2) and mechanical properties on CPB performance. Also, this research aims to address the influences of drying shrinkage on microstructural, mechanical and hydraulic performance and durability of CPB structures. Our literature review on recent studies (i.e., Belem et al., 2006; Helinsky et al., 2006; Fall and Samb, 2006; Yilmaz et al., 2009; Nasir and Fall, 2010) shows that coupled THMC interactions have not yet been addressed. This has inspired the authors to conduct the current research to study the long term evolution of coupled THMC processes of CPB by column experiments, which include the effect of curing time and use of large curing specimens compared to conventional small cylinders. The findings of this study can contribute to a better understanding of CPB behaviour, and thus lead to a more cost-effective, safe and durable design of CPB structures.

### **3.3.2. Materials, methods and experimental program**

#### **3.3.2.1. Materials**

##### **- Binder and mixing water**

In this study, ordinary Portland cement type I (PCI) was used as binder. Tap water was used to mix the binder and tailings.

##### **- Tailings**

The ground silica tailings (ST), which is made of quartz mineral (99.8% by weight) was used. The main objective of selecting the ST was to control the chemical and mineralogical composition of the tailings, and hence reduce the uncertainties of the results. Natural tailings such as sulfide-rich tailings may contain high amounts of sulfate and reactive minerals. The sulphate and these minerals can interact with cement. Moreover, these minerals can be oxidized during the preparation and curing processes of CPB. This will significantly affect the analysis and interpretation of the results (Pokharel and Fall, 2011). Silica tailings has about 45 wt. % fine particles ( $<20\ \mu m$ ) and can be classified as sandy silt with low plasticity in the ML group, according to the Unified Soil Classification System (USCS). Also, it has a grain size distribution close to the average of nine mine tailings from eastern Canadian mines.

#### **3.3.2.2. CPB preparation and mix proportions**

Required amounts of tailings, binder and water were mixed in a concrete mixer until a homogeneous paste was obtained. The mixing time was 10 min. The mix proportions adopted for this study were 4.5% PCI and a water to cement ratio (w/c) equal to 7.6. The slump or the consistency of the paste mixtures was equal to 18 cm, which is the most frequently used slump value in CPB preparation.

After the CPB mixtures were produced, the columns were filled up with the fresh backfill to the height of 150 cm in three filling sequences of 50 cm each. Each lift was allowed to set for 24 hrs, and then a new layer was added. This filling strategy allows us to understand the effect of several factors, such as filling rate, filling sequence, formation of a plug and unexpected backfilling interruption on CPB behaviour. The w/c ratio, cement proportions and slump value were kept constant in all of the mixes used to fill the columns.

### **3.3.2.3. Experimental set-up of the column experiments**

A schematic diagram of the column experimental set-up is shown in Figure 3.2. The columns were constructed with cardboard form tubes with 20 cm inner diameter and 150 cm height. To construct each column, a tube with 20 cm diameter was placed in a tube with 30 cm diameter. The gap between them was then filled with expansive insulating foam sealant. It prevented any thermal interactions of the CPB mixture with the surrounding environment. The bottom of the column was fitted with an impermeable cap to maintain an undrained condition. The top of the column was open to atmosphere in order to consider the effect of evaporation on THMC behaviour of CPB. It allowed us to simulate a backfilled mine stope conditions such that the surface of the backfill is exposed to the environment, while the sides and the bottom are surrounded by the adjacent rocks. Temperature and relative humidity of the curing room was continuously measured. In total, six columns were manufactured which comprised two columns for instrumentation and four columns for sampling purposes at 7, 28, 90 and 150 days. Each column was dismantled over a period of three days and then CPB samples were taken from different heights: 10, 25, 40, 60, 75, 90, 110, 125, 140 and 145 cm for the experimental testing program.

In order to prepare the samples with the required size for the different laboratory tests, the insulating layer was first removed and then the column was mechanically cut into small parts at the different heights mentioned above. Immediately, samples were taken for moisture content and density measurement at different heights. Then required samples for the engineering tests, such as uniaxial compressive strength (UCS), saturated hydraulic conductivity, direct shear tests were trimmed with coping saw and spatula into required size and shape. The whole column dismantling procedure was carried out in less than 3 hrs in order to minimize moisture loss and samples oxidation. All the samples were kept in sealed plastic bags and cooler until tests. To determine the index properties of each sample, measured moisture contents were transformed into saturation degrees, based on the weight of water, solid parts, initial void ratio and specific gravity. Bulk density and porosity were determined gravimetrically. The time-dependent evolutions of the physical properties are detailed in technical paper I (Section 2.3).

### **3.3.2.4. Column instrumentation and monitoring**

Monitoring columns were equipped with various sensors in order to investigate the variations of temperature, pore pressure, suction and settlement in different height of the column. The design locations of the sensors, filling sequence and sampling locations are illustrated in Figure 3.2. The sensors were connected to a data acquisition system. Temperature sensors (model TH-T) were installed in the middle of each layer at heights of 25, 75 and 125 cm to monitor the temperature

evolution due to cement hydration reactions. Dielectric water potential sensors, model MPS-1, were installed at heights of 25, 75, 125, 140 and 145 cm. It allowed us to monitor the suction evolution within the CPB. A WP2100 vibrating wire piezometer was calibrated and installed at the 15 cm depth to measure the evolution of the pore pressure with time. To measure settlement due to the self-weight pressure as well as vertical drying shrinkage due to evaporation, a *LVDT* was installed at the top immediately after pouring the last layer into the column. The details of the monitoring results of the temperature, pore pressure and suction are presented in technical paper I (Section 2.3).

### **3.3.2.5. Experimental test program**

#### **- Microstructural tests**

A series of microstructural analyses that included examination of the pore structure and evolution of binder hydration products was carried out. The microstructure of the studied CPB samples was investigated by mercury intrusion porosimetry (MIP) and SEM observations. The SEM observations were carried out with a Hitachi S4800 field emission microscope. The samples were first dried at 50°C up to mass stabilization in a vacuum oven to remove the free water. The SEM observation was performed with many different magnifications to study the particle size distribution, texture of the CPB and morphology of cement hydration products. MIP tests were performed by PMI Mercury/Nonmercury Intrusion Porosimeter to evaluate pore size distribution and total porosity. Prior to tests, all samples were first oven dried at 50°C until mass stabilization. Drying at this temperature did not appear to cause cracking. MIP testing and SEM imaging were implemented on 4 samples taken from the column at heights of 10, 60, 110 and 140 cm at 7 and 150 days of curing. In addition, extensive physical testing was conducted to understand the evolution of the void ratio or porosity from early to advanced ages. Void ratio ( $e$ ) and porosity ( $n$ ) were determined for the entire columns.

#### **- Analysis of the pore fluid chemistry**

Pore fluid chemistry analysis was performed on CPB samples to understand the evolution of the pore fluid ion concentrations with time. Seven specimens were sampled from height of 60 cm and at the ages of 0 hr, 3 hrs, 1, 2, 7, 28 and 150 days. In addition, 3 samples from a height of 10 cm and at the ages of 1, 2 and 150 days were sampled from the columns in order to investigate the evolution of the pore fluid chemistry with time and within the column. For the samples less than 7 days, the 40 mm diameter hole saw was employed to extract the samples from the column and the holes were then refilled immediately with insulation foam. 0 hr sample was taken directly from the fresh CPB mixture after its preparation in the mixer. Pore fluids were then extracted from the CPB samples by using the

steel die high pressure (squeezing) technique and pressure up to 120 N/mm<sup>2</sup> which is similar to that described by Longuet et al. (1973) and Barneyback and Diamond (1981). The squeezer apparatus was designed and manufactured at the University of Ottawa specifically for CPB applications. Water samples collected from the squeezer were immediately filtered at 0.1 µm and stored at 4 °C until analysis. The total concentration of various major cations (e.g., Mg<sup>2+</sup>, K<sup>+</sup>, Al<sup>3+</sup>, Ca<sup>2+</sup>, Na<sup>+</sup>, Fe<sup>2+</sup>), anions (e.g., hydroxide (OH<sup>-</sup>), SO<sub>4</sub><sup>-</sup>) and pH were determined for each sample. The concentrations of elements analyzed were determined by the inductively coupled plasma atomic emission spectroscopy (ICP-AES) method. Sulphate (SO<sub>4</sub>) concentrations were also measured by the automated colorimetry method.

### **- Mechanical tests**

The mechanical tests included unconfined compression strength (UCS) and direct shear tests. They were performed on the CPB specimens at 7, 28, 90 and 150 days and at different heights of the columns. A minimum of two samples were tested in order to ensure the repeatability and reliability of the results. UCS tests were conducted according to ASTM C39, by means of a computer-controlled mechanical press. The compression tests were carried out at a constant deformation rate of 1.14 mm/min. Despite some inherent problems (e.g., principal stress rotation, stress non-uniformity, failure plane definition), direct shear test was carried out to measure the shear strength properties, because of its simplicity and efficiency in conducting all of the required tests on each layer and on the same day. The tests were performed in accordance with ASTM D3080-04 (2011) at a controlled strain rate of 1.0 mm/min. A minimum of 4 specimens were tested, each under a different normal load, to determine the effects on shear resistance and displacement, and strength properties, such as Mohr strength envelopes. The repeatability of the results was verified by performing each test twice.

## **3.3.3. Results and discussion**

### **3.3.3.1. Evolution of mechanical (M) properties**

#### **- Unconfined compressive strength (UCS)**

Unconfined compression tests were conducted on approximately 70 CPB samples for different curing times. Figure 3.20 presents the variations in UCS against different heights of the column at the curing times of 7, 28, 90 and 150 days. It can be observed that the UCS values for all of the column heights increase with time. This time-dependent increase in strength is due to the combined effect of the progress of cement hydration (increase in cement hydration products) and suction development

within the CPB as discussed below. Moreover, the variations in UCS seem to be dictated not only by the curing time and the self-weight pressure, but also by the sequence of filling. The first layer of filling (0-50 cm) shows lower values of UCS compared to the second layer (50-100 cm) for 28, 90 and 150 days of curing. This behaviour can also be observed from the different rates of suction development inside the column (Figure 3.21). Second layer can drain its water (because of gravity) through the sub-layer and therefore behaves as a drained (or partially drained) material. This resulted in a lower rate of suction development at the bottom of the column (as shown in Figure 3.21) and associated lower rate of strength development. Figure 3.22 demonstrates the variation of UCS against the effective void ratio. The concept of effective void ratio ( $e'$ ) was originally proposed by Jongpradist et al. (2011) and rewritten into a new format in this study. They explained that with a wide range of water content and in unsaturated conditions, both void ratio and water content values should be considered to describe volume changes. It can be observed from Figure 3.22 that the UCS value increases while the effective void ratio decreases. A good correlation between the evolution of the UCS and void ratio (thus porosity) reduction as a result of the pore refinement is noticeable ( $R^2 = 0.8$ ). Due to the cement hydration reactions, capillary pores in the CPB matrix were filled by cement hydration products and hence the void ratio decreases with time. This process led to a dense matrix and increase in UCS values. The laboratory test findings were supported by the SEM images which will be discussed in a later section. Also, it can be seen that the relationship between the effective void ratio and the UCS for each curing time is not a perfect match. This means that aside from the reduction in porosity or void ratio induced by cement hydration, additional factors significantly affect the UCS. One important factor is the suction development within the CPB column.

Figure 3.23 illustrates the evolution of the UCS against suction with respect to the different heights and curing times, respectively. From Figure 3.23a, it can be noticed that an increase in suction has led to an increase in UCS values at different heights of columns. In other words, there is hydro-mechanical coupled relationship. Also, the variation of UCS–suction is not uniform inside the column. A lower value of UCS–suction at the bottom (height of 25 cm) can be associated with the accumulation of drained water from the upper lifts and hence lower rate of suction development as shown in Figure 3.21. A significant growth in suction for the samples close to the top of the column and for curing times of 90 and 150 days can be noticed (Figure 3.21). This can be attributed to both the effect of self-desiccation and evaporation on suction development. As a result of the increase in suction, the mechanical properties increase. It is well understood that suction development can lead to an increase in the material strength in the unsaturated state (Fredlund and Rahardjo, 1993). Suction development can decrease the pore pressure and thus increase the effective stress inside the CPB material (see section 3.2). Figure 3.23b presents the evolution of UCS versus suction from a different

point of view. From this figure, it can be observed that at curing times of 7 and 28 days, there is an increase in the UCS with suction development. However, at 90 and 150 days, the maximum values of UCS can be observed in the middle of the column (height of 75 cm) and then a reduction in the UCS is noticeable even with existing high rates of suction. These points are marked on Figure 3.23b with a dashed line. This behaviour can be related to the effects of shrinkage and crack developments on the strength loss of the CPB samples. Micro-cracks can cause mechanical degradation and thereby reduce the mechanical strength. The obtained results from the SEM observations support this argument and will be discussed later in more detail. The current findings clearly show that neglecting the effect of suction in the estimation of material strength can lead to a conservative approach and overdesign of a CPB structures.

Figure 3.24 illustrates the coupled hydro-mechanical behaviour of CPB material. A direct relationship exists between the UCS and the hydraulic conductivity at any curing time. The results show that evolution of the UCS is an evidence of the progress of binder hydration and microstructure development, and hence strongly affects the hydraulic conductivity. Fall et al. (2009) proposed a model to predict the time dependent evolution of saturated hydraulic conductivity based on the UCS values:

$$k_{sat} = k_T \cdot A \cdot (UCS_t / UCS_{max})^B \quad (Eq.3.6)$$

where  $k_T$  is the saturated hydraulic conductivity of the tailings used,  $UCS_t$  (kPa) is the UCS of hardening CPB for a given time,  $UCS_{max}$  (kPa) is the maximum UCS of the CPB (considered as the UCS of 150 day CPB sample in this study); and A and B are dimensionless fitting parameters to be determined for each mix. As can be observed, a good correlation ( $R^2=0.84$ ) exists between the obtained experimental data.

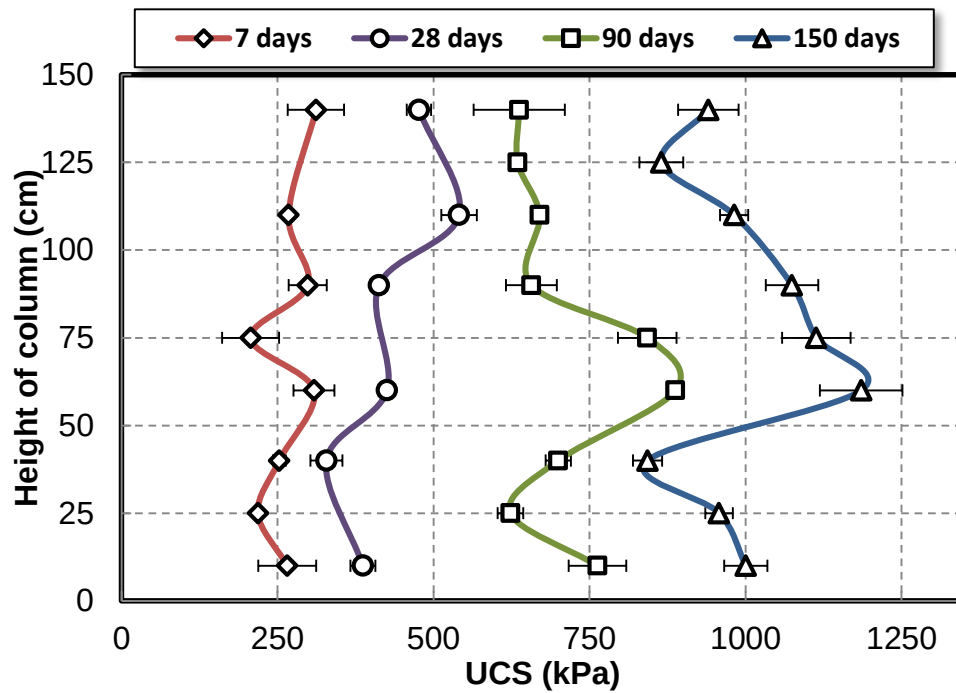


Figure 3.20. Evolution of UCS within the column for different curing times

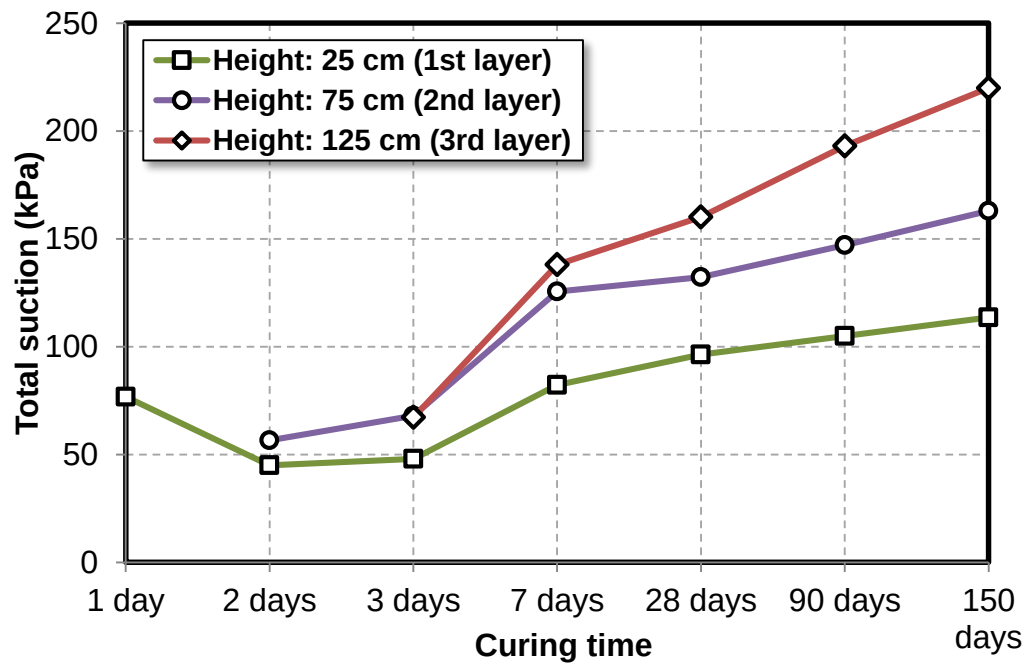


Figure 3.21. Evolution of the total suction at different heights of the column for different curing times

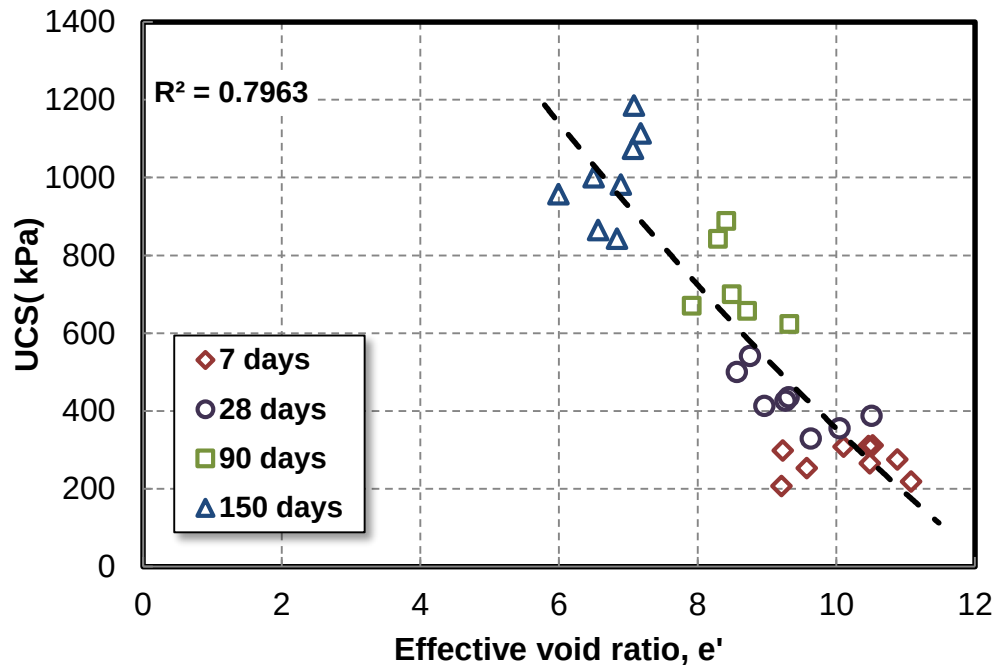


Figure 3.22. UCS against effective void ratio,  $e'$  ( $e' = \omega \times \ln(e/c)$ ,  $\omega$  is the gravimetric water content,  $e$  is the void ratio for specific cured samples and  $c$  is the cement content)

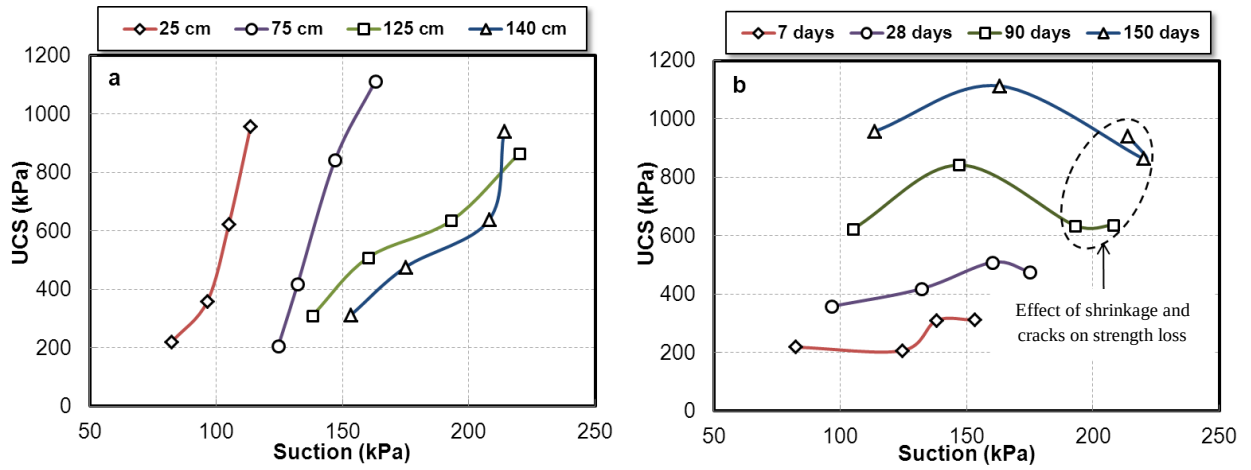


Figure 3.23. Variation of UCS with suction with respect to (a) height and (b) curing time

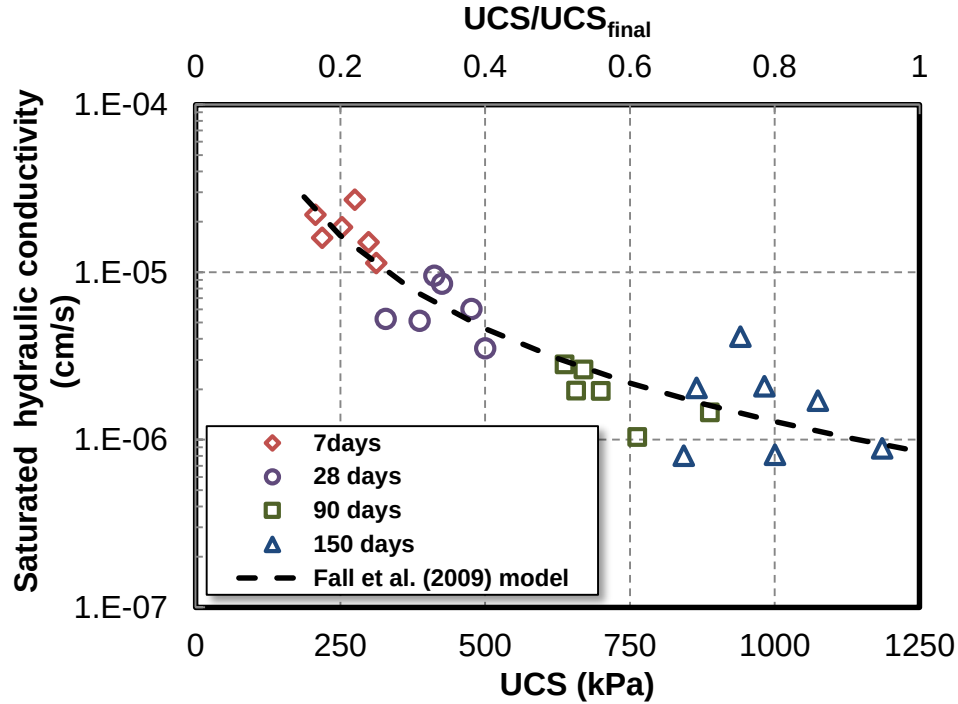


**Figure 3.24. Coupled H-M behaviour of CPB material in column experiment**

#### - Modulus of elasticity

Figure 3.25a and 3.25b show the evolution of the modulus of elasticity ( $E$ ) obtained from the UCS test for different column heights and time. The secant modulus of elasticity in a stress-strain curve at half of the unconfined compressive strength was considered in calculating  $E$  values. It can be observed that as the binder hydration progresses or the curing time increases, the  $E$  value increases except at the top of the column for curing time of 150 days (will be discussed later). It can be also seen that the  $E$  values remain almost constant along the column height for curing time of 7 days. However, from 28 to 150 days, significant variations of the  $E$  values are observed from the bottom to the top of the columns. Overall, the middle part of the column (50-100 cm) shows higher modulus of elasticity values compared to the lower and upper parts for curing time above 28 days. These higher  $E$  values can be attributed to the combined effects of the drainage of water from the middle layer to the sub-layer and the self-weight pressure as previously explained. Once the middle layer was loaded into the column, the excess water (added during the mixing) can be drained due to relatively high permeability of the unhardened CPB. A decrease in modulus of elasticity can be observed at the top of the column cured for 150 days. It can be attributed to the effect of evaporation on the mechanical properties of CPB materials. Surface evaporation has induced the development of tensile stresses and therefore shrinkage and micro-crack propagation. The SEM images of the samples obtained from the

surface of the 150 days column support this argument. The SEM results will be discussed in a later section. These cracks affect the modulus of elasticity of the CPB samples that were taken close to the surface.

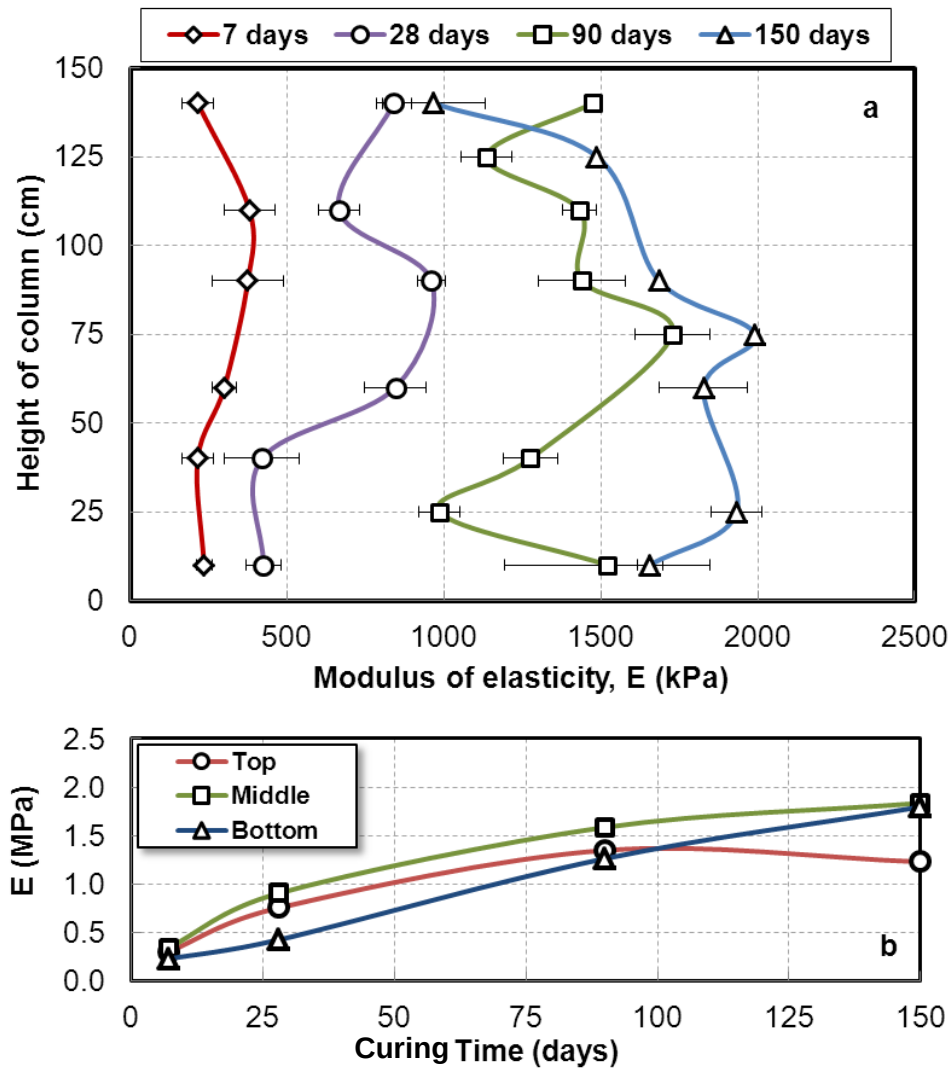


**Figure 3.25. Evolution of modulus of elasticity (a) within the column and (b) at different curing times**

#### - Stress-strain behaviour

The stress-strain properties of CPB samples were investigated for different curing times. Figure 3.26 illustrates some typical stress-strain curves that are the results of the UCS tests. It can be observed that the shape of the stress-strain curves is affected by the curing time. For example, the peak stress is achieved for larger strain values of the CPB specimens at 7 and 28 days compared to the advanced ages (90 and 150 days). The slope and shape of the stress-strain curves change with increases in the UCS values. It can be seen that this results in higher modulus of elasticity for samples

at 150 days compared to 7 days. Also, the CPB samples at early ages show a plastic behaviour, but transitions into more brittle deformation at 150 days which corresponds to higher UCS values. The aforementioned behaviour can be attributed to the fact that the CPB sample at an advanced age has a higher value in strength and hence can absorb more energy up to the peak stress compared with that at early ages. This can result in the propagation of cracks and rapid deformation at the time of failure, and therefore a sharp reduction in stress-strain curves (Fall et al., 2007).

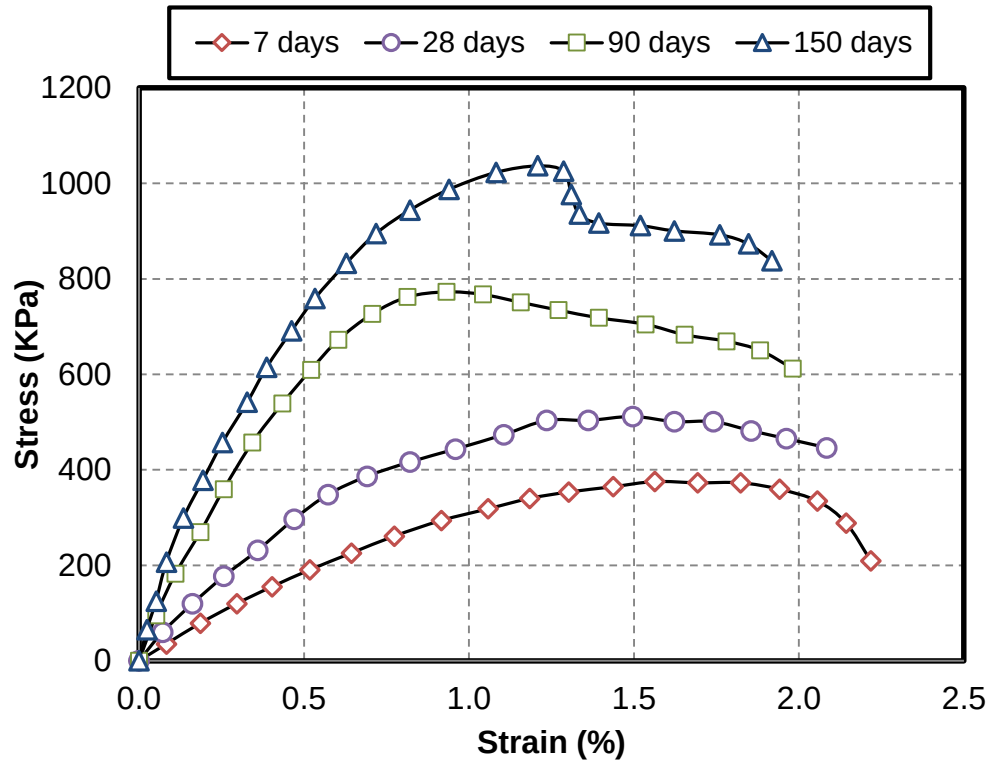


Figure 3.26. Typical stress-strain curves at different curing times

#### - Shear strength parameters

Shear strength parameters which include friction angle ( $\phi$ ), and cohesion ( $c$ ) were determined from direct shear tests conducted on the CPB samples and the results are plotted in Figure 3.27. It should be noted that in the current experiments, almost all values of cohesions obtained from the direct shear tests are approximately half of the UCS values. Also, it can be seen that there is no significant change in  $\phi$  values with time. The average value of  $\phi$  is  $46.1^\circ$  for all the curing times. This means that the evolution of shear strength is mainly governed by the development of cohesion rather than internal friction. In other words, the strength parameter mainly responsible for the

evolution of shear strength is the cohesion or bonding between the tailings particles as a result of cement hydration.

Le Roux et al. (2005) reported  $\phi$  values between  $32^\circ$  and  $37^\circ$  based on triaxial test results conducted on undisturbed samples cured for 90 days obtained from a CPB mine stope. Rankine and Sivakugan (2007) reported  $\phi$  values between  $31.7^\circ$  and  $44.1^\circ$  for CPB samples cured in plastic moulds for 7 and 28 days. The obtained result from the column experiments showed similar to slightly higher  $\phi$  values compared to the field values. These slightly higher values can be attributed to the different types of tailings and binder content. From Figure 3.27, it can be seen that cohesion considerably changes with curing time and reaches the highest value at 90 days of curing. Also, cohesion of the middle part of the column shows the highest values compared to the bottom and top. This should be partially attributed to drained conditions, stronger bonded particles and more strength gain in the middle of the column. The results of the suction monitoring showed higher rates of suction development in the middle of the column compared to the bottom (Figure 3.21), which can lead to greater  $c$  values. In addition, this part was not affected by surface shrinkage and associated deterioration as it occurred for the upper part of the column. From Figure 3.27, it can be observed that effective cohesion reaches a maximum value at 90 days and then decreases to a lower value at 150 days. The top part of the column loses around 40% and 20% of  $c$  and  $\phi$  values, respectively. This is due to the effect of surface drying shrinkage and crack development due to the advanced curing age and therefore, strength deterioration of the CPB. Observation of SEM images also showed the development of micro-cracks and changes in the microstructural characteristics. This can be an important issue where drying shrinkage and cracks occur, such as mine stope surfaces that are exposed to the atmosphere, and the interface of CPB and surrounding rock walls. Interface properties between the CPB/rock mass play a significant role in the mechanism of the load transfer from CPB to rock walls, which is known as the arching effect (Nasir and Fall, 2008). Significant arching reduces the vertical stress development inside CPB mass to a lower value of self-weight stress (Li et al., 2003). Drying shrinkage at the CPB/rock interface can lead to a decrease in shear strength parameters and thus overestimate the design of the arching effects and stress distribution in the CPB structure, and can result in potential failure. This issue should be taken into consideration where there is a high risk of drying shrinkage in a mine stope.

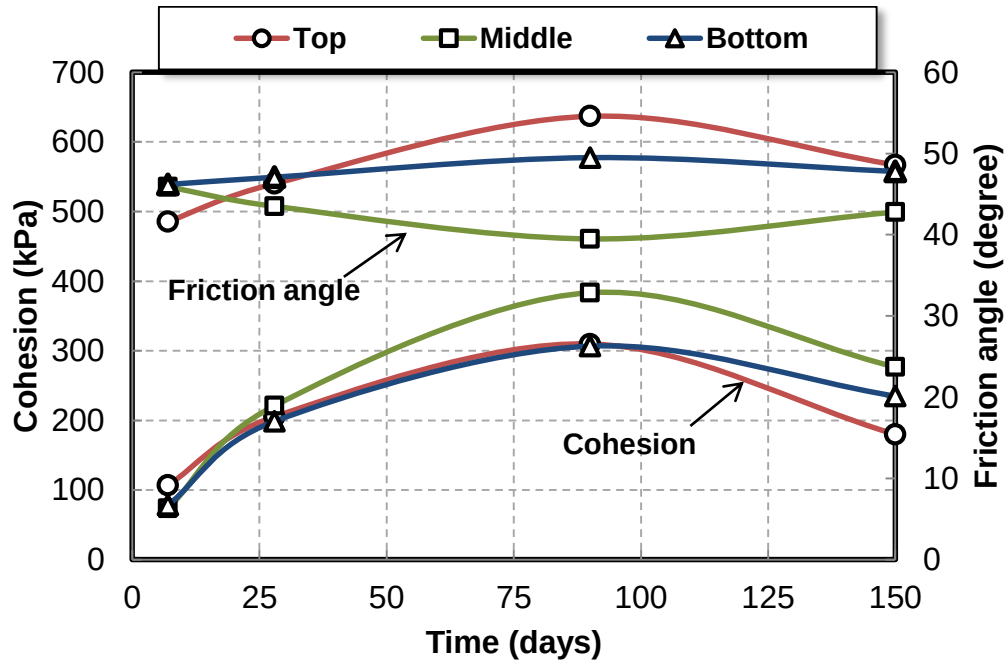


Figure 3.27. Evolution of shear strength parameters in the column and for different curing time

#### - Vertical settlement

Figure 3.28 demonstrates the results of vertical settlement with time right after finishing the column loading. The settlement reaches the highest value (8.6 millistrains) 2.5 hrs after placement, followed by lower increments up to 8 hrs and eventually maintains almost a straight line with time. This settlement behaviour is due to the coupled effect of self-desiccation and self-weight pressure. At very early ages, effective stress is reduced to a very low value due to the high development of excess pore water pressure (PWP) and self-weight pressure of the CPB material can consolidate the pore voids generated due to self-desiccation. Due to the undrained conditions in the column experiment, the consolidation mechanism is not similar to conventional consolidation where excess pore water can be drained by applied or/and self-weight pressures. In CPB materials, self-desiccation dominates pore pressure changes during cement hydration processes in undrained condition. The coupled processes lead to high rates of vertical settlement at very early ages. Then, due to cement hydration progress and dissipation of the PWP, rapid development of suction due to self-desiccation takes place (Figure 3.21). In turn, mechanical properties (e.g., strength, stiffness) starts to build up and hence the vertical settlement can no longer be significantly affected by the self-weight pressure. Therefore, vertical settlement reaches to an almost constant value during advanced curing time.

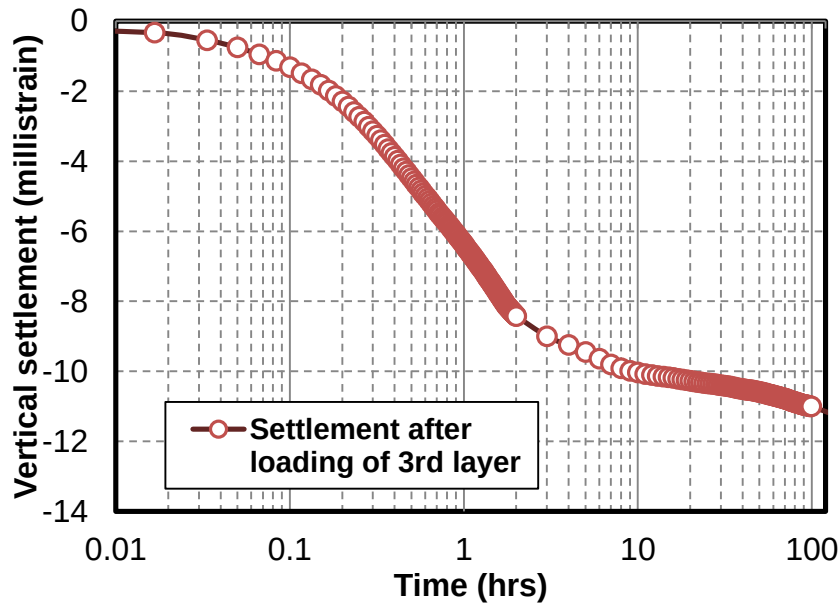


**Figure 3.28. Variation of vertical settlement with time**

#### **- Shrinkage and cracks**

There are different types of shrinkage that take place in cementitious materials. For example, autogenous shrinkage is a type of deformation that occurs at constant temperatures without moisture transfer to the surrounding environment (Barcelo et al., 2005). Drying shrinkage is the volume change which results from water loss to the environment due to evaporation. Other types of shrinkage can occur, such as thermal and carbonation shrinkage, which are mostly considered in long-term behaviour (Holt and Leivo, 2005). The shrinkage of the upper part of the columns is related to the loss of moisture due to evaporation which can be considered as drying shrinkage. A higher moisture loss can generate a greater magnitude of drying shrinkage. This normally happens in cement based materials with a high w/c ratio because there is more unbounded water (Holt and Leivo, 2004). After backfill placement, the degree of saturation decreases with time as a result of surface evaporation and self-desiccation, and hence the air permeability increases. In this case, preferential air flow may develop where drying shrinkage occurs near the surface and/or rock-stope boundaries, and therefore the CPB can be deteriorated by sulfide oxidation (i.e., chemical reactions of sulfide minerals with oxygen).

The column studies showed that the effect of evaporation is limited to the surface of the column and also depends upon the relative humidity (*RH*) of the ambient environment (see section 2.3). The magnitude of the drying shrinkage should be individually studied for specific mine stopes to understand the depth of the cracks and air/water flow path into the materials. After mine closure and

flooding of the area, the groundwater can flow to the mine area and contaminants may transfer through the CPB to the groundwater. The durability of a CPB structure is primarily controlled by the surface area and surrounding rock-CPB structure interface. These two regions can provide a protective barrier against the entry of undesirable fluids and therefore should be protected against drying shrinkage and cracks (MEND report, 2006). The understanding of the environmental effects on the performance and durability of CPB structures is still far from complete. Susceptibility to Acid Mine Drainage (AMD) and leakage of contaminants into the mine areas are important environmental design criteria for CPB structures. The ability of AMD generation is related to the presence of reactive tailings in the CPB as well as the ability to transfer fluids (e.g., water and oxygen) through the CPB matrix (Fall et al., 2009).

The drying shrinkage of CPB materials has not been addressed in the literature so far. To understand this behaviour, long term monitoring of drying shrinkage and micro-cracks on the CPB surface was conducted with the CPB column after measuring the CPB settlement as a result of self-weight pressure. The results for 150 days are plotted in Figure 3.29. It can be seen that the drying shrinkage starts at the curing time of 6 days and increases to less than 3.5 millistrains after 150 days of curing. The shrinkage strains show a lower rate of increase after 65 days. The current study shows that CPB materials can experience high magnitudes of shrinkage at early ages. Free shrinkage magnitude above 1 millistrain is associated with a high risk of cracking in concrete materials (Holt and Leivo, 2004). Therefore, there is the need to investigate the development of cracks at a micro-scale. The possibility of propagation of surface cracks was studied by conducting SEM image analysis on a CPB column that was cured for 150 days. The SEM image results for two different samples obtained from the surface and 10 cm below the surface are presented in Figure 3.30. It can be seen that there are scattered air voids throughout the entire CPB matrix. The presence of empty air voids are mainly due to surface evaporation. Also, these images show well-developed void spaces and micro-cracks inside the CPB matrix. Moreover, interfacial shrinking zones between tailings particles and hardened cement paste products can be considered as the weak zones for crack propagation. The main cause of these cracks is that the cement paste shrinks during the evaporation process and hence micro-cracks can develop in the CPB medium, especially in tailings particles and cement paste interfaces. It is important to point out that this finding clearly accounts for the higher values of hydraulic conductivity in the upper part of the column. It is found that the average value of hydraulic conductivity is  $2.75 \times 10^{-6}$  cm/s for the upper part,  $1.3 \times 10^{-6}$  cm/s for the middle part, and  $8.8 \times 10^{-7}$  cm/s for the bottom of the column as also detailed in section 2.3. The variation in the hydraulic conductivity inside the column is not uniform. For the column that was cured at 150 days, the hydraulic conductivity values increase in the area close to the surface. Although the SEM

observations were limited to samples taken from the surface and 10 cm below, there was a significant increase in the saturated hydraulic conductivity as indicated by the  $k_{sat}$  values from a height of 125 cm ( $k_{sat} = 2.04 \times 10^{-6}$  cm/s) to the surface (150 cm) ( $k_{sat} = 4.2 \times 10^{-6}$  cm/s). This is caused by the changes in the CPB microstructure due to the cracks from drying shrinkage which led to a preferential flow path network, thereby increasing the  $k_{sat}$  values for the surface CPB materials.

Fall et al. (2008) conducted an experimental analysis and argued that there is the risk of micro-crack development in CPB under applied pressures, such as traffic loads or other surcharges. In field CPB with developed cracks due to drying shrinkage at the surface and propagation of micro-cracks inside the stope due to applied pressures, the risk of the formation of connected cracks (from surface to depth of structure) for fluid flow inside a CPB structure can be significant. The findings of the column experiment showed that the depth of crack penetration is only limited to the surface. However, for CPB prepared with high sulfide-rich tailings, the shrinkage cracks can act as a pathway for water and oxygen intrusion into the backfill structure. This can eventually cause progressive degradation of backfill structures due to the reactivity of the tailings. This can also be a potential source of Acid Mine Drainage (AMD) after mine closures. It should be more extensively investigated by conducting experimental analyses on sulfide-rich tailings and considering the long term durability of CPB structures as suggested in MEND report (2006). This is beyond the scope of the current study.

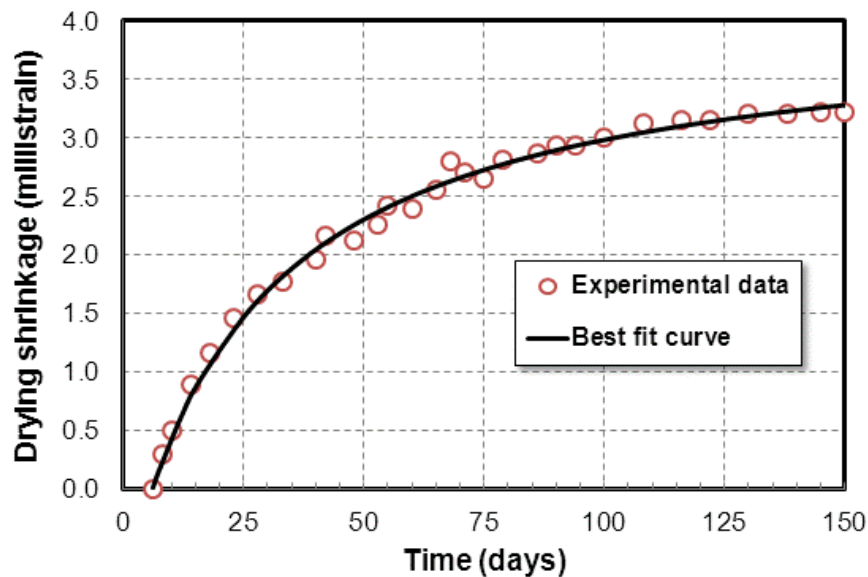


Figure 3.29. Measured drying shrinkage with curing time

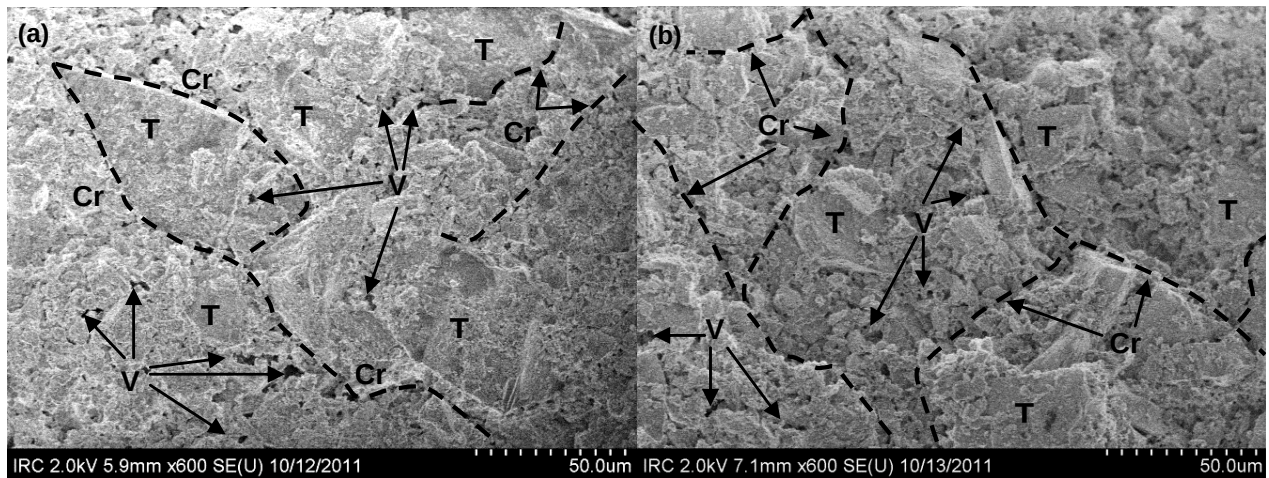


**Figure 3.30. SEM images show effect of evaporation on CPB microstructure at 150 days curing, sample obtained from (a) surface and (b) at 10 cm depth below the surface of column. V: air voids; Cr: crack; T: tailings particle**

### 3.3.3.2. Evolution of chemical (C) properties

#### - Pore fluid chemistry

The pore fluid of cement-based materials such as CPB contains a significant amount of ions (Chen and Brouwers, 2010). The most important types of ions in the pore solution which has been investigated in the different literatures (e.g., Ramlochan et al., 2004; Lothenbach et al., 2007), are commonly referred to as cations, such as potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe), and anions, including OH and SO<sub>4</sub>. The results of the chemical analysis on the pore solution are presented in Figure 3.31. Due to the hydration of the cement clinker within the first few hours of hydration, the concentration of ions such as Ca, Na, K, OH and SO<sub>4</sub> increases in the pore solution and remains constant for the first 3 hours of hydration. It can be explained by the very quick dissolution reactions of cement compounds, such as tricalcium silicate (C<sub>3</sub>S), which is the primary anhydrous phase of cement (Benzaazoua et al., 2004). The concentration of Al, Mg and Fe is considerably lower than other ion concentrations (e.g., Ca, Na and K) during this period and after.

The pore solution composition noticeably changed between 3 to 48 hrs of hydration. Due to the formation of ettringite, the concentration of Ca decreased while the OH increased (Figure 3.31b&d). An increase in pH values led to lower and higher concentrations of Ca and Al, respectively (Lothenbach et al., 2007). The concentration of SO<sub>4</sub> was almost constant during this period, probably due to the presence of gypsum (CaSO<sub>4</sub>.2H<sub>2</sub>O) (Lothenbach and Wieland, 2006). This period of hydration (3-48 hrs) can be considered as the setting time of CPB which defines the onset of

solidification of the CPB. However, setting time in other types of cementitious materials (e.g., mortar and concrete) is considerably shorter than that observed in CPB. The reason is the fact that lower w/c ratio can accelerate setting time (Taylor et al., 2007). Concrete typically has w/c commonly less than 0.5 which is considerably lower than that of CPB (often w/c > 5).

After 48 hrs of curing, a considerable depletion of Ca and SO<sub>4</sub> can be noticed from Figure 3.31. Ca is reduced from the solution mainly due to the formation of C-S-H and CH (Taylor, 1997). These reactions are also reflected in the depletion of Fe from the pore solution up to 7 days of hydration. It can be attributed to the reaction of the C<sub>3</sub>S and at the later stages to the hydration of dicalcium silicate (C<sub>2</sub>S). This results in rapid growths in ettringite and the formation of C-S-H and CH as reported by Double (1983). The concentration of other ions such as Na and K shows a slight increase after 48 hrs and then remains stable up to 150 days. This can be attributed to the decrease in the volume of the pore solution as the result of cement hydration, even when a small part of these ions was consumed to form C-S-H (Lothenbach and Wieland, 2006).

The same qualitative trend in terms of concentration of major ions such as K, Na, Ca and SO<sub>4</sub> can be observed in other type of cementitious materials (e.g., cement paste) as reported in previous studies (e.g., Lothenbach and Winnefeld, 2006; Brouwers and van Eijk, 2003; Rothstein et al., 2002). However, some factors such as initial ion concentrations in pore solution, setting time and rate of cement reactions seem to be different between cement paste and CPB materials. It can be attributed to the differences in cement composition and w/c ratio used in different studies.

The pore solution concentration for advanced ages (approximately after 28 days of curing) showed a more stable concentration of Ca and SO<sub>4</sub>. During this period, C-S-H and CH formed at a slow pace and at the same time, the less stable ettringite started to change into more stable forms, such as AFm (Lothenbach et al., 2007). During the advanced age of curing, hydration products gradually fill the pores resulting in further pore refinement in a slower rate. This statement is supported by the MIP-results presented in Figure 3.33 (will be discussed later). From this figure, it can be clearly noticed that the pore structure of the 7 days-60cm-sample is coarser than that of the 150 days-60cm-sample. This pore refinement results in higher strength (Figure 3.22) and lower hydraulic conductivity (Figure 3.24)

pH analysis showed that the pH ranges between 11.4 for fresh CPB and 12.1 for 28 days of hydration. The obtained pH for CPB is somewhat lower than that of Portland cement concretes (typically 13.5 or higher) (Ramlochan et al., 2004). It can be attributed to a higher volume of the pore solution due to the dilution of alkalis in the pore solution by the high w/c ratio at the time of CPB preparation.

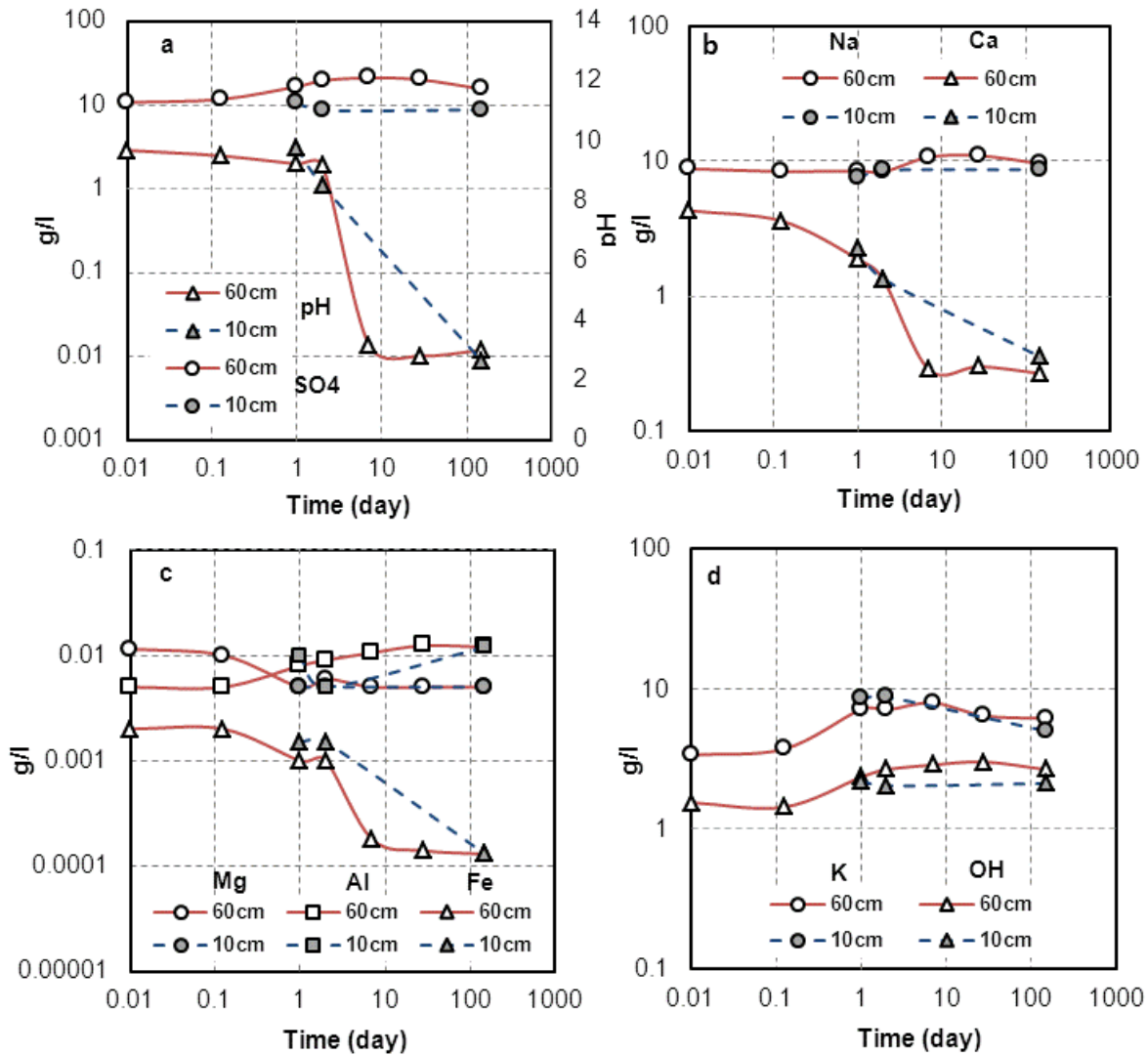


Figure 3.31. Evolution of pore fluid ion concentrations with curing time

### 3.3.3.3. Pore structure

#### - SEM images

In cement-based materials (e.g., CPB), the transformation process from a paste phase into a rigid solid phase can be understood from the properties of their constituents. The chemical reactions between cement and water take place at different rates and times of curing (Bentz and Stutzman, 1994). There are four phases of cement (hydration) products in the cement paste microstructure: unreacted cement, surface products (contain connected pores), pore products (with no connected pores), and capillary pore space (Cabeza et al., 2006). In the SEM image obtained from the sample at 7 days (see Figure 3.32b) the evolution of the primary cement hydration products is obvious. Surface

products such as C-S-H gel can be observed as the major CPB microstructure component. CH as a pore product with a polycrystalline shape is another dominant cement hydration product. Capillary pore spaces between the solid particles are created as the result of self-desiccation and suction development inside the CPB materials (Abdul-Hussain, 2010). This mechanism leads to the removal of water out from the water filled voids which is consumed by hydration reactions. It should be noted that the rate of water depletion from the voids is much faster than the rate of precipitation of the hydration products and hence the connected capillary pores can be created at early ages of curing. These capillary pores will be filled by hydration products (e.g., C-S-H and CH) at advanced ages of curing. According to the MIP test result (Figure 3.33), the capillary pores generally range between around 0.1 to 3 microns in size. The evolution of the CPB microstructure can be observed by the SEM images. Figures 3.32c and 3.32d show the SEM images of CPB samples obtained from the column at a depth of 60 cm at 7 and 90 days of curing. The presence of relatively large connected capillary pores can be observed from the SEM images of the 7 day sample. The high connectivity of pores creates capillary networks that act as internal water paths. Higher values of saturated hydraulic conductivity for the 7 day samples ( $k_{7\text{days}} = 1.85 \times 10^{-5}$  cm/s at 60 cm of the column height) compared to those of 90 days ( $k_{90\text{days}} = 1.55 \times 10^{-6}$  cm/s at 60 cm of the column height) are proof of this particle arrangement. The SEM image of the sample cured for 90 days show that the tailings particles are more connected and cement hydration products completely surround the tailings particles. The pores between the tailing particles are filled with cemented products, which create a dense matrix with filled intergranular spaces. A few isolated connected pores as well as a denser and compacted structure can be seen. The development of self-desiccation disconnects the capillary and pore networks. This microstructure can result in higher strength parameters and lower hydraulic conductivity as reported in the hydro-mechanical results presented above.

Studies on Portland cement have shown that ettringite is formed during the first few hours of hydration, followed by precipitation of CH after three hrs (Lothenbach and Wieland, 2006). Formation of ettringite as rod-like crystals in the early stages of reaction and massive filling of capillary pores can be observed in Figure 3.32a. It's important to note that the analysis of the SEM images obtained from the samples with different curing times showed that the most prevalent cement hydration products formed at early ages (e.g., less than 7 days) are ettringite, with less growth of CH. The presence of C-S-H formation was not considerable at the early ages (Figure 3.32a). Ettringite and CH grow in water-filled spaces (capillary pores) and can be considered as the responsible products for early age setting and strengthening. On the contrary, the SEM images of 90 and 150 days samples showed a massive formation of C-S-H and minor presence of ettringite. C-S-H can be considered as

an important product to bond the tailings particles and fill the capillary forms during a long term chemical process.

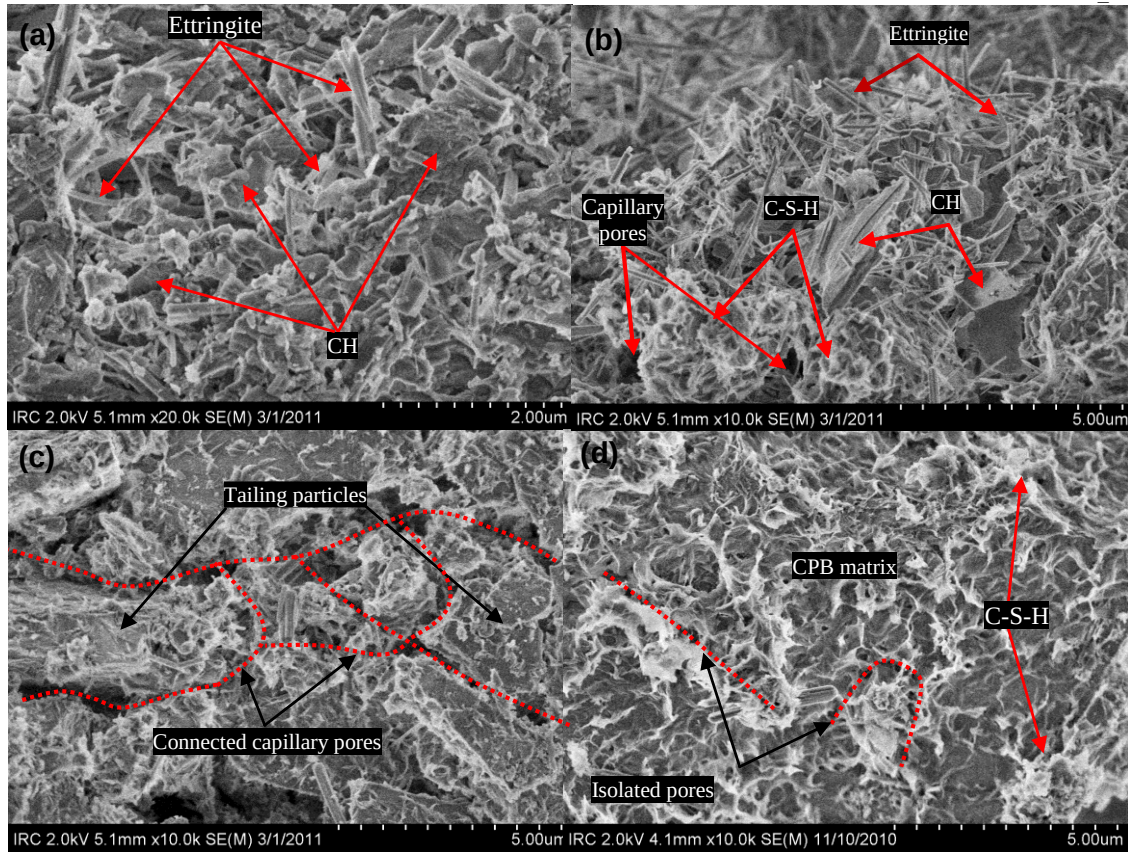


**Figure 3.32. SEM images show (a) hydration products at 7 days; (b) different phases of hydration products at 7 days; (c) CPB microstructure at 7 days; and (d) CPB microstructure at 90 days**

#### - MIP results

The MIP tests were carried out on 7 day samples obtained at 60 cm of the column height and 150 day samples obtained at 10, 60, 110, 140 cm of the column height. This allows us to understand the effect of cement hydration, self-weight pressure, self-desiccation and surface evaporation on the CPB pore structure. The MIP results are presented in Figure 3.33. By comparing the results of the samples taken at 150 days of curing at different depths, a finer pore structure can be observed in the middle of the column (sample taken at 60 cm), except near the column surface (140 cm). This is due to the coupled effects of water drainage from the middle layer to the sub-layer (which reduces the w/c ratio in the middle layer, and results in faster cement hydration) and the self-weight pressure of the upper layer on the middle part (reduces the porosity) of the column. This behaviour results in a finer pore structure due to the precipitation of cement hydration products and higher rate of suction development due to self-desiccation. In addition, it can be seen that the sample at 140 cm (close to

the surface) shows the finest matrix of the entire column. This is due to surface evaporation and therefore associated drying shrinkage which can reduce the porosity or void ratio of CPB material located on the surface of the column. As observed in Figure 3.4, a very low void ratio of the samples close to the surface (Figure 3.4a) under high drying shrinkage conditions as well as high decrease of the water saturation degree (Figure 3.4b) close to the surface (or high development of suction, Figure 3.21) prove the refinement of pore structures due to evaporation.

By comparing the obtained MIP results of the 7 and 150 day samples, the evolution of the pore structure due to the cement hydration process can be understood. Around 71% of the pore distribution at 7 days range from 1 to 3 microns. After 150 days, the pore distribution shifts to a finer size in that around 59% of the pores range from 0.5 to 1 micron. The evolution of the micro-pores (less than 0.5 micron) at 150 days can be observed from the graph. This can be attributed to the filling of very fine pores by cement hydration products which reached the dense and finer pore structure. This means that the CPB became less porous after 150 days of curing. The SEM images of the 150 day sample also demonstrate that after 150 days of curing, the CPB matrix became very dense and less porous (associated to less permeable matrix). However, it should be stressed that the presence of shrinkage cracks can open new water paths and consequently, increase hydraulic conductivity.

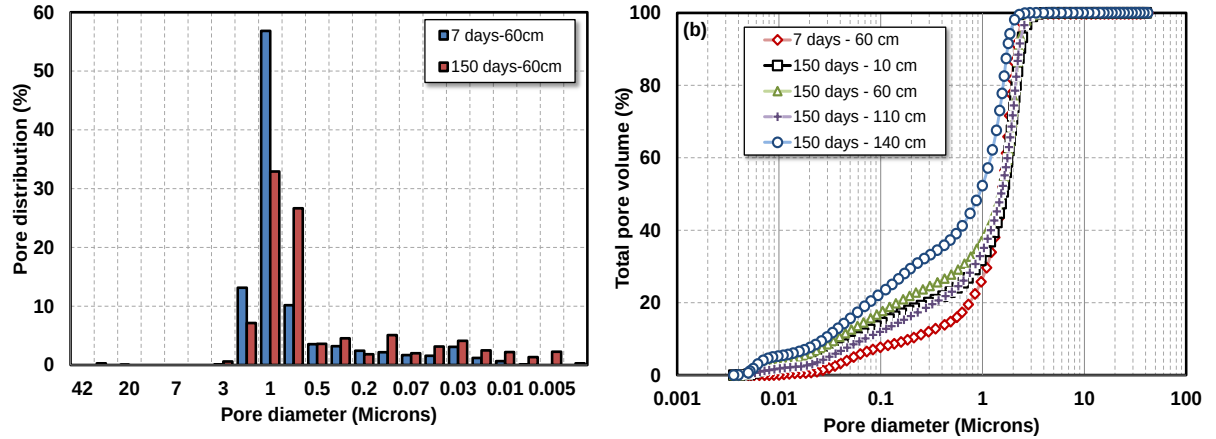


**Figure 3.33. MIP results (a) pore size distribution and (b) pore volume distribution**

#### 3.3.3.4. Discussion on coupled THMC behaviour

Experimental results obtained from the monitoring of the CPB columns are presented in Figure 3.34. This figure shows the simultaneous evolution of the heat of cement hydration (a Thermal factor), settlement (a Mechanical factor), pore fluid concentration (a Chemical factor) and pore water pressure (Hydraulic factor) as well as the interactions between these THMC factors. The variation of

Ca concentration with time was considered as an indicator of the evolution of the pore fluid chemistry.

According to this figure, three different phases of structure formation can be considered. Right after CPB placement, large volume change (settlement) along with the dissipation of pore pressure take place up to the first 3 hrs of curing. A small increase in temperature took place during this period mainly due to the preliminary production of ettringite and less CH (e.g., Meinhard and Lackner, 2008). The Ca concentration was almost stable in this period (Figures 3.31b and 3.35) mainly due to the continuous release of ions into the pore solution as a result of initial hydration of  $C_3S$  (Lothenbach and Wieland, 2006). Settlement increase and pore pressure decrease (Figure 3.34) were the dominant HM coupled processes in this stage which is considered as the initiation of the material transition from liquid stage (a suspension of solid particles in the solution) to skeleton formation (setting starts to occur). Skeleton formation connects tailing particles together as a result of the precipitation of hydration products as well as the development of capillary pressure due to self-desiccation. The large settlement in this stage results from the rearrangement of solid particles under self-weight pressure which causes large volume changes in the material. Addition of high amount of water during CPB preparation in order to increase its workability causes a high plastic behaviour in CPB material. It will result in large volume change during the early hours after placement.

The period that takes place between 3 to about 48 hrs of curing time represents the period of skeleton formation. Two distinguished behaviours can be observed from the Figure 3.34. They include considerable increase in the heat of cement hydration as well as rapid suction development which helps CPB in skeleton formation. Suction increase and peak temperature of cement hydration show the strong contribution of a coupled TH processes to CPB skeleton formation. It should be noted that an increase in settlement at this stage is not comparable to the previous increase. The settlement that occurs at this stage is due to a significant reduction in capillary pore sizes (as a result of developed suction) due to a mechanism which is called chemical shrinkage. Chemical shrinkage causes the creation of empty pores and a reduction in the internal relative humidity ( $RH$ ) due to self-desiccation (Bentz, 2008). During the self-desiccation, the volume of the hydration products upon the reactions between unhydrated cement and water is lower than the total volume of cement and water (Bentz, 2008; Abdul-Hussain and Fall, 2012). This self-desiccation also leads to a reduction in the total volume of the CPB materials. There are two important aspects related to the temperature evolution curve in the Figure 3.34. From 3 to 17 hrs of cement hydration, a sharp increase in the temperature took place which reached a maximum value after about 17 hrs. More contribution from the hydration of  $C_3A$  and  $C_2S$  in addition to the ongoing hydration of  $C_3S$  is the primary mechanism responsible for increasing the temperature to the peak value (Double, 1983). A rapid reduction in Ca

concentration reflects these reactions and the effect of temperature on the chemical reactions (TC) is significant in this period. Cement hydration consumes the capillary water filled large voids and simultaneously, the cement products gradually fill the voids. This process causes rapid development in suction as previously demonstrated (e.g. Figure 3.21). By filling the voids between the tailings particles with cement products, the initial setting takes place. Numerous contact points or cohesion points are formed which play an important role in stiffening the paste (Soroka, 1980). Between 17 to 48 hrs, the heat of hydration started to decrease. During this stage, the continuous formation of C-S-H and CH can be traced by the depletion of Ca concentration in the pore solution (Benzaazoua et al., 2004). A considerable reduction in pore pressure was noticeable as a result of self-desiccation (Figure 3.34). It can be seen that rate of settlement decreased after 17 hrs of hydration and was a strong indication of the progressive setting process of CPB.

After 48 hrs of hydration, the transition from a skeleton formation to a long process of the hardening phase took place. During this stage, C-S-H and CH form at a slow rate and eventually fill most of the pores in the CPB matrix as observed from the SEM images (see Figure 3.32d). This leads to the evolution of the physical and hydro-mechanical properties. In CPB materials, the process of filling the capillary pores continues up to 90 to 150 days which results in gradual refinement of the pores and reduction in porosity (or void ratio) as demonstrated by Figures 15 and 16a. The final hardening time is quite difficult to predict, since it depends upon several factors, such as binder content and type, curing condition, tailing properties, etc. From about 48 hrs to a few days after, CPB material started to cool down and the rate of increase in settlement and suction slowed down too (Figure 3.34).

Evaporation is a mechanism which basically cannot influence the interior part of the column. Because only a small part of a CPB structure is affected by evaporation, even during a long period of time. However, the contribution of evaporation is important in terms of long term drying shrinkage and related surface micro-cracks. From Figure 3.34, the rate of evaporation after about 48 hrs (through skeleton formation) started to increase, which is due to the development of capillary pressure at the surface and associated reduction in rate of evaporation. Due to evaporation, menisci can be created between the tailings particles and generate capillary tension in water and therefore slow down the rate of evaporation (see section 3.2.3.2).

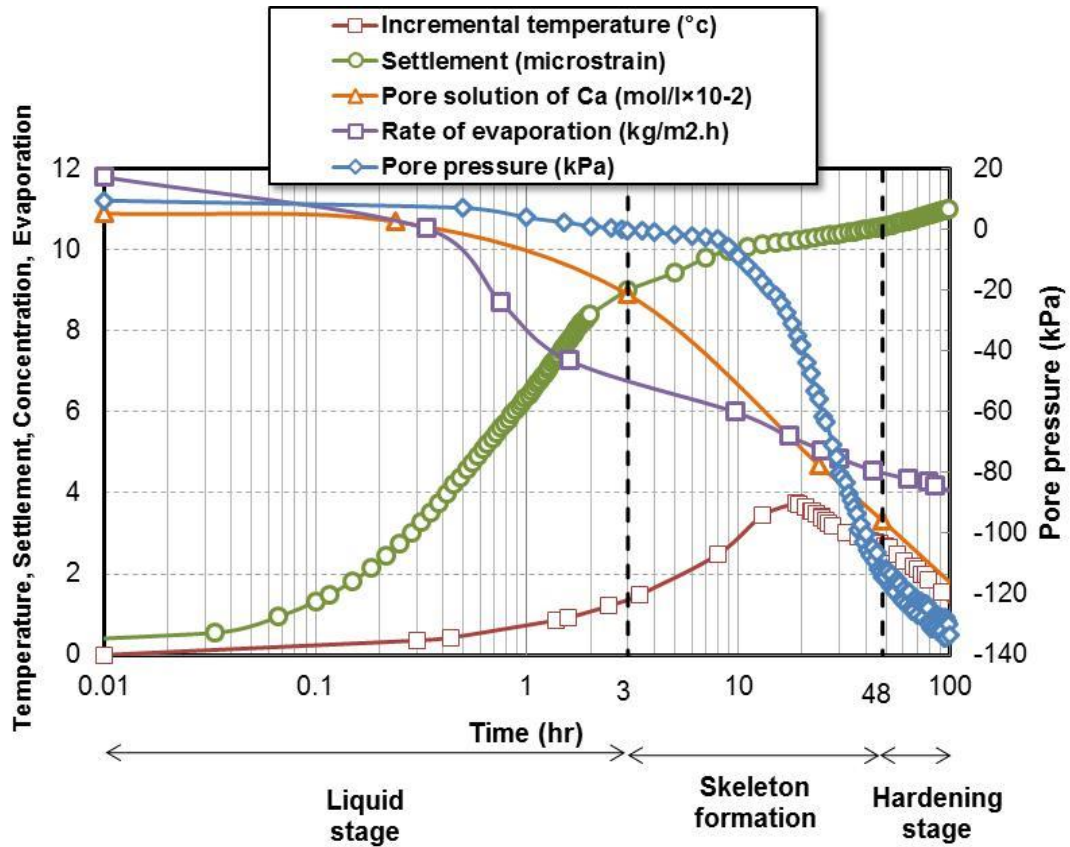


**Figure 3.34. Coupled evolution of heat of cement hydration, settlement, pore pressure, pore fluid concentration and evaporation in column experiment at early ages**

### 3.3.4. Summary and conclusion

This section presents the mechanical, chemical and microstructural properties as some of the important factors in the evolution of coupled THMC processes in CPB material by means of a column experiment. The obtained results show that mechanical properties, including the UCS and modulus of elasticity are highly variable with time and column height. The effect of the filling sequence which includes the moving of water from the upper to the lower part of the column changes the void ratio and water content variation through the column, and hence lead to different UCS and saturated hydraulic conductivity values. The results indicate that there is a strong correlation between the UCS and void ratio. Also, strong coupled HM behaviour exists inside the CPB materials, including coupled relationships between suction and UCS as well as UCS and saturated hydraulic conductivity. Also, the UCS results indicated by stress-strain curves show that the CPB at advanced ages and with higher UCS values exhibit more brittle behaviour compared to that at early ages. The findings of the shear strength tests demonstrate that internal friction angle in CPB is not a time

dependent parameter, while cohesion considerably changes with curing time as a result of the bonding of tailing particles due to cement hydration processes.

The results of monitoring of settlement and drying shrinkage reveal that CPB materials undergo large volume changes after placement in the column as a result of self-weight settlements before the setting of CPB occurs. In addition, the long term monitoring of drying shrinkage shows a significant shrinkage at the surface of the column after 150 days. This can lead to the propagation of micro-cracks on the surface and outmost top of the column. The results from the SEM observations support this argument. The presence of cracks is an important issue in terms of increase in fluid transfer ability, and decrease in mechanical and environmental performance for the area limited to the surface of the column.

In terms of chemical properties, the monitoring of pore water chemistry shows the mechanism of the hardening process in CPB material. The different types of cement hydration products as well as microstructural evolution in the CPB matrix have been captured from SEM images and MIP results. The study of the pore structure of CPB can illustrate the hydro-mechanical evolution of CPB from early to advanced ages.

Finally, the obtained results show that the THMC properties of CPB are strongly coupled. This THMC behaviour is highly dependent on the cement hydration processes in CPB material. Self-desiccation, heat development and self-weight pressure can be considered as important internal mechanisms that affect the short-term THMC behaviour of CPB structures. However, the effects of evaporation and resulting drying shrinkage and cracks should be considered as long-term factors which can influence the durability of CPB structures. This study has demonstrated that the coupled effect of THMC factors on CPB performance is important for the designing of cost-effective, safe and durable CPB structures. However, the effect of overburden pressure has not been studied in the column experiment which is an important factor in field CPB. This factor should be included in further studies on coupled THMC behaviour. Nevertheless, this column study has helped to provide better understanding of the fundamental mechanisms of THMC processes in CPB at a laboratory scale.

### **3.4. Conclusion**

In chapter three the THMC coupled processes in CPB material by using high column experiments was investigated. Various THMC properties and processes were determined in CPB and the relationships between these factors were established by using the geotechnical tests and experimental monitoring. In addition to that the effects of other factors such as filling sequence, evaporation and shrinkage on THMC behaviour of CPB have been studied.

Despite the comprehensive contribution of the height column experiments to simulate the mine stope condition in laboratory scale as well as identify and correlate the different THMC processes, the main important factor which is the self-weight pressure in mine backfill was not simulated. Self-weight pressure due to progressive increase in height of the backfill induced significant vertical stress in the mine backfill. Therefore, for a more realistic simulation it is necessary to apply vertical stress during curing and monitoring to study the THMC properties of CPB. That is the reason in the second phase of current study a novel THMC cell pressure were developed in order to overcome the limitation of column experiments. In the following chapters of four and five, the THMC properties and processes have been investigated using the cell pressure apparatus.

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## **Chapter 4: Load Cell Experiments (Early age behaviour)**

### **ABSTRACT**

Once cemented paste backfill (CPB) is poured into a mine stope, it is subjected to strongly coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) processes. A laboratory investigation was performed to understand the THMC behaviour of CPB at early ages. A novel experimental apparatus was designed and developed to study the THMC behaviour of CPB. The testing and monitoring were conducted in undrained condition, with and without pressure application, and took into consideration two types of tailings (artificial and natural). The evolutions of the total pressure, pore pressure, suction, temperature and electrical conductivity were monitored for a period of 7 days. Also, the CPB samples were tested or analyzed with regards to their shear strength properties, hydraulic conductivity, thermal conductivity, and physical and microstructural characteristics at 1, 3 and 7 days. The fundamental relationships governing the THMC processes in CPB cured under stress were investigated in this part of the studies.

In the second part, different curing scenarios are adopted to investigate the effects of important factors consisting of self-weight pressure, filling rate, filling sequence (i.e., staged filling) and drainage condition on the CPB strength and deformation behaviour. Various scenarios were simulated, including: (i) drained and undrained conditions, (ii) effect of different filling rates, (iii) effect of filling sequence (i.e., simulation of 1 and 3 curing days plug), and effect of curing stress. The early age evolution of the strength (uniaxial compressive strength) and deformation behaviour of CPB when subjected to above-mentioned curing scenarios were studied.

The obtained results show that the THMC properties of CPB are strongly coupled due to several mechanisms, such as curing stress, heat of hydration, self-desiccation and pore fluid chemistry. Also, curing conditions, such as drainage, curing stress, curing time, filling rate and filling sequence influence the mechanical and deformation behaviour of CPB materials. Coupled effects of consolidation, drainage and suction contribute to strength development of drained CPB subjected to curing stress. While, particle rearrangement due to applied pressure and suction development due to self-desiccation play role in strength gain of undrained CPB cured under stress.

The results presented in this study will provide a better understanding of the THMC behaviour of CPB at early ages and thus contribute to a better design of CPB structures. The findings also can help mine operators in managing the backfilling strategy while designing a cost-effective and safe backfill and barricades structures.

## **4.1. Introduction**

This chapter consists of two technical papers (papers III and IV), which mainly focus on the THMC coupled processes in CPB by using cell pressure apparatus at early age of curing (up to 7 days). In technical paper III the THMC behaviour of CPB has been investigated on CPB samples cured under stress and prepared with two tailing types (artificial silica and natural tailings). The aim of this study is to study the THMC processes while investigating the effects of curing under stress on the studied factors.

The main purpose of technical paper IV is to investigate the mechanical strength and deformation behaviour of CPB at early ages. Different factors that are important to design a mine backfill as well as to plan the backfilling strategy were investigated. The CPB samples were subjected to various curing conditions, considering the effect of curing stress, filling rate, filling sequence and drainage.

## **4.2. Technical Paper III: Coupled Behaviour of Cemented Paste Backfill at Early Ages<sup>3</sup>**

### **4.2.1. Introduction**

During ore rock extraction, mining operations produce huge quantities of tailings and waste rock (Ritcey, 2005; Kesimal et al., 2005). The disposal of tailings on the surface can cause serious geoenvironmental problems (Yilmaz et al., 2003; Huynh et al., 2006; Ercikdi et al., 2009; Fall et al., 2010b; Mahlaba et al., 2011; Farkish and Fall, 2013, Wu et al., 2013). Additionally, the creation of mined-out underground spaces (stopes) results in surface subsidence and mining workplace instability (Rankine et al., 2001; Li and Aubertin, 2009). A common practice for rectifying this problem is to utilize the waste tailings in filling mine stopes with cemented paste backfill (CPB). CPB is a mixture of dewatered mill tailings and binding agent, with added water to achieve the required consistency for transporting the CPB to the mine stope (Fall et al., 2005 & 2010a; Kesimal et al., 2005; Huang et al., 2011; Cihangir et al., 2012).

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<sup>3</sup> Published in Geotechnical and Geological Engineering Journal (2015), 33(5): 9892-6; Alireza Ghirian, Mamadou Fall

Once placed, the CPB structure is subjected to strong coupled thermal (T), hydraulic (H), mechanical (M) and chemical (C) (THMC) processes or factors (Figure 4.1). An understanding of the interplays between these different processes demands a comprehensive study of the fully coupled THMC behaviour which is crucial for a reliable and cost-effective design of the backfill structure. Although there have been many studies that investigate each specific factor (e.g., Hassani and Archibald, 1998; Yilmaz et al., 2004; Kesimal et al., 2005; Klein and Simon, 2006; Ercikdi et al., 2010; Orejarena and Fall, 2010 & 2011; Nasir and Fall, 2009 & 2010; Cihangir et al., 2012; Wu et al., 2012; Yin et al., 2012), to date, no comprehensive study has been conducted to address the coupled THMC behaviour of CPB cured under stresses comparable to those generated by the CPB weight.

CPB filled stopes must have sufficient mechanical stability (usually evaluated by the strength of the CPB) in order to remain stable or self-supporting during the recovery of the adjacent stopes (Fall et al., 2007). A common practice that is used to assess the backfill strength is to conduct unconfined compressive strength (UCS) tests on small laboratory samples (20×10 cm or 10×5 cm) of CPB cured in conventional plastic moulds at atmospheric pressure and temperature conditions. The obtained information is limited since the influence of various important factors, such as self-weight pressure, filling rate, drainage condition, and heat of cement hydration, cannot be included in the strength assessment. This can result in a conservative design approach, which in turn, increases the cost in terms of cement consumption, barricade construction and stope cycle times (e.g., le Roux et al., 2005; Thompson et al., 2009). Furthermore, backfill strength gain depends on the suction development as a result of self-desiccation and/or drainage, or sometimes desaturation (drying out) (Helinski et al., 2006; Abdul-Hussain and Fall, 2011). Suction can increase the effective stress, which in turn, decreases the vertical stress in the backfill as well as reduces the horizontal stress on a barricade as observed through the in-situ instrumentation of some mine stopes (e.g., Thompson et al., 2009). Only a few studies have been experimentally conducted to study the effect of self-weight pressure (e.g., Belem et al., 2002; Yilmaz et al., 2009 & 2014), suction development as a result of self-desiccation (e.g., Helinski, 2007); and heat of hydration (e.g., Fall and Samb, 2009; Fall et al., 2010a) on backfill strength assessment. However, no studies have been performed to investigate the coupled effect of the THMC processes on the strength of CPB cured under different stresses. Furthermore, there are no studies on the THMC behaviour of CPB cured under stress and the effect of these THMC processes on other relevant design factors of CPB, such as thermal (e.g., thermal conductivity, heat of hydration), hydraulic (e.g., pore water pressure (PWP), suction, permeability), chemical (e.g., evolution of pore water chemistry, binder hydration), mechanical (e.g., deformation), and physical (microstructure, density) factors (see Figure 4.1).

In chapter three the THMC behaviour of CPB by means of a high column experiment was investigated to understand the governing coupled processes in an almost stress-free state. Since the tops of the columns were open to the atmosphere, the effect of evaporation and associated surface shrinkage on the hydro-mechanical behaviour of CPB was studied as well. However, the effect of mechanical load as a result of self-weight pressure on THMC behaviour was not considered in their studies. In the current study, a pressure cell apparatus is developed to investigate the THMC coupled processes in CPB. The new setup grants privileges to simulate curing conditions relatively close to underground mine stope conditions at a laboratory scale with controlled rate of loading (i.e., stope filling). It also enables to cure samples that are relatively large in size for testing purposes.

The objective of this chapter is to investigate the early age THMC behaviour of CPB cured under various stresses. The main coupled interactions between different processes were determined and the effect of the curing stress on each individual factor was studied. Furthermore, by conducting THMC studies on two types of tailings (natural and artificial), the effect of tailings type and its chemical composition on the THMC performance of CPB material was investigated.

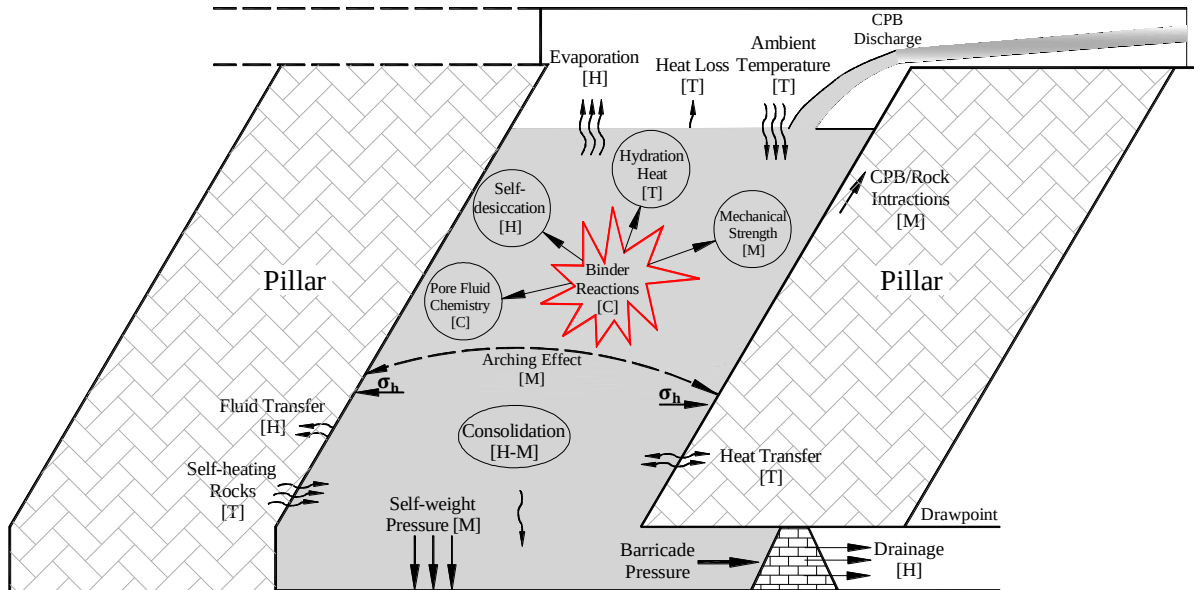


**Figure 4.1. Schematic diagram of different THMC coupled processes in a backfill structure (static condition)**

## 4.2.2. Materials and Methods

### 4.2.2.1. Materials

The materials used for the CPB preparation include binder, tailings, and water.

## - Tailings

Two types of tailings, which include natural zinc tailings (ZnT) and artificial silica tailings (ST), were used to prepare the fresh CPB. The natural tailings used in this study are fine-grained tailings from a mine located north of Canada, one of Canada's largest zinc mines. The artificial tailings contain ground silica with 99.8% SiO<sub>2</sub>. The main benefit of the use of non-reactive ST is to accurately control the chemical and mineralogical compositions. Natural tailings may contain several reactive chemical elements and often, sulphide minerals, which can interact with cement and thus, affect the interpretation of the results and/or introduce significant uncertainties in the results obtained (Nasir and Fall, 2008). The mineral compositions of both types of tailings used for the CPB preparation were obtained from an x-ray diffraction (XRD) analysis, and presented in Table 4.1. More than 50% of the silica particles are smaller than 25  $\mu\text{m}$  ( $D_{50}$ ) and 10% are smaller than 2  $\mu\text{m}$  ( $D_{10}$ ). According to the Unified Soil Classification System (USCS), both the ST and ZnT are non-plastic silt (ML), as are most of the tailings produced by hard rock mines (Orejarena and Fall, 2008 & 2011). The grain size distribution of the ST and the ZnT are presented in Figure 4.2, which are close to the average of nine Canadian hard-rock metal mine tailings (Orejarena and Fall, 2008). The physical properties of both types of tailings are tabulated in Table 4.2.

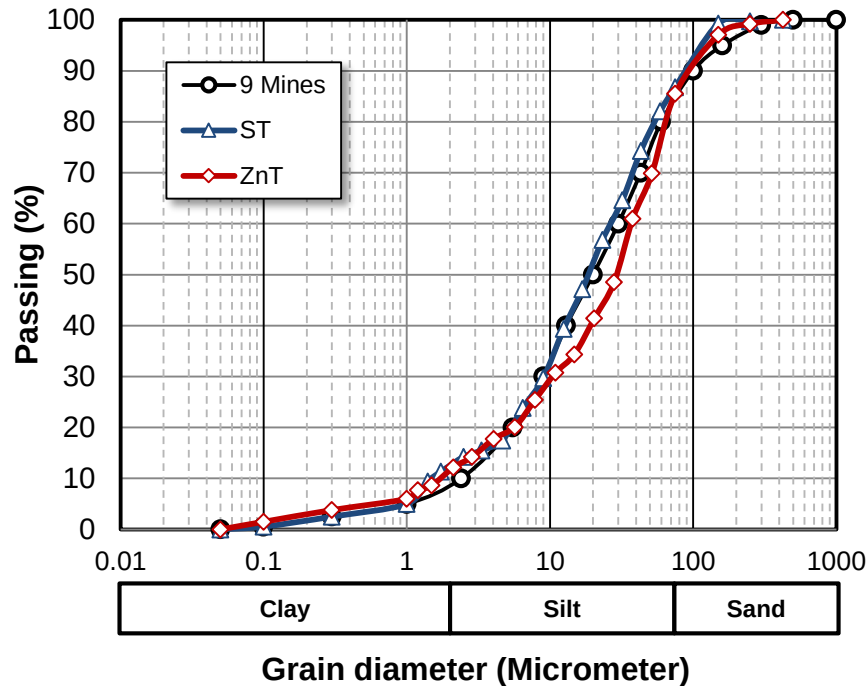


Figure 4.2. Grain size distribution of studied tailings compared with the average of 9 Canadian hard-rock metal mine tailings

**Table 4.1. Mineral composition of the tailings used (obtained by XRD)**

| Element/<br>Tailings | Quartz | Dolomite | Chlorite | Magnetite | Pyrite | Talc | Magnetite | Actinolite | Pyrrhotite | Spinel | Others |
|----------------------|--------|----------|----------|-----------|--------|------|-----------|------------|------------|--------|--------|
| ZnT (wt%)            | 11.9   | 5.7      | 18.2     | 11.4      | 15.4   | 16.4 | 7.6       | 3.2        | 3.1        | 3.2    | 3.9    |
| ST (wt%)             | 99.8   | -        | -        | -         | -      | -    | -         | -          | -          | -      | -      |

**Table 4.2. Physical properties of the tailings used**

| Tailings | G <sub>s</sub> | D <sub>10</sub><br>(μm) | D <sub>30</sub><br>(μm) | D <sub>50</sub><br>(μm) | D <sub>60</sub><br>(μm) | C <sub>u</sub> | C <sub>c</sub> |
|----------|----------------|-------------------------|-------------------------|-------------------------|-------------------------|----------------|----------------|
| ST       | 2.70           | 1.9                     | 9.0                     | 22.5                    | 31.5                    | 16.6           | 1.3            |
| ZnT      | 3.34           | 1.6                     | 10.9                    | 29.9                    | 37.8                    | 23.6           | 2.0            |

#### - Cement and Water

The most popular cement used in backfill preparation is ordinary Portland cement type I (PC-type I) which is used in this study. The characteristics of the cement used in this study are presented in Table 4.3. Tap water was used to mix the cement and tailings.

**Table 4.3. Characteristics of Portland cement type I**

| Type of binder | MgO (%) | CaO (%) | SiO <sub>2</sub> (%) | Al <sub>2</sub> O <sub>3</sub> (%) | Fe <sub>2</sub> O <sub>3</sub> (%) | SO <sub>3</sub> (%) | Relative density | Specific surface (m <sup>2</sup> /g) |
|----------------|---------|---------|----------------------|------------------------------------|------------------------------------|---------------------|------------------|--------------------------------------|
| PCI            | 2.65    | 62.82   | 18.03                | 4.53                               | 2.70                               | 3.82                | 3.10             | 1.30                                 |

#### 4.2.2.2. Specimen preparation and mix proportions

The CPB mix design included PCI (4.5%wt), and a water to cement ratio (w/c) equal to 7.6. The tailings material, cement and water were mixed and homogenized in a food mixer for about 7 minutes. In all of the mixes, the w/c ratio and cement proportions were kept constant. The slump or the consistency of the paste mixtures was measured by a slump test in accordance with ASTM C143. The slump values for the CPB prepared with ST and ZnT were about 18 cm and 22 cm, respectively, which belong to the most frequent slump values used in CPB preparation and transportation into mine stopes. The average values of the initial physical characteristics of the fresh CPB made of ST or ZnT are presented in Table 4.4. The CPB mixtures were mixed and then loaded onto a pressure cell

apparatus. In total, three test series were conducted: (i) C-ST test series (or control tests) were conducted on samples prepared with ST and cured without applying any vertical pressure, and the results were considered as the reference values in order to compare the effect of pressure application on THMC evolution; (ii) CUS-ST test series, and (iii) CUS-ZnT test series, which were conducted under curing stress, and the CPB specimens were prepared with ST or ZnT, respectively.

**Table 4.4. Mean values of initial physical characteristics of CPB prepared with ST and ZnT**

| Properties                         | ST   | ZnT  |
|------------------------------------|------|------|
| Void ratio, $e$                    | 1.15 | 1.92 |
| Specific gravity, $G_s$            | 2.71 | 3.34 |
| Degree of saturation, $S_r$ (%)    | 100  | 100  |
| Solid content by mass, $C_w$ (%)   | 74.4 | 74.8 |
| Solid content by volume, $C_v$ (%) | 39.7 | 33.1 |
| Water content, $\omega$ (%)        | 33.7 | 35.4 |
| Water to solid ratio (w/s)         | 0.34 | 0.34 |
| Slump (cm)                         | 18   | 22   |
| W/C                                | 7.6  | 7.6  |

#### 4.2.2.3. Developed pressure cell apparatus

The main purpose of the developed experimental setup is to simulate the mine stope filling sequence and overburden pressure (self-weight stress) during the curing of CPB. Furthermore, the setup provides a facility that monitors the evolution of the key THMC factors, such as the evolution of pore water pressure, suction, binder hydration, deformation and temperature of the CPB with time for a mix design. Furthermore, the setup allows the sampling of CPB specimens cured under the above-mentioned mine stope conditions for the purpose of conducting the required geotechnical, microstructural and chemical testing, such as uniaxial compressive strength (UCS), shear strength, saturated hydraulic conductivity and thermal property tests, and microstructural and chemical analyses to investigate the THMC properties of the CPB material. Figure 4.3 presents a schematic diagram of the developed experimental setup (pressure cell apparatus to measure THMC). A Perspex (acrylic plastic) cylinder with the diameter of 101.6 mm (4 inches) and height of 304.8 mm (12 inches) was employed as the main framework to hold the samples at a one-dimensional vertical pressure. An axial piston was mounted on the upper portion of the cylinder to apply the required pressure up to 600 kPa, which is equal to approximately 35 m on a mine stope. Compressed air pressure was used as the driving force on the piston. The pressure increment was controlled by a regulator and pressure gauge. A top and a bottom plate with three tie rods were used to support the Perspex mould against leakage and internal pressure. Only 200 mm of the cylinder was filled with

CPB and the remaining space served as an air chamber to apply pressure on the piston. In all of the experiments, the length-to-diameter ratio of the CPB specimens was kept in the order of two.

In total, five cells were engineered and manufactured, including one cell for instrumentation and four cells for curing CPB samples at different curing times (1, 3 and 7 days). Studies have shown that undrained backfill exhibits weaker mechanical properties than drained backfill (e.g., le Roux et al., 2005). Therefore, in consideration of this case scenario, an undrained condition was adopted for all of the experiments. This represents a conservative approach with regards to the mechanical stability of field CPB structure.

In underground mine stopes, cement hydration is usually the main source of temperature increase within the backfill structure (Fall et al., 2010a). Thermal factors, such as heat of hydration, can accelerate the rate of the binder hydration, and thus the rate of the strength gain in CPB materials (Fall et al., 2010a). This can be considered as the coupled effect of temperature and chemical reactions (thermo-chemical coupling). Therefore, in this study, all of the cells were covered with a 100 mm heat insulation glass wool blanket after loading the CPB. This enables to restrict heat loss from the CPB as well as maintain the heat of hydration during the curing time to investigate its effect on the THMC behaviour of the CPB.

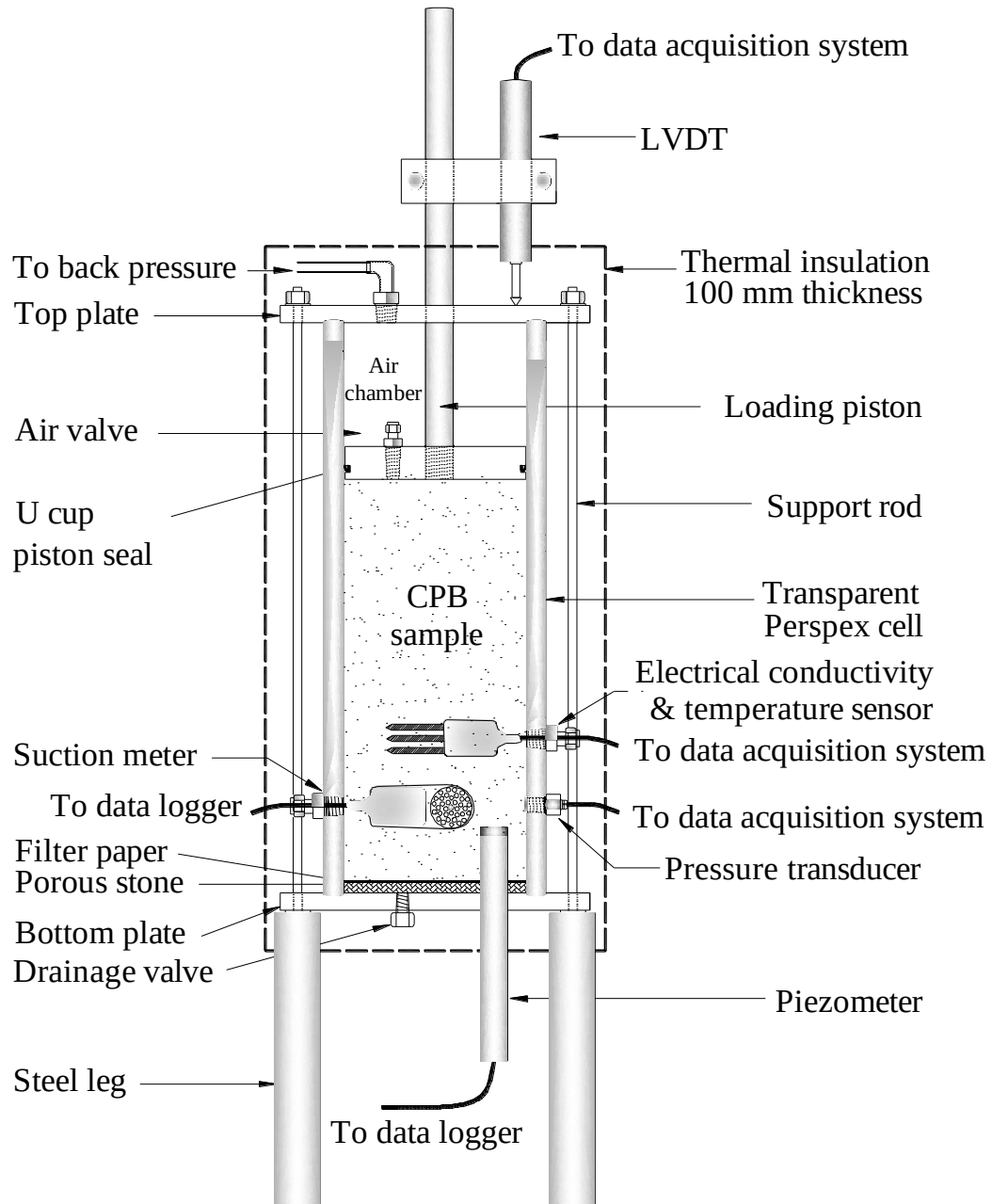


**Figure 4.3. Schematic diagram of the developed experimental set-up and arrangement of sensors**

#### **- Applied vertical pressure**

In this study, an average filling rate equal to 0.131 m/h is chosen to find the corresponding increments of applied pressure and equivalent mine backfill height. Figure 4.4 presents the pressure application scheme that simulates mine stope backfilling over a period of seven days. The applied vertical pressure due to stope filling and corresponding equivalent backfill height ( $h = \sigma_v / \gamma$ ) were calculated based on the CPB bulk unit weight which is equal to 17.2 kN/m<sup>3</sup>. It should be noted that

the arching effect is not included in this study due to the mechanism of the pressure cell (one-dimensional vertical pressure). The pressure was gradually increased every 3 hrs for the first 12 hrs and up to 150 kPa in order to simulate a more realistic self-weight pressure on the specimen. Then, the pressure was increased every 24 hrs up to 600 kPa, which is equivalent to 34.9 m or an average filling rate of 0.31 m/h.

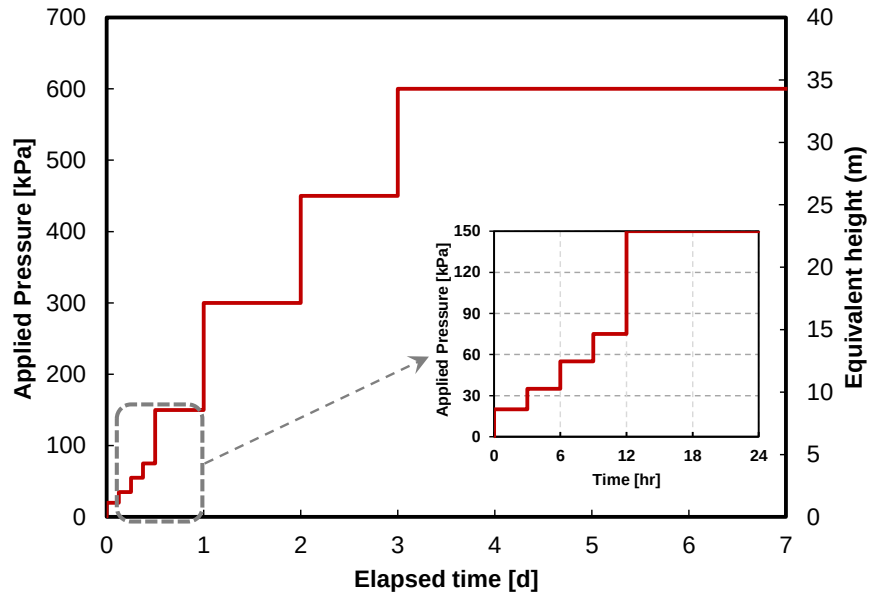


**Figure 4.4. Pressure application scheme (simulating a 30m mine stope, average filling rate of 0.31 m/h)**

#### **- Pressure cell instrumentation and monitoring**

One of the five cells was equipped with various sensors, including a pressure transducer, a vibrating wire piezometer, a suction meter and an electrical conductivity (EC) sensor located at the lower portion of the cell. A linear variable differential transformer (LVDT) was also attached to the piston rod at the top of the cell to record any deformations as a result of applied pressure and/or binder hydration. The locations of all the sensors are schematically illustrated in Figure 4.4. The THMC evolution of the CPB was continuously monitored in terms of the heat of cement hydration, total pressure, pore water pressure (PWP) response, suction evolution, electrical conductivity evolution and deformation for a period of 7 days. All of the sensors were connected to the appropriate data loggers to record the data with time. The monitoring of suction development with time was conducted by using a dielectric water potential sensor, model MPS-2. This sensor is capable of measuring suction between -10 and -500 kPa. The pressure transducer and suction meter were installed 40 mm above the cell bottom in order to monitor the total pressure and suction evolution

with time. A vibrating wire piezometer was employed to monitor the consequences of sequential pressure application on the pore pressure evolution. For this purpose, a calibrated VW2100 standard vibrating wire piezometer with a 1 MPa pressure range and  $\pm 0.1\%$  accuracy equipped with a standard air entry value ceramic disk was used. The tip of sensor was installed 30 mm above the bottom of the cell. The piezometer was equipped with a thermistor to measure the temperature as well. The ECH2O-5TE capacitance sensor was installed in the cell to measure the electrical conductivity with an accuracy of about  $\pm 10\%$ . EC is the ability of a material to conduct electricity. The sensor helped to monitor the setting time and rate of chemical reactions with time.

#### 4.2.2.4. Experimental test program

In addition to the monitoring program described above, comprehensive laboratory tests were performed on the CPB samples cured at different ages to understand the THMC properties of the CPB material, as outlined in Table 4.5. All of the CPB samples were tested in terms of their thermal (i.e., thermal conductivity), hydraulic (i.e., saturated hydraulic conductivity), mechanical (UCS and shear strength parameters) and chemical properties (pore fluid chemistry). In addition, the physical properties and microstructure were evaluated (i.e., by mercury intrusion porosimetry (MIP) and scanning electron microscopy (SEM)) to understand the evolution of the index properties and pore structure of the CPB at early ages. The gravimetric water content ( $\omega$ ) and bulk density ( $\gamma$ ) of the samples were determined in accordance with ASTM D2216-10 and D7263-09, respectively. Then, the void ratio ( $e$ ) and porosity ( $n$ ) were calculated at various curing times. The obtained test results are presented in the coming sections.

**Table 4.5. Summary of laboratory experimental testing and monitoring program**

| Test Types       | Mechanical<br>(M)                          | Hydraulic<br>(H)       | Thermal<br>(T)       | Chemical<br>(C)         | Physical-<br>Microstructural                  |
|------------------|--------------------------------------------|------------------------|----------------------|-------------------------|-----------------------------------------------|
| Testing/Analysis | UCS, shear strength, modulus of elasticity | Hydraulic conductivity | Thermal conductivity | Pore fluid chemistry    | Porosity, density, moisture; by using SEM/MIP |
| Monitoring       | Settlement                                 | Pore pressure, suction | Heat of hydration    | Electrical conductivity | -                                             |

#### - Mechanical tests

Unconfined compression tests were performed on the CPB specimens at 1, 3 and 7 days of curing. A minimum of two samples (to ensure the repeatability of the results) were tested at each

curing age in accordance with a standard test, ASTM C39, by means of a computer-controlled mechanical press. The compression tests were carried out at a constant deformation rate of 0.8 mm/min. Direct shear tests were carried out to determine the shear strength behaviour and parameters (internal frictional angle and cohesion) of the CPB samples. This test is efficient and fast enough to conduct the tests at specific curing times. The test was performed in accordance with ASTM D3080-04 at a controlled strain rate of 1.0 mm/min. A minimum of four specimens were tested with different normal loads of 50, 100, 150 and 200 kPa to determine the failure envelopes.

#### **- Hydraulic conductivity test**

Saturated hydraulic conductivity tests were performed by using a TRI-FLEX II on the CPB specimens at each specific curing time. The flexible wall technique was used to determine the saturated hydraulic conductivity of the CPB. The procedure for this method is described in ASTM D5084 and was conducted in the constant head mode equal to 10 kPa. All of the samples were backpressure saturated. The saturation was also verified by determining the degree of the saturation of the samples at the completion of the hydraulic conductivity tests. The samples showed on average, final degrees of saturation that are higher than 99%. Two samples were tested and at least three readings were done, and the average value was the saturated hydraulic conductivity of the sample tested.

#### **- Thermal conductivity test**

A KD2 thermal conductivity probe was utilized to measure the thermal conductivity of the CPB at different ages. This device computes the values of thermal conductivity by monitoring the dissipation in heat from a line source given a known voltage with  $\pm 5$ -10% accuracy. To measure the thermal conductivity, first, a pilot hole with a diameter of 2.80 mm was drilled and then a thermal probe was inserted into the hole. To maximize the contact between the needle probe and the hole sidewall, a silver polysynthetic compound with high thermal conductivity was used ( $k=8$  w/m.k). Each test was performed at least three times to verify the repeatability of the results.

#### **- Analysis of the pore fluid chemistry**

A pore fluid chemistry analysis was performed to understand the evolution of the pore fluid chemical composition of the CPB samples with time. In total, six samples prepared with ST and ZnT were tested at 1, 3 and 7 days. Pore fluids were extracted from the CPB samples by using a pore fluid extractor that is especially engineered for this purpose based on the steel die high pressure technique (Barneyback and Diamond, 1981) to investigate the evolution of the ion concentration in the liquid

phase within the pores of the CPB. The concentration of various major cations ( $\text{Mg}^{2+}$ ,  $\text{K}^+$ ,  $\text{Al}^{3+}$ ,  $\text{Ca}^{2+}$ ,  $\text{Na}^+$ ,  $\text{Fe}^{2+}$ ,  $\text{Si}^{4+}$ ) and anions ( $\text{SO}_4^{2-}$ ), and the pH were determined for each sample. The concentrations of the analyzed elements were determined by inductively coupled plasma atomic emission spectroscopy (ICP-AES). Sulphate ion ( $\text{SO}_4^{2-}$ ) concentrations were measured using automated calorimetry.

#### **- Microstructural tests**

The microstructure of the studied CPB samples was investigated by MIP and SEM. Although it has some limitations, MIP has been used to evaluate the pore-size distribution (PSD) of cementitious materials for many years (e.g, Cook and Hover, 1999; Diamond, 2004; Fall and Samb, 2008). SEM was carried out with a Hitachi 4800 field emission microscope at different magnifications to study the texture of the CPB and morphology of the cement hydration products. MIP was performed using PMI Mercury/Nonmercury Intrusion Porosimeter instrument to evaluate the pore size distribution and total porosity. Prior to the conducting of MIP and SEM, all of the samples were dried at 50°C to a constant mass in a vacuum oven to remove the free water and stop the cement hydration reactions. Moist samples may evaporate under high vacuum in the microscope and can lead to formation of micro-cracks (Ramachandran and Beaudoin, 1999). Therefore, the samples should be completely dry prior the performing the SEM analysis. Also, drying at this temperature did not appear to cause cracking.

### **4.2.3. Results and Discussion**

#### **4.2.3.1. Evolution of physical properties**

The evolution of the physical properties including void ratio ( $e$ ), porosity ( $n$ ), bulk density ( $\gamma$ ) and water content ( $\omega$ ) with time was measured for the C-ST, CUS-ZnT and CUS-ST samples and the results are presented in Figure 4.5. It is observed that there is a relationship between the evolution of the bulk properties and curing conditions. From Figure 4.5a, it can be observed that in all of the samples, the porosity decreases as the curing time increases. This is due to the ongoing cement hydration process and the associated heat generation (Figure 4.16) which produce larger amounts of hydration products, which in turn, cause the refinement of the pore structure with time (Fall and Samb, 2008). Moreover, the CUS-ST sample shows lower porosity compared to the control sample (C-ST). This is mainly due to the pore refinement as a result of the pressure application. Applied pressure can lead to a more compacted CPB matrix, which in turn, decreases the physical properties, such as porosity. This is experimentally supported by the results of the MIP analyses presented in Section 4.2.3.6 (to be discussed later). Also, the porosity evolution in the CUS-ZnT sample shows the

same behaviour as that of the CUS-ST. However, the porosity values of the CPB made from Zn-tailings are considerably higher than those of the silica samples, primarily due to the differences in water content and tailings specific gravity and mineralogy (see Table 4.1 and 4.2). Figure 4.5b shows that the gravimetric water content of all the samples decreases with curing time mainly due to the consumption of water as a result of the cement hydration reactions. The water content variation of the CUS-ST and C-ST samples is almost the same. This means that pressure application has no significant effect on water content variation in undrained loading conditions. However, the water content of the CUS-ZnT sample is considerably reduced with curing time. The overall trend in Figure 4.5c shows that the dry bulk density ( $\gamma_{dry}$ ) increases with curing time. The dry bulk density at 7 days of curing shows a higher value compared with one day of curing. This is due to the refinement of the pore structure (Fall et al., 2009a) and reduction of the void ratio or porosity (Figure 4.5a) as the pore voids are filled with cement hydration products in the cemented matrix, which eventually produce a CPB material with a higher dry density. Moreover, the dry bulk density of CUS-ZnT shows a lower value compared to that of the CUS-ST. This is attributed to the higher void ratio and porosity of the CUS-ZnT (Table 4.4, Figure 4.5a) and therefore, lower dry bulk density. However, curing under stress tests conducted on CPB made of both ST and ZnT followed the same qualitative behaviour. It is observed from Figure 4.5d that there is a direct relationship between water content and the void ratio for a degree of saturation above 80%. The void ratio decreases with water content for all of the test series. In considering that CPB with higher water content will have a greater void volume that is filled with water and therefore higher void ratio (Fall et al., 2008), this behaviour was observed for both types of tailings.

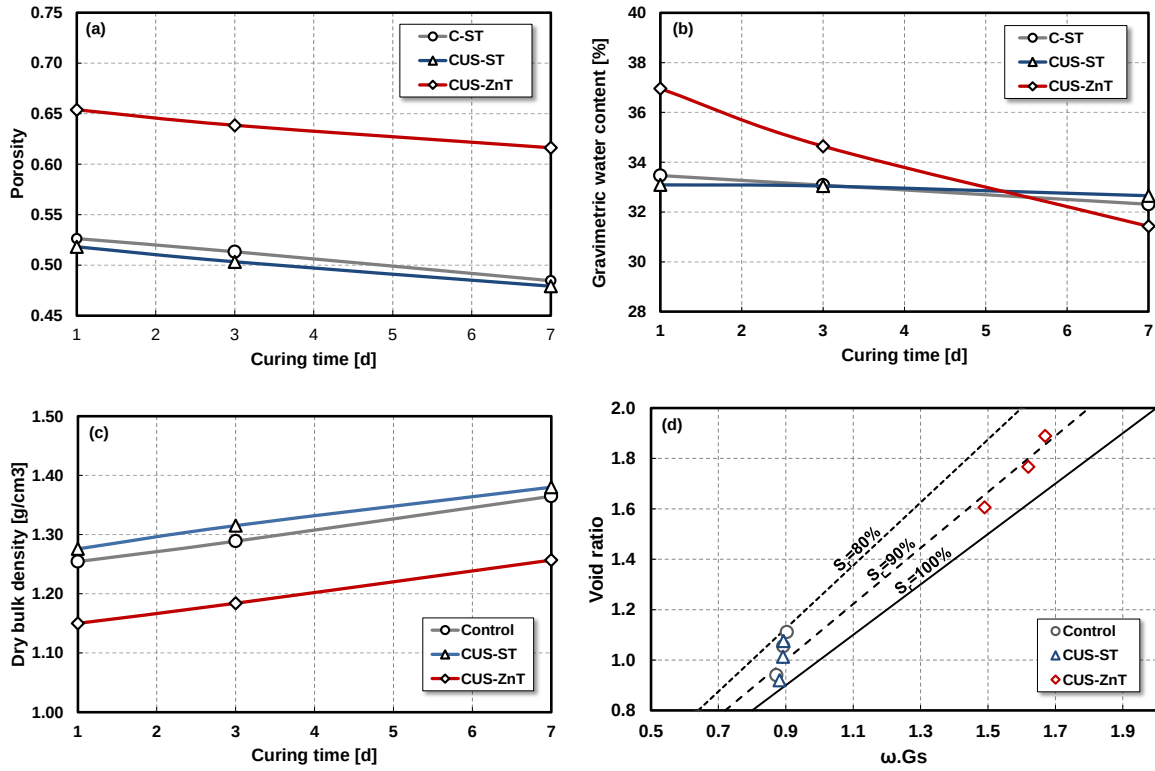


**Figure 4.5. Evolution of the physical properties: (a) porosity; (b) gravimetric water content; (c) dry bulk density; and (d) void ratio versus water content based on multiple specific gravity**

#### 4.2.3.2. Evolution of mechanical properties

##### - Unconfined compressive strength (UCS)

The UCS test results showed that the UCS values for all of the samples increase with curing time (Figure 4.6). The reason for this behaviour is an increase in the degree of cement hydration with time and the associated refinement of the pore structure of the CPB (due to the precipitation of a larger amount of hydration products), and self-desiccation induced suction increase within the CPB (Figures 4.7 and 4.14). This time-dependent increase in the degree of cement hydration and the associated refinement of the pore structure have already been demonstrated by several previous studies (e.g., Taylor, 1997; Espinos and Franke, 2006; Fall and Samb, 2008). When compared to the C-ST samples (control), the CUS-ST samples exhibited considerably higher compressive strength. This can be explained by the effect of the pressure application on the microstructure or pore structure changes. Curing under stress increases the packing density of the material through decrease in total porosity and void ratio (Figure 4.5a), which results in denser pore structure (Figure 4.20). This decrease in porosity and a denser pore structure leads to compressive strength gain (Fall et al., 2005). An additional factor can be suggested as a contributor to the stress induced strength increase of CPB

at early ages. This factor is the curing stress induced increase of cement hydration degree at early ages (Zhou and Beaudoin, 2003).

From Figure 4.6, it can be also observed that the CUS-ZnT samples exhibited a much lower mechanical strength than that of the CUS-ST samples. This observation confirms the importance of the physical properties (e.g., specific gravity, strength of the tailings particles) and mineralogical composition/chemistry of the tailings (see comparison in Table 4.1), and the chemical composition of its pore water (see comparison in Table 4.6) in the response of the CPB. This strength difference is attributed to the combined effects of the aforementioned factors that are related to the tailings and its pore water chemistry. The specific gravity of ZnT (3.34) is higher than that of ST (2.70) (Table 4.2). Thus, for a given  $w/c$  ratio (7.6 in this study), CPB made of ZnT will have a higher initial void ratio (1.92) or porosity than the samples made of ST (1.15; Table 4.4, Figure 4.5a). It is well known that, for a given type of CPB or porous medium, the strength often decreases as the void ratio or porosity increases (e.g., Kesimal et al., 2003; Fall et al., 2010a; Ercikdi et al., 2013) as demonstrated in Figure 4.7a (will be discussed later). In fact, there is evidence which confirms that the aggregate mineralogy and chemistry influence Portland cement based materials due to chemical interactions between the aggregates, and the cement pore fluid and cementitious matrix as demonstrated in previous studies (e.g., Pacheco-Torgal et al., 2007). However, it should be emphasized that this subject still requires further extensive studies to provide a complete understanding of the interactions between tailings type and hydration of cement as well as the importance of the mineralogical and chemical properties of tailings on the strength development of CPB. An additional factor that contributes to a lower strength of the CUS-ZnT is attributed to the relatively high concentration of sulphate present in the pore water of the ZnT (Table 4.6). The presence of chemical elements, especially sulphate, can significantly inhibit binder hydration (e.g., Tzouvalas et al., 2004; Fall and Pokharel, 2010) and thereby slow down the strength development inside the backfill (Fall and Benzaazoua, 2005). Furthermore, sulphate induced inhibition of cement hydration results in lower generation of heat within the CUS-ZnT samples than within the CUS-ST samples as shown by Figure 4.16. It is well established that the curing temperature can significantly increase the rate of early age strength gain and strength of the CPB (Fall et al., 2010a).

From Figure 4.7a, it is seen that the UCS value increases while the porosity decreases. A strong correlation between the evolution of the UCS and porosity reduction as the result of the refinement of pores is noticeable. Due to the cement hydration process, capillary pores in the CPB matrix are filled with cement hydration products and hence the porosity decreases with time (Fall et al., 2009a). This process leads to a denser matrix and increase in the UCS values. The test results are supported by the SEM images and MIP results which will be discussed later. From Figure 4.7b, it can

be noticed that an increase in suction leads to an increase in the UCS values in all of the samples, or in other words, there are H-M coupled processes. Suction development as a result of self-desiccation can lead to an increase in the backfill strength (e.g., Abdul-Hussain and Fall, 2011). Suction development can decrease the pore pressure and thus increase the effective stress inside the backfill. It is seen that both effect of applied pressure and suction are noticeable on strength growth. However, the contribution of pressure application is higher than that of suction (Figure 4.7b).

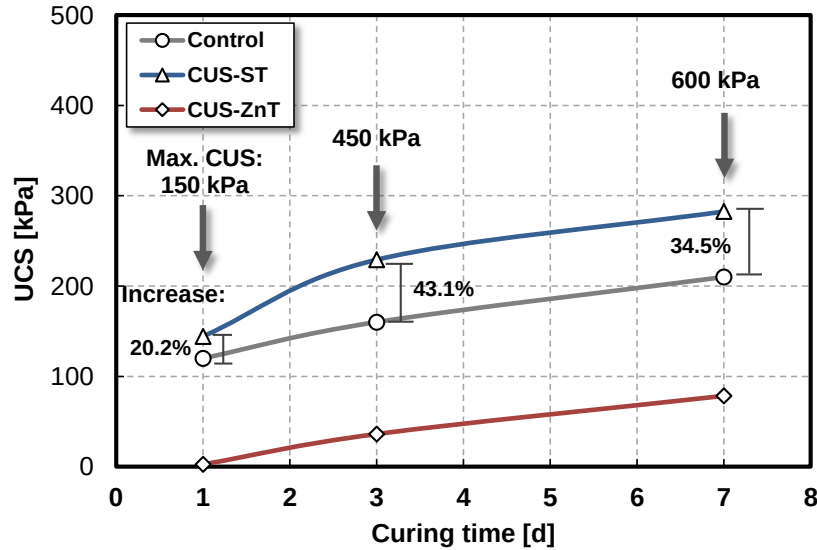


Figure 4.6. Effect of curing under stress on UCS development

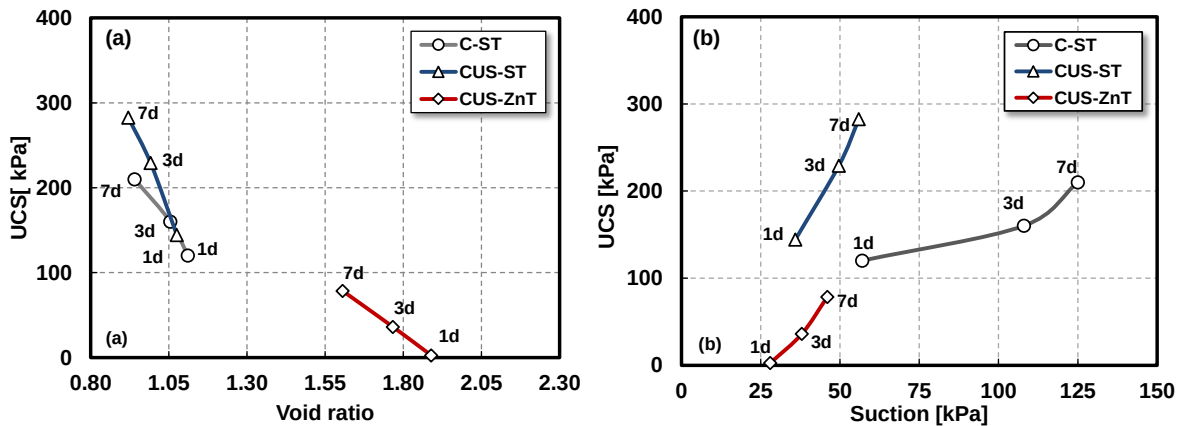


Figure 4.7. (a): UCS vs. void ratio, (b) UCS vs. suction

**Table 4.6. Chemical composition of pore water of zinc tailings**

| Elements | pH  | Sulphate<br>(mg/l) | Al<br>(mg/l) | Ca<br>(mg/l) | Fe<br>(mg/l) | Mg<br>(mg/l) | K<br>(mg/l) | Si<br>(mg/l) | Na<br>(mg/l) |
|----------|-----|--------------------|--------------|--------------|--------------|--------------|-------------|--------------|--------------|
| ZnT      | 5.3 | 2600               | 2.2          | 60000        | 19           | 2300         | 200         | 15           | 53           |

### - Stress-strain behaviour

The stress-strain properties of the CPB samples were investigated for different curing times. As can be seen from Figure 4.8a, the shape of the stress–strain curves is affected by the curing time. For example, the peak stress is achieved for large strain values of the CPB samples at 1 day compared to 7 days for both the C-ST and CUS-ST samples. The slope and shape of the stress-strain curve of both C-ST and CUS-ST samples at 1 day curing change with increases in the UCS values. Also, the CPB samples at a very early age (1 day) for both C-ST and CUS-ST show a plastic behaviour, but transitions into less “plastic” deformation at 7 days which corresponds to the higher UCS values. The aforementioned behaviour is due to the fact that the CPB sample at 7 days has a higher value in strength and hence can absorb more energy up to the peak stress compared to the 1 day sample. This can result in the propagation of cracks and rapid deformation at the time of failure, and therefore, a sharp reduction in the stress-strain curves (Fall et al., 2007). Furthermore, the curing pressure has no significant impact on the shape of the stress-strain curve of the CPBs studied. For example, the C-ST and CUS-ST samples at 7 days have relatively “brittle” behaviour. It is interesting to note that the CUS-ZnT sample at 7 days of curing showed a very plastic behaviour compared to the CUS-ST sample at the same age. This underlines again the importance of the physical characteristics and mineralogy/chemistry of the tailings and its pore chemistry, and their consequences on the cement hydration process and the amount of heat generated on the mechanical behaviour of CPB as discussed above.

Figure 4.8b shows the evolution of the modulus of elasticity ( $E$ ) acquired from the stress-strain curve of the UCS results at different curing times. The secant modulus of elasticity in a stress-strain curve at half of the unconfined compressive strength was considered to calculate  $E$  values as explained by Duncan and Bursey (2013). It is observed that as the binder hydration progresses or the curing time increases, the  $E$  value increases for both the C-ST and CUS-ST samples. Also, it can be seen that the effect of the pressure application is noticeable for the CUS-ST sample at 7 days of curing. This can be attributed to the fact that backfill with higher cohesion exhibits higher modulus of elasticity (Hassani and Archibald, 1998). Since curing stress improves the cohesion (Figure 4.9a), a higher modulus of elasticity can be expected. Due to the very low UCS values of the samples prepared with zinc tailings, the modulus of elasticity of the CUS-ZnT samples cannot be reported.

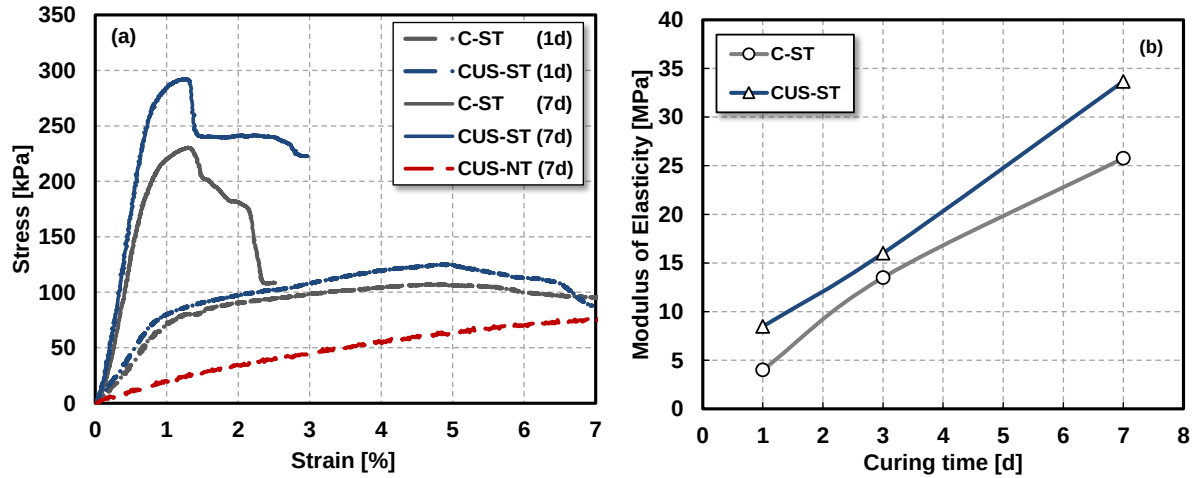


Figure 4.8. Effect of curing under stress on (a) stress-strain behaviour, (b) modulus of elasticity

#### - Shear strength parameters

The shear strength parameters, including friction angle ( $\phi$ ), and cohesion ( $c$ ), were determined from direct shear tests (Figure 4.9). From Figure 4.9b, it can be seen that there is no significant change in the  $\phi$  values with time for all of the samples. The average value of  $\phi$  is  $38.9^\circ$  and  $34.7^\circ$  for the ST (control and CUS) and ZnT samples, respectively. The cohesion ( $c$ ) of the C-ST and CUS-ST samples ranges from 55 to 100 kPa and 67 to 115 kPa, respectively. This finding shows that both  $c$  and  $\phi$  considerably contribute to the development of the shear strength. However, the time dependent evolution of the shear strength mainly depends upon the development of  $c$  rather than  $\phi$  in the long-term behaviour. Similar observations were made by Rankine et al., 2001. This can be explained by the fact that CPB at an early age has weak cementation and instead, internal friction between the tailings particles plays a role in the shear strength development of backfill (le Roux et al., 2005). The lower mean value of friction angle of the ZnT samples compared with the ST samples can be related to the differences in tailings type and lower mechanical strength which can result in the reduction of the friction angles.

Moreover, it should be noted that pressure application has considerable effects on cohesion improvement (Figure 4.9a). This behaviour is attributed to the curing stress induced refinement of the pore structure or densification of the CPB. The effect of curing stress on the cement hydration can be considered as an additional factor that contributes to this observed behaviour (Zhou and Beaudoin, 2003). However, it can be observed that pressure application has no major impact on friction angle improvement of the studied CPBs. Similar observations were made by Ahnberg (2007) who conducted tri-axial tests on soils stabilized with cement.

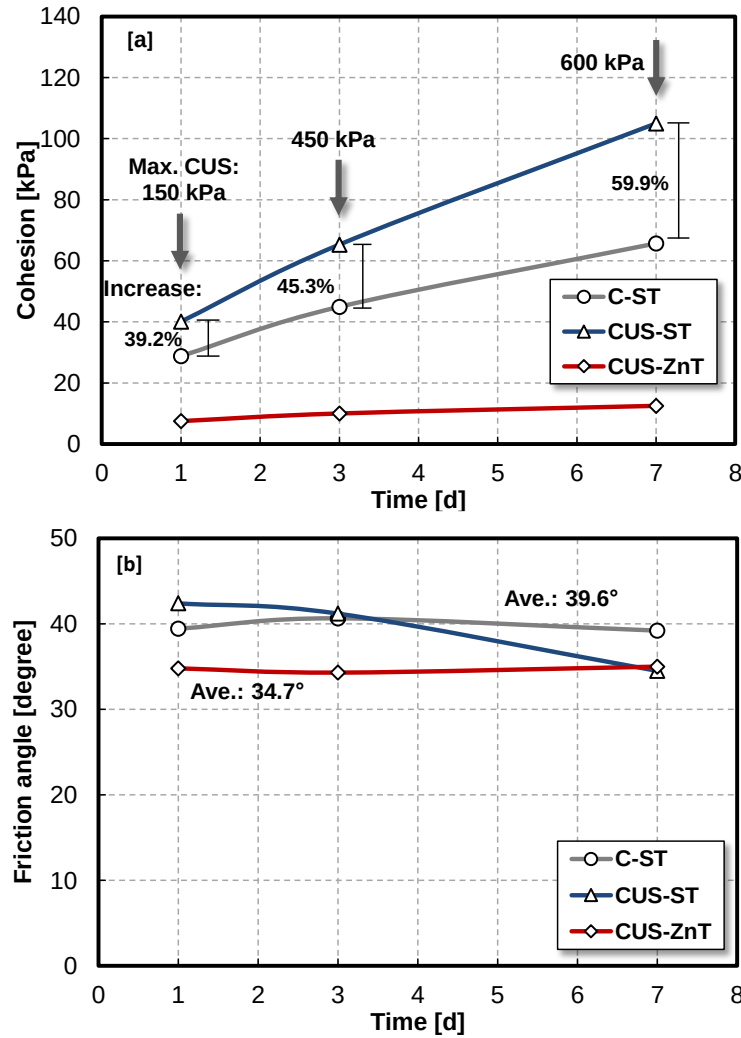


Figure 4.9. Effect of curing under stress on shear strength properties: (a) cohesion [ $c$ ] and (b) friction angle [ $\phi$ ]

#### - Deformation

Figure 4.10 illustrates the results of vertical deformation with time as well as the load-deformation curves. In the case of the CUS-ST test, during the first 12 hrs, the deformation considerably increases up to 3.2 mm which corresponds to a vertical pressure of 150 kPa. This is followed by lower increments up to 3.63 mm within 24 hrs and eventually maintains almost a straight line with time. The same qualitative behaviour can also be observed in the zinc tailings. However, due to a higher initial void ratio and the chemical and mineralogical characteristics of the tailings and pore water, lower strength and longer setting time (the latter is observed from the electrical conductivity, Figure 4.18), and higher deformation was observed when compared with the CUS-ST test.

This measured CPB deformation is mainly due to the combined effects of three factors as follows: (i) the rearrangement of the tailings particles; this rearrangement takes place within a few hours after placement (0-3 hrs in this study; see Figure 4.11). Fresh CPB has relatively high unbound water and high solid density, in which the tailings are suspended in the paste (Landriault, 2001). Any pressure application (e.g., self-weight pressure generated in the field backfill) can rearrange the tailing particles, which in turn, can cause large deformations shortly after placement, (ii) self-desiccation induced shrinkage (chemical shrinkage); this is linked to the cement hydration process and the consequence of the lowering of the internal relative humidity ( $RH$ ) in the CPB as capillary or loosely bound water is consumed by the cement reaction. It is well established that the progress of the cement hydration reaction induces decreases in the internal  $RH$  within the hydrating cementitious system (this is evidenced by the evolution of the pore water pressure shown in Figure 4.14), thus resulting not only in the formation of a solid skeleton of the CPB (hereafter simply referred to as solid skeleton) with filled and refined coarse capillary spaces, but also air-filled spaces (Meddah et al., 2011) (Figure 4.11). Hence, a decrease in the  $RH$  results in an increase in the capillary pressure. A consequence of increasing capillary pressure is the growing compressive pressure exerted by the pore fluids onto the solid skeleton. This pressure results in negative strains of the solid skeleton, i.e., shrinkage strains (Gawin et al., 2007), (iii) thermal shrinkage, which is the volume reduction of the CPB due a decrease in the binder hydration induced temperature after the CPB reaches its peak temperature. This decrease in temperature after the peak is illustrated in Figure 4.16. Similar observations have been made in concrete materials (e.g., Meddah et al., 2011).

These findings with regards to self-desiccation induced volume change suggest that, even in undrained conditions (i.e., no dissipation of excess of pore water pressure by drainage), the CPB structure can be subjected to consolidation at early ages. However, it should be emphasized that due to the undrained conditions that govern the whole system, this consolidation mechanism (self-desiccation induced consolidation) is not similar to the conventional consolidation mechanism known in soil mechanics where excess pore water can be drained out by applied pressure. In fact, water is drained by the self-desiccation process from the micro-pores due to cement hydration reactions. This is the period (3 to 48 hrs in this study) in which the backfill setting takes place (transformation from paste to formation of solid skeleton; Figure 4.11). In this period of time, reduction in pore pressure (suction) due to self-desiccation and development of effective stress occur in the backfill. Mechanical properties (e.g., strength, stiffness) can be built up and hence the voids can no longer be significantly affected by the applied pressure in this study. Therefore, vertical deformation reaches an almost constant value after the setting time. The period after 48 hrs can be considered as the hardening

process. Continual growth of cement hydration products, strength development and no further significant volume changes are the key properties of the backfill during this period of time.

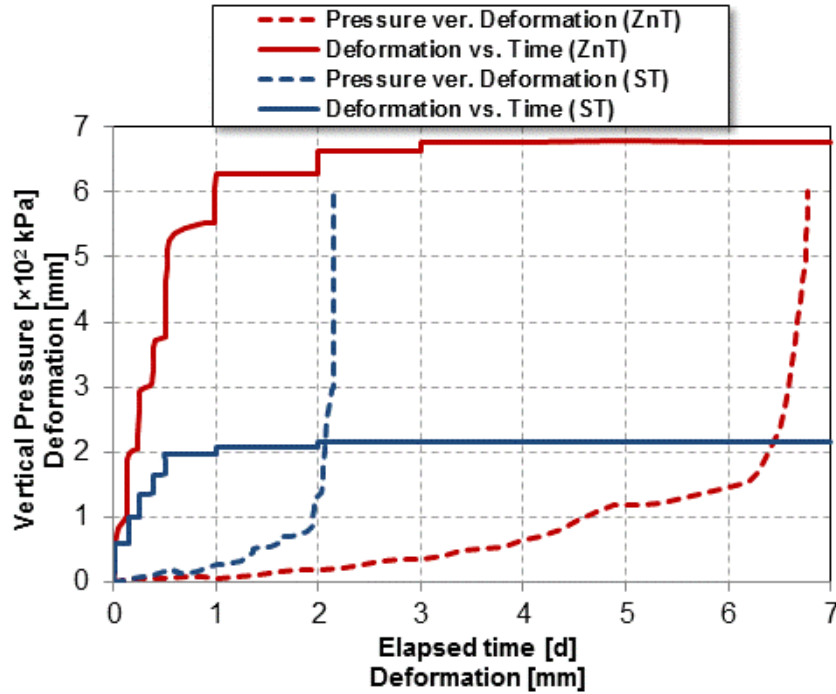


Figure 4.10. Vertical pressure versus deformation; and deformation versus curing time

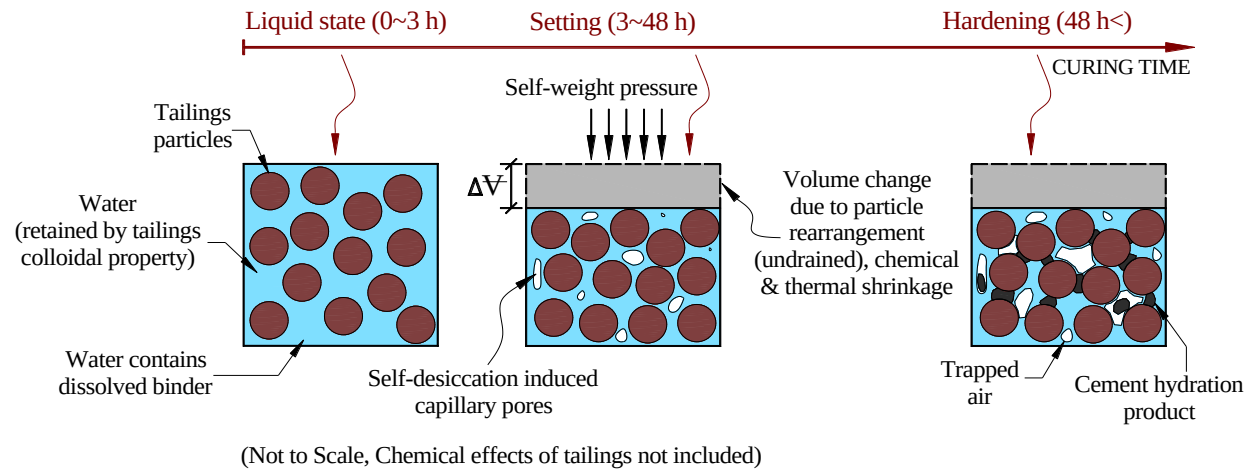


Figure 4.11. Schematic presentation of the coupled effect of cement hydration, self-desiccation and pressure application in the studied CPB at early ages and in undrained conditions

#### 4.2.3.3. Evolution of hydraulic properties

##### - Hydraulic conductivity

The evolution of the saturated hydraulic conductivity ( $k_{sat}$ ) with curing time is shown in Figure 4.12. It is seen that the values of  $k_{sat}$  decrease with time for all of the samples. This decrease in the  $k_{sat}$  is due to the refinement of the pores as a result of the cement hydration process. This is evidenced by Figures 4.5a and 4.13a, which confirm that, as the curing time advances, the void ratio decreases (Figure 4.5a), which results in lower  $k_{sat}$  values (Figure 4.13a), regardless of the curing conditions (stress-free or under stress). Reduction in capillary porosity during hydration and a denser cemented matrix eventually reduce the fluid transportability of the CPB. Similar observations and conclusions have been made in several previous studies (e.g., Godbout, 2005; Fall et al., 2009a). However, from Figure 4.12, it can be noticed that the  $k_{sat}$  is not only controlled by the evolution of the void ratio due to the progress of binder hydration, but other factors, such as applied pressure, can significantly decrease the hydraulic conductivity. A comparison of the  $k_{sat}$  values in the C-ST and CUS-ST samples showed that pressure application has a significant effect on hydraulic conductivity values. When compared to the control test, the CUS-ST samples show a decrease in hydraulic conductivity of 65%, 77% and 78% for curing times of 1, 3 and 7 days, respectively. Also, the CUS-ZnT sample shows similar behaviour as the CUS-ST sample in terms of the effect of pressure application which results in decreased saturated hydraulic conductivity. This pressure induced decrease in hydraulic conductivity is explained by the fact that the curing pressure contributes to reducing the void ratio or porosity of the CPB, and thus the hydraulic conductivity. A lower void ratio of the CUS-ST sample compared with the C-ST sample at the same curing time supports this statement (Figure 4.5a). The reason for the decrease of the CPB void ratio is because of the curing stress, which has already been explained in the previous section. This observation is confirmed by the MIP tests conducted on the C-ST and CUS-ST samples at 7 days of curing which will be discussed later. Based on the MIP results, lower hydraulic conductivity was observed on samples with lower porosity, lower threshold diameter and finer PSD (Figure 4.20). As evident in Figure 4.13b, there is a strongly coupled H-M process, i.e. between the UCS and the hydraulic conductivity of the backfill at any curing time.

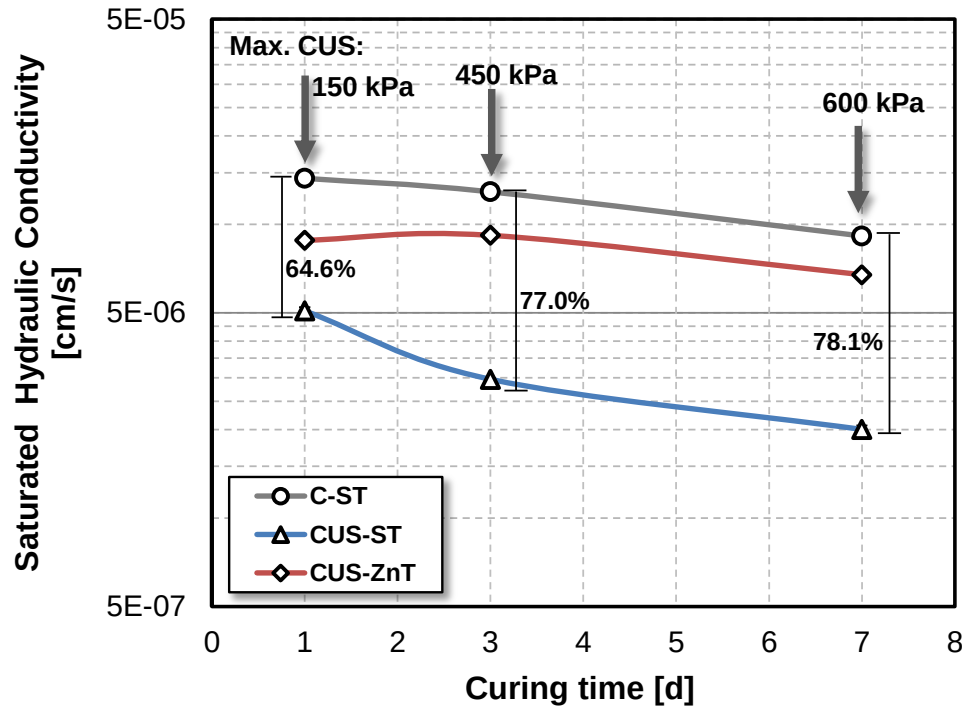


Figure 4.12. Effect of curing under stress on saturated hydraulic conductivity development

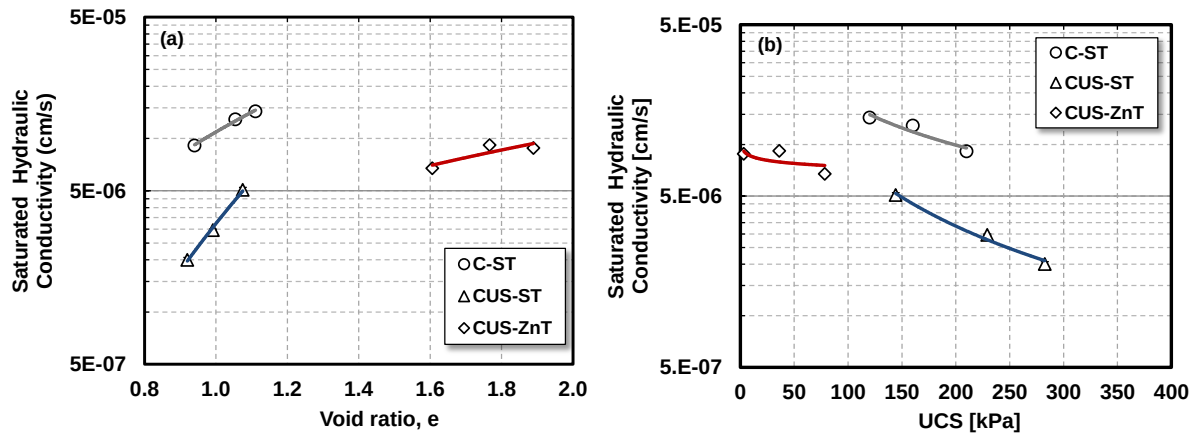


Figure 4.13. (a) Saturated hydraulic conductivity vs. void ratio, (b) Relationship between UCS and saturated hydraulic conductivity

#### - Pore pressure and suction response

The designing of a safe and stable barricade erected on the draw-point of a mine stope is one of the most important design aspects of the CPB. For this purpose, an understanding of backfill behaviour in terms of pore pressure ( $u$ ), suction and evolution of effective stress ( $\sigma'$ ) is of foremost importance for designers. This is especially true in the early hours of backfilling, when the pore

pressure development at the draw-point is important and its theoretical evaluation is highly dependent on variable factors, such as backfill hydraulic conductivity, rate of self-desiccation, drainage, consolidation arching effects and cement hydration (Fall et al., 2009a; Li and Aubertin, 2009).

The total pressure, cumulative pore pressure reduction and suction data obtained from installed sensors for a period of 7 days are shown in Figure 4.14 for the CUS-ST and CUS-ZnT samples. The minimum detectable reading of the suction meter is -12 kPa. Therefore, the suction reading obtained for the C-ST sample started from this value at about 13 hrs of curing. However, it should be noted that the onset of suction (PWP=0 kPa) started at an earlier time, about 3-4 hrs after loading. For the C-ST sample, rapid evolution of suction can be observed during the first 24 hrs of curing, followed with a lower rate of suction development from 24 to 72 hrs. After 3 days and up to 7 days, very low evolution of suction can be noticed. This is attributed to the lower rate of cement hydration reaction (lower rate of self-desiccation) associated with lower rate of pore refinement within this period of time. The maximum value of the suction at 7 days of curing is about 110 kPa for the C-ST sample.

In terms of samples cured under stress (UCS-ST and UCS-ZnT samples), the pressure was gradually increased every 3 hrs up to 150 kPa for the first 12 hrs after the CPB placement. Then, the pressure increment was 150 kPa for the next 12 hrs and then 150 kPa per day up to 600 kPa (Figure 4.3). The increments of the curing pressure can be observed in the total pressure (TP) curve. The obtained results have shown that the pore pressure gradually increased according to the applied pressure up to 65 kPa during the first 9 hrs of curing. This pressure increment corresponds to a pressure application of 75 kPa during this period of time. The pore pressure was considerably high in the early hours of curing. This is an indication of low effective stress at very early ages and the existing high pore pressure since the backfill behaves almost like a fluid. However, due to self-desiccation as a result of cement hydration, the pore pressure declined after about 6 hrs and 2 days for CUS-ST and CUS-ZnT, respectively. Moreover, the results of the cumulative pore pressure reduction (CPR) are presented in Figure 4.14. Rapid development of negative pore pressure (suction) started after 6 hrs and 2 days for CUS-ST and CUS-ZnT, respectively. It is noticed that the development of suction is affected by the sequence of pressure application. For example, in the CPR curve for the ST sample, the pressure increments at first and second days caused a significant rise in the pore pressure and then gradually started to decrease. The pressure increment at third day and after had not an important influence on CPR curve (Figure 4.14). It is attributed to the fact that backfill pore structure reached to a hard matrix and cannot be consolidated by the pressure application. Pressure increase excited the CPR (ZnT) curve to a positive value at both first and second days of curing. This means that effective stress and associated strength gain can not strongly develop in the ZnT samples up to about two days of curing. This can be observed from the UCS results of the CUS-ZnT samples at 1

and 3 days which exhibited very low strength in the early days of curing. These observations suggest that differences in tailings mineralogy and chemistry (CUS-ST, CUS-ZnT) can significantly affect the hydration behaviour, and hence the PWP evolution within a CPB.

The obtained results also shown that after each pressure increment at 2 and 3 days of curing, the pore pressure curves for CUS-ST and CUS-ZnT samples were considerably lower than the total pressure curve. This is due to the fact that CPB transforms from a liquid stage (paste) to the formation of a solid skeleton after 6 and 48 hrs with respect to the CUS-ST and CUS-ZnT samples (Figure 4.11), respectively. Therefore, much of the applied vertical pressure is carried by the tailings particles. So, due to the formation of strong bonding between the tailings particles, pressure application will not be able to considerably interrupt the evolution of the pore pressure after this point.

Suction readings obtained from a suction meter for both the UCS-ST and CUS-ZnT samples are also presented in the graph and labeled as SU (ST) and SU (ZnT), respectively. Theoretically, the SU curve should be matched with the CPR curve. Although the suction curves for both the ST and ZnT samples show the same qualitative behaviour as the piezometer readings, there are some differences in the actual values. For example, the negative pore pressure obtained from the suction meter shows higher values compared to the corresponding reading obtained from the piezometer which is plotted in a CPR curve. This can be due to the different sensing mechanisms of the sensors. VW piezometer directly measures the water pressure and then converts the water pressure into a frequency signal via a diaphragm; it can be later translated into a numeric value. However, the suction meter has an indirect mechanism; it measures the water content of a porous ceramic disk mounted on top of the sensor and then converts the volume to a suction value by using the water characteristic curve (WCC) of the ceramic disk (MPS-2 manual, 2014). The suction reading for the ZnT sample is -25 kPa at 7 days of curing which is considerably lower than that of ST sample which is -80.1 kPa. Further studies should address this issue.

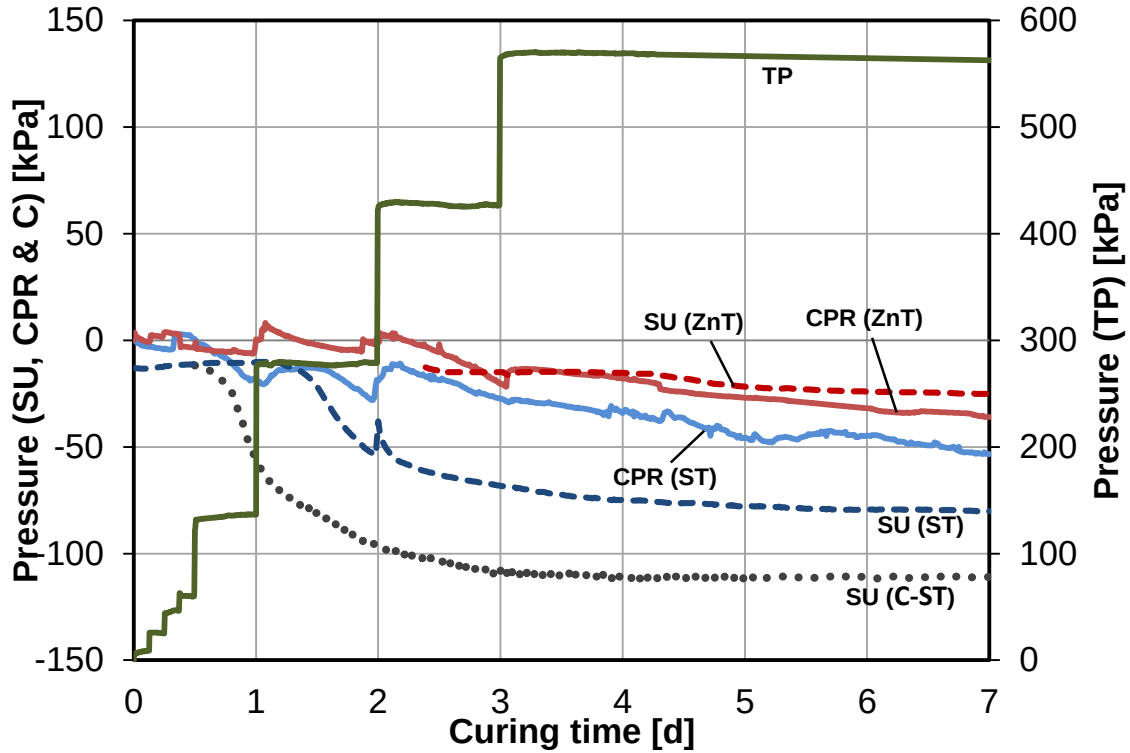


Figure 4.14. Sensor readings, TP: Total pressure; CPR: Cumulative pore pressure reduction; SU: Suction

#### 4.2.3.4. Evolution of thermal properties and heat development

##### - Thermal conductivity properties

The evolution of thermal conductivity with time was investigated for all of the samples and the results are shown in Figure 4.15. It is seen that for samples prepared with silica tailings, the thermal conductivity ( $k$ ) values slightly decrease as the curing time is increased from 1 to 7 days. This behaviour is mainly attributed to the strong coupling between  $k$  and the degree of saturation. Indeed, as the curing time increases, the suction of the CPB increases or the degree of saturation decreases because of self-desiccation. This decrease in suction is supported by the experimental evidence shown in Figure 4.14. The variation in the degree of saturation with time is a main factor that can change the  $k$  values (Kim et al., 2003; Celestin and Fall, 2009). Since air has lower  $k$  than water, desaturation as a result of self-desiccation followed by an increase in air voids can reduce the  $k$  of the CPB materials. So, similar to the concrete material reported by Khan (2002), the  $k$  of CPB decreases with a decrease in the degree of saturation (Celestin and Fall, 2009).

The thermal conductivity of the CUS-ZnT samples shows lower values compared with the ST samples regardless of the curing stress. This is due to the effect of the porosity or void ratio and the mineralogical composition of the tailings on the thermal conductivity. Lower porosity or void ratio leads to denser cemented materials, thereby to higher thermal conductivity (Khan, 2002; Celestin and Fall, 2009). The void ratio (and porosity) of the CUS-ZnT samples is considerably higher than that of the C-ST and CUS-ST samples, which in turn, present lower  $k$  values (Figure 4.5a). The experimental tests performed by Celestin and Fall (2009) have revealed that the mineralogical composition of tailings or the proportion of quartz present in the tailings materials has a significant impact on the thermal properties of the CPB. The thermal conductivity of the CPB increases with an increase in the quartz content. This is because the thermal conductivity of quartz is much higher than that of other minerals (e.g.  $K=7.7$  W/m°C for quartz, 2.25 W/m°C for feldspar, 2.03 W/m°C for mica, and 3.46 W/m°C for amphibole according to Horai, 1971) and also other components of CPB (water and cement paste). It is shown in Table 4.1 that the ZnT tailings contain only 11.9% quartz whereas the silica tailings (ST) comprise 99.8% quartz.

Moreover, for the CUS-ZnT samples, the  $k$  values from time of preparation increased up to 3 days and remained constant. For zinc tailings used in this study, the curing time of 48-60 hrs can be considered as the time of solid skeleton formation. The electrical conductivity monitoring of the CUS-ZnT samples compared with that of the CUS-ST support this argument (see Figure 4.18). During the setting period, the cement hydration products slightly filled the large pores, while unbound water was consumed by cement hydration, which in turn, increased the contribution of the tailings volume fraction on the thermal conductivity (Khan, 2002). Between 3 and 7 days of curing, the moisture content (and degree of saturation) in the backfill started to decrease as a result of the associated cement hydration, which in turn, decreased the  $k$  values up to 7 days.

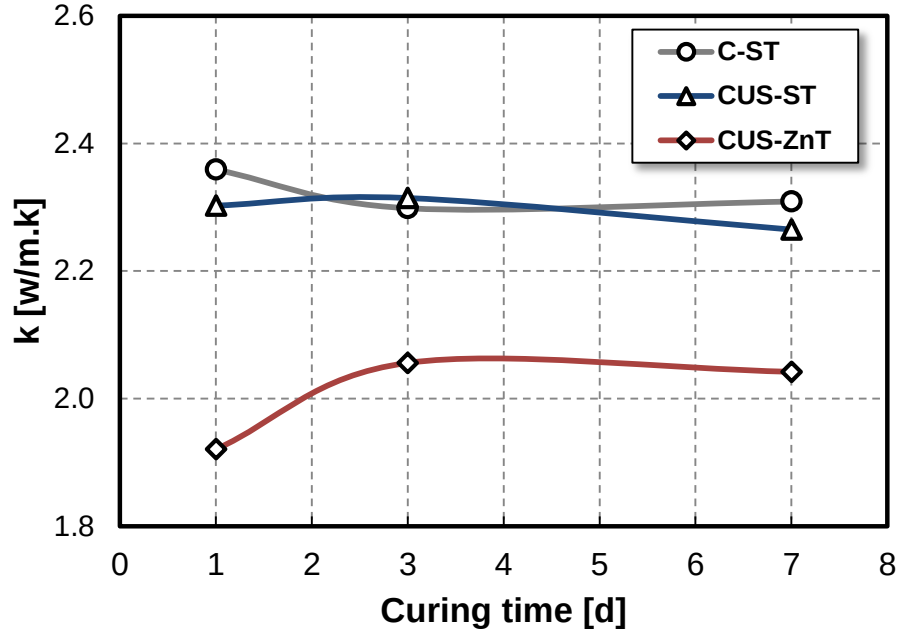


Figure 4.15. Effect of curing stress under stress on evolution of thermal conductivity

#### - Heat of cement hydration

From the temperature evolution curves in Figure 4.16, it is seen that all the samples showed qualitatively the same behaviour. The temperature increments vary between 2.6°C and 3.5°C. The heat of hydration quickly reaches the upmost value after about 11 and 16 hrs in the ST (CUS and control) and ZnT samples, respectively. The most important part of the generated heat of hydration can be related to the exothermic reactions of aluminate ( $C_3A$ ) with gypsum to form ettringite as well as the hydration of tricalcium silicate ( $C_3S$ ) to form calcium silicate hydrate (C-S-H) (Taylor, 1997; Swaddiwudhipong et al., 2002). From the CUS-ST curve, it is seen that there is a significant amount of heat up to 2 days of curing which can contribute to the acceleration of the cement hydration reactions and associated self-desiccation. Between about 2 and 7 days of curing, the CPB sample started to gradually cool down and reached a temperature close to ambient.

The development of suction in the cells had a strong coupled relationship with heat of hydration. As presented earlier in Figure 4.14, the evolution of suction for both the CUS-CT and C-ST samples has the highest rate of increase during the first 2 days after placement. The maximum rate of suction development was achieved at the time of utmost temperature, thus supporting that there was strongly coupled T-H behaviour in the studied material. This process is stronger when large amounts of CPB are backfilled into a mine stope. In a typical backfill structure, the temperature as a

result of hydration can reach 50°C depending on the binder type and content as well as the size of the filled stope (e.g., Nasir and Fall, 2010; Fall et al., 2010a).

By comparing the CUS-ST and C-ST tests, it can be seen that the pressure application has no significant impacts on the temperature evolution of the studied CPBs. The CUS-ZnT sample had less heat of hydration compared to the CUS-ST sample. This lower heat of hydration is attributed to the chemical interactions between the tailings and its initial pore water chemistry, and the cement hydration process. The presence of a relatively high amount of chemical impurities (e.g., sulphate ions; see Table 4.6) decreased the rate of hydration, which in turn, resulted in lower heat generation. The presence of high quantities of sulphate in the cement matrix significantly retards the hydration reaction of the cement (Pokharel and Fall, 2011). It is well known that sulphate strongly inhibits the hydration of  $C_3A$ . The hydration of  $C_3A$  is one of the major contributors to heat generation during the hydration of a cement system (e.g., Taylor, 1997). The retardation phenomenon can be adequately explained on the basis of the reduced solubility of the  $C_3A$  in solutions that are saturated with sulphate (Mehta and Monteiro, 2013).

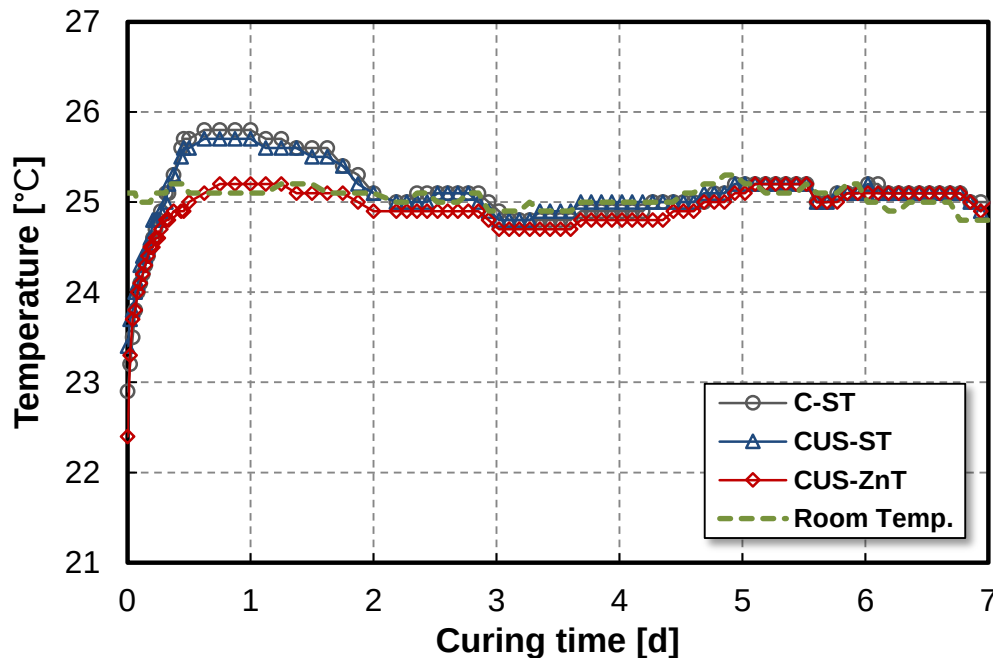


Figure 4.16. Evolution of heat of cement hydration with time for different samples

#### 4.2.3.5. Evolution of chemical properties

##### - Pore fluid chemistry

To understand the chemical evolution of CPB and its relationship to the THM factors, the concentration of some important cations, such as potassium (K), sodium (Na), calcium (Ca), magnesium (Mg), aluminum (Al), iron (Fe) and silicon (Si), as well as anion concentration, including  $\text{SO}_4$ , are investigated in this study. CPB as a cement-based material gains strength with the formation of various specific cement hydration products (e.g., C-S-H, CH) (Benzaazoua et al., 2004). When water is added to CPB, the cement clinker that contains four primary types of minerals (i.e.,  $\text{C}_3\text{S}$ , dicalcium silicate ( $\text{C}_2\text{S}$ ),  $\text{C}_3\text{A}$  and ferrite ( $\text{C}_4\text{AF}$ )) releases some ions into the pore solution (Double, 1983). This process will change the anhydrous compositions to hydrated products, which is mainly called a cement hydration reaction. The process ultimately ends up with the precipitation of three important cement hydration products, including C-S-H, calcium hydroxide (CH) and ettringite (Hansen et al., 1973). The results of the obtained chemical analysis of the pore solution are shown in Figure 4.17. The analysis was conducted on two samples of CUS-ST and CUS-ZnT at 1, 3 and 7 days of curing. The cement hydration reactions commenced with the hydration of the cement clinkers (Double, 1983). These processes changed the anhydrous compositions to hydrated products and as a result, the concentration of some ions, such as Ca, Na, K and  $\text{SO}_4$ , increased in the pore solution. This is the reason that a high concentration of these ions can be noticed in the first 24 hrs of hydration, see Figure 4.17.

The concentrations of Ca and  $\text{SO}_4$  are close to 1000 g/l on the first day of curing both the CUS-ST and CUS-ZnT samples. The initial concentrations of these cations depend on the cement composition and w/c ratio (Lothenbach et al., 2006). The quick dissolution of  $\text{C}_3\text{S}$ , which is the primary anhydrous phase of cement, release these cations into the pore solution (Taylor, 1997). The concentrations of the other cations (Al, Mg, Si and Fe) are considerably lower, between about 1 and 10 g/l.

The pore solution composition considerably changes from day 1 to day 3 of the hydration. The concentrations of  $\text{SO}_4$  and Ca are limited by the presence of CH and gypsum (Lothenbach et al., 2006). The  $\text{SO}_4$  and Ca concentrations decrease during this period of time. The Ca concentrations decrease from 680 to 380 g/l and 1520 to 1120 g/l for CUS-ST and CUS-ZnT, respectively. Also, the  $\text{SO}_4$  concentration is reduced from 2400 to 1700 g/l for the CUS-ZnT sample between 1 and 3 days of curing.

The Ca was reduced from the solution to form C-S-H and CH (Benzaazoua et al., 2004). Other cations, such as Al, Fe and Mg, were reacted with  $\text{SO}_4$  and OH to produce a greater volume of

ettringite and more stable monosulfate (AFm; Lothenbach et al., 2007). These reactions were reflected in the depletion of Fe and Mg from the pore solution up to 7 days of hydration. The same dissolution reaction by  $C_3S$  can still take place, although other cement constituents had increased involvement, such as  $C_3A$ , and at later stages, by the hydration of  $C_2S$ . This results in rapid growth in ettringite and the formation of C-S-H and CH (Taylor 1997; Lothenbach et al., 2007). The rapid reduction in the Ca and  $SO_4$  concentration is considerable due to these reactions.

The concentration of alkalis, such as Na and K, shows slight increases for both the CUS-ST and CUS-ZnT samples between 1 day and 7 days of curing. The average concentration of K is about 957 g/l and 1052 g/l for the CUS-ST and CUS-ZnT samples, respectively. Also, for the same period of time, the concentration of Na is 207 g/l and 161 g/l for CUS-ST and CUS-ZnT, respectively. This is attributed to the decrease in the volume of the pore solution as the result of cement hydration and slow release of alkalis from the cement clinker, even when a small portion of these ions was consumed to form C-S-H (Lothenbach and Wieland, 2006). The evolution of the CPB strength can be observed from increases in the UCS values at about 53% from 3 to 7 days for the CUS-ZnT samples. Also, the hydraulic conductivity evolves about 35% between 3 and 7 days for the CUS-ZnT samples. This indicates the precipitation of C-S-H and CH products with time and shows that a strong coupled relationship exists between the chemical and hydro-mechanical properties of CPB.

The results showed that the pH values did not change considerably during the studied period. The average pH value for the CUS-ST and CUS-ZnT samples were measured to be about 12.7 and 11.5, respectively. In addition, the pH value of the sample prepared with zinc tailing was lower than that of the ST. This can be attributed to the different tailings mineralogy and chemistry which affect the pH and also initial concentration of ions in the pore solution. However, it should be noted that the same trend for pore solution evolution was observed for both studied tailings which means that similar chemical reactions can have taken place in both pore solutions.

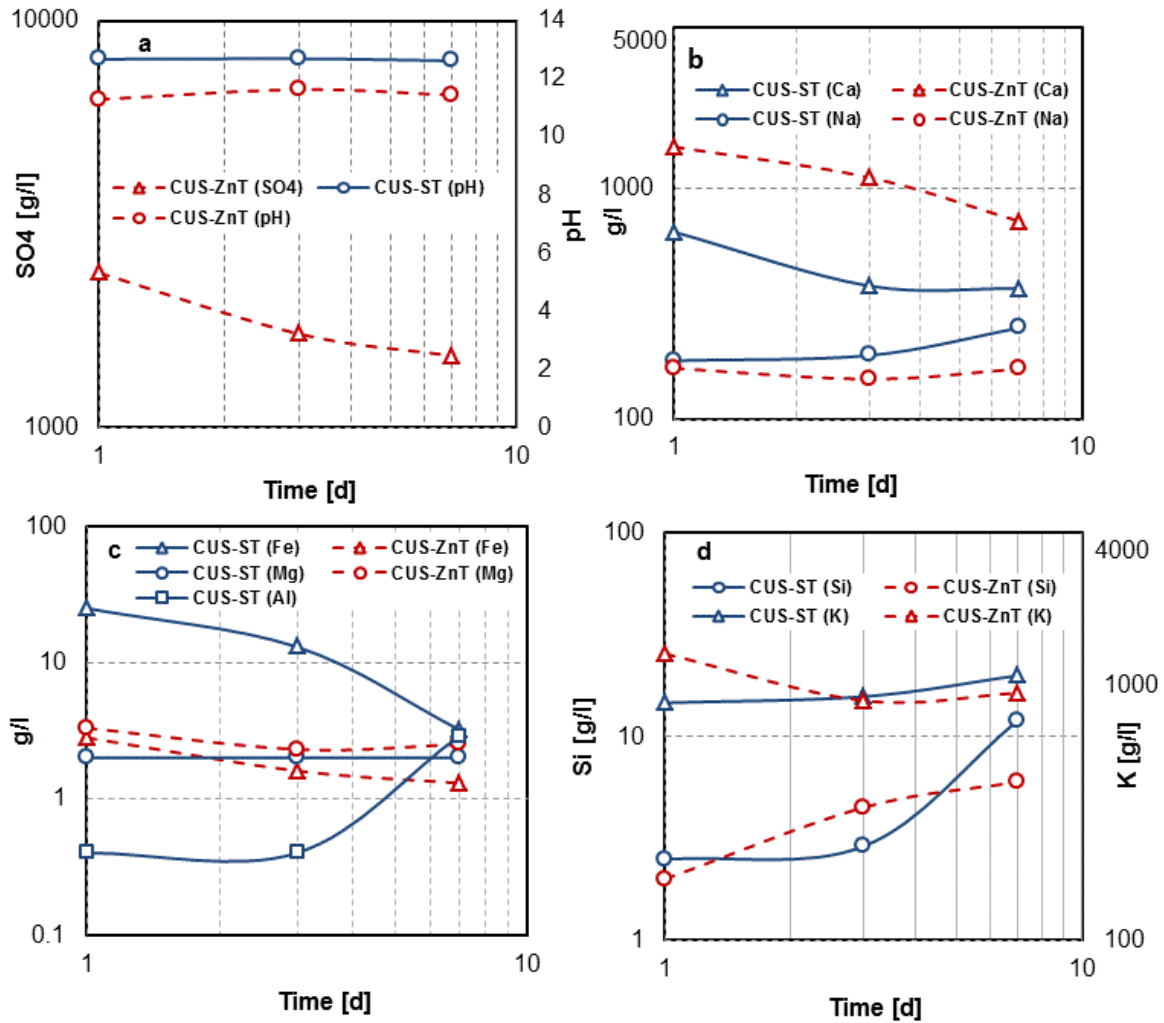


Figure 4.17. Evolution of pore fluid concentration with time

#### - Electrical conductivity

The electrical conductivity was determined from the dielectric properties of the studied material. The change in ionic concentrations in the pore fluid as a result of cement hydration can be detected by the electrical conductivity of the backfill (Thottarath, 2010). From Figure 4.18, it is seen that all of the studied samples show the same qualitative behaviour. Soon after mixing, the electrical conductivity (EC) started to gradually increase to reach the peak value. This increase in the EC can be explained by an increase of the ion concentration in the pore fluid as well as temperature increase (Figure 4.16) as a result of the exothermic cement reaction (Levita et al., 2000). The peak value in the EC curve can be corresponded to the initial setting (transforming from the paste phase to solid skeleton formation) of the backfill. Afterward, the electrical conductivity started to decrease with time which is due to the reduction in unbound water as a result of self-desiccation and less connected capillary pores, which in turn, increase the ion path flow (Levita et al., 2000).

In Figure 4.18, the setting time in the sample cured under pressure (CUS-ST) shifts to a longer hydration time compared to the C-ST sample. This means that the setting of the former took place at about 12 hrs of curing which is longer than that of the latter (6 hrs). This results from the effect of the applied pressure on the excess pore pressure in the CUS-ST sample. Samples cured under stress experience relatively high pore pressures in the early hours of curing (compared to the C-ST sample), which in turn, need more time for setting to occur. Therefore, the setting of CPB which is related to the onset of effective stress requires a longer time. Moreover, the CUS-ST sample exhibits a considerably lower conductivity value after about 4 days of curing compared with the C-ST sample. This is due to the fact that the applying of curing pressure leads to tailings rearrangement and hence, higher packing density of the tailings particles. This causes reduction in the total porosity (Figure 4.5a) and void ratio of the CPB (Fall et al., 2005). Therefore, less connected capillary pores as explained above can result in the increase of tortuosity and longer flow path for ions and therefore reduction in the electrical conductivity.

The CUS-ZnT sample shows a very prolonged EC peak value at about 2 days of curing. After the peak value, the EC remains almost constant at around 3 ds/m, which means that cement hydration reactions took place at much slower rates compared to the CUS-ST sample. This behaviour can also be supported by the UCS test results. The UCS values for 1 (and also 3 day) cured samples indicate a very low strength and after 7 days of curing, the UCS values of the CUS-ZnT sample are considerably lower than those of the CUS-ST sample. This slower cement hydration rate can be explained by the chemical interactions between the: (i) cemented matrix of the CPB with the tailings; and (ii) the cemented matrix of the CPB and its pore solutions as explained earlier. This underlines again the importance of the tailings type in the THMC response of CPB. This subject requires further investigation.

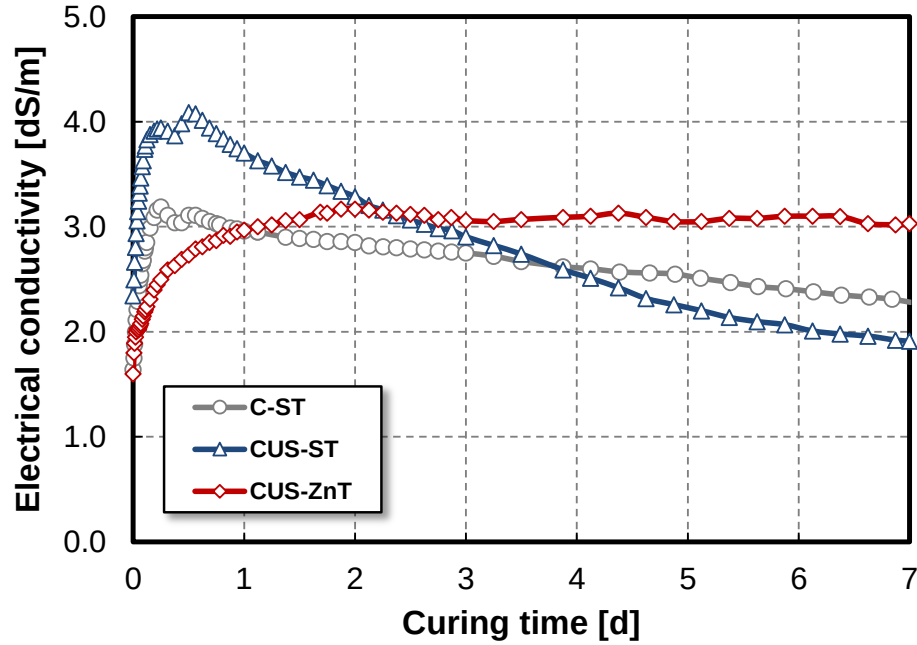


Figure 4.18. Evolution of electrical conductivity with curing time

#### 4.2.3.6. Pore structure

##### - SEM images

The pore size distribution, pore shape and porosity are important microstructural characteristics that can affect the thermo-hydro-mechanical performance of CPB. To understand the effect of curing under stress on the pore structure, samples cured with and without pressure application at 7 days of curing time were used to conduct the SEM. Typical results are presented in Figure 4.19. It is seen that two types of pore spaces can be distinguished. The interconnected pores within the CPB structure which can transport fluid across a medium (Dullien, 1992) versus the isolated pores that are dispersed over the CPB structure. It is seen that in the C-ST sample, most of the large pores are connected by interconnected micro paths and relatively large connected capillary pores are observed from the SEM images. Capillary spaces between the solid particles are de-saturated as the result of self-desiccation and therefore cause suction development inside the CPB matrix. This mechanism leads to the removal of some of the water out of the saturated voids during the cement hydration reactions and hence interconnected capillary pores can be observed in these images (Figure 4.11). These capillary pores will be filled with hydration products (e.g., C-S-H and CH) at advanced ages of curing. The high connectivity of the pores creates capillary networks that act as internal water paths which cause higher tortuosity, thus reducing the hydraulic conductivity (Dullien, 1992).

The SEM image of the CUS-ST sample shows that the curing pressure considerably refines the pore structures, see Figure 4.19. The tailings particles are more bonded and cement hydration products surround the tailings particles. The pores between the tailings are filled with cemented products, which create a dense matrix with filled intergranular spaces. A few isolated connected pores as well as a much denser and compacted structure can be seen in the CUS-ST sample. This can be explained by the fact that the development of self-desiccation as well as pressure application disconnect the capillary pore networks. Therefore higher shear strength parameters and lower hydraulic conductivity as reported in the HM results presented before can be expected. Moreover, the most prevalent cement hydration products formed at early ages are ettringite, with less CH and C-S-H growth as observed by Ghirian and Fall (2013).

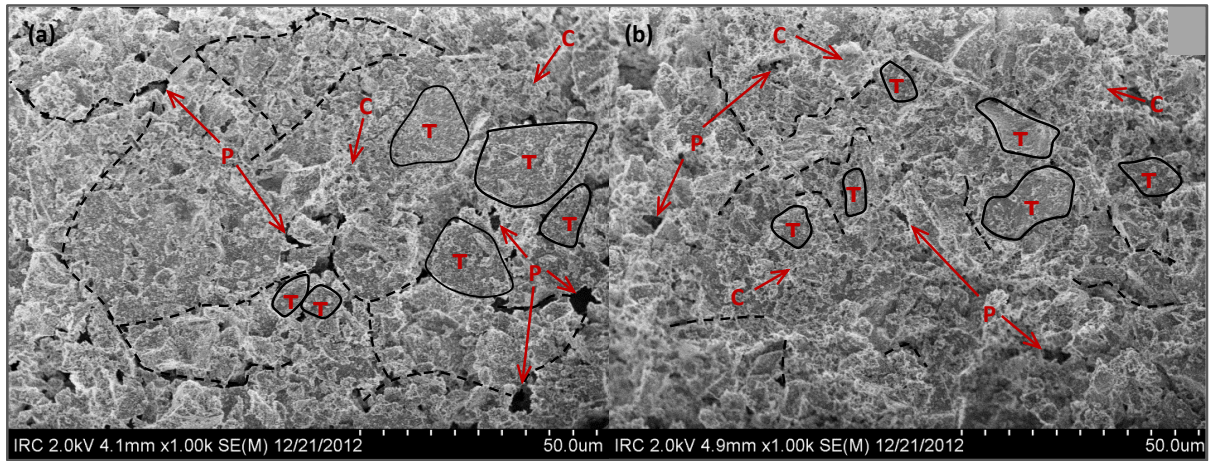


**Figure 4.19. SEM images show effect of curing under pressure on CPB microstructure at 7 days of curing time (a) without pressure (C-ST); (b) with pressure (CUS-ST). P: capillary pores; T: tailings particle; C: cement products; dashed line: interconnected pores**

#### - MIP results

The MIP tests were carried out on samples made of silica tailings and cured for periods of 7 days with and without pressure application. This allows us to understand the effect of cement hydration and curing under stress on the CPB pore structure. Also, the result can be used to investigate the effect of curing stress on the H-M evolution of CPB. Typical MIP results are shown in Figure 4.20 and presented in increments for the mercury intrusion porosity and total pore volume.

Figure 4.20a shows the changes in critical diameter ( $d_{cr}$ ) and threshold diameter ( $d_{th}$ ) as a result of pressure application for both the CUS-ST and C-ST samples. The critical diameter (the pore size that corresponds to the maximum mercury intrusion) for both samples is presented. The critical

diameter is reduced from  $2.29 \mu\text{m}$  for the C-ST sample to  $1.33 \mu\text{m}$  for the CUS-ST sample. This is attributed to the coupled effect of filling of very fine pores with cement hydration products and pressure application which reaches the dense and finer pore structure. The threshold diameter ( $d_{th}$ ) is the largest pore diameter at which mercury starts to continuously intrude into the pores (Manmohan and Mehta, 1981). It is seen that, based on the MIP results, the threshold diameter is reduced when curing pressure is applied. For the CUS-ST sample, the threshold diameter is  $7.42 \mu\text{m}$  and after pressure application, this value is reduced to  $4.61 \mu\text{m}$ . This means that CPB cured under pressure has lower fluid transportability and higher strength properties as demonstrated in Figure 4.12. For example, a 37.9% reduction in the threshold diameter results in a 78.1% reduction in the saturated hydraulic conductivity (Figure 4.12) for a 7 days cured sample. This is caused by the refinement of the pores and a denser CPB matrix (Figure 4.5) as well as smaller capillary networks which can result in the H-M improvement of CPB material.

Figure 4.20b shows that the pore size distribution of the CPB cured under pressure (CUS-ST) is finer than that of the specimen cured without pressure (C-ST). The incremental pore size distribution curve shifts toward a finer pore diameter as a result of curing pressure application. This can result in lower porosity and higher density as observed in the examination of the physical properties. Also, it is observed that the CPB cured under pressure has a finer pore structure. The volume of the macro-pores that are less than  $1 \mu\text{m}$  in size for the CUS-ST sample is 57% compared with the C-ST sample which is 15%. This clearly shows the effect of curing under stress on pore refinement. The SEM images of the 7 day sample also demonstrate that after pressure application, the CPB matrix becomes very dense and less permeable.

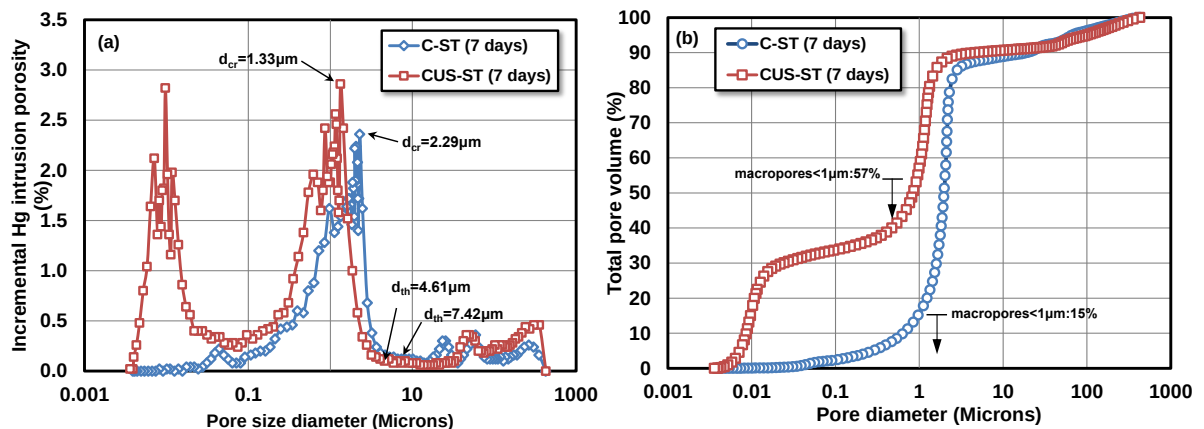


**Figure 4.20. MIP test results for CUS-ST and C-ST samples, (a) incremental mercury intrusion porosity and (b) total pore volume**

#### 4.2.3.7. Discussion on coupled THMC processes at early ages

THMC coupled processes in backfill materials are governed by the evolution of different important factors, including the heat of cement hydration (T), pore pressure (H), mechanical strength (M) (e.g., settlement) and chemical reactions (C). Figure 4.21 shows a schematic diagram of the THMC coupled processes (without the effect of the chemical alteration of tailings) at early ages (curing time  $\leq 7$  days), which were obtained from the monitoring test of the CUS-ST samples. Each curve in this graph represents one process in the system, and is developed based on the experimental data gained from the CPB monitoring. Different stages in the evolution of the THMC processes can be observed from the graph. Right after the placement of backfill in the cell apparatus, the temperature started to increase due to the exothermic nature of the cement reaction. The peak value of the temperature was obtained at about 12 hrs of curing. The hydration of  $C_3A$  and  $C_2S$  in addition to the ongoing hydration of  $C_3S$  was primarily the responsible mechanism for increasing the temperature to the peak value (Swaddiwudhipong et al., 2002). Simultaneously, different factors, such as electrical conductivity, as an indication of chemical reactions, started to increase and reached a peak value after about 12 hrs. In addition, the deformation rapidly increased while the applied pressure was increased during the first early hours of curing. The large deformation in this period is due to the rearrangement of tailings particles under pressure application which causes large volume changes in the backfill as explained earlier. The addition of a large amount of water during the backfill preparation causes very plastic behaviour in the CPB materials at early ages. It is interesting to mention that the electric conductivity (EC) peak value took place almost at the same time of the temperature peak, which means that the generated heat of cement hydration can considerably accelerate the cement reactions. This can be observed by an increase in the EC value as a result of the increase in ion concentration in the pore solution. Also, after about 12 hrs of curing, the negative pore pressure started to concurrently develop with the temperature peak. This shows coupled T-H behaviour. Such coupled interactions can lead to the transition of backfill from the liquid stage to solid skeleton formation; mainly due to the bonding of the tailing particles by the precipitation of the hydration products as well as the development of capillary pressure due to self-desiccation (see Figure 4.11). In this study, the age of 12 hrs of the backfill (CUS-ST sample) can be considered as the maximum contribution of THMC processes in solid skeleton formation. A curing time of 48 hrs can be considered as the period of solid skeleton formation, since the response to pressure increments from 300 to 450 kPa at 48 hrs of curing is only a negligible deformation in backfill materials, which means that by the onset of solid skeleton formation, any further pressure can be truly supported by the backfill formation (i.e., matrix of tailings and cement products). After 48 hrs, a rapid development in suction was noticeable. The effective stress started to develop as a result of the reduction in pore

pressure. Cement reactions consumed the large water filled capillary voids and at the same time, the cement hydration products gradually filled the voids (Belem et al., 2001). This process caused rapid development in suction. Between 12 to 48 hrs, the heat of hydration started to decrease. Also, during this period of time, the continuous formation of hydration products can be traced by a reduction of the electrical conductivity as an indication of ion depletion from the pore solution (see Figure 4.18).

After 48 hrs of curing time, the hardening process of backfilling started to occur. No significant settlement was observed beyond this point, even under relatively high curing pressures (600 kPa). Gradual precipitation of cement hydration products (such as CH and C-S-H) refined the pore structure and caused the evolution of the engineering properties of backfill (Fall et al., 2010). It should be stressed that the current experimental observations describe the THMC behaviour of the studied material and the results may vary for other types of backfills, depending on binder content and type, curing condition (e.g., temperature), tailings properties, chemical composition of water used in the backfill preparation, etc. Furthermore, it should be expected that in the field, due to the large size of the CPB, the magnitude of the observed coupled THMC processes will be greater.

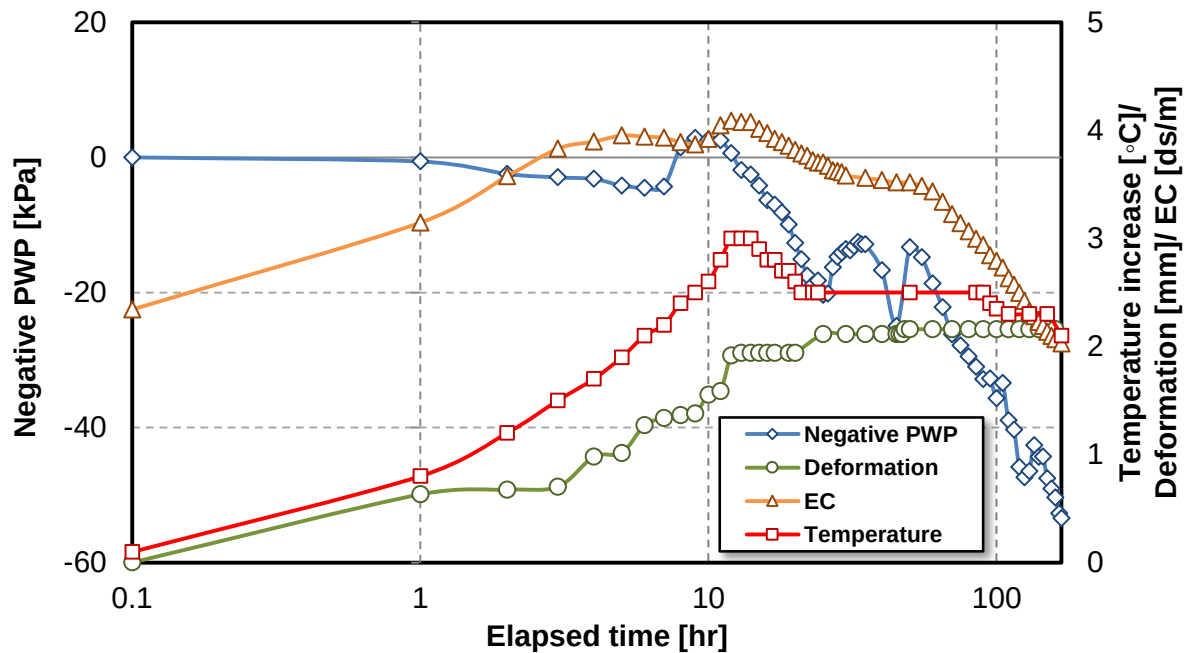


Figure 4.21. Schematic diagram of THMC coupled processes in pressure cell experiments (Silica Tailings)

#### 4.2.4. Summary and conclusion

This chapter has assessed and discussed the coupled THMC evolution of CPB material by means of a developed pressure cell apparatus. A comprehensive instrumentation program which is employed on pressure cell can successfully be used to investigate the coupled THMC processes in cemented backfill materials. The main purpose is to simulate self-weight pressure during curing time by means of a controlled pressure application rate and investigate its effects on the THMC coupled behaviour of CPB in undrained conditions. The obtained results show that the physical properties of CPB, such as void ratio (and porosity), water content and bulk density, are variable with time. Also, it is noticed that the pressure application can significantly change the physical properties of the CPB. The evolution of these properties can influence the coupled THM factors and performance of a CPB. For example, pore refinement and porosity reduction can lead to improvement in mechanical strength and hydraulic conductivity. Also, the porosity and water content are two parameters that control the evolution of thermal conductivity in CPB materials.

The obtained results show that mechanical properties, including the UCS and modulus of elasticity, are considerably influenced by pressure application and curing time. The results indicate that there is a strong correlation between the UCS and void ratio. Suction evolution as a result of cement chemical reaction induced self-desiccation and curing stress are the main mechanisms in strength development, especially in the early hours (before setting). Also, strongly H-M coupled processes govern backfill behaviour, which include coupled relationships between self-desiccation and pressure application (consolidation). The stress-strain curves show that the backfill at 7 days of curing exhibits more “brittle” behaviour compared to that of the 1 day cured sample. In terms of shear strength parameters, the internal friction angle obtained for all of the samples (ST and ZnT) is not a time dependent parameter, while cohesion considerably changes with time and applied curing stress. The results of the monitoring of the settlement reveal that CPB materials can undergo large volume changes after placement due to the coupled effects of pressure application induced tailings rearrangement before the setting of the CPB occurs, chemical shrinkage (self-desiccation induced consolidation) and thermal shrinkage.

The heat of cement hydration (and also curing temperature) can facilitate cement chemical reactions and therefore lead to faster strength development by increases in the rate of the suction development and decreases in the setting time. Studies have shown that curing under pressure does not have an impact on the rate of cement hydration, which means that the mechanical factors cannot significantly affect the chemical reactions in a CPB system (weak coupling). The monitoring of the pore fluid chemistry and electrical conductivity shows the mechanism of the setting time and hardening process, and contribution of chemical factors in the THMC coupled process. MIP and

SEM observations support the physical mechanism of pore refinement as a result of pressure application.

A THMC behaviour investigation on backfill prepared with ZnT, which contains significant chemical impurities, reveals that the chemical and mineralogical properties of tailings as well as the pore water chemistry of the tailings can significantly alter the H-M performance, binder hydration and setting time of the CPB. The obtained results show that the THMC properties of the CPB are strongly coupled. This type of THMC behaviour is fully dependent on cement hydration processes in the CPB material. Cement hydration, self-desiccation, heat development and curing stress are considered as important internal mechanisms that can affect the short-term THMC behaviour of CPB structures. The developed pressure cell set-up helps to simulate a backfill close to in-situ conditions and provide a better understanding of the fundamental mechanisms of THMC processes at a laboratory scale. Findings presented in this chapter will contribute to a better understanding of the THMC coupled processes in CPB and their behaviours, and can help to design safe, economic and durable backfill structures.

### **4.3: Technical Paper IV: Strength Evolution and Deformation Behaviour of Cemented Paste Backfill at Early Ages: Effect of Curing stress, Filling strategy and Drainage<sup>4</sup>**

#### **4.3.1. Introduction**

Cemented paste backfilling is a technology widely used in mining operations to fill mine openings or stopes (Grice, 1998; Klein and Simon, 2006; Helinski et al., 2010). Cemented paste backfill (CPB) provides ground stability to mine stopes, improves ore recovery and also maintains a safe working environment for mine workers and mining equipment (Hassani and Archibald 1998; Ercikdi et al., 2009; Nasir and Fall, 2009; Pokharel and Fall, 2013). It also benefits the environment by reducing the amount of tailings required for deposition onto the earth surface (Fall and Benzaazoua, 2005).

CPB is a mixture of thickened tailings from the milling or processing of mines, hydraulic binders and a large volume of water. It is delivered to the underground by pumping and/or using gravity flow systems at a controlled consistency and filling rate (Hewitt et al., 2009; Wu et al., 2013). Backfill material is used to provide a free-standing wall while the adjacent stope is mined out (Landriault, 2001). At the early ages, the backfill is held in place by retaining walls structures called barricades (or bulkheads) at the drawpoint drifts that access the mining stope prior to stope filling (Hassani and Archibald, 1998; Fall et al., 2009a). In most of the mines, a sequential filling strategy is implemented to fill up the mine voids, which consists of first pouring the plug fill (typically a CPB with higher cement content) up to 2-3 meters (typically) above the drawpoint followed by curing time which can take up to several days. Afterwards, the main pour (or residual fill) is poured to fill the rest of the mine stope (Yumlu and Guresci, 2007; Thompson et al., 2009). This strategy contributes to maintaining low pore water pressure (PWP) and stress in the backfill and on the barricades.

The backfilling of underground mine voids by using CPB is a complex mining/geotechnical process. This complexity is mainly due to the fact that the properties and behaviour of CPB are controlled by several factors which are also interactive, which include mechanical (M), thermal (T), hydraulic (H) and chemical (C) factors (e.g., Wu et al., 2012; 2013; Ghirian and Fall, 2013; 2014), as schematized in Figure 4.22. Some key factors that play a critical role are curing stress (M factor),

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<sup>4</sup> International Journal of Mining Science and Technology; Alireza Ghirian and Mamadou Fall (In Press)

drainage and suction (H factor), curing temperature (T factor), filling rate and sequence (F factors) and cement hydration reactions (C factor) (e.g., Fahey et al., 2009; Yilmaz et al., 2014; Ghirian and Fall, 2013; 2014). For example, curing temperature increases the rate of cement hydration reactions (Fall et al., 2010). Higher self-desiccation due to the development of suction development and drainage increases the mechanical strength (e.g., Helinski, 2007). These THMC factors and filling process (F) directly influence the key design criteria of paste backfill, such as the mechanical stability of CPB, as well as the mining plan and cycle time. Subsequently, this knowledge is utilized to determine the required cement content and slump (Slottee, 2004; Veenstra, 2013).

The unconfined compressive strength (UCS) of CPB is the most frequent property used to assess the mechanical stability of CPB structures (Klein and Simon, 2006; Pokharel and Fall, 2011; Cihangir et al., 2012) because UCS testing is relatively inexpensive and quick, and can be easily incorporated into routine quality control programs at the mine (Fall et al., 2010). CPB must reach a certain UCS in a time period that allows the mining activities (blasting, hauling, etc.) to continue on schedule (Slottee, 2004). A mechanically stable CPB structure at the early ages is especially important for the opening of the barricades, thereby reducing the mining cycle time, and thus increasing mining efficiency and improving production (Pokharel and Fall, 2011). Besides the UCS, in the ground support role, the deformation behaviour and stiffness (Young's modulus) of the CPB are also key design properties of major interest (Fall et al., 2007; 2010).

Despite the intensive and increasing use of cemented paste backfilling in mining operations, it remains a relatively new technology. Consequently, many fundamental aspects, such as the effects of curing stress, drainage and filling strategy (filling rate and sequence) and their interactions on the strength development and deformation behaviour of CPB at the early ages, are still not well understood. A literature review shows that there is still a paucity of information or data on the impact of the aforementioned factors and their interactions on the strength and deformation behaviour of CPB materials. The limited information has been mainly attributed to the lack of adequate laboratory experimental setups which can enable the production and testing of CPB samples simultaneously, while subjected to various curing stresses and drainage conditions as well as various filling rates and sequences. This research gap has motivated the authors to develop a pressure cell apparatus to investigate the influence of the aforementioned factors and their interactions on the strength and deformation behaviour of CPB. The pressure cell has the ability to simulate curing conditions close to underground mine stope conditions at the laboratory scale with the application of controlled vertical pressure and drainage conditions. Furthermore, the rate of loading (or filling rate) as well as the filling sequences can be controlled in the apparatus as well as relatively large size samples can be cured for laboratory testing purposes. This chapter describes the developed experimental setup and

presents the results of the investigation of the influence on the filling factors (filling rate and sequence), drainage conditions and curing stress and their interactions on the evolution of the strength and deformation behaviour of CPB at the early ages.

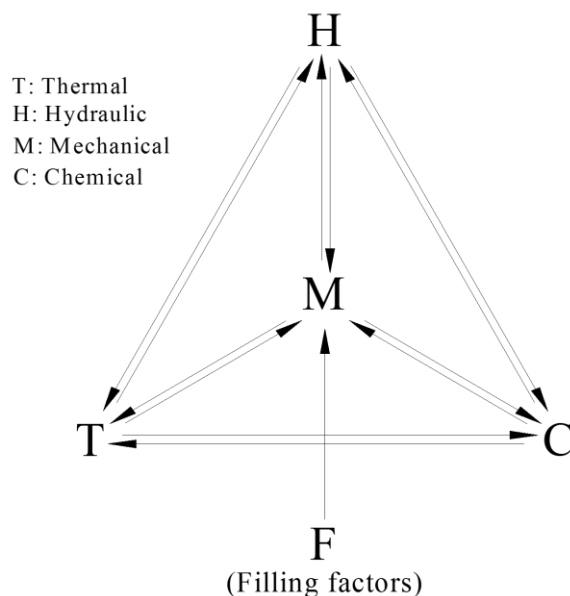


**Figure 4.22. THMC-F factors and their interactions in CPB material**

## 4.3.2. Experimental Program

### 4.3.2.1. Materials and mix design

The materials used for the CPB preparation include binder, tailings, and water. The most popular type of cement used in backfill operations is ordinary Portland cement Type I (PCI), which is also used in this study. Tap water was used as the mixing water. Commercially available artificial silica tailings were used to prepare the fresh CPB. These tailings are made from ground silica, which contains 99.8% silicon dioxide ( $\text{SiO}_2$ ). The grain size of the silica tailings is physically very similar to the natural tailings available in the mining sites of eastern Canada (Fall et al., 2009b). Natural tailings can contain several reactive chemical elements and often, sulphide minerals, which can interact with cement hydration and thus bring uncertainties to the interpretation of testing results. The use of silica tailings will minimize the uncertainties induced by these interactions.

Silica tailings, cement and water were mixed and homogenized in a food mixer for about 7 minutes. In all of the mixes, the cement proportion and water to cement ratio (w/c) were kept constant

at 4.5% and 7.6, respectively. The prepared fresh CPB mixtures were then poured into the developed pressure cell apparatus, which is described below.

#### **4.3.2.2. Developed pressure cell apparatus**

The main part of the developed apparatus is presented in Figure 4.3. It includes a transparent Perspex (acrylic plastic) cylinder with the diameter of 101.6 mm and height of 304.8 mm. Therefore, CPB specimens can be readily observed during the curing process through the transparent cylinder. Two plates cover the top and bottom of the cylinder. These plates are secured with three supporting steel rods. Only 200 mm of the height of the cylinder was filled with fresh CPB to keep the length-to-diameter ratio ( $H/W$ ) of the sample in the order of two. A piston is mounted on the upper portion of the cylinder to (gradually) apply the required pressure. A maximum pressure of 600 kPa can be applied as the cell pressure, which gives the ability to simulate mine backfill up to a height of approximately 35 m, depending on the density of the backfill material. The top plate is connected to a compressed air storage tank through an air valve to exert pressure onto the piston. A pressure regulator and a pressure gauge were used to control the rate of pressure application. The loading system was calibrated so that the vertical load application corresponds to the controlled filling rate during the simulated stope filling. It was also assumed that arching does not occur. This means that the ratio of the stope height ( $H$ ) to the width ( $B$ ) is small enough ( $H/B < 1$ ) so that the arching effect becomes negligible (Li and Aubertin, 2010; El Mkadmi et al., 2014; Ghirian and Fall, 2015). Thereby, the total self-weight stress governs the system.

To minimize the friction effect between the CPB and the cylinder wall, the inside of the cylinder body was pre-lubricated for optimum performance. The bottom plate was equipped with a porous stone and a drainage valve, which can be closed or open to allow different drainage conditions (undrained to fully drained) during CPB curing. In total, eight cells were engineered and manufactured, including two cells for instrumentation (monitoring) purposes and six cells for curing samples (under stress and various drainage conditions at different curing times), which were used for the mechanical and microstructural tests. The monitoring cells were equipped with various sensors, including a vibrating wire piezometer at the bottom of the cells, a pressure transducer and a suction meter mounted on the lower portions of the Perspex wall (Figure 4.3). After pouring the CPB into the cells, they were then completely insulated with a thermal insulation glass wool blanket (100 mm in thickness). This helps to maintain the heat from the cement hydration and consider its effects on the backfill behaviour. Then, a variety of curing scenarios or conditions was applied to the CPB.

#### 4.3.2.3. Simulated scenarios

Four different experimental scenarios are adopted in this study to assess and better understand the effects of drainage conditions (undrained versus fully drained), curing stress, backfilling rate and the use of plugs on the mechanical properties and behaviour (strength, deformation) of CPB. These scenarios, which are illustrated in Figure 4.23, include:

- \* Scenario A (Figure 4.23a: undrained vs. drained testing with filling rate of 0.31 m/h (curing under stress (CUS), 0.31-D)): compares the fully drained and undrained conditions while maintaining the same filling rate (0.31 m/h). The drainage ability of a mine backfill (degree of drainage) is a function of several factors, such as the stope geometry, drawpoint locations, barricade and backfill permeabilities, permeability of the rock mass adjacent to the backfill, backfill consolidation and stiffness characteristics, backfill temperature and tailings chemistry (Helinski et al., 2011; Pokharel and Fall, 2013; El Mkadmi et al., 2014; Yilmaz et al., 2015). The degree of drainage in a mine backfill can be classified between undrained and fully drained depending on the complex interactions between the above mentioned parameters. An undrained condition represents a conservative condition with regards to the mechanical stability of the CPB. However, it should be emphasized that in most of the field cases, the CPB structure is not fully drained.

- \* Scenario B (Figure 4.23b: undrained test with three different filling rates): investigates the effect of filling rates in undrained conditions on the mechanical response of the tested CPB. Three different filling rates were studied: 0.155 m/h (CUS, 0.155-U), 0.31 m/h (CUS, 0.31-U), and 0.62 m/h (CUS, 0.62-U).

- \* Scenario C (Figure 4.23c): studies the influence of plugs and their curing time on the mechanical response of the tested CPBs under undrained conditions. The following scenarios were considered: (i) continuous filling (CUS, 0.31-U); (ii) with a plug cured for 1 day (CUS, 0.31-1d plug), and with a plug cured for 3 days (CUS, 0.31-3d plug). The backfill filling rate was 0.31 m/h.

- \* Scenario D (control): CPB samples are cured in both drained (C-D) and undrained (C-U) conditions. This scenario represents the curing conditions of the control samples, which are commonly used in backfill practice; this means there is no application of stress.

In Scenarios A, B and C, pressure was gradually increased in the first 12 h (every 3 h) and up to 150 kPa in order to simulate a more realistic application of self-weight pressure on the specimen at the early hours of curing. Then, the pressure was increased every 24 h up to 600 kPa depending on the simulation scenario. In Scenario C, a 1 day and a 3 day delay were used between 150 kPa to 600 kPa load increments.

In addition to these four scenarios, a paste backfill sample was prepared without adding cement and then subjected to a filling rate of 0.31 m/h and drained condition (sample: CUS, 0.31-D [no

cement])). The PWP and suction evolution were monitored for up to 7 days. The results were used as reference values to study the effect of cementation on PWP and suction.

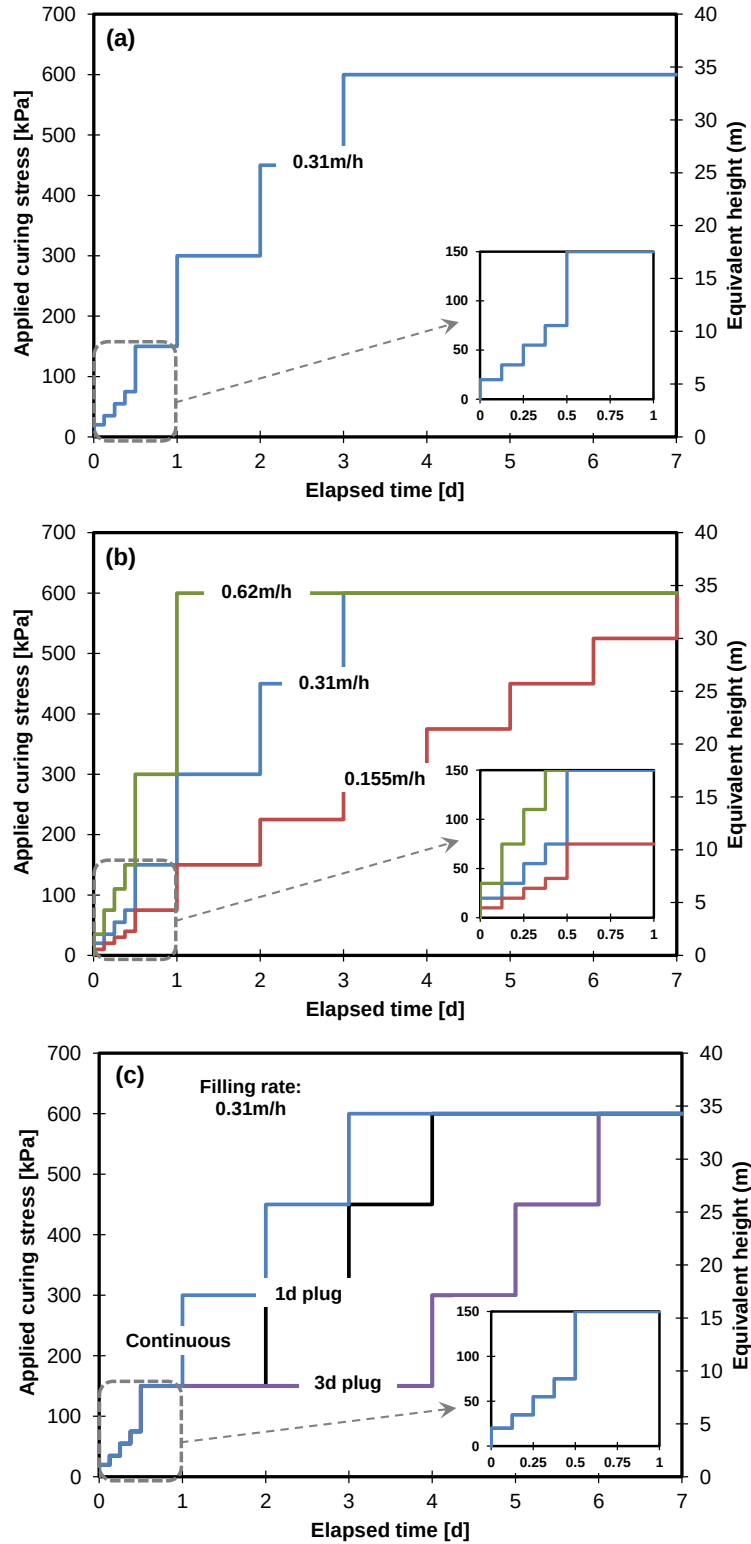


Figure 4.23. Load application scenarios: (a) Scenario A: filling rate of .31 m/h used in drained and undrained tests; (b) Scenario B: different filling rates used in undrained tests; (c) Scenario C: sequential filling (continuous filling, plugs cured for 1 day and 3 days) in undrained tests

### **4.3.3. Testing and monitoring program**

#### **4.3.3.1. Monitoring program**

The evolution of the PWP, total pressure (TP) and suction were continuously monitored for a period of 7 days. A WP2100 vibrating wire piezometer with a pressure range up to 1000 kPa and accuracy of 0.1 kPa was used to measure the changes in the PWP in the CPB samples. The instrument allowed us to monitor the evolution of the PWP resultant of the application of pressure. A miniature flush diaphragm pressure transducer with a reading range up to 1 MPa was mounted on the pressure cell to directly measure the TP resultant of the application of pressure. The evolution of the suction was measured by using a dielectric water potential sensor (model MPS-2), which was installed 40 mm above the cell bottom. This sensor is capable of measuring matric potential (or matric suction) between -10 and -500 kPa (Decagon Devices, 2014).

#### **4.3.3.2. Testing program**

##### **- Mechanical test**

In addition to the monitoring program, CPB samples that were sized 10×20 cm were cured in the pressure cell apparatus in accordance with the scenarios previously described to perform the UCS tests. A total of 48 CPB samples were prepared. Curing times of 1, 3 and 7 days were adopted for this purpose. Once the required curing time was achieved, the pressure cell apparatus was dismantled and the CPB samples were extracted from the Perspex cells by means of a hydraulic extruder to minimize any disturbances. Then, the samples were gently cut and trimmed with a coping saw and spatula into 50 (D) × 100 (H) mm. ASTM C39 standard was followed to perform the UCS tests. At least two CPB samples were tested for each curing time to ensure the repeatability of the results. A computer-controlled mechanical press with a constant deformation rate of 0.8 mm/min was used and the stress-strain data were recorded for each sample.

#### **4.3.3.3. Physical and microstructural analysis**

The physical properties of the CPB samples cured under the different studied scenarios were examined at 1, 3 and 7 days. The physical properties, including porosity, void ratio and bulk density, were determined immediately after sample extraction and preparation to avoid any moisture loss. Different techniques were employed to study the microstructure of the CPB samples. These techniques included mercury intrusion porosimetry (MIP), scanning electron microscopy (SEM) and

thermogravimetric analysis (TGA), which were performed on selected CPB and cement paste specimens cured under the various curing scenarios. MIP measurements were performed to study the effect of curing stress and drainage condition on the pore-size distribution (PSD) and total porosity of the CPB samples. A PMI mercury/nonmercury intrusion porosimeter was used to run the MIP analysis. SEM observations were performed with an EVO-MA10 scanning electron microscope with variable pressure capability in order to investigate the microstructure and formation of hydration products in the CPB samples. Prior to performing the MIP and SEM analyses, the CPB samples were first dried at 50°C until they reached mass stabilization. Drying at this temperature did not appear to cause cracking. The thermal analysis (TGA) was undertaken by using a Q 5000 IR thermogravimetric analyzer from TA Instruments, which allows for the simultaneous registration of weight loss and heat flow along the thermal treatment of the sample. The various (dried) samples (about 20 mg each) were heated in an inert nitrogen atmosphere at a rate of 10°C per minute up to a temperature of 1000°C. The thermal analysis allowed us to study the binder hydration products that formed in the CPB system cured under stress-free or stress-controlled conditions.

#### **4.3.4. Results and discussion**

##### **4.3.4.1. Effect of curing stress on early age strength of CPB**

Figure 4.24 illustrates the effect of curing stress on the UCS values between 1 to 7 days of curing. It is seen that the UCS values increase as the curing time increases for all the studied samples regardless of the curing stress. This behaviour is attributed to the combined effect of several factors that contribute to the strength development of CPB. A longer curing time is associated with the precipitation of higher amounts of cement hydration products (Taylor, 1997). This results in the development and strengthening of the cohesion between tailings particles, which in turn, leads to a stronger cemented matrix (Fall et al., 2007; Ercikdi et al., 2009; Fall and Pokharel, 2010). Furthermore, an increase in cement hydration products leads to the refinement of the pore structure (lower porosity), which in turn, improves the strength. This refinement of the pore structure is experimentally demonstrated by the results of the total porosity evolution of the tested CPB presented in Figure 4.25. This figure shows that in general, regardless of the curing stress, the porosity of the CPB decreases as the age of the CPB increases. In addition to these factors, the progression of cement hydration reactions leads to higher consumption of water in the CPB system (stronger self-desiccation) and subsequently in the increase of the suction in the CPB system as demonstrated by Figure 4.26. A higher suction is commonly associated with higher strength in cemented backfills (Ghirian and Fall, 2014) and porous media (Fredlund and Rahardjo, 1993).

Also from Figure 4.24, it can be seen that not only the curing time, but also the curing stress, has a significant effect on the strength development of the studied CPBs. It can be noticed that samples cured under stress have higher mechanical strength than those cured under stress free conditions (control samples). For example, the difference between the UCS values of the CUS, 0.31-U and C-U samples is 20.1%, 37.6% and 14.9% at 1, 3 and 7 days of curing, respectively. This observed stress-induced increase of the strength of CPB in undrained conditions is attributed to the combined effect of two main mechanisms. First, a higher curing stress can increase the packing density of the tailings particles at early ages due to their rearrangement, and thus leads to refinement of the pore structure of the CPB and porosity reduction (Ghirian and Fall, 2015). This is in good agreement with the results of the total porosity measurements and MIP tests presented in Figures 4.25 and 4.27, respectively. These figures show that the samples cured under stress have a finer pore structure (Figure 4.27) and lower total porosity (Figure 4.25) than those cured under stress free conditions. Since lower porosity in similar backfill material is generally associated with higher mechanical strength (Fall et al., 2004; Lian et al., 2011), therefore, a higher curing stress delivers higher mechanical strength. Secondly, a comparative analysis of the thermal analysis results of the cemented paste of CPB cured under stress and stress free conditions presented in Figure 4.28 indicates that a slightly higher proportion of hydration products (e.g. calcium silicate hydrate [C-S-H]) has formed in the samples cured under stress. This suggests that curing stress may have accelerated the cement hydration process, which contributes to the formation of more cement hydration products and thus to lower porosity and finer pore structure of the cement matrix as also demonstrated in Figures 4.25 and 4.28. Indeed, endothermic peaks can be seen in the 75°C–200°C, 450°C and 650°C ranges (Figure 4.28). The peak at 100°C –200°C underlines the presence of C-S-H gel and ettringite (Fall and Samb, 2008). A comparison of the two diagrams shows that the endothermic peak or weight loss at 100°C–200°C are slightly higher for cemented paste cured under stress, thus suggesting the presence of a slightly higher amount of C-S-H gel and ettringite in the sample cured under stress. These results are also in agreement with the findings of Zhou and Beaudoin (2003). They observed that cement paste samples cured under applied hydrostatic stress have higher degrees of hydration or more hydration products formed. Also, they showed that this higher degree of hydration occurs if the application of the curing stress takes place within the first 48 h of curing.

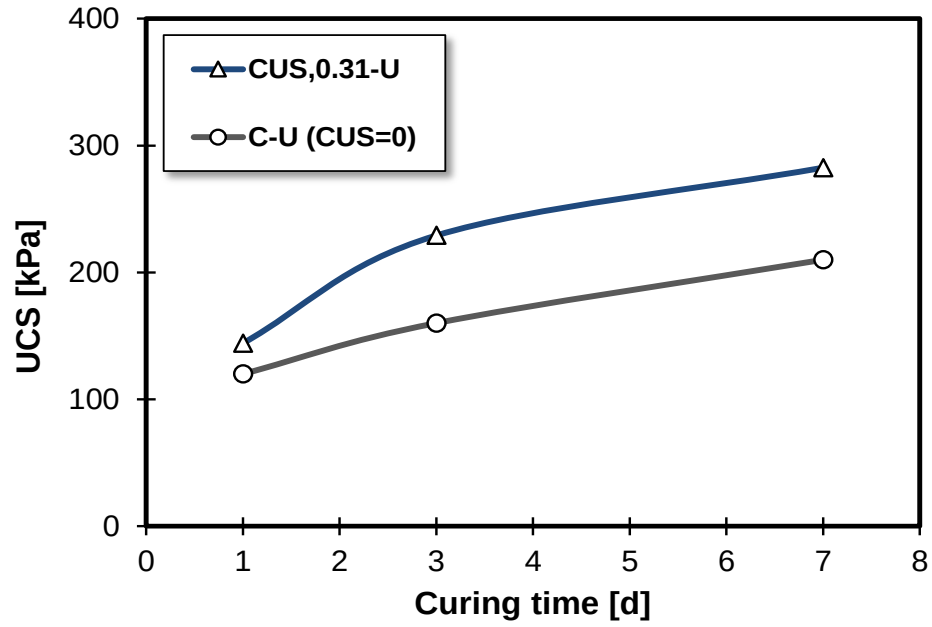


Figure 4.24. Effect of curing stress on the early age strength of CPB

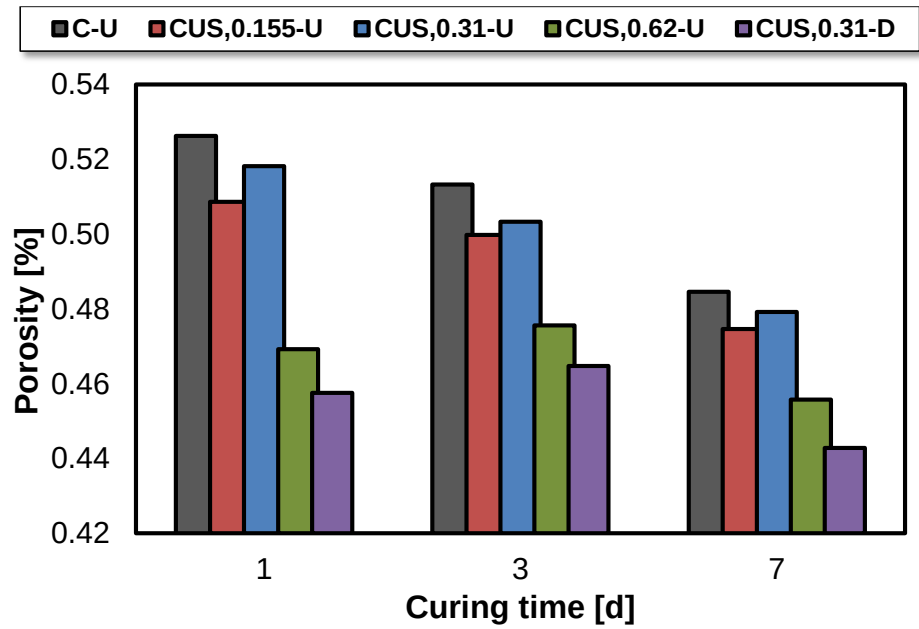


Figure 4.25. Evolution of porosity under curing stress and different loading rates

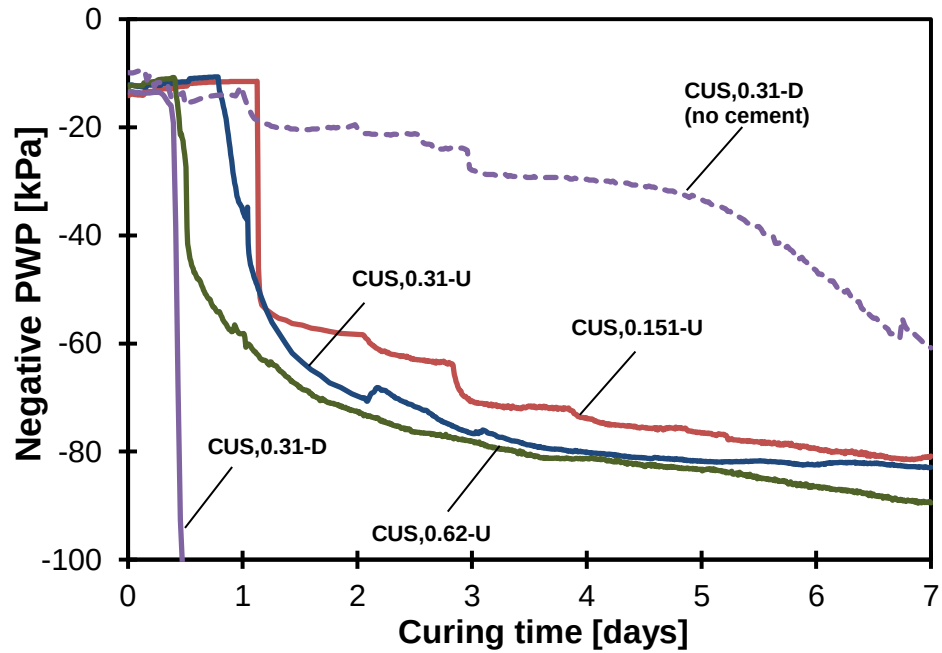


Figure 4.26. Suction (negative PWP) development versus curing time for different loading scenarios

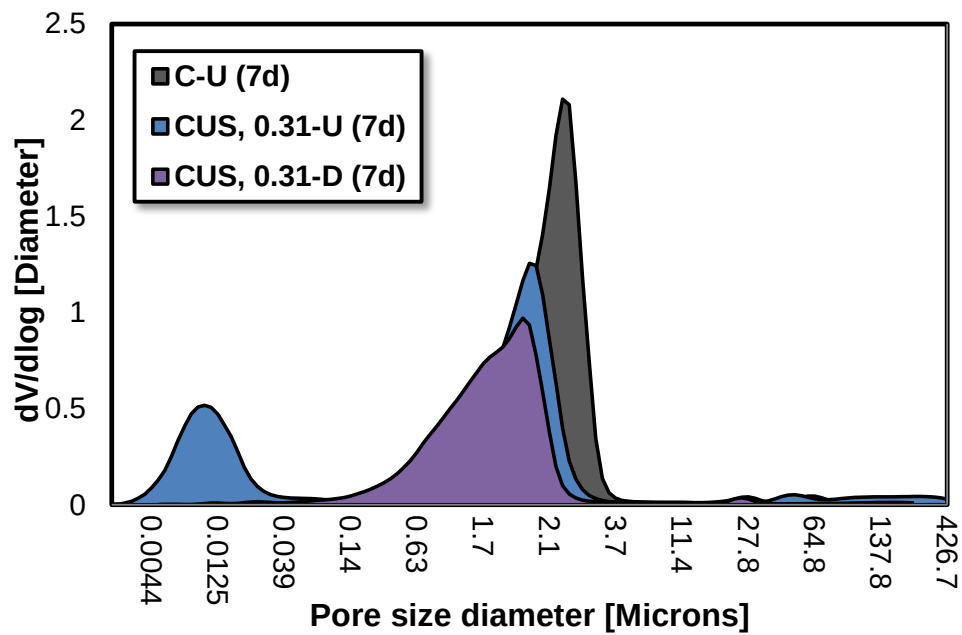


Figure 4.27. Effects of curing stress and drainage on pore size distribution

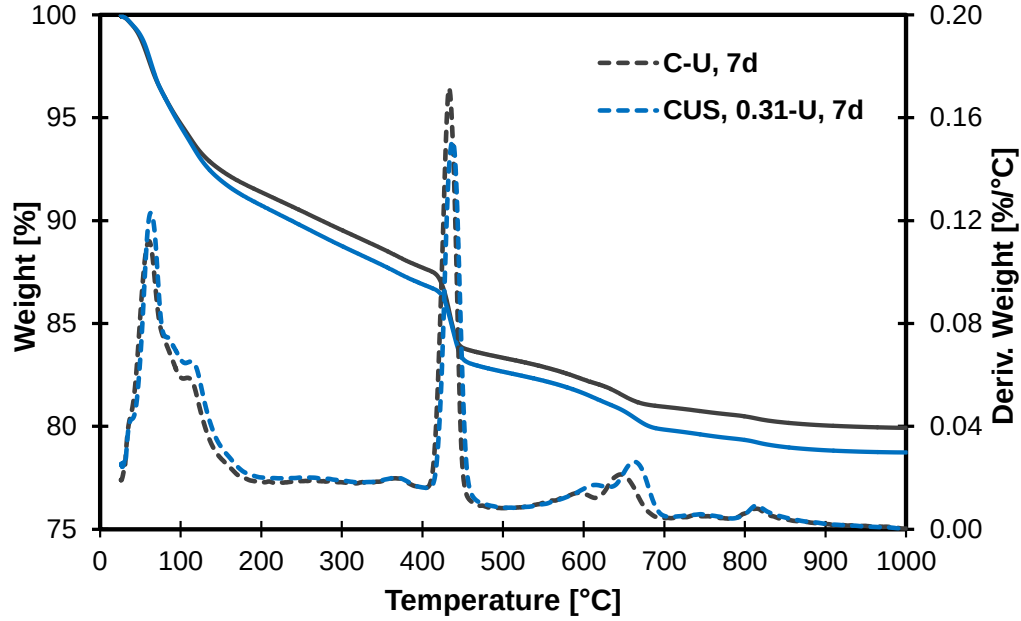


**Figure 4.28. Thermal analysis results of cemented paste cured under stress (CUS, 0.31-U, 7d) and stress-free (C-U, 7d) conditions**

#### 4.3.4.2. Effect of drainage on early age strength of CPB

The effects of (full) drainage on the UCS development of CPB cured under stress and stress-free conditions are presented in Figure 4.29. This figure shows the effect of water drainage (with and without the application of curing stress) on the UCS development of the tested specimens. It can be observed that the fully drained samples (cured with and without stress) exhibit higher UCS values compared to the control sample (undrained and cured under zero stress, C-U (CUS=0)). The UCS of the CPB drained and cured under stress (CUS, 0.31-D) has the highest value for all of the curing times. The UCS values of the CUS, 0.31-D samples are 296, 436 and 811 kPa at 1, 3 and 7 days, respectively. It can be observed that there is a strength improvement of 147%, 172% and 286% on the 1st, 3rd and 7th day of curing, when compared to the control sample (C-U (CUS=0)). The UCS values of the drained CPB with stress-free curing conditions (C-D) are 266, 343 and 457 kPa on the 1st, 3rd and 7th day of curing, respectively, which demonstrate an improvement of 121%, 114% and 116% with respect to the corresponding values in the control samples (C-U). It can be noticed that the drainage itself, even without the application of curing stress, considerably contributes to the strength improvement.

Two different mechanisms contribute to the strength development of the fully drained CPB samples. First, the drained samples are cured under higher effective stress, which in turn, is associated with higher mechanical strength. The dissipation of excess PWP as a result of the

compression of the CPB matrix and drainage, causes higher effective stress in the samples, which then leads to the formation of stronger bonding between the tailings and cement hydrates (Ahnberg, 2007; Yilmaz et al., 2009; Fahey et al., 2011; Abdul-Hussain and Fall, 2012). Another mechanism of strength development is the effect of the w/c on the mechanical strength of the CPB samples. The drainage of excess water due to load application (consolidation) or gravity drainage as is the case with the C-D, (CUS=0) sample results in a lower w/c. Several experimental studies on cementitious materials, such as cement paste and concrete (e.g., Bentz et al., 2009) and CPB (e.g., Kesimal et al., 2005; Fall et al., 2008) have demonstrated that a lower w/c is associated with a higher mechanical strength (or UCS). Therefore, CPB cured with a lower w/c delivers higher UCS.

In addition to these two mechanisms, drainage and pressure application consolidate the CPB pore structure, which in turn, result in pore refinement (Figure 4.27) and porosity reduction (Figure 4.25). This pore refinement is experimentally demonstrated in Figure 4.27 which shows the results of the MIP test performed on the control samples, undrained samples cured under stress (CUS, 0.31U), and drained samples cured under stress (CUS, 0.31D) at 7 days. The porosity reduction with time is shown in Figure 4.25. According to Figure 4.27, the threshold diameter ( $d_{th}$ ) for the drained sample is lower than that of the undrained and control samples, which provides evidence that pressure application causes refinement in the pore size.

Suction development has a significant influence on strength acquisition. Water drainage results in reduction of the PWP (or suction development). Furthermore, higher suction is generally associated with higher strength (Fredlund and Rahardjo, 1993). This argument that water drainage induces an increase in suction is supported by the results from monitoring the suction of the drained and undrained samples as presented in Figure 4.26. This figure shows three different mechanisms of suction development in CPB materials. In the undrained condition (e.g., CUS, 0.31-U), self-desiccation as a result of cement hydration generates suction. However, in the drained condition (CUS, 0.31-D), the combined effects of self-desiccation and drainage due to pressure application (consolidation) means the development of higher suction in the CPB matrix. Furthermore, it is observed that drainage itself without self-desiccation, as observed in the control sample (CUS, 0.31-D; without cement), means that a significant amount of suction develops in the CPB sample, which is equal to 61.0 kPa at 7 days of curing. Suction development in this case is lower than that of both the cemented drained and undrained samples. However, the combined effects of drainage and self-desiccation, as can be observed from the test with the CUS, 0.31-D sample, cause the rapid development of suction (i.e., 100.2 kPa after 12 h of curing).

The drainage behaviour of the CPB samples is presented in more detail in Figure 4.30. This figure shows the variation of the drained water with respect to the curing time and curing pressure in

the CUS, 0.31D samples (cured under stress and drained) prepared with and without cement. From this figure, it can be seen that in the cemented sample, the water drainage starts to decrease after 12 h of curing and reaches its peak after about 1 day. Approximately 7.5% of the total volume of water added at the time of preparation drained at the end of the test. It should be noted that the contribution of drainage in the hardening process and setting of CPB is significant during the first 12 h of curing. Also, with reference to Figure 4.30, it can be observed that the application of pressure beyond 150 kPa does not result in a significant increase of the water drainage in the CUS, 0.31D (cemented) samples. However, in the uncemented samples, water drainage increases as pressure increases up to the end of the test. Approximately 60% of the water added during the sample preparation drained when the pressure reached 600 kPa at the end of the test. The difference in the amount of drained water between the cemented and uncemented samples is due to the water consumption by the cement hydration reactions, as well as increase in holding water capacity as a result of stiffness development (Ghirian and Fall, 2013). A larger amount of water is drained in the uncemented samples which have lower stiffness and a softer structure.

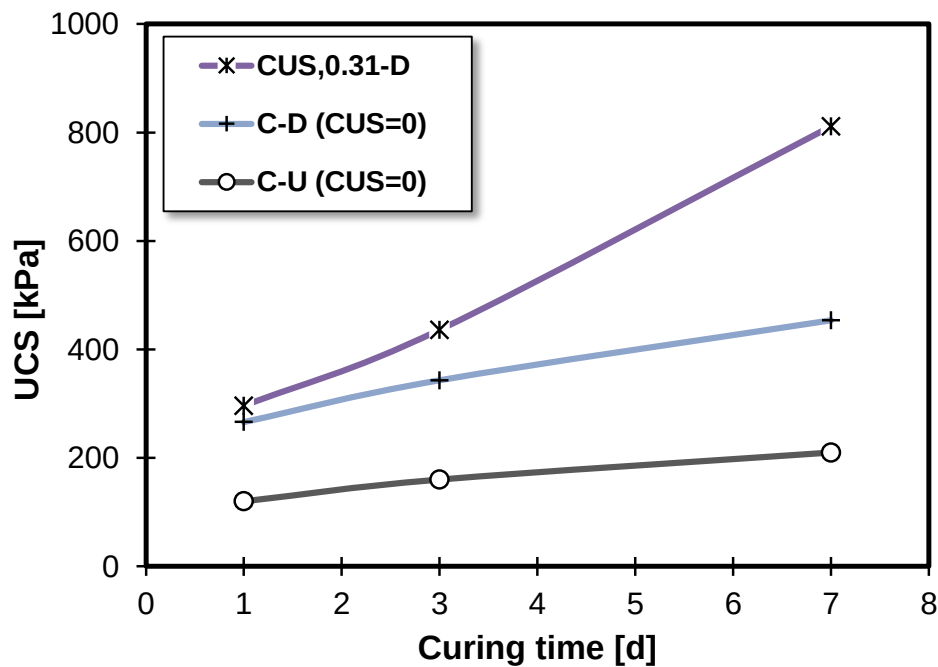


**Figure 4.29. Effect of drainage on the early age strength of CPB**

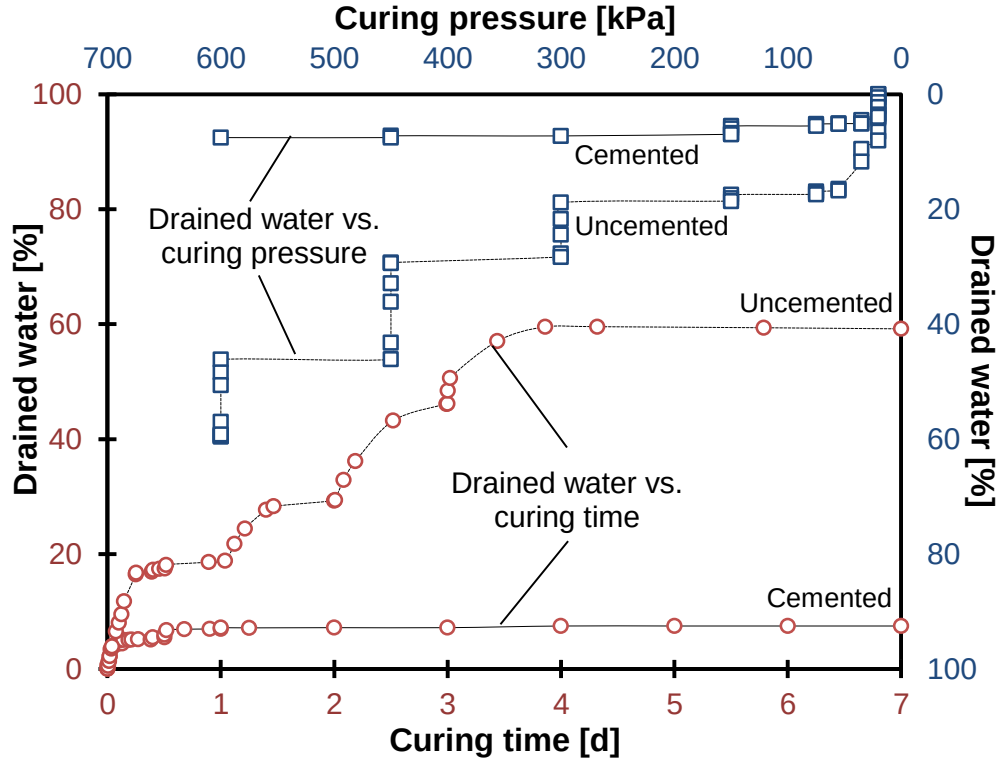


**Figure 4.30. Water drainage versus curing time and curing pressure for CUS, 0.31D samples prepared with and without cement**

#### 4.3.4.3. Effect of filling rate on early age strength of CPB

Figure 4.31 demonstrates the effect of the filling rate on the evolution of the UCS. It can be observed that all of the undrained samples cured under different filling rates exhibit similar qualitative behaviour. They generally demonstrate higher mechanical strength than the control sample. As explained before, this higher mechanical strength is related to the effect of the curing stress on the refinement of the pore structure as a result of particle rearrangement and increase in the packing density of the materials (Figures 4.35 and 4.37).

Samples with a faster filling rate exhibit higher UCS values for different curing times (except for the 0.62U-1d sample). For instance, the UCS values of the CUS, 0.62-U sample increase from 111 to 275 kPa (from 1 day to 7 days), while the UCS of the CUS, 0.155-U sample increases from 125 to 247 kPa for the same curing time. By comparing the mean values of the UCS of these two tests, it is observed that there is about 15% in mechanical strength improvement due to the application of higher curing stress.

However, it should be noted that the 0.62-U sample after 1 day of curing exhibits the lowest UCS value of 111 kPa compared to the others, which is an even lower value than that of the control

sample of 120 kPa. This can be related to the fact that a fast filling rate at the early hours of curing leads to the development of high PWP in the sample (see Figure 4.32) and therefore reduces the effective stress almost close to a nil value. The results of the PWP measurements (Figure 4.32) indicate that a faster filling rate generates higher PWP in the samples. It should be noted that the filling rate directly influences the stress in the backfill and applied forces on the barricade. Another plausible mechanism can be the mechanical damage due to fast load application. Cemented paste subjected to excessive curing stress has a weak microstructure at the very early ages and thereby the points of contacts between the cement hydration products are prone to microcracking and displacement (Zhou and Beaudouin, 2003; Ghirian and Fall, 2015). The SEM images of CUS, 0.62U after 24 h of curing (Figure 4.33) demonstrate this argument and show that there are several weak points or zones with zero contact between the tailings particles, possibly due to the effects of high PWP (zero effective stress), as well as micro-cracks.

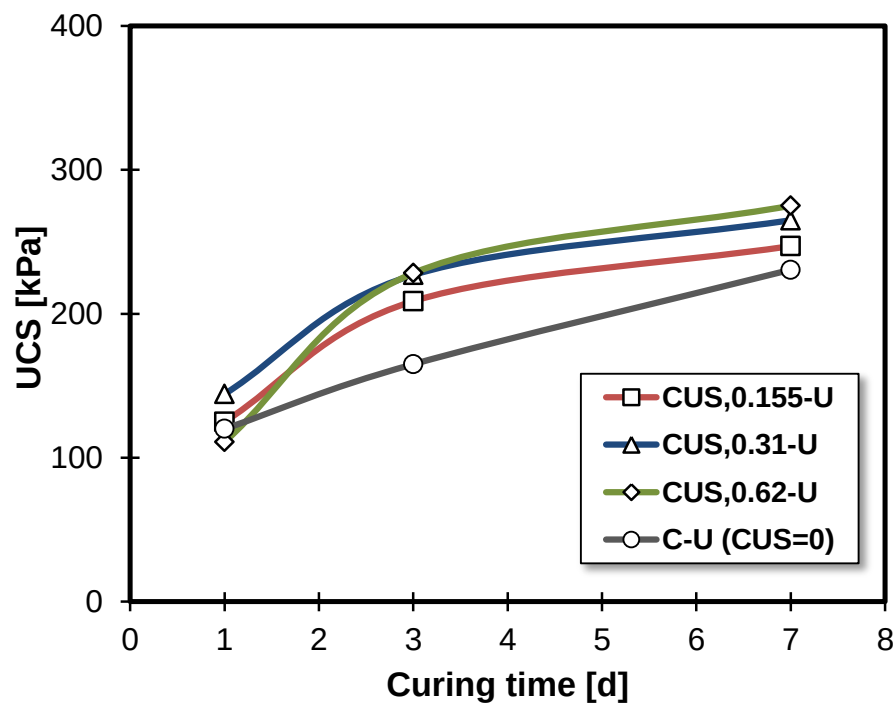


Figure 4.31. Effect of filling rate on the early age strength of CPB

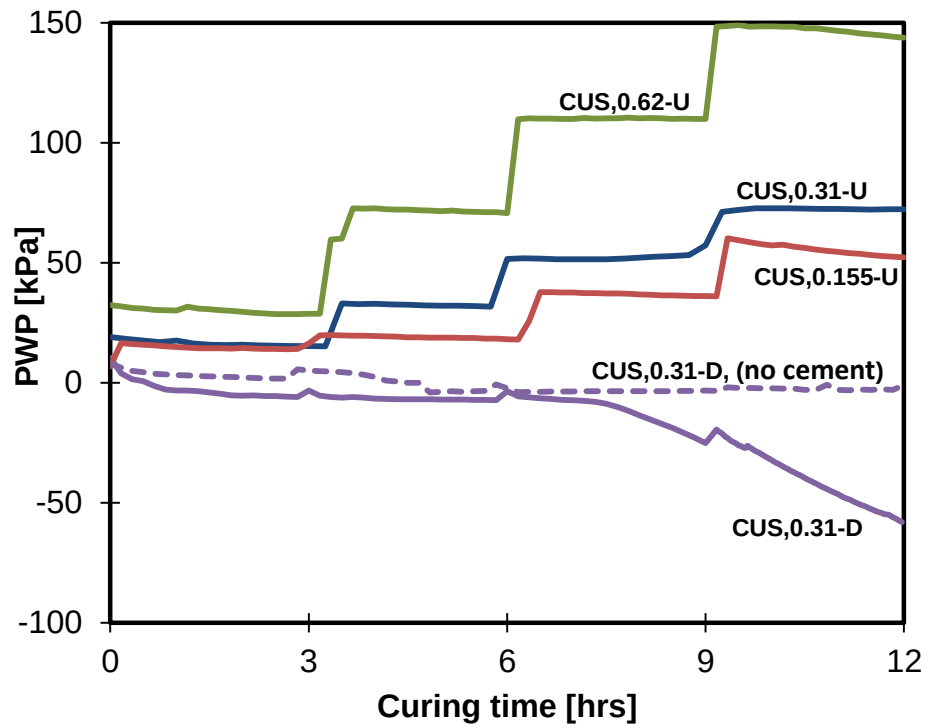


Figure 4.32. Evolution of pore pressure of CPB samples cured under different loading scenarios

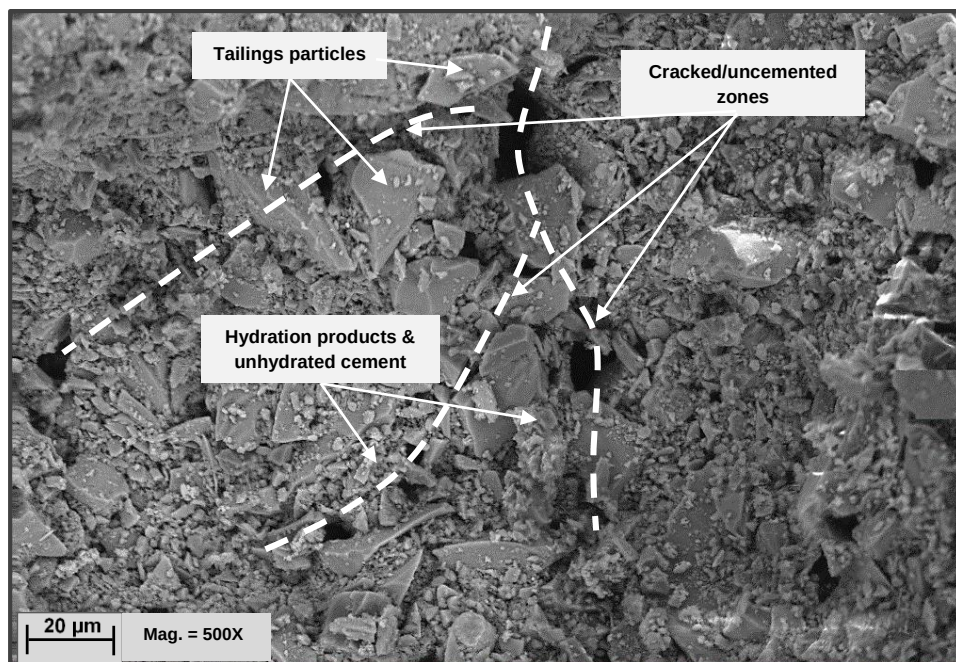


Figure 4.33. CPB microstructure cured under stress (filling rate of 0.62 m/h after cured for 1 day)

#### 4.3.4.4. Effect of filling sequence on early age strength of CPB

Figure 4.34 shows the UCS test results for the filling carried out in stages versus continuous filling in the undrained condition to study the mechanical behaviour of the plug fill. It can be observed that up to 3 days of curing, all of the CPB specimens show relatively similar values in strength, regardless whether the filling sequence is continuous or takes place in stages. However, at 7 days of curing, the 1 d plug and continuously filled CPB samples have higher UCS than the CPB with a plug fill for a curing period of 3 days (3 d plug samples). This can mainly be attributed to the development of a denser pore structure (induced by stress) in the 1 d plug and continuously filled CPB samples, which in turn, results in a CPB with higher mechanical strength. However, it should be emphasized that this phenomenon still requires further and extensive studies to provide a complete understanding of the observations.

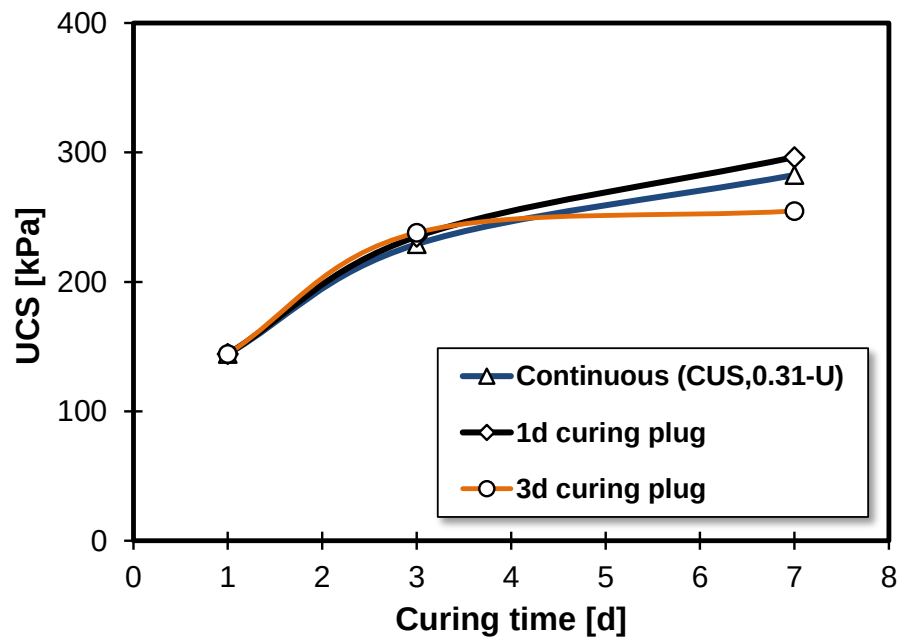


Figure 4.34. Effect of continuous and sequential filling on the early age strength of CPB

#### 4.3.4.5. Effect of studied factors on deformation behaviour of CPB

The deformation behaviour of the CPB samples are presented in Figures 4.35 and 4.36 with stress–strain curves for 1 and 7 day samples cured under the different loading scenarios. Figure 4.35 shows that all of the studied samples cured for 1 day (except for CUS, 0.31D) exhibit more plastic behaviour compared to the 7 day samples, irrespective of the curing stress and drainage condition. The 1 day samples cured under different filling rates also exhibited plastic behaviour (Figure 4.36).

For instance, these samples have similar qualitative behaviour, approximately 4-6% strain (or 4-6 mm deformation) at failure. It is interesting to note that the 1 day drained sample (CUS, 0.31D-1d) shows a similar qualitative behaviour as the 7 day undrained sample (CUS, 0.31U-7d). This behaviour is attributed to the effect of consolidation (curing under stress and drainage) on the hardening of the CPB as explained earlier, which results in the CPB sample with less “plastic behaviour” at very early ages.

Furthermore, with respect to Figures 4.35 and 4.36, it can be seen that the strain at failure is approximately between 1% and 2% after 7 days of curing. This means that the CPB shows less ductile behaviour when the curing time increases. It should be noted that the curing conditions such as drainage itself, curing under stress (undrained condition) and curing under zero stress (both drained and undrained conditions) do not significantly influence the deformation behaviour (from a qualitative point of view) of the studied CPB samples.

The modulus of elasticity and strain values at failure were derived from the stress–strain curves (Figures 4.35 and 4.36) and their relationship is presented in Figure 4.37. This figure shows how drainage condition, filling rate and curing time affect the deformation behaviour of CPB. For instance, as expected, the CUS, 0.62U-1d sample shows the lowest modulus of elasticity (8.5 MPa) and highest strain value at failure (6.2%). This behaviour can be mainly attributed to the fact that the application of pressure at a faster rate in the early hours of curing leads to higher development of PWP inside the CPB sample (undrained condition) as shown in Figure 4.32. This curing condition in turn leads to the formation of a CPB with a relatively soft structure and weak cementation, compared with the CUS, 0.31D-7d sample.

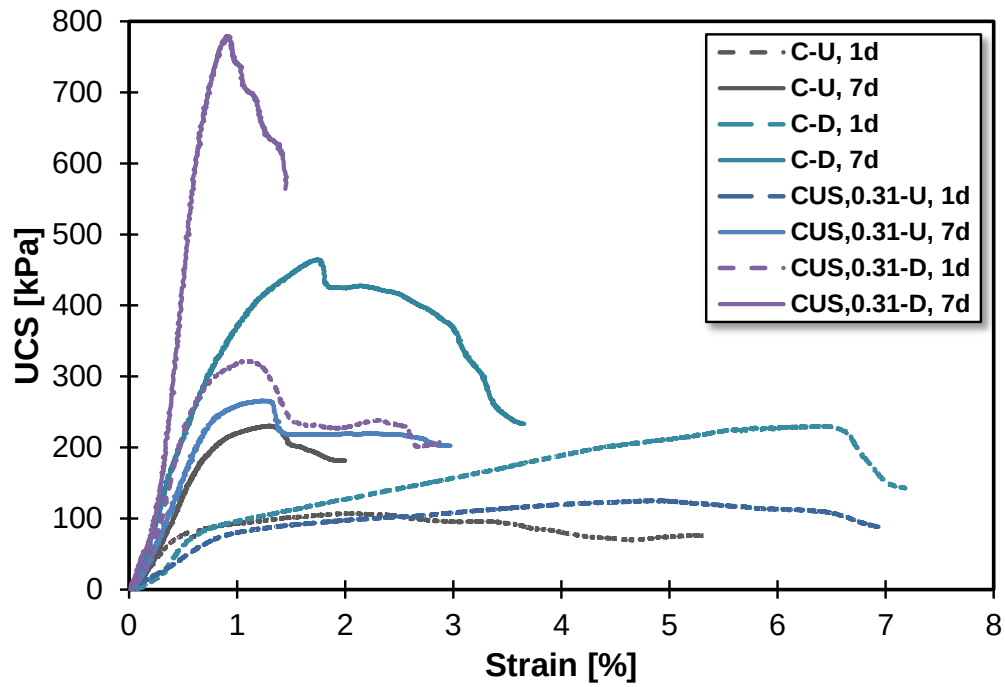


Figure 4.35. Coupled effect of curing stress and drainage on the early age deformation behaviour of CPB

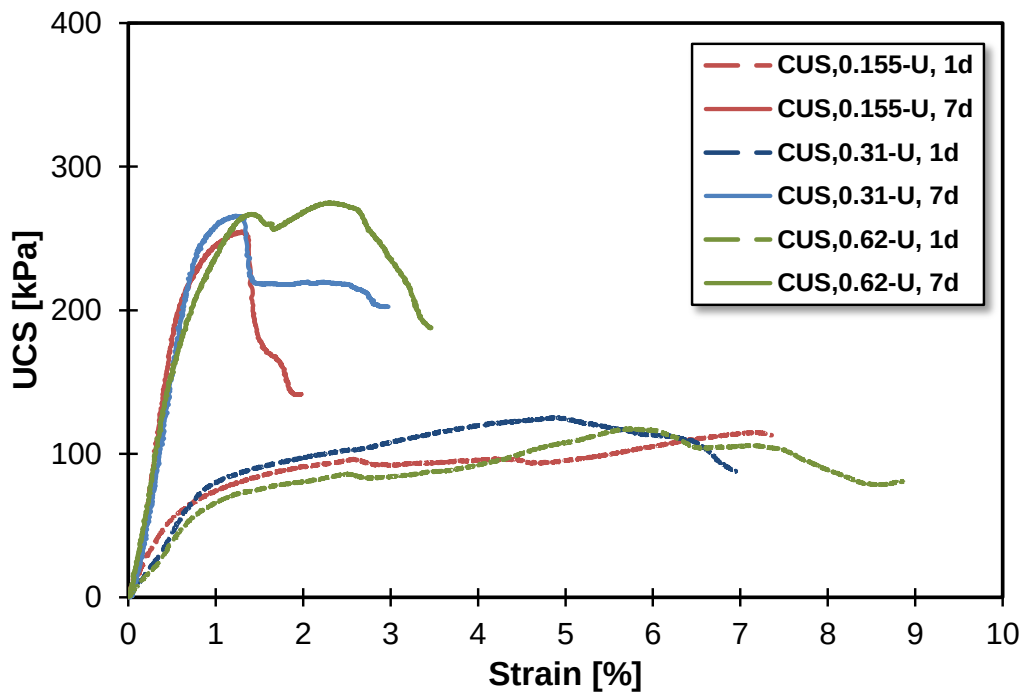


Figure 4.36. Coupled effect of curing stress and filling rate on the early age deformation behaviour of CPB

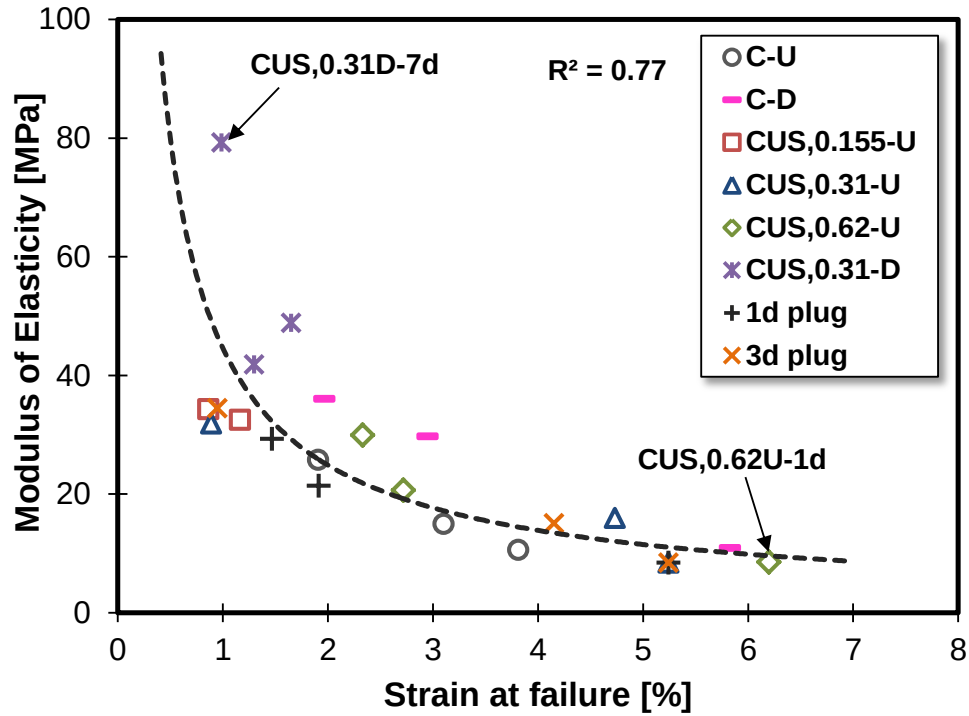


**Figure 4.37. Relationship between modulus of elasticity and strain at failure**

Figure 4.38 shows the relationship between the UCS and modulus of elasticity ( $E$ ) obtained from the UCS test results. The results are presented for all of the studied CPB samples cured under various filling rates, drainage conditions and filling sequences. It can be seen that there is a strong relationship between the  $E$  and UCS values for both the drained and undrained samples regardless of the curing conditions. The  $E$  values typically vary between 9.5 and 38.6 MPa for undrained backfill and 26.8 and 58.5 MPa for drained backfill. The CPB samples typically have modulus elasticity values between 10 and 20 MPa at the early ages, and 100 MPa and 1.2 GPa at more advanced ages. These results are in agreement reported in other studies (e.g. Yilmaz et al., 2014) based on the values. It can be observed that the samples cured under fast filling rates (CUS, 0.62U) exhibit slightly higher modulus of elasticity than the other samples cured under slower filling rates. Also, the drained samples have significantly higher modulus of elasticity than the undrained samples regardless of the curing time.

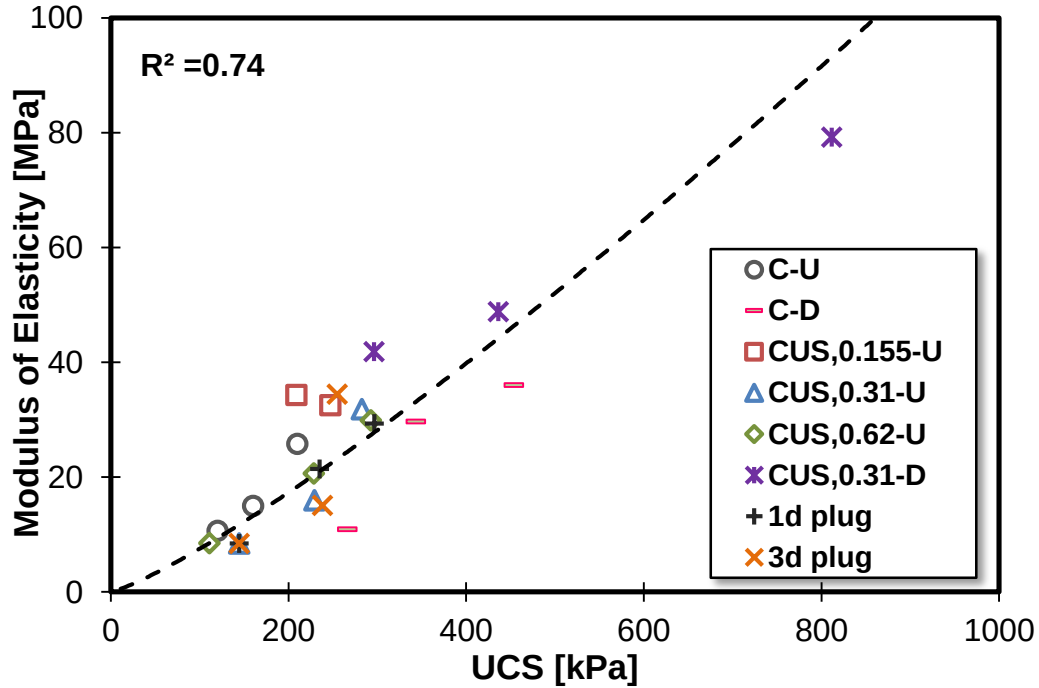


Figure 4.38. Relationship between UCS and modulus of elasticity

#### 4.3.5. Conclusion

The effects of curing stress, filling strategy and drainage on the mechanical strength and deformation behaviour of CPB at the early ages have been investigated in this chapter. Different curing scenarios are adopted to simulate the stress state in CPB that is similar to in-situ conditions. Suction and PWP are measured, and the UCS of CPB is determined after 1, 3 and 7 days of curing for various scenarios. The obtained results show that curing time and curing stress improve the mechanical and deformation behaviour of CPB samples at the early ages. Longer curing time causes the formation of more cement hydrates and thereby pore refinement. Curing stress causes particle rearrangement in the undrained samples, which in turn, results in higher packing density and lower porosity. Also, the thermal analysis has revealed that curing stress can slightly contribute to increasing the rate of binder hydration.

The drainage of water from CPB right after placement in the drained sample cured under zero stress results in significant increases in the mechanical strength. Higher improvement in strength is observed once both drainage and curing stress (or consolidation) take place in the sample. The application of curing stress during the early hours of curing on the drained samples causes suction to quickly develop, which in turn, results in effective stress increase and strength gain.

In the undrained samples, the application of greater stress generally leads to higher strength in the CPB depending on the rate of the load application. However, if a high curing stress is applied during the early hours of curing (e.g., less than 48 h) in the undrained condition, excessive PWP develops in the CPB. This in turn, can cause mechanical damage within the CPB matrix, and thus results in lower UCS compared to the control sample.

The curing stress, filling rate and drainage condition also influence the CPB deformation behaviour. Drained samples cured under stress exhibit the highest modulus of elasticity and the lowest strain at failure, while undrained samples cured under 0.62 m/h (which corresponds to a fast filling rate) deliver the lowest modulus of elasticity and the highest strain at failure. Undrained CPB samples show more plastic behaviour compared to the drained samples. Similar behaviour is observed with respect to the curing time, since very early age samples (i.e., 1 day) have more plastic behaviour compared to more aged samples.

The summary of the findings shows that the stress state in backfill significantly depends on the degree of consolidation (and degree of drainage), rate of suction development and degree of hydration reactions. Therefore, when there are more uncertainties related to these factors, this can cause complexity in the assessment of the stress and strength in the backfill and consequently affect the design procedure. Application of the current results can aid mine engineers with the designing of a better backfill structure while reducing the cost of backfilling operations and enhancing mine productivity.

#### **4.4. Chapter Conclusion**

The main objectives of chapter four (technical papers III and IV) were to study the THMC coupled processes and factors, as well as mechanical strength and deformation behaviour of CPB under different curing/stress scenarios, by using cell pressure apparatus at early age (less than 7 days). The findings of this chapter help the mine designers and operators to optimize the mine backfill design and mine cycles to enhance the productivity. Although, the short term design of a mine stope is highly important, the long term performance also needs to be studied in order to assure the long term safety and acceptable environmental performance of CPB structures. Therefore, in the next chapter, Chapter five, the long-term THMC properties and processes in CPB has been investigated by using the cell pressure apparatus.

#### **4.5. References**

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## **Chapter 5: Load Cell Experiments (Advanced age behaviour)**

### **Technical paper V: Long-term Coupled Behaviour of Cemented Paste Backfill in Load Cell Experiments<sup>5</sup>**

#### **ABSTRACT**

Cemented paste backfill (CPB) is a relatively new backfilling material that is increasingly being used in underground mines across the world. One of the critical issues in backfill design is the long-term mechanical stability of a CPB structure and its durability. In most of the design cases, the stability design of a backfill structure is assessed based on the mechanical performance of laboratory prepared samples (cylindrical mould samples). Such a strategy is often conservative, since CPB is subjected to coupled processes in the field but these are not included in the assessments of CPB performance. These coupled interactions significantly affect the long-term stability and durability of a CPB structure which indeed cannot be accounted when using the traditional laboratory mould samples. Therefore, a pressure cell apparatus has been developed in this research work to study the long-term hydro-mechanical behaviour of CPB material cured under applied stress. The samples are cured for 7, 28, 90 and 150 days and the evolution of their mechanical, hydraulic, physical and microstructural properties is studied. Also, the suction, temperature and electrical conductivity are monitored for a period of 150 days of curing. The testing and monitoring program are conducted in undrained conditions, with and without pressure application. The obtained results show that the curing stress affects the hydro-mechanical behaviour of CPB up to 28 days. Within this curing period, the CPB exhibits enhanced hydro-mechanical performance. However, application of sustained excessive curing stress on CPB samples induces the propagation of microcracks in the backfill structure, thus causing lower mechanical strength and higher fluid permeability at more advanced ages (90 and 150 days). Furthermore, mineralogical and chemical compositions of the tailings (e.g., sulfidic tailings) can significantly alter the mechanical strength properties (uniaxial compressive strength and elastic modulus) and the permeability of the CPB. CPBs made of such tailings exhibit low development of suction and temperature and high electrical conductivity as observed from the instrumentation measurements. The evolution of the thermal-hydro-mechanical-chemical (THMC)

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properties and characteristics of the CPB at an early age control and influence its long-term behaviour and performance. The obtained information can aid mine engineers in better understanding long-term hydro-mechanical behaviour of backfill cemented material and the factors that can affect it.

## 5.1. Introduction

Cemented paste backfill (CPB) has gained popularity in underground mining operations around the world, particularly in Canada (Tariq and Yanful, 2013; Fall et al., 2009). The main benefit of its application is the reduction in the disposal of surface mine tailings and the associated environmental impacts, such as the formation of Acid Mine Drainage (AMD) and water pollution (Yilmaz et al., 2003; Nasir and Fall, 2008, 2010; Ercikdi et al., 2009; Fall et al., 2010; Wu et al., 2013). Also, CPB provides ground support and stability while maximizing the efficiency and productivity of mine operations (Celestin and Fall, 2009; Fall and Samb, 2009; Yilmaz et al., 2014).

The main components of CPB include mixing water (fresh or mine processing water), dewatered mine tailings (70-85 wt% solids) and hydraulic binders (usually 3-7 wt%), that are often Portland cement (Fall et al., 2005; Kesimal et al., 2005; Cihangir et al., 2012; Yi et al., 2015). The main role of the binder agent is to provide enough cohesion and strength to the CPB to meet the mechanical design requirements of a mine backfill system (Fall et al., 2007).

Mechanical stability, durability and environmental performance are the most important performance or design criteria of CPB. CPB placed in an underground stope (excavated zone created by the extraction of ore-bearing rock) must have sufficient mechanical stability in order to remain stable or self-supporting during the extraction of the adjacent stopes to ensure the safety of the mine workers and equipment (Fall and Benzaazoua, 2005; Fall et al., 2007). Unconfined compressive strength (UCS) is typically used in current practices to assess the mechanical stability of backfill. This is because the assessment of UCS is relatively quick and inexpensive, and thus can be used in the regular quality control of the mines (Fall and Benzaazoua, 2005). In addition, knowledge of the deformation (stress-strain) behaviour and elastic modulus of CPB is required to determine the stress distribution throughout the mine backfill. This knowledge is particularly important when numerical models are used to design and perform stability analysis of backfill (e.g., Li and Aubertin, 2009; El Mkadmi et al., 2014). This information is usually obtained by performing UCS tests on laboratory specimens of CPB cured in conventional plastic moulds and at atmospheric pressure and room temperature conditions (Kesimal et al., 2004; Cihangir et al., 2012; Pokharel and Fall, 2013). However, the obtained information is not representative of the field mechanical properties or behaviour of CPB. This is because this conventional curing and testing method of CPB does not allow engineers to consider the coupled processes during mechanical assessments, particularly the effects of curing stress due to self-weight pressure, to which the CPB is subjected in the field. This often leads to a conservative design, which means high costs of cement (high cement consumption), over-designed barricade structure and long mine cycle times. This is obviously associated with a reduction in the profitability of the mine.

The mechanical load induced by mine backfill under its own self-weight applies relatively high magnitudes of stress during curing time (Helinski et al., 2011; Doherty, 2015). Some researchers (e.g., Yilmaz et al., 2009, 2014, 2015a, 2015b; Fahey et al., 2011; Ghirian and Fall, 2015) have experimentally conducted studies on the effects of self-weight (or curing stress) on the mechanical behaviour of CPB. However, these studies were performed on CPB samples cured up to only 28 days (early ages). There are no previous studies on the long-term evolution of the UCS and stress-strain behaviour of CPB cured under stress conditions.

Moreover, one of the most important factors that influence the mechanical strength of CPB is suction (Simms and Grabinsky, 2009; Abdul-Hussain and Fall, 2012; Ghirian and Fall, 2014). The development of suction in CPB materials leads to an increase in strength (Ghirian and Fall, 2014). Suction causes the isotropic compression of solid skeletons and can be considered as a form of confinement stress around a CPB sample (e.g., Burlion et al., 2005). As a result, the compression strength of the CPB structure increases, which influences the stability and durability of the backfill. Suction can be generated by self-desiccation in CPB and also occurs in all types of cementitious materials. Binder reactions consume the water in the pores which results in the reduction of the internal relative humidity (RH) and creation of capillary tension within the pores (Bentz, 2008), and thus in the generation of matric suction or capillary pressure. Information on suction development in CPB is very limited and there is no previous work that has studied the long-term evolution of suction in CPB cured under stress.

Furthermore, one of the most important parameters that affects the environmental performance and durability of CPB is permeability (Fall et al., 2009). Backfills that contain sulphide-rich mine tailings can be susceptible to AMD. Sulphide minerals, such as pyrite and pyrrhotite, are reactive in the presence of water and oxygen, and produce acidic water and toxic metal ions (Ouellet et al., 2006; Farkish and Fall, 2013). AMD is a serious geoenvironmental concern since it can result in severe environmental issues or groundwater contamination (Akcil and Koldas, 2006). The reactivity of CPB materials mostly depends on the fluid transportability of the backfill material and the type and quantity of sulphide minerals present in the CPB (Fall et al., 2009). The long-term hydraulic conductivity or permeability provides useful information when the durability and environmental performance of CPB need to be assessed. Knowledge of the evolution of hydraulic conductivity is a key parameter that is used to evaluate the groundwater flow regime in the backfill structure after mine flooding (Levens et al., 1996). Permeability and the micro-structure characteristics of CPB control the transport of contaminants and leachate potential from acidic mine backfill into the surrounding environment (Benzaazoua et al., 2004). Despite the tremendous progress made in understanding the hydraulic conductivity and the factors that affect hydraulic conductivity, all of the

previous studies (e.g., Godbout, 2005; Fall et al., 2009; Abdul-Hussain and Fall, 2012; Ghirian and Fall, 2013 & 2014) have been limited to investigating the hydraulic conductivity of backfill samples cured in “conventional” small cylindrical moulds under zero stress. No previous studies have been performed that investigate the long-term evolution of the saturated hydraulic conductivity of CBP cured under stress conditions.

In this chapter, laboratory studies are undertaken to investigate the long-term hydraulic and mechanical behaviour and performance of CPB samples cured under stress. A pressure cell apparatus is developed for this purpose to cure backfill samples under applied vertical stress. The mechanical properties, deformation behaviour and the permeability of the samples are studied up to 150 days, while the samples are stressed under simulated self-pressure loads similar to those that CPB experiences in the field. Furthermore, the effect of the mineralogical and chemical characteristics of the tailings on the hydro-mechanical behaviour of CPB is studied.

## **5.2. Materials, methods and experimental program**

### **5.2.1. Materials used for CPB preparation**

The materials used in the experiments for the preparation of the CPB samples include tailings, Portland cement and water. Two types of tailings were used, including commercially available artificial silica tailings (ST) and natural zinc tailings (ZnT). The natural tailings were obtained from a Canadian zinc mine. The primary reason for using ST was to accurately control the mineralogical and chemical compositions of the tailings. This will keep the uncertainty related to the interaction between some of the reactive components of natural tailings (e.g. sulphide minerals) and cement hydration to a minimum level (this interaction may affect the interpretation of the results). Table 5.1 presents the mineralogical compositions of the ST and ZnT obtained from an x-ray diffraction (XRD) analysis. The ZnT is mainly made of chlorite, talc, pyrite, quartz, magnetite and magnetite, whereas ST is essentially made of quartz (one of the dominant minerals in Canadian hard rock mines). The grain size distributions of the ST and the ZnT are presented in Figure 5.1. They are close to the average of nine types of mine tailings found in Canadian hard-rock metal mines. Approximately 50% of the ST and ZnT particles are smaller than 20  $\mu\text{m}$  and 30 $\mu\text{m}$ , respectively. Based on the Unified Soil Classification System (USCS), both tailings are non-plastic silt (ML). ML is typical of tailings produced by hard rock mines (Orejarena and Fall, 2008). Ordinary Portland cement type I (PCI) was used as the binder, whereas tap water was used to mix the tailings and the binder. Table 5.2 shows the chemical composition of the pore water of the ZnT. A relatively high concentration of sulphate is observed.

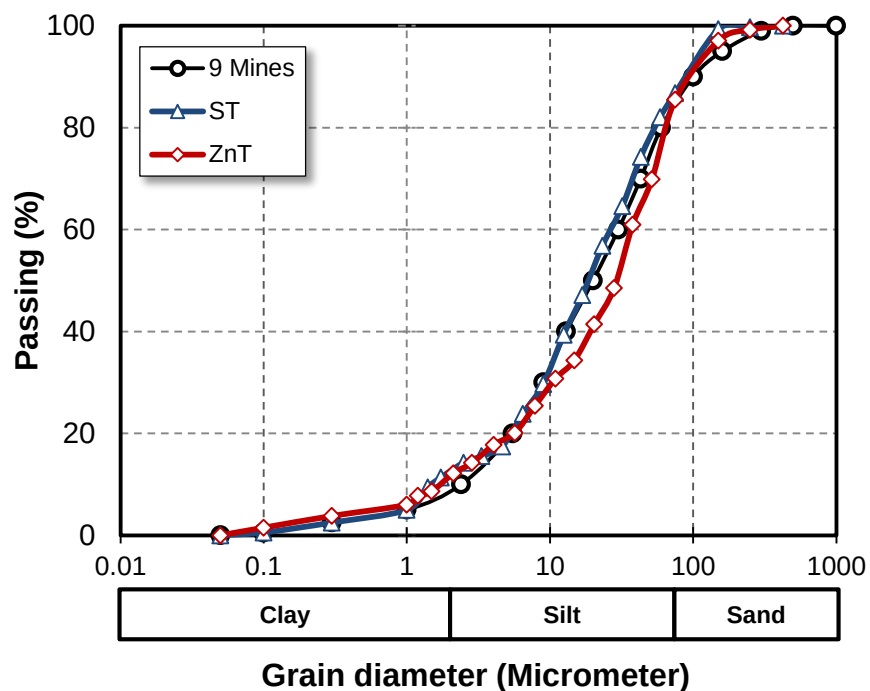


Figure 5.1. Grain size distribution of the tailings that are used compared with that of the average of nine types of tailings from Canadian hard-rock metal mines

Table 5.1. Mineralogical composition of the tailings used

| Element/<br>Tailings | Quartz | Dolomite | Chlorite | Magnetite | Pyrite | Talc | Magnetite | Actinolite | Pyrrhotite | Spinel | Others |
|----------------------|--------|----------|----------|-----------|--------|------|-----------|------------|------------|--------|--------|
| ZnT (wt%)            | 11.9   | 5.7      | 18.2     | 11.4      | 15.4   | 16.4 | 7.6       | 3.2        | 3.1        | 3.2    | 3.9    |
| ST (wt%)             | 99.8   | -        | -        | -         | -      | -    | -         | -          | -          | -      | -      |

Table 5.2. Chemical composition and pH of the pore water of the zinc tailings

| Elements | pH  | Sulphate<br>(mg/l) | Al<br>(mg/l) | Ca<br>(mg/l) | Fe<br>(mg/l) | Mg<br>(mg/l) | K<br>(mg/l) | Si<br>(mg/l) | Na<br>(mg/l) |
|----------|-----|--------------------|--------------|--------------|--------------|--------------|-------------|--------------|--------------|
| Zn-T     | 5.3 | 2600               | 2.2          | 60000        | 19           | 2300         | 200         | 15           | 53           |

### 5.2.2. Sample mix proportions and preparation

The CPB mix proportion consisted of 4.5% wt of Portland cement type I (PCI), tailings (ST or ZnT) and a water to cement ratio (w/c) equal to 7.6. All the CPB ingredients were mixed and homogenized in a food mixer for about 7 minutes. The slump or the consistency of the CPB mixtures was measured by using a slump test in accordance with ASTM C143. The slump values for the CPB prepared with ST and ZnT were about 18 cm and 22 cm, respectively. Right after mixing, the fresh CPB mixtures were poured into pressure cells as described below and then cured under stress-free conditions (control condition) or stress-controlled conditions for specific curing times. In total, three sets of CPB specimens were prepared. These sets are differentiated by the type of tailings used (ST or ZnT) or the curing stress conditions applied to the samples (stress-free or stress-controlled). These sets of samples are: (i) C-ST samples (or control samples), prepared with ST and cured without applying any vertical pressure as commonly done so in backfill practices; (ii) CUS-ST samples, and (iii) CUS-ZnT samples, which were prepared with ST and ZnT, respectively, and cured under controlled stress conditions as described below. After the curing was completed, mechanical and hydraulic conductivity tests were performed on the CPB specimens. Moreover, microstructural analyses (e.g., scanning electron microscopy (SEM)) were performed on some of the samples.

In addition to the aforementioned CPB specimens, specimens made of cement paste with a high w/c ratio (w/c = 2; to simulate the cement matrix of CPB) were also prepared and cured under the same conditions (stress-free, stress-controlled) as the CPB for specific curing times. After the curing was completed, microstructural (thermal) analyses were performed on the cement specimens.

### 5.2.3. Developed pressure cell apparatus and curing conditions

A pressure cell apparatus (Figure 4.3) was developed and engineered in order to simulate the gradual filling and self-weight pressure of mine backfill during the curing of CPB. Furthermore, the apparatus enables the monitoring of the CPB behaviour during its curing, as well as the sampling of CPB specimens cured under various conditions for the purpose of conducting the required mechanical, hydraulic and microstructural tests and/or analyses.

Figure 4.3 presents a schematic diagram of the developed experimental apparatus. It consists of a Perspex (acrylic plastic) cylinder with the diameter of 101.6 mm (4 inches) and height of 304.8 mm (12 inches) and an axial piston located on the top. The piston is pressed down onto the CPB sample by using high pressure air, supplied by a pressured air system in the laboratory. Due to laboratory safety regulations, the air pressure was limited to 600 kPa, which is equal to a backfill height of approximately 30 to 35 m, depending on the density of the CPB mix. The pressure on the samples

was regulated by means of a series of pressure regulators and pressure gauges. Only 200 mm of the cylinder was filled with fresh CPB and the remaining space served as the air chamber to apply pressure onto the piston. In all of the experiments, the length-to-diameter ratio of the CPB samples was two.

In total, eight cells were manufactured, including two cells equipped with various sensors for monitoring and six cells to cure the CPB samples for different times (7, 28, 90 and 150 days) and under different conditions.

Undrained CPB typically presents lower mechanical strength than drained backfill (le Roux et al., 2005; Nasir and Fall, 2010; El Mkadmi et al., 2014). Therefore, in consideration of this conservative case scenario, an undrained curing condition was adopted for all of the experiments. After filling the cell with fresh CPB mix and connecting the cell to the air supply, the pressure cells were covered with a heat insulation glass wool blanket with a thickness of 100 mm. The objective of the insulation was not to create adiabatic curing conditions, but to slow down the heat (generated by the cement hydration) transfer between the backfill material and the surrounding environment (where it was room temperature,  $\sim 23^{\circ}\text{C}$ ), in order to mimic the heat transfer between a narrow cemented backfill structure and the surrounding rock mass in the field.

Two different stress curing conditions were applied by using the developed setup: stress-free curing conditions on the C-ST samples, and stress-controlled curing conditions on the CUS-ST and CUS-ZnT samples. The filling rate in a typical mine stope ranges between 0.2 m/h to 0.5 m/h (Yumlu, 2008; Thompson et al., 2012; Veenstra, 2013). Therefore, an average filling rate equal to 0.31 m/h is adopted for this study to simulate the corresponding mine backfill height (or pressure increments). Table 5.3 shows the pressure application scheme that simulates mine stope backfilling over a period of 150 days. The bulk unit weight of the CPB was determined to be equal to  $17.2 \text{ kN/m}^3$  and equivalent backfill heights were calculated accordingly. It should be mentioned that the arching effect is not considered in this study as the apparatus operated under a one-dimensional vertical pressure. The pressure was progressively increased every 3 hrs for the first 12 hrs up to 150 kPa in order to simulate a more realistic self-weight of the specimen. Then, the pressure was increased 150 kPa every 24 hrs up to 600 kPa, which is equivalent to a final height of 34.9 m of the backfill. Then, the pressure was kept constant and equal to 600 kPa until 150 days.

**Table 5.3. Pressure application scheme which simulates a 30 m mine stope or 30 m backfill height with average filling rate of 0.31 m/h**

| Elapsed time | Applied vertical pressure (kPa) | Equivalent height (m) | Equivalent filling rate (m/hr) |
|--------------|---------------------------------|-----------------------|--------------------------------|
| start        | 20                              | 1.1                   | 0.33                           |
| 3h           | 35                              | 2.0                   | 0.28                           |
| 6h           | 55                              | 3.2                   | 0.33                           |
| 9h           | 75                              | 4.3                   | 0.33                           |
| 12h          | 150                             | 8.7                   | 0.31                           |
| 1d           | 300                             | 17.4                  | 0.31                           |
| 2d           | 450                             | 26.2                  | 0.31                           |
| 3d to 150d   | 600                             | 34.9                  | 0.31                           |

#### 5.2.4. Instrumentation and monitoring

The pressure cells, which contained the CPB samples, were monitored for the evolution of suction, temperature and electrical conductivity (EC) for a minimum period of 150 days after loading. The locations of all the sensors used are shown in Figure 4.3. The evolution of the suction was determined by using a dielectric water potential sensor, model MPS-2, which was installed 40 mm above the cell bottom. This sensor is capable of measuring matric potential (or matric suction) between -10 and -500 kPa (MPS-2 Operator's manual, 2014). The monitoring of the suction provides information about the self-desiccation of the CPB. An ECH2O-5TE capacitance sensor was installed in the cell to monitor the electrical conductivity with an accuracy of about  $\pm 10\%$ . Both sensors are able to measure the temperature; therefore, the evolution of temperature as a result of cement hydration was also monitored during the experiments. The monitoring of the electrical conductivity (EC) is an effective means of assessing the progress of cement hydration, and tracking the structural changes that occur within the hydrating CPB during its curing (Courard et al., 2014). A wall mounted miniature pressure transducer (with a working pressure of 1 MPa) was used to monitor the internal cell pressure during the experiments. All of the sensors were connected to the appropriate data loggers to record the data with time.

#### 5.2.5. Testing program

##### 5.2.5.1. Mechanical tests

Unconfined compressive strength (UCS) tests were performed on the CPB samples after a given curing time. In this study, the procedure described in ASTM C39 is adopted to perform the

testing on the CPB samples cured for 7, 28, 90 and 150 days. A minimum of two samples (to ensure the repeatability of the results) were tested for each curing time. A computer-controlled mechanical press with a constant deformation rate of 0.8 mm/min was used and the stress-strain data were recorded for each sample.

#### **5.2.5.2. Saturated hydraulic conductivity**

Saturated hydraulic conductivity testing was performed by using a TRI-FLEX II on the CPB specimens cured under stress and without stress for 7, 28, 90 and 150 days. The flexible wall technique was used to determine the saturated hydraulic conductivity of the CPB. The procedure for this method is described in ASTM D5084 and was conducted in the constant head mode equal to 10 kPa. All of the samples were backpressure saturated prior to the testing. The saturation was also verified by determining the degree of saturation of the samples at the completion of the hydraulic conductivity tests. The samples showed on average, final degrees of saturation that are higher than 97%. Two samples were tested and at least three readings were made, and the average value was the saturated hydraulic conductivity of the sample tested.

#### **5.2.5.3. Microstructural analysis**

A combination of several techniques was employed to investigate the microstructural properties of the prepared CPB and cemented paste specimens cured under various conditions and curing times. The microstructural properties of the CPB samples were investigated by observation with SEM. SEM observations were performed with a variable pressure SEM machine, EVO-MA10. This helped to visually study the microstructure of the CPB matrix, cement hydration products as well as to assess the formation of microcracks. The samples were first dried at 50°C up to mass stabilization in a vacuum oven to remove the free water. Drying at this temperature did not appear to cause cracking. After that, the samples were impregnated with cold epoxy resin and then polished. The samples were observed in backscatter electron mode.

Furthermore, the microstructure of the prepared and cured cement paste samples was investigated with thermal analyses (TGA/DTG). The thermal analyses were undertaken by using a TGA Q 5000 IR from TA Instruments, which allows for the simultaneous registration of weight loss and heat flow along with the thermal treatment of the sample. The various (dried) samples (about 20 mg each) were heated in an inert nitrogen atmosphere at the rate of 10°C per minute up to a

temperature of 1000°C. The thermal analyses allowed the binder hydration products that formed in the CPB system cured under stress-free or stress-controlled conditions to be studied.

## **5.3. Results and discussion**

### **5.3.1. Evolution of the mechanical properties and behaviour**

#### **5.3.1.1. Unconfined compressive strength**

The results of unconfined compressive strength (UCS) tests for the studied CPB samples are presented in Figure 5.2. It shows, as expected, that the UCS values increase as the curing time increases regardless of the stress curing conditions (except for the ZnT sample after 28 days; will be discussed later). This behaviour is mainly attributed to the increase in solidification and hardening of the backfill due to the formation of a larger amount of cement hydration products, such as calcium silicate hydrate (C-S-H), calcium hydroxide (CH) and ettringite (Taylor, 1990; Klein and Simon, 2006; Fall et al., 2010) or increased binder hydration as the curing time is increased. The precipitation of cement hydration products in the CPB pores also causes pore refinement (decrease in porosity or void ratio), which is favourable for strength development (Fall et al., 2008). This relationship between void ratio and strength development is graphically demonstrated by the results presented in Figure 5.3, which illustrates the effect of CPB pore refinement on the evolution of the mechanical strength. The overall trend shows that the UCS increases as the void ratio decreases. However, there is an additional factor which should be taken into consideration as a contributor to the strength increase of CPB induced by curing time. This factor is the suction development due to self-desiccation (caused by the cement hydration) that occurred within the CPB, especially at early ages. Higher suction is commonly associated with a strength increase of the porous media (e.g., Fredlund and Rahardjo, 1993). Suction development increases the effective stress, which in turn, provides higher mechanical strength to the CPB. This suction increase induced by self-desiccation was experimentally confirmed by the results of the suction monitoring and presented in Figure 5.11 (will be discussed in more detail below). From this figure, it can be observed that the suction of the CPB specimen increases as the curing time is increased. This increase is particularly significant at the early ages, which corresponds to the period where the cement hydration reactions are intense (e.g., Taylor, 1990; Loukili et al., 1999)

Figure 5.2 also depicts that for the same type of tailings, CPB cured under stress has higher UCS values until 28 days. A comparison of the UCS test results of the CUS-ST and C-ST samples shows that curing stress increases the UCS values up to approximately 18.2% and 26.3% at 7 and 28

days, respectively. This can be primarily explained by the effect of the pressure application on the pore structure of CPB at the early ages. In considering that the curing stress was applied since the beginning of the experiment, the curing pressure increases the packing density of the backfill materials during the initial curing. This increase in packing density (tailings and cement particles arranged closer together) enhances the formation of cementation bonds (e.g., Dalla Rosa et al., 2008; Rabbi et al., 2011) and leads to a denser pore structure or a reduction in porosity of the CPB at early ages. This decrease in porosity and a denser pore structure are associated with compressive strength gain (Fall et al., 2004; Ahnberg, 2007; Dalla Rosa et al., 2008). This argument with regards to curing pressure induced densification or porosity decrease of the CPB at the early ages is demonstrated by the results of porosity determination of CPBs cured under stress and no stress, see Figure 5.4. From this figure, it can be noted that for a curing time  $\leq 28$  days (early ages), the CPB samples cured under stress (CUS-ST) have a lower porosity than those (C-ST) cured under no stress.

In addition to the above factor, a second parameter may have contributed to the stress induced strength increase of the CPB for curing times  $\leq 28$  days. This parameter is the effect of stress on the degree of cement hydration. Several studies have documented acceleration in the rate of cement hydration under pressure (e.g., Oyefesobi and Roy, 1976; Rahman and Double, 1982; Bresson et al., 2002; Zhou and Beaudoin, 2003; Méducin et al., 2007; Jupe et al., 2008). For example, Bresson et al. (2002) concluded that a pressure up to 100 MPa accelerates the rate of cement hydration. These findings are in agreement with those of Méducin et al. (2007). Zhou and Beaudoin (2003) found that the application of a curing pressure of 6.80 MPa at the early age stages of the hydration of Portland cement results in greater degree of hydration and a denser microstructure, normally within 48 h. These observations with respect to the effect of pressure on cement hydration are consistent with the results of the thermal analyses of the cemented pastes of CPB performed in this study and presented in Figure 5.5. This figure is a comparison of the derivative thermogravimetric analysis/differential thermal analysis (DTG/DTA) diagrams of the 7 day old cement pastes cured under stress and no stress (control). The thermogravimetric analysis (TGA) locates the ranges that correspond to the thermal decompositions in the different phases of the paste, while the DTG simultaneously gives the rate of weight loss due to these decompositions. This figure shows on the whole, three main endothermic peaks that are associated with rapid weight loss and major phase transformations. The first peak or weight loss is located between 75°C and 200°C, which is attributed to the evaporation of free water (up to 120°C) and dehydration reaction of several of the hydrates (C–S–H, carboaluminates, ettringite, etc.). The second main peak or weight loss, observed at 400–500°C, is due to the dehydroxylation of portlandite (CH) (e.g., Noumowé, 1995; Anderberg, 1997; Zhou and Glasser, 2001; Fall and Samb, 2008; Fall et al., 2010). The third peak or weight loss, located between

600°C and 700°C, is resultant of the decomposition of calcite ( $\text{CaCO}_3$ ) and generation of  $\text{CO}_2$  as observed in other types of cementitious materials (e.g., Noumowé, 1995; Zhou and Glasser, 2001). A comparison of the TGA/DTG diagrams shows that the first endothermic peak and weight loss are slightly higher for cement paste cured under stress. This behaviour means that the curing stress can affect cement hydration reactions in CPB materials and therefore samples cured under stress produce more hydration products compared to the control sample. However, it should be emphasized that this observed effect of stress on cement hydration in backfill systems is minor compared to that on concrete reported in the aforementioned previous studies. This is because the stresses considered in previous studies on concrete systems (6 - 100 MPa) are much higher than that considered in this study (600 kPa) or commonly encountered in mine backfill practices (usually < 4 MPa).

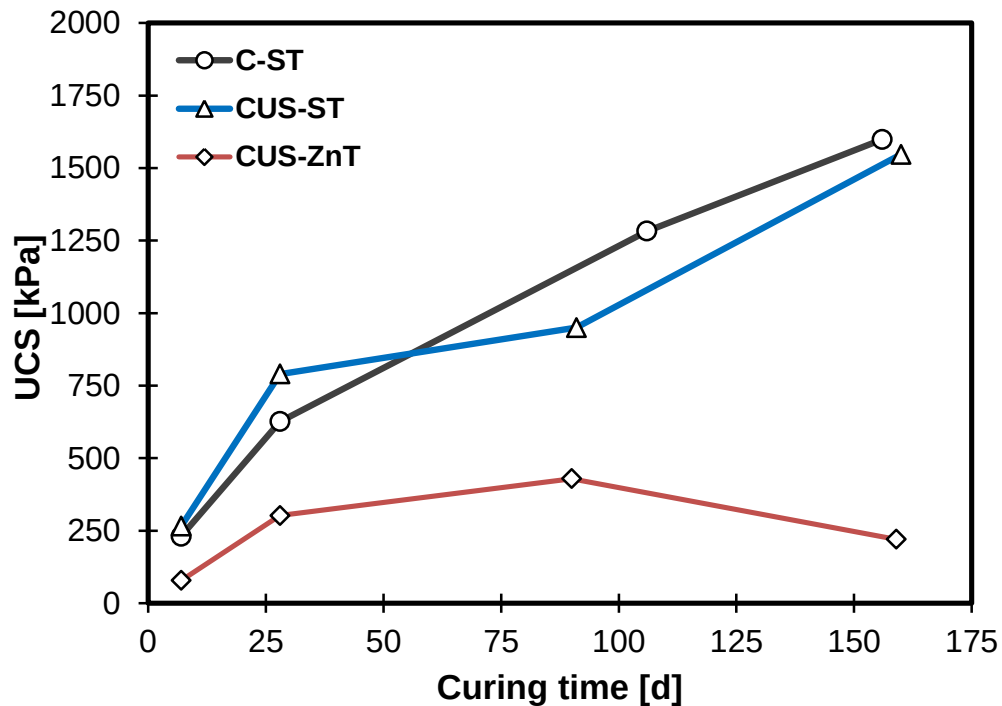


Figure 5.2. Long-term evolution of UCS with curing time with consideration of curing stress

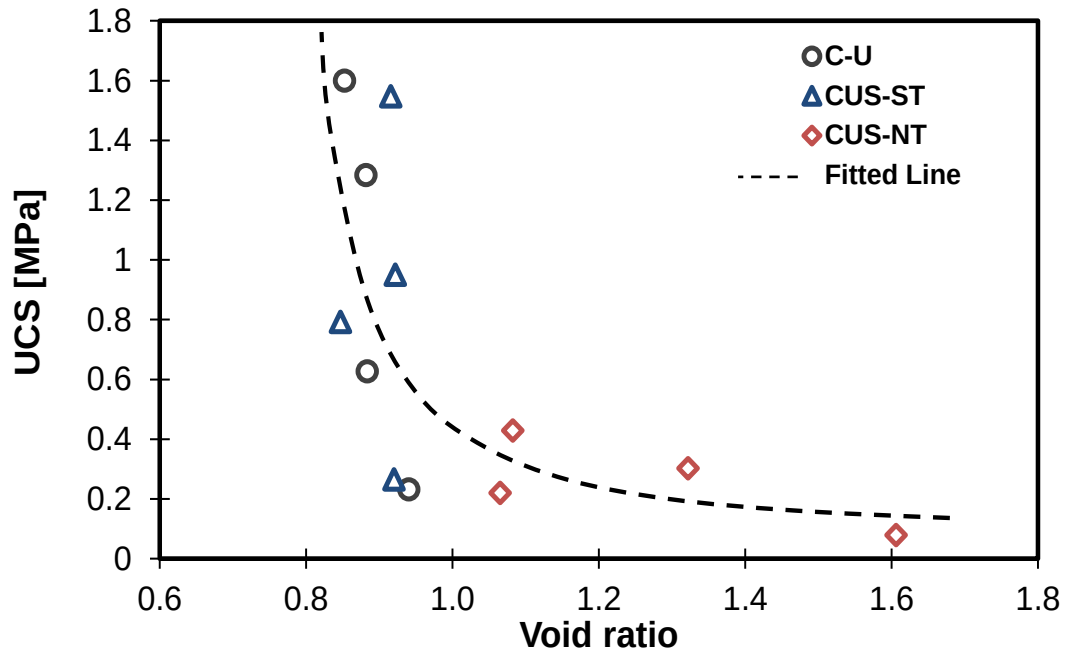


Figure 5.3. Relationship between void ratio and UCS

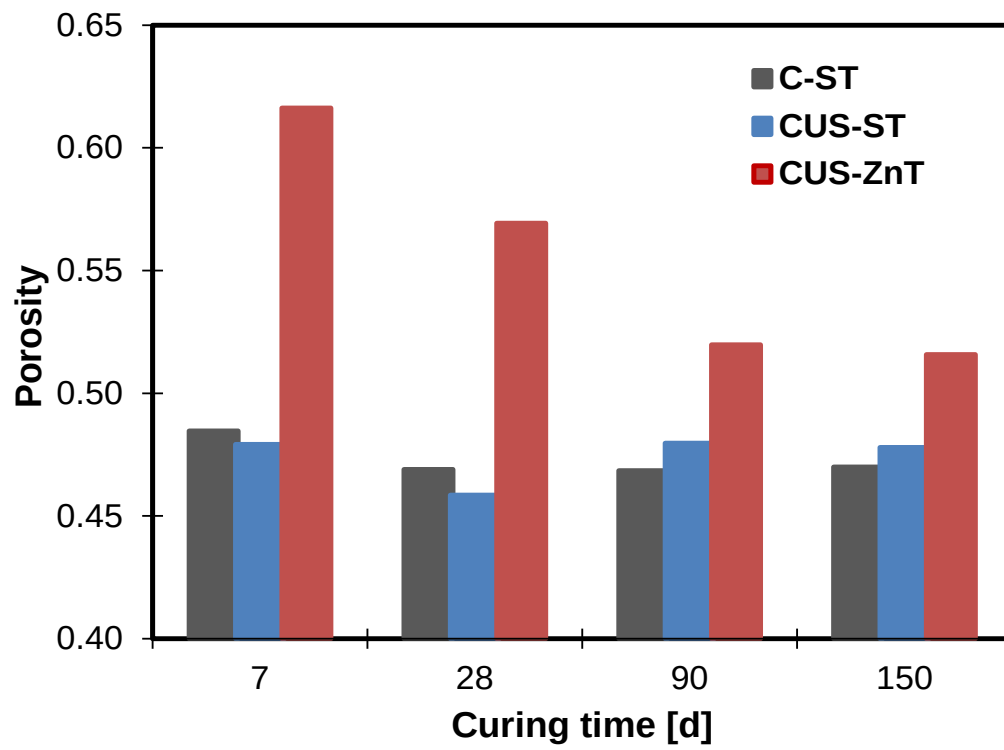


Figure 5.4. Long-term evolution of porosity with curing time with consideration of curing stress

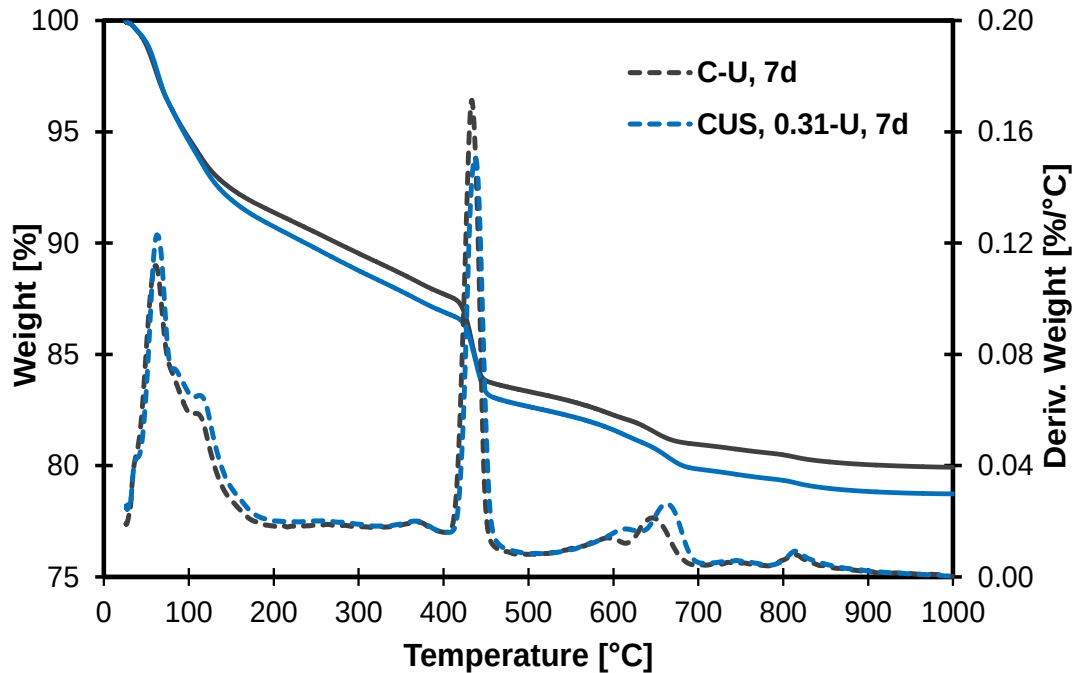


**Figure 5.5. TGA analysis on cement paste cured with and without stress at 7 days**

However, different behaviours were observed at more advanced ages (>28 days) with regards to the UCS evolution. Figure 5.2 illustrates that for the same type of tailings at 90 and 150 days, the UCS values of the samples cured under stress are lower than those cured without stress. This behaviour can be attributed to the fact that the CPB cured under stress might have been mechanically damaged by the applied stress (excessive stress/strength ratio), which resulted in the formation of microcracks within the CPB. This argument with respect to stress-induced microcracking is in substantial agreement with the results of SEM observations on CPB cured under stress and no stress which are presented in Figure 5.6. It can be observed that the CPB samples cured under (excessive) stresses (Figure 5.6b) show cracks in their matrix, especially at the interface transition zone (ITZ) between the coarser tailings particles and the cement matrix. These cracks, not observed in CPB samples cured without stress (Figure 5.6a), result from the fact that the constant application of high levels of stress for a long period of time leads to the generation and propagation of micro-cracks in the ITZ between the tailings particles and cement hydration products (Fall et al., 2008). This stress induced micro-cracking of CPB is also confirmed by the results of the hydraulic conductivity tests performed on the studied CPB and illustrated in Figure 5.12. From this figure, it can be observed that the 90 and 150 day CPB samples cured under stress exhibit higher permeability values than those cured under no stress, which indicates the coarsening of the pore structure. Indeed, permeability is directly proportional to the capillary pore size or the coarseness of the pore structure (Fall et al., 2009). This observed microcracking of the studied CPB induced by excessive stress is also consistent

with the findings of Bisschop (2011) on Portland cement paste, who concluded that at load levels higher than 0.5 times the compressive strength, applied stress may lead to the microcracking of the cemented paste material.

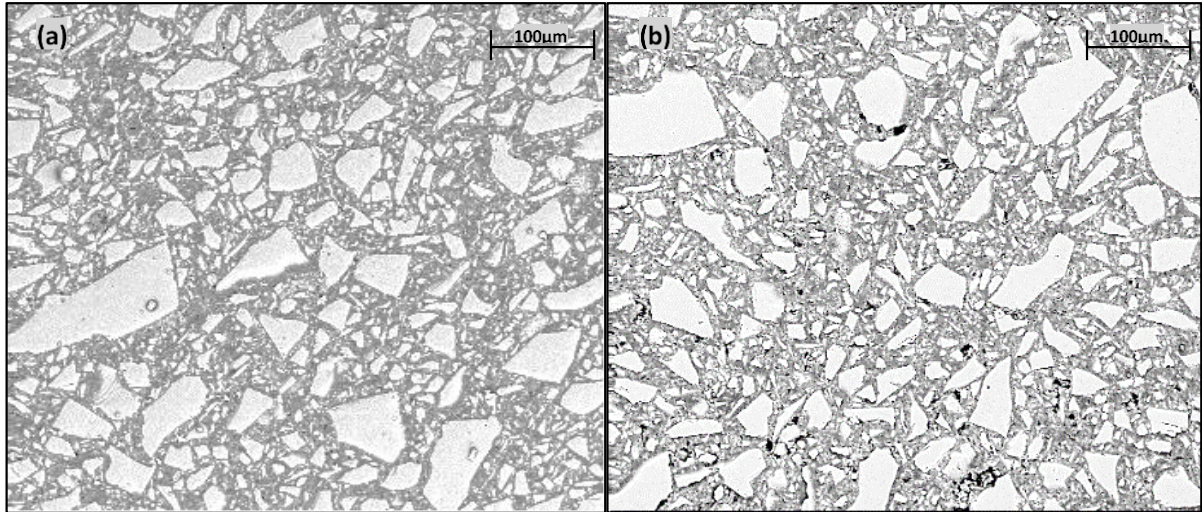


**Figure 5.6. SEM images that show effect of curing under pressure on CPB microstructure at 150 days (a) cured without stress (C-ST), and (b) cured under stress (CUS-ST) (dark areas show the cracks)**

Furthermore, it can be observed from Figure 5.2 that the type of tailings has a significant influence on the strength response of CPB cured under stress. The CUS-ZnT samples exhibit a much lower mechanical strength than the CUS-ST samples. For example, the UCS values of CUS-ST and CUS-ZnT are 950 and 429 kPa at 90 days, respectively. This lower strength of the CUS-ZnT is related to the effects of the mineralogical composition/chemistry of the ZnT used (see composition in Table 5.1), shape and strength of the tailings particles, as well as the chemical composition of the tailings pore water (see composition in Table 5.2) on the mechanical performance of the backfill materials. These observations are in agreement with the conclusions made by Ghirian and Fall (2015), which emphasized the importance of the mineralogical, physical and chemical properties of tailings on the strength development of CPB. Moreover, the relatively high concentration of sulphate present in the pore water of the ZnT (Table 5.2) has significantly inhibited or retarded the binder hydration reactions in the CUS-ZnT samples, thus contributing to the decrease of their strength in comparison to the CUS-ST samples. This sulphate induced inhibition and retardation effect in the CPB system was also observed in previous studies (e.g., Tzouvalas et al., 2004; Fall and Pokharel, 2010) and is experimentally supported by the monitoring results on suction (presented in Section 3.2), electrical conductivity and evolution of the temperature of the studied CPB samples. For example, Figure 5.7 shows that the CUS-ZnT sample has a significantly lower suction value (44 kPa) than the CUS-ST sample (113 kPa) at 150 days. As discussed earlier, suction development is one of

the important factors that contribute to strength development in CPB. Suction due to self-desiccation is directly related to the rate of the cement hydration reaction. Therefore, there is a slower rate of hydration reaction of the binder in the ZnT sample with a relatively high sulphate concentration, which means less intense self-desiccation. The retardation of the cement hydration in the CUS-ZnT samples can also be observed from the electrical conductivity (EC) measurements in Figure 5.7, in which compared to the CUS-ST sample, there is a clear shift of the conductivity peaks in the CUS-ZnT sample to longer times of hydration in the early ages, which indicates that the rate of the hydration reaction is reduced by the sulphate in the CUS-ZnT sample during this period. Moreover, the monitoring results of the evolution of the temperature in the CPB presented in Figure 5.7, also support the aforementioned inhibition and retardation of cement hydration. It can be observed that the generation rate and amount of heat of hydration are different between the CUS-ST and CUS-ZnT samples. Temperature increases due to cement hydration reactions quickly reaches the maximum value in the CUS-ST sample, while the CUS-ZnT sample exhibits a prolonged delay in initial heat generation after commencement of the experiments. Moreover, more heat of hydration is generated in the CUS-ST sample compared to the CUS-ZnT sample. These indicate both the retardation of cement hydration and its reduced intensity in the sulphated CUS-ZnT samples.

Moreover, from Figure 5.2, it can be noticed that the UCS of the CUS-ZnT sample at 150 days is reduced compared to the 90 day sample. The UCS is reduced from 429 kPa at 90 days to 220 kPa at 150 days (about 50% strength loss). This behaviour can be attributed to the sulphate attack on the mechanical strength of the CUS-ZnT (Fall and Pokharel, 2010). Indeed, the reactions of the sulphate ions, initially present in the CUS-ZnT sample, with  $C_3A$  from the cement clinker and CH generated by the cement hydration may have led to the formation of expansive minerals, such as ettringite and gypsum, within the CPB matrix. These minerals in turn, exert expansive pressure onto the CPB pore structure and induce deterioration (micro-cracking) of the CPB as well as coarsening of the pores, which is obviously associated with a strength decrease of the backfill material (Fall and Benzaazoua 2005; Kesimal et al., 2005; Pokharel and Fall, 2011). This argument agrees with the results of the tests on the saturated hydraulic conductivity of the CUS-ZnT samples presented in Figure 5.12. As can be observed, the CUS-ZnT sample has higher permeability at 150 days than the 90 day sample, which is an indication of the coarsening of the pore structure (micro-cracking) of the former.

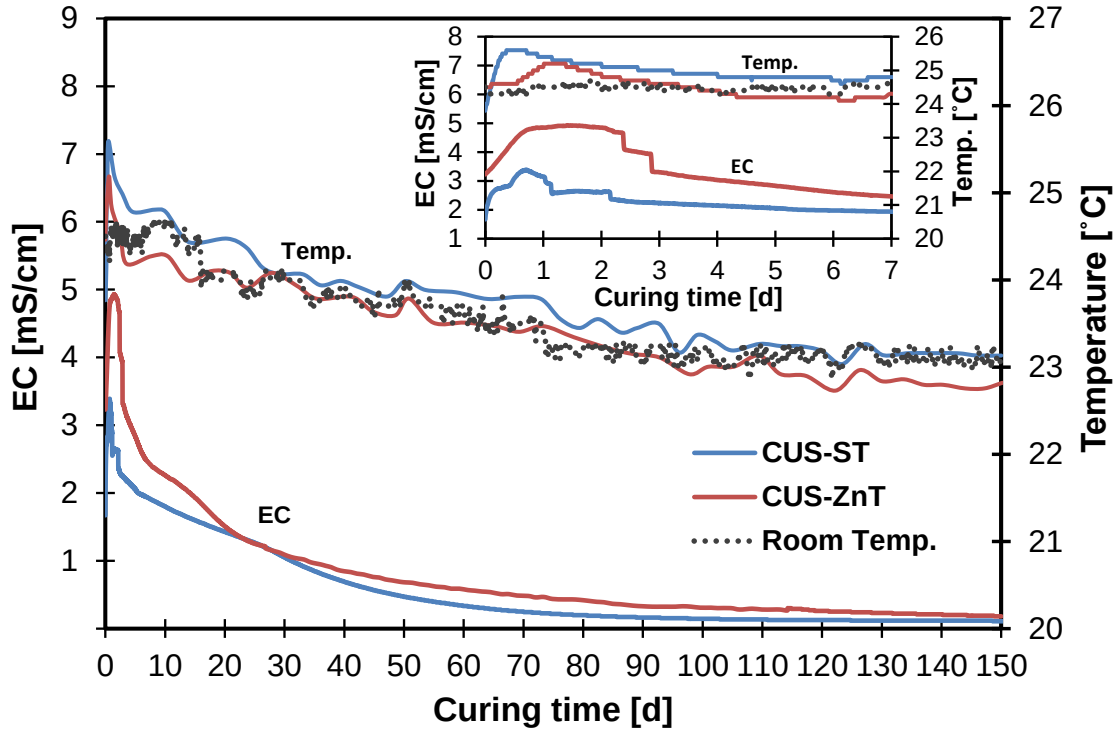


Figure 5.7. Long term evolution of EC and temperature of CPB samples with curing time

### 5.3.1.2. Stress- strain behaviour

The stress-strain behaviour of the studied CPB samples was investigated and typical results are presented in Figure 5.8. It is seen that the curing time affects the shape of the stress–strain curves. The curves show that the strains at the peak stress and the overall ductility of the CPB samples depend on the curing time. Also, it is observed that the curing pressure has no significant impact on the shape of the stress-strain curve of the studied CPB samples, since the samples cured under both stress and zero stress exhibit the same qualitative behaviour. As a general trend, it can be noticed that for almost all of the studied samples (control and cured under stress) the stress-strain curves are concave at lower stress ( $< 0.5q_u$ ) and then become a convex shape close to the maximum strength. The strain at the peak stress is generally greater for lower curing times. For example, the strain at the peak stress for the CUS-ST sample is about 1.55% at 28 days, while this value is 1.05% for the CUS-ST sample cured for 160 days. Also, the stress-strain curves exhibit clear peaks and less plastic deformation before the peak for the samples at an advanced age (e.g., 150 days). On the contrary, for the CPB samples at 7 days of curing, more plastic behaviour can be observed before and even after the peak strength. This behaviour is mainly attributed to the fact that the CPB sample at 150 days has a higher value in strength and hence can absorb more energy up to the peak stress compared to the 7

day sample. This can result in the propagation of cracks and rapid deformation at the time of failure, and therefore, a sharp reduction in the stress-strain curves (Fall et al., 2007). This behaviour is also observed from the deformation and the failure pattern of the sample. The CPB sample at early ages of curing has a different failure pattern compared to the advanced age as shown in Figure 5.9. The CUS-ST sample that is cured for 7 days has a single inclined shear failure surface accrued at approximately a 70 degree angle. However, the CUS-ST sample at 160 days exhibits an inclined shear failure surface with some vertical minor shear failure connected to the inclined shear surface.

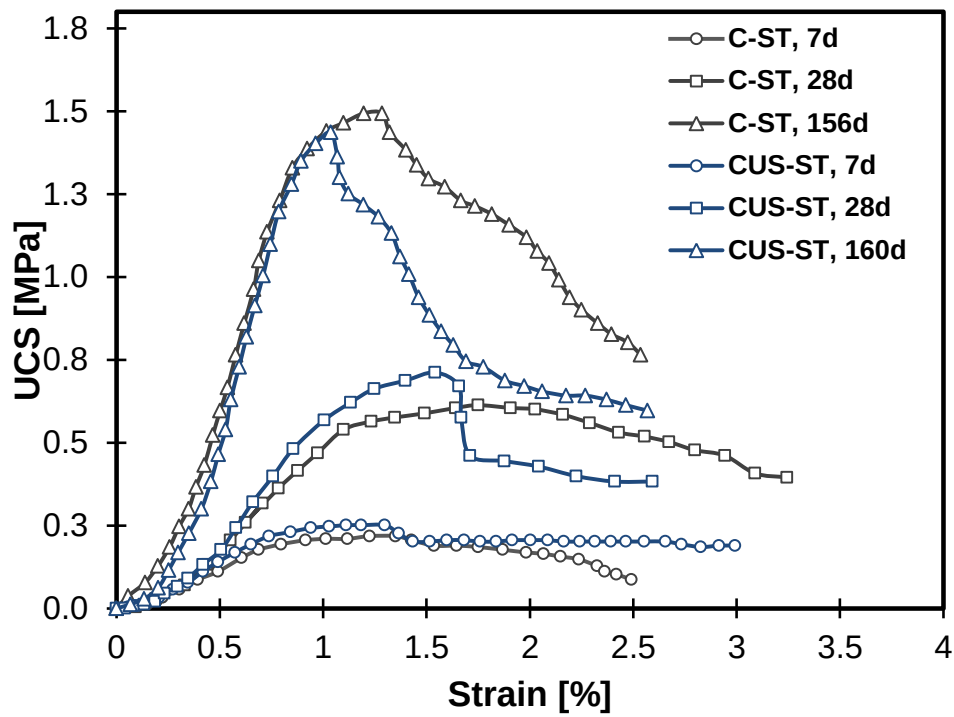


Figure 5.8. Stress-strain behaviour of CPB samples cured under stress at early to advanced ages

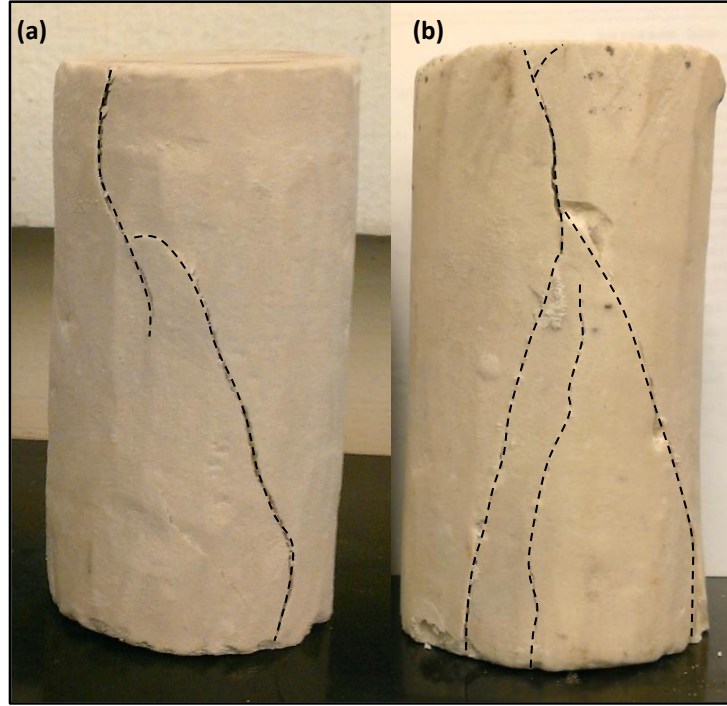


**Figure 5.9. Failure patterns of CPB samples cured under stress: (a) CUS-ST, 7 d and (b) CUS-ST, 160 d**

Figure 5.10 shows the evolution of the modulus of elasticity ( $E$ ) obtained from the stress-strain curve of the uniaxial compressive test results at different curing times and curing stress conditions. It is observed that there is a relationship between the curing time and modulus of elasticity. As the curing time increases or the cement hydration progresses, the  $E$  value increases for both the C-ST and CUS-ST samples. Also, it is observed that the effect of the curing stress is noticeable for the CUS-ST sample at 7 and 28 days of curing, since it causes an increase in the  $E$  values. This is attributed to the effects of cohesion on the modulus of elasticity since curing stress improves cohesion due to the rearrangement of the tailings particles and improved cohesive bonding in the CPB sample as explained above. However, at more advanced ages, the modulus of elasticity of the CUS-ST samples shows lower values compared to the control samples. The reason for this behaviour is already explained above. The mechanical strength and elasticity moduli of CPB are interrelated, which means that any reduction in the UCS values will affect the  $E$  values as well (Fall et al., 2007).

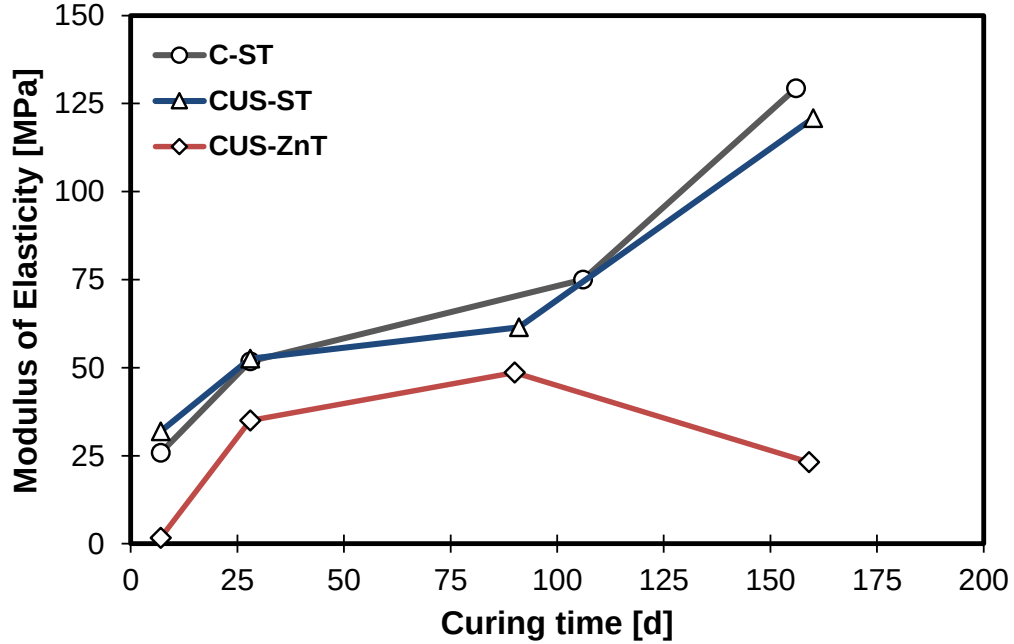


Figure 5.10. Evolution of the modulus of elasticity of CPB samples cured under stress and no stress

### 5.3.2. Evolution of the hydraulic properties

#### 5.3.2.1. Suction development

The results of the suction measurements obtained for the C-ST, UCS-ST and CUS-ZnT samples are presented in Figure 5.11. The results show that the evolution of the suction for all of the studied samples has a similar qualitative behaviour. A comparison of the data from the CUS-ST and C-ST samples reveals that the curing stress significantly influences the short-term and long-term development of suction in the CPB samples. The suction value obtained from the C-ST samples is higher than that of the CUS-ST samples during the studied period. The suction value for the CUS-ST and C-ST samples was measured under a pressure of 113 and 159 kPa at 150 days, respectively. The lower suction value of the CUS-ST sample is attributed to the fact that applying stress causes development of excess pore water pressure (PWP) and the refinement of the pore structure at an early age (Figure 5.4) in the CPB sample, and hence less suction develops. Furthermore, this figure illustrates that the curing time at which the initial increase in suction occurs is different between the samples. The suction in the C-ST sample started to evolve after about 16 hrs, while this value is about 22 hrs for the CUS-ST sample. This observed delay in suction development in the CPB cured under stress can be attributed to stress-induced generation of excess of pore water pressure (suction will develop after the dissipation of the excess pore pressure) and refinement of the pore structure (fewer

capillary pores available for water and air) of the CUS-ST sample. This behaviour also affects the long-term evolution of suction.

Also, from the results presented in Figure 5.11, it is noticed that the magnitude of the suction generated in the CUS-ZnT samples is much lower than that of the CUS-ST samples. For example, the suction measurements for the CUS-ZnT and CUS-ST samples are 45.0 and 113 kPa at 150 days, respectively, which shows about a 151% difference. The suction development in the CPB samples in undrained conditions is mostly related to self-desiccation as a result of the cement hydration reaction. The chemical composition of the ZnT (sulphate content, see Table 5.2) significantly influences the cement hydration reactions (slowing down the chemical reactions) and therefore, lower rate of self-desiccation and associated suction development can be expected. The commencement of suction of the ZnT CPB sample occurs after about 100 hrs. For this sample, the coupled effects of sulphate induced cement hydration inhibition/retardation, the stress induced development of excess pore water pressure and pore structure refinement cause a significant delay in the initial evolution of suction. As demonstrated in Figure 5.2 and discussed earlier, the delayed development of suction affects the short-term and long-term mechanical strength development of CPB.

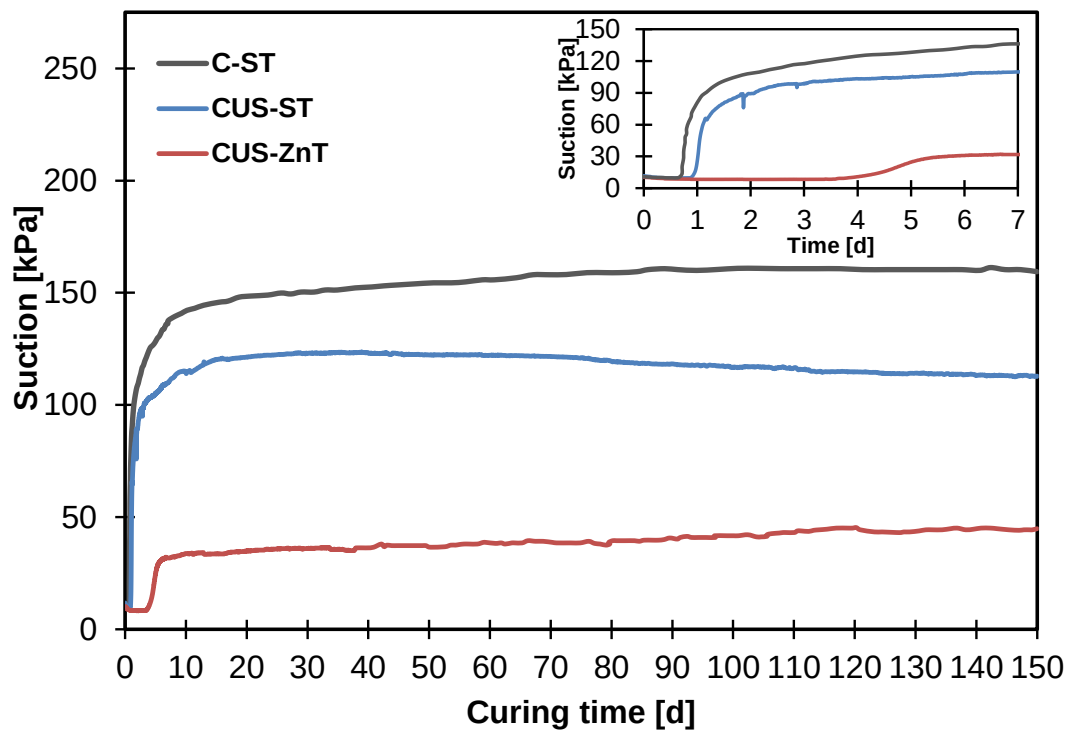


**Figure 5.11. Evolution of suction with curing time for the studied CPB samples**

The results of the development of suction are also in agreement with the temperature and electrical conductivity (EC) measurements presented in Figure 5.7. The measurements of the evolution of temperature show that the rate and amount of heat of hydration are different between the CUS-ST and CUS-ZnT samples. Temperature increases due to hydration reactions quickly reach the maximum value in the CUS-ST sample, while the CUS-ZnT sample shows a prolonged delay in the initial heat generation after commencement of the experiments. Moreover, increased heat of hydration is generated in the CUS-ST sample compared to the CUS-ZnT sample. The lower amount of generated heat in the CUS-ZnT sample is attributed to the chemistry of the tailings that are used. As presented in Table 5.2, ZnT contains relatively high amounts of sulphate ions which significantly alter hydration reactions by slowing down the rate of hydration and associated heat generation. This in turn, results in the delayed development of suction (Figure 5.11) and mechanical strength (Figure 5.2) in the sample.

#### 5.3.2.2. Saturated hydraulic conductivity

The effect of curing time and curing pressure on the long-term evolution of the saturated hydraulic conductivity ( $k_{sat}$ ) is depicted in Figure 5.12. It is seen that the values of  $k_{sat}$  decrease as the curing time increases for all of the samples (except for the 150 day CPB made with ZnT). The reduction in the  $k_{sat}$  with curing time is attributed to the refinement of the pores as cement hydration progresses (Fall et al., 2009).

Furthermore, by comparing the  $k_{sat}$  values of the C-ST and CUS-ST samples, it is seen that pressure application has a significant effect on hydraulic conductivity. The  $k_{sat}$  values are reduced by 204% at 7 days and 54% at 28 days due to the application of pressure. This is mainly attributed to the fact that the curing pressure contributes to the void ratio or porosity reduction of the CPB at early ages as discussed earlier, and thus to the decrease of the hydraulic conductivity. A lower void ratio of the CUS-ST sample compared to the C-ST sample for the same curing time supports this statement (Figure 5.4). However, at more advanced ages (91 and 160 days), the  $k_{sat}$  of the CUS-ST samples shows higher values compared to the C-ST samples. The reason is that there is mechanical damage of the CPB caused by excessive curing stress as explained earlier. This results in the formation and propagation of connected networks of microcracks, which lead to increase in permeability. These microcracks are observed in the SEM images as presented in Figure 5.6. Similar observations were made in CPB and other cementitious materials cured under sustained axial stress (Picandet et al., 2001; Fall et al., 2009).

The  $k_{sat}$  values of the CUS-ZnT sample show similar qualitative behaviour as the CUS-ST sample. This means that the  $k_{sat}$  decreases as the curing time is increased. However, the  $k_{sat}$  value

of the CUS-ZnT sample is considerably increased at 150 days. This can be related to the pore coarsening of the CPB matrix due to the excessive pressure applied by the expansive minerals (ettringite, gypsum) formed within the CUS-ZnT sample as explained earlier. The coarsening of the pores ultimately leads to increases in permeability.

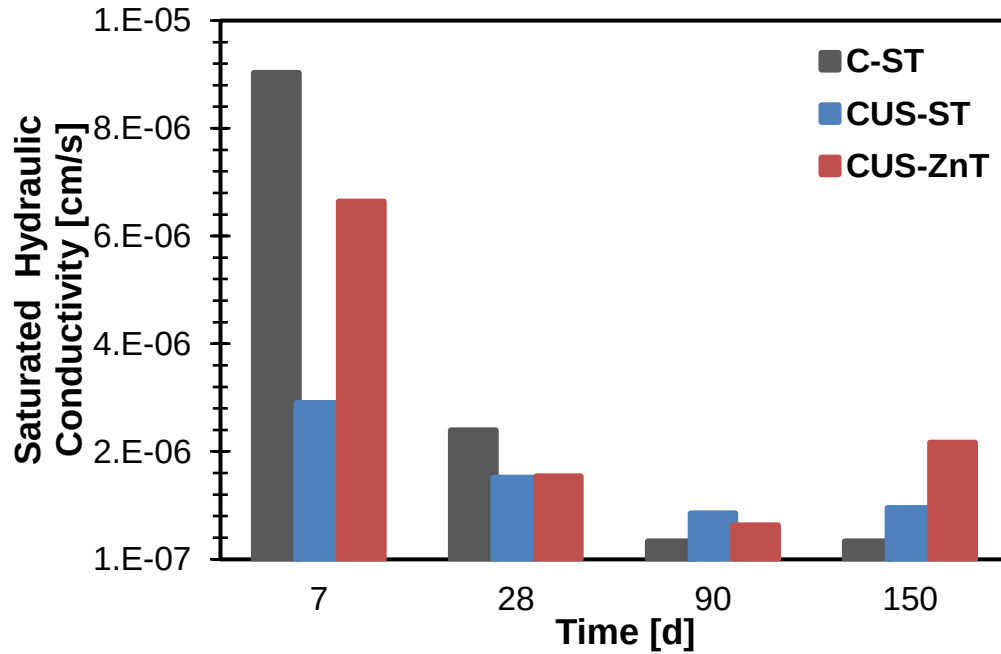


Figure 5.12. Long-term evolution of saturated hydraulic conductivity with curing time

#### 5.4. Summary and conclusion

In this chapter, the long-term evolution of the mechanical and hydraulic properties and behaviour of CPB samples cured under various stress conditions is investigated. Stress from self-weight during different curing times is simulated by means of a developed load cell with controlled loading rates in undrained conditions. The obtained results reveal that the application of pressure increases the mechanical properties (UCS and elastic modulus) of the CPB samples cured up to 28 days. This improvement in the mechanical properties is mostly related to the rearrangement of the tailings particles due to curing under stress, which results in the porosity reduction of the backfill samples. The mechanical properties of the samples cured under stress show lower values compared to the control samples at advanced ages of curing (at 90 and 150 days). Curing that is carried out under the constant application of high levels (excessive) of stress for a long period of time can lead to the generation and propagation of micro-cracks in the ITZ between the tailings particles and cement

hydration products as observed from the SEM images. These mechanical damage induced microcracks reduce the UCS and elastic modulus of the backfill at 90 and 150 days.

The obtained results demonstrate that the deformation and the failure pattern of the CPB sample at an early age of curing are different than those at advanced ages. These differences in the stress-strain behaviour and failure patterns are more related to the curing time, rather than the curing stress.

The curing stress also reduces the saturated hydraulic conductivity of the CPB samples cured up to 28 days. This is attributed to the reduction in the porosity due to the application of pressure, and therefore decreases in the hydraulic conductivity. The CPB samples at advanced ages (90 and 150 days); however, exhibit higher hydraulic conductivity compared to the control sample (curing under stress free condition). This behaviour is explained by the fact that excessive curing stress induces microcracking, which in turn, results in a preferential fluid path, thus increasing the hydraulic conductivity.

The experimental results show that the chemical and mineralogical compositions of mine tailings, as observed in the CPB samples prepared with ZnT, significantly influence the long-term hydro-mechanical performance of CPB. This is mainly due to the inhibition of hydration reactions at early ages of curing, which consequently alters the long-term behaviour of CPB, such as significantly low UCS and high fluid transportability. The delay in the development of suction (with prolonged delay in commencement) and temperature, and higher electrical conductivity of the CPB prepared with ZnT compared with the ST based CPB support this behaviour. Also, the reaction of the sulphate ions with the cement and hydration products produces expansive minerals, which in turn, cause strength deterioration. Reductions in the UCS and increases in hydraulic conductivity which are observed in the behaviour of the CPB samples prepared with ZnT at 150 days, are the consequence of this sulphate effect.

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## **Chapter 6: Implications for the geotechnical design of CPB structures**

### **6.1. Introduction**

An important objective of this research is to study and highlight the importance of coupled THMC processes in understanding of CPB behaviour. Furthermore, the findings can be employed to optimize the design of backfilling systems (including CPB fill and barricade) in an underground mine while safely maintaining optimal mining cycles. However, a backfill system design is not limited to that, as other parameters, such as the filling rate, rheology, mix design and required mechanical strength (static and dynamic), should be determined during the design stage. Therefore, the analysis and discussion of the geotechnical implications of the results presented in this thesis can help researchers and mine operators to understand some of the key design criteria, such as how the THMC properties of CPB evolve with time, how to use knowledge of these THMC interactions to design an optimal CPB structure, how to design and construct a safe barricade, and how to evaluate the CPB mechanical strength development (i.e., required for self-supporting and free-standing fills), and finally, how effective stress, pore pressure and suction evolve within the backfill. The implications of the obtained results for the geotechnical design of CPB structures will be discussed and summarized in this chapter.

### **6.2. Relevant coupled THMC processes in CPB**

The coupled processes that are mainly found in the geotechnical behaviour of cemented paste backfill (CPB) poured into mine stopes can be classified as thermal (T), hydraulic (H), mechanical (M) and chemical (T) processes or factors. These factors are related and have interactions. The magnitude of the effect of coupling in one direction may be different from that in the opposite direction. Therefore, coupled factors have either weak or strong interactions. Strong interactions control the geotechnical performance of backfill structures. The results obtained in this research enables the development and proposal of the THMC processes in CPB structures and the strong or weak interactions between these processes, as shown in Figure 6.1. The identification of strong and weak coupled processes in CPB is crucial for the cost-effective designing of CPB structures.

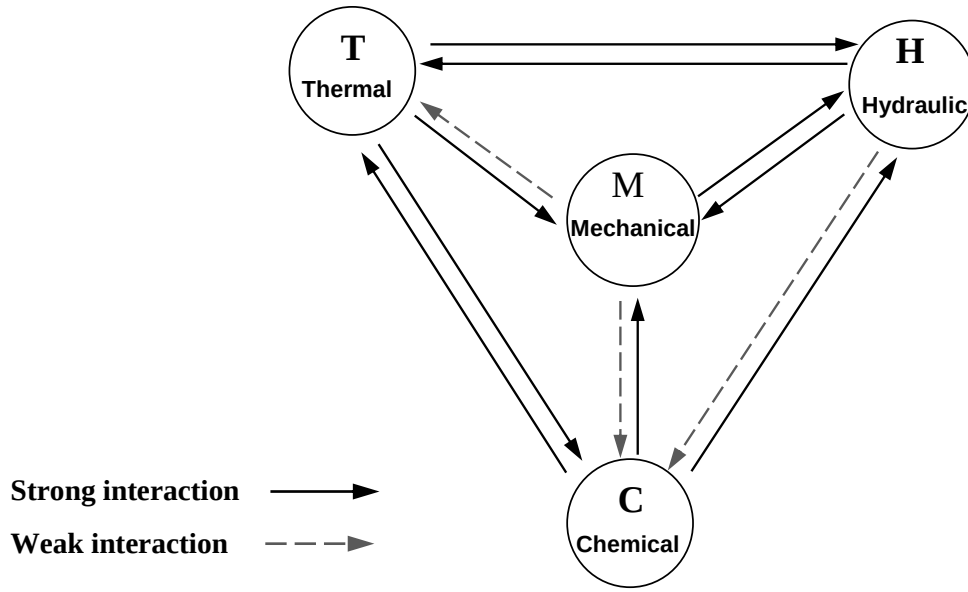


**Figure 6.1. Primary multiphysics processes in CPB material and their interactions**

The main THMC interactions are summarized below. It should be noted that although these are the most important interactions that can take place in a backfill structure, the interactions are not limited to them.

- $T \rightarrow H$ : The main source of temperature increase in mine backfill comes from binder hydration reactions as observed from the results of the temperature monitoring (see Figures 3.19; 4.16). Higher temperature induces faster rate of suction development and PWP reduction in mine backfill (Figures 3.13; 4.14). Also, temperature increase can lead to a decrease in the fluid transportability of the backfill by advancing the rate of binder hydration and pore refinement of the backfill (Figures 3.35; 4.21).

Also, weak interaction can be the effect of temperature increase on the decreasing of fluid viscosity or increasing of fluidity of the mine backfill. The viscosities of liquids tend to decrease with an increase in temperature. As a consequence, the backfill hydraulic conductivity tends to increase (Fredlund and Rahardjo, 1993). This effect is not investigated in this research.

- $T \rightarrow M$ : Temperature increase in mine backfill causes the reaction rate of the binder to increase (Figure 4.18), which in turn, leads to the production of more cement hydration products. More hydration products result in a finer and denser backfill pore structure (Figure 3.32), which consequently allows higher mechanical strength and shear strength properties in the backfill to develop (Figures 3.27; 4.21).

○  $T \rightarrow C$ : Temperature increase in mine backfill can induce a faster rate of binder hydration (Figures 3.35; 5.8). This is a strong coupling interaction that influences the pore water chemical concentration as well (Figure 3.31).

○  $H \rightarrow T$ : Hydraulic factors, such as the degree of saturation, directly influence thermal factors, such as the thermal conductivity of backfill. Reductions in the degree of saturation (or desaturation: increasing air voids in the CPB matrix) due to self-desiccation (Figure 4.11) and/or evaporation (Figure 3.16) reduce the thermal conductivity of backfill (Figure 3.18). Air has a lower thermal conductivity than water and thereby the thermal conductivity is reduced. This interaction is strong in a CPB system.

○  $H \rightarrow M$ : Suction development as a result of self-desiccation is one of the important hydraulic factors that can affect mechanical factors (Figure 3.24). Self-desiccation induces suction as a result of binder reactions and thereby results in the decrease of the PWP (Figure 3.13) and increase in the effective stress (strength increase).

Evaporation as a hydraulic factor also induces the development of surface shrinkage and associated microcracks (Figure 3.30). The presence of microcracks in turn reduces the mechanical strength of backfill by inducing preferential failure in planes of weakness in the backfill structure (Figure 3.20). This process is investigated in this study and can be considered as a weak interaction as long as the backfill remains in a saturated or near saturation condition, or the air-backfill interface cannot be identified in the mine stope.

○  $H \rightarrow C$ : Hydraulic factors, such as drainage, evaporation and self-desiccation, can indirectly influence pore fluid ion concentrations. Water removal from the backfill pore structure results in increases in ion concentration by reversing the dilution effect. This is a weak interaction and not studied in this research.

○  $M \rightarrow T$ : Not a significant interaction.

○  $M \rightarrow H$ : Consolidation is a strong coupled interaction found in any mine backfill (Figure 4.1). Backfill consolidates under self-weight pressure in drained conditions. During the consolidation process, the pore water expelled from the backfill pores lead to a reduction in the excess PWP. Reductions in the PWP, in turn, increase the effective stress in the backfill. An increase in the effective stress is similar to curing backfill under stress which results in significant improvements to the mechanical strength of backfill (Figures 4.6; 4.9). Consolidation also reduces the porosity of backfill, which in turn, results in reduction of the hydraulic conductivity (Figure 4.12).

Mechanical damage, such as stress, can induce microcracking. Crack propagation at a micro scale may be found in backfill cured under sustained stress (Figure 5.6). Connected microcracks act

as preferential liquid paths in the backfill which results in decreases in tortuosity, and increases in the hydraulic conductivity (Figure 5.12).

- $M \rightarrow C$ : Curing under stress induces a slightly faster rate of binder hydration reactions. However, due to the low stress encountered in practice with mine backfill compared to concrete structures, the effect of stress on the progress of the cement hydration in CPB is weak (Figure 5.5). This can be considered as a weak interaction in mine backfill.

- $C \rightarrow T$ : Binder hydration reactions are an exothermic reaction. Therefore, cement hydration produces heat and increases the temperature in mine backfill. This is one of the most important and strong interactions in backfill (Figure 5.7).

- $C \rightarrow H$ : Binder hydration reactions, as a chemical factor, directly influences the porosity of mine backfill. Cement reactions produce cement hydration products, such as calcium hydroxide (CH) and calcium silicate hydrates (CSH) (Figure 3.32) and therefore causes pore refinement in the backfill matrix (Figures 3.33; 3.4). Lower porosity results in lower water permeability in backfill (Figure 3.9). This is a strong reaction in mine backfill.

- $C \rightarrow M$ : As explained above, binder hydration reactions cause pore refinement. Lower porosity also increases the mechanical strength of backfill (Figure 3.22). Furthermore, the progress of binder hydration is associated with the production of cement hydration products (e.g., C-S-H, CH), which provide cohesive strength to the CPB. This is a strong interaction.

The aim of this research is to investigate the important THMC coupled processes in CPB material, mostly in terms of the intrinsic properties. However, other external factors can also induce and/or initiate a process/factor. A comprehensive list of the coupled THMC factors and the intrinsic and external factors that can affect them are tabulated in Table 6.1.

**Table 6.1. Coupled THMC factors that affect the behaviour of CPB structures**

| Coupled process |                                 | Source                                                                                          | Influential property/parameter*                                                    |                                                                                        |
|-----------------|---------------------------------|-------------------------------------------------------------------------------------------------|------------------------------------------------------------------------------------|----------------------------------------------------------------------------------------|
|                 |                                 |                                                                                                 | Intrinsic property                                                                 | External parameter                                                                     |
| Thermal (T)     | Intrinsic Thermal Property      | Thermal conductivity & Heat capacity                                                            | Tailings type & fineness; CPB porosity & degree of saturation                      | -                                                                                      |
|                 | External Thermal Loading        | Heat of binder hydration<br>Self-heating mechanism<br>Environment temperature (cold/hot mining) | Chemical reactions<br>Host rock mineralogy<br>-                                    | Stope size; Filling rate; Binder content & type<br><br>Geographic location; Mine depth |
| Hydraulic (H)   | Intrinsic Hydraulic Properties  | Hydraulic conductivity (saturated & unsaturated conditions)                                     | Porosity; intrinsic permeability; degree of saturation; water retention properties | Binder content & type; Tailings fineness                                               |
|                 |                                 | Suction                                                                                         | Self-desiccation, cement reaction rate                                             | Drainage                                                                               |
|                 |                                 | Pore pressure                                                                                   | Consolidation properties                                                           | Drainage                                                                               |
|                 |                                 | Evaporation                                                                                     | Ambient humidity & temperature                                                     | Geographic location; Mine depth; Exposed backfill                                      |
|                 | External Hydraulic Loading      | Ground water flow (after mine closure)                                                          | -                                                                                  |                                                                                        |
| Mechanical (H)  | Intrinsic Mechanical Properties | UCS; Shear strength; Deformation;                                                               | Porosity; Tailings fineness; Density of tailings                                   | -                                                                                      |
|                 |                                 | Consolidation                                                                                   | Hydraulic conductivity                                                             | Drainage; Filling rate                                                                 |
|                 |                                 | Shrinkage & cracks                                                                              | Evaporation                                                                        | Sustained stress                                                                       |
|                 | External Mechanical Loading     | Self-weight pressure                                                                            | Backfill density                                                                   | Drainage; Filling rate                                                                 |
|                 |                                 | Stress regime & Arching<br>Traffic loads                                                        | Consolidation properties<br>-                                                      | Stope geometry<br>Drainage condition<br>Stope design                                   |
| Chemical (C)    | Intrinsic Chemical Properties   | Pore fluid chemistry                                                                            | Chemical reactions                                                                 | Binder content; Binder type, Sulphate content                                          |
|                 |                                 | Electrical conductivity                                                                         | Cement reactions                                                                   | -                                                                                      |
|                 |                                 | Tailings & mixing water chemical composition                                                    | Tailings/water mineralogy & chemistry                                              | -                                                                                      |
|                 |                                 | Rate of chemical reactions                                                                      | Stress                                                                             | Binder content & Type; Temperature                                                     |
|                 | External Chemical Loading       | Sulphate effect<br>Tailings reactivity                                                          | Sulphate concentration<br>Tailings mineralogy & chemistry                          | Temperature<br>-                                                                       |

\* The table only shows the most important influencing factors; other minor factors may also have a role.

### 6.3. Mechanical stability of CPB structures

The mechanical stability of mine backfill is a key criterion in designing CPB structures. The mechanical stability and performance of mine backfill are typically assessed by an evaluation of the mechanical strength, such as the UCS and shear strength properties. Therefore, understanding the factors that can affect the mechanical strength of CPB, as well as implementing them into the assessment of backfill strength are highly important. This study has shown that different important THMC coupled processes and factors can influence the mechanical strength of backfill. These processes and factors are shown in Figure 6.2. This figure shows the necessity of the THMC-F factors that need to be considered in specimen curing in order to obtain a realistic UCS assessment. This technique can substitute for the use of a typical cylindrical moulded sample to cure backfill specimens for UCS assessment. Therefore, it can lead to a better assessment of mechanical strength and avoid conservative or unsafe design of CPB structures. Adopting such an approach can help to minimize the costs by reducing binder usage and/or cycle time, as well as improve productivity.

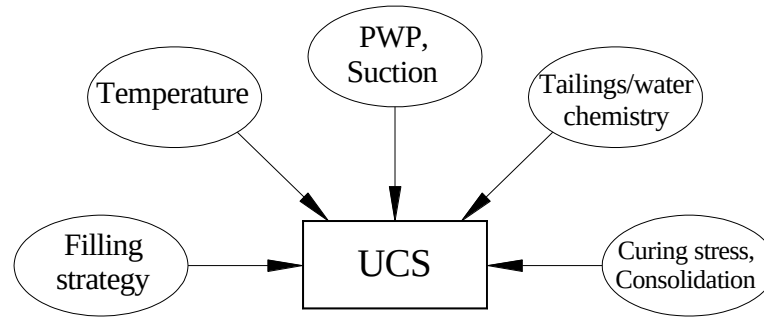


**Figure 6.2. Main coupled THMC-F factors that need to be considered in assessment of UCS in CPB.**

Temperature increases in mine backfill as a result of cement hydration reactions can increase the mechanical strength. In a typical CPB structure, the temperature increment increase usually varies between 10°C and 45°C depending on several factors, such as the binder type and content. This temperature increase should be included in UCS assessments by curing CPB samples in a controlled temperature chamber. The evolution of temperature with time similar to the studied mine backfill should be simulated and then a temperature gradient is applied onto the specimen during the curing period.

The effect of suction due to self-desiccation on mechanical strength needs to be considered during the early age strength assessment of backfill. This study has shown that the evolution of suction in backfill has a direct relationship with the evolution of strength. The contribution of suction to the mechanical and shear strengths is crucial during the early hours (and days) of curing.

The self-weight pressure of mine backfill has significant effects on mechanical behaviour as observed from the experimental results. Curing stress should be simulated in accordance with the actual filling rate and sequence, as well as the total stress obtained from the studied mine. Then, CPB samples should be subjected to curing stress during the curing period, in order to include the improvement of strength as a result of the curing stress in UCS assessments.

The mineralogy and chemistry of the tailings and water used in backfill preparation need to be carefully studied and measured prior to the UCS test. This study shows that the chemistry of the mine tailings, such as the presence of sulphate, as well as high ion concentrations inhibits binder hydration reactions and thereby reduce the mechanical strength. Therefore, the effect of chemicals needs to be included in short-term and long-term UCS measurements for more realistic assessments. Also, to foresee the chemical interactions on mechanical performance, sulphate can be artificially added to the CPB during preparation and simulated curing condition.

An analytical solution proposed by Mitchell et al. (1982) has been used to model a typical mine backfill. The purpose of this modeling is to understand how the safety factors ( $F.S.$ ) of a mine backfill can be affected by the accuracy of mechanical strength assessment. Figure 6.3 shows a vertical backfill with an exposed face and sliding mechanism. Equation (6.1) can be used to calculate the factor safety against sliding. In backfill designs, typical allowable FS are determined and then the required mechanical strength for stability (UCS or cohesion) is calculated.

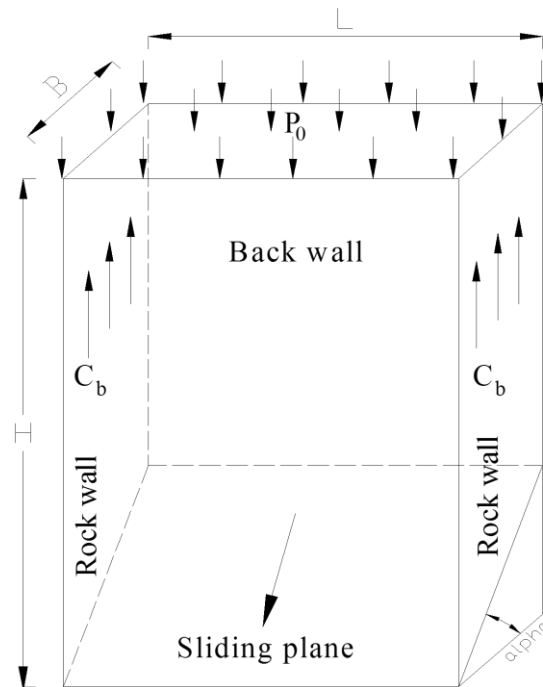


**Figure 6.3. Confined block with shear resistance mechanism (Mitchell et al., 1982)**

$$FS = \frac{\tan \varphi}{\tan \alpha} + \frac{2CL}{H^*(\gamma L - 2C_b) \sin 2\alpha} \quad (6.1)$$

where  $\varphi$  and  $C$  are the internal friction angle and cohesion of the backfill, respectively.  $\varphi = 39.5^\circ$  and the cohesion values are obtained from the direct shear test results conducted on CUS-ST and C-ST samples at 1, 3 and 7 days;  $\alpha$  is the angle between the sliding wedge and horizontal planes ( $\alpha = 45 + \frac{\varphi}{2}$ );  $H^* = H - (B \tan \alpha)/2$  is the equivalent height of the wedge block;  $H = \text{var.}$ ,  $B = 10 \text{ m}$ , and  $L = 18 \text{ m}$  are the backfill height, width, and length, respectively;  $\gamma = 21 \text{ kN/m}^3$  is the unit weight of the backfill; and  $C_b$  is the bound cohesion along the interface between the side walls and backfill, which is assumed equal to the backfill cohesion. Figure 6.4 provides the  $FS$  calculation for a typical backfill with strength properties obtained from control and cured under stress samples. It can be observed that a realistic assessment of the cohesion of backfill can lead to a higher factor of safety at different curing times. Therefore, avoiding such a conservative approach can reduce the required amount of binder and shorten the mining cycle time.

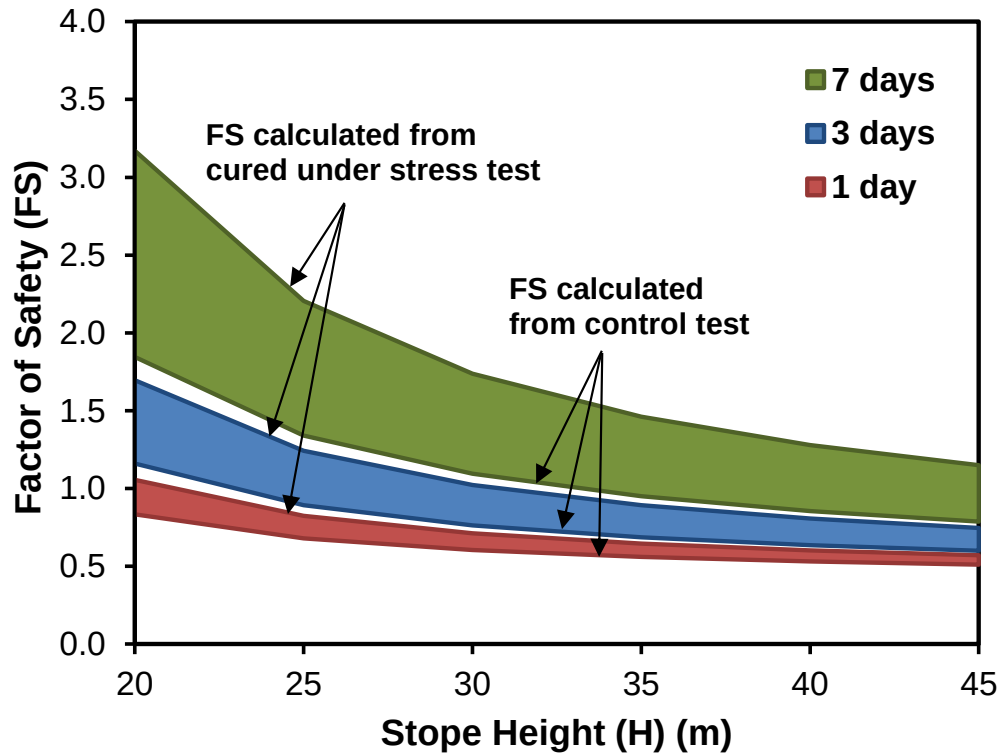


Figure 6.4. Example of factor of safety calculation for a typical backfill structure with strength properties obtained from control and cured under stress samples

## **6.4. Barricade stability**

Barricades are typically located at the bottom of mine stopes and the entrance of mine drifts. The stability of barricades is extremely important to ensure the safety of mine workers while working in the adjacent stopes, as well as the equipment. The stress applied on the barricade is directly related to the stress state (i.e., horizontal effective stress and PWP) in the backfill near the bottom of the stope. Therefore, information about the amount of stress applied is crucial to designing safe yet economical barricades. This study also shows that the stress in backfill is directly influenced by the evolution of temperature, PWP, suction and effective stress. After placement of CPB, the effective stress is almost nil and the PWP is equal to the total stress. The total stress is almost equal to the self-weight pressure in the early hours after pouring. Different factors need to be considered when assessing the stress state in backfill. Temperature increases in the backfill due to cement hydration reactions accelerate the development of suction or decrease the PWP acting on the barricades. Also, cement hydration reactions are affected by the filling rate and sequence, and binder content and type. A fast filling rate disturbs binder hydration reactions and therefore slows down binder reactions. Binder reactions, the permeability of the barricades, drainage, and consolidation behaviour of backfill control the evolution of PWP and stress applied on the barricade.

Furthermore, current experimental studies show that the chemistry of the tailings and mixing water directly influence the development of suction and PWP in backfill. Sulphide-rich mine tailings delay binder reactions and associated self-desiccation, which in turn, means that a slower reduction in PWP takes place in the backfill. Tailings/water chemistry, filling rate and sequence, and the effects of temperature and suction need to be considered in the assessment of pressure applied on the barricade. This information is site specific and should be investigated uniquely for each mine site.

## **6.5. Environmental performance**

The environmental performance of CPB structures is one of the most important design criteria. In particular, the susceptibility of backfill to Acid Mine Drainage (AMD) is an important issue that needs to be considered for their long-term performance. Fluid transportability (or permeability) of the hardened CPB directly influences the environmental performance of a mine backfill. The reactivity or oxidation in backfill takes place when water and oxygen enter the CPB matrix. They cause the oxidation of the sulphate minerals available in the tailings and consequently AMD generation. Significant findings have been obtained with regard to the hydraulic conductivity of CPB material. The results show that the physical properties and microstructure characteristics of backfill influence the evolution of hydraulic conductivity. There are coupled interactions between mechanical strength and hydraulic conductivity. CPB with higher strength deliver lower permeability. Also, curing stress

due to self-weight pressure affect the permeability behaviour of CPB. Curing stress causes porosity reduction or pore refinement which in turn, benefits the permeability of backfill.

The tailings chemistry, especially with the presence of sulphate in sulphate-rich mine tailings, inhibits cement hydration reactions and therefore fewer cement hydration products fill the pore structure. This in turn may result in the formation of CPB with a coarser pore structure (or porosity) and higher permeability. In addition, the experimental investigations show that CPB, when in contact with air, can experience surface shrinkage and possible formation of surface microcracks. The combined effects of sulphate attack and microcracks can result in significant long-term structural degradation of backfill, which in turn, will affect its environmental performance. The performance of CPB structures, especially with regard to the long-term behaviour of backfill after mine closure, needs to be investigated in order to ensure that the backfill has an acceptable performance level against AMD.

## **6.6. Mining cycles**

The cycle time in mining operations is an important factor that influences the cost of the entire mining operation. Adopting measures that can help to shorten the cycle time will result in significant cost savings and increased revenues. CPB with higher early age mechanical strength reduces the mining waiting time, as well as speeding up the cycle time. Therefore, realistic information on the evolution of strength in the backfill particularly during the early hours (and days) of curing helps mine operators to develop optimal mine cycles for opening barricades and proceed with mining sequences. There would be a significant reduction in the operation costs and cycle time if continuous pour is used in mining instead of a stage pour procedure and/or a faster filling rate. These techniques may lead to shorter cycle times, but at the same time, increase the risk of backfill and barricade failure. In order to optimize both the cycle time and factor of safety against failure, the key is to determine the real-time evolution of the mechanical strength in the CPB. The current study reveals that mechanical strength at the early ages can be thoroughly assessed if there is information on when the backfill transforms from a fresh paste (hydrostatic condition) to a hardened state (non-hydrostatic condition). This transition is usually called the setting time in other unloaded cementitious materials. This is a complex process and unique for each mine stope, because several factors control the process. Current studies show that aside from external factors, such as the geometry of the stope, some other intrinsic factors and processes also have a significant role. CPB experiences incremental self-weight pressure as well as THMC loadings right after placement in a mine stope. THMC investigations have proven that the concurrent real-time coupled interactions of temperature, suction, settlement (or volume changes), consolidation and changes in the pore fluid chemistry control the

time for the transition. For example, as demonstrated in this study, tailings with a high sulphate content and other chemicals have a significantly longer waiting time for the transition due to hydrostatic conditions. This is mainly due to cement hydration retardation because of the presence of chemicals. Also, other factors significantly control this transition time. According to the findings, fast filling rates incur higher PWP and lower suction in backfill. Backfill with higher PWP tends to incur a longer waiting time for the transition to take place, which in turn, results in longer mine cycles. Therefore, information on real-time suction, PWP and evolution of stress helps mine operators to develop optimum cycle times while maintaining the safety of the barricades and stability of the backfill.

### **6.7. Binder consumption**

The cost of backfilling in underground mining typically varies between 10% and 20% of the total mine operating costs. Also, the cost of the binder used in CPB preparation can typically reach up to 75% of the backfilling costs (Grice, 1998). Therefore, optimization of binder consumption can lead to considerable cost savings in mining operational costs. Information about the PWP and the evolution of stress, as well as the effect of THMC loading on mechanical behaviour can lead to the design of a CPB with reduced binder consumption. In the current study, the consolidation behaviour of backfill, especially if drainage in backfill takes place and an optimal filling rate is used, is shown to result in significant mechanical strength improvement of the backfill. Therefore, if this is taken into consideration during the backfill design, the required binder content in the CPB mix can be optimized to reduce the cost of backfill preparation.

### **6.8. References**

- Fredlund, D.G. and Rahardjo, H., 1993. Soil mechanics for unsaturated soils. John-Wiley & Sons Inc., New York.
- Grice, A.G., 1998. Underground mining with backfill, The 2<sup>nd</sup> Annual Summit—Mine Tailings Disposal Systems, 24–25, November 1998, Brisbane, Australia, 14 pp.
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## Chapter 7: General Conclusions and Recommendations

### 7.1. Conclusions

The main goal of this research was to experimentally investigate the coupled THMC processes and factors in CPB materials. In Phase One of this study, experiments carried out with developed high columns were used to investigate coupled THMC interactions, as well as the effects of surface evaporation and microcracks on CPB performance. In Phase Two, a novel THMC pressure cell apparatus was developed and utilized to study coupled THMC processes at early and advanced ages while investigating the effects of curing under stress (or self-weight loads), loading rate (or filling rate), filling sequence (or filling by stages), tailings type (or tailings characteristics and chemistry) and drainage conditions on CPB behaviour.

- i) The main outcomes of the high column experiments are summarized below:
  - The physical index properties of CPB, such as void ratio (porosity), water content and degree of saturation, are highly variable with time and height of the columns.
  - The filling sequence influences the hydraulic conductivity and evolution of suction. Drainage of water from the upper to the lower part of the column, as well as increase in total stress due to filling stages influence the pore pressure and suction development.
  - Surface evaporation can alter the hydro-mechanical and physical properties of CPB. Drying shrinkage as a result of evaporation causes development of microcracks on the top surface of the columns. This can lead to an increase in fluid transferability and strength loss of the backfill material at advanced ages.
  - The heat from cement hydration (and also the curing temperature) accelerates the rate of cement hydration reactions and hence leads to faster strength gain.
  - The compressive strength and modulus of elasticity are highly variable with time and column height. The results show a strong correlation between the UCS and void ratio, as well as UCS and saturated hydraulic conductivity.
  - The internal friction angle in backfill material is not a time dependent parameter, while cohesion considerably varies with curing time, mainly due to the strong bonding of the tailings particles due to the cement hydration process.
  - The analysis on the pore water chemistry shows the mechanism of the hardening process in CPB material. Furthermore, the rate of the stiffness and strength increase as well as suction development in the backfill material is related to the rate of the depletion of the major ions from the pore solution.

- The porosity and degree of saturation are two parameters that control the evolution of the thermal conductivity in backfill material. An equation has been proposed to predict the thermal conductivity of backfill with respect to curing time.

- The column experiments show that the THMC properties of CPB are strongly related in different ways. The monitoring of the settlement, PWP, temperature and ion concentration which represent the self-weight pressure, self-desiccation, heat of hydration and cement-water reaction respectively, support these interactions.

ii) The major conclusions related to the pressure cell experiments are outlined below:

- The developed pressure cell apparatus can be used to monitor the THMC processes in CPB samples, by simulating the curing stress experienced during and after placement into a mine stope. This will help mine design engineers and mine operators to accurately predict and understand the backfill behaviour prior to placement into mine stopes.

- The mechanical properties of backfill are considerably influenced by the application of stress and curing time. The working mechanisms are the UCS-void ratio relationship, suction development due to self-desiccation and curing stress specifically in the early hours after placement. In addition, strong H-M coupled processes significantly influence the backfill behaviour, which include coupled relationships between self-desiccation and pressure application (consolidation).

- The monitoring of the settlement shows that CPB undergoes large volume changes after placement and prior to setting, due to the coupled effects of tailings rearrangement induced by the application of pressure, as well as shrinkage due to chemicals (self-desiccation induced consolidation) and heat.

- The temperature of the cement hydration accelerates the cement hydration rate, which leads to faster strength development. It increases the rate of suction development and reduces the setting time.

- Not a significant coupled M-C behaviour is observed in the experiments, which means that curing stress does not significantly influence the rate of cement hydration reaction in CPB systems (weak coupling).

- The THMC experiments carried out on natural tailings with significant chemical impurities (e.g., sulphides) reveal that the chemical and mineralogical properties of the tailings and the pore water chemistry significantly alter the H-M performance, binder hydration and setting time of the CPB.

- Cement hydration, self-desiccation, heat development and curing stress can be considered as important internal mechanisms that affect the THMC behaviour of backfill structures in the short-term.

- The physical properties of backfill, such as the void ratio (porosity), water content and bulk density, evolve with curing time. The application of pressure refines the pore structure and reduces the porosity. The evolution of these properties can influence the hydro-mechanical properties of CPB.

- The following factors contribute to the strength of CPB: (1) cementation, which produces bonding between the tailings particles and cement hydration products; (2) suction due to self-desiccation, which produces apparent cohesion; (3) curing stress due to self-weight pressure, which causes increased packing density through rearrangements of the tailings particles (undrained behaviour); (4) curing stress, which expels water from the pores and therefore consolidation takes place (drained behaviour); and (5) temperature increase as a result of hydration reaction, which causes the formation of more hydration products and a denser pore structure, which in turn, forms a more durable CPB with higher strength.

- Drainage in CPB samples takes place quickly after placement into the apparatus. Drained samples cured with and without stress exhibits higher mechanical strength compared to undrained sample cured under stress. This behaviour emphasises the importance of drainage in strength acquisition of CPB materials.

- There are two extreme curing conditions: drained and slow filling rate versus undrained and fast filling rate. Earlier one results in higher UCS and modulus of elasticity along with less plastic behaviour, while the later one shows opposite behaviour.

- Long term THMC study of CPB behaviour reveals that mechanical and hydraulic conductivity properties are improved by stress application, mainly due to the tailings particle rearrangement (higher packing density). However, at advanced ages of curing (at 90 and 150 days) no improvement was observed with respect to the control sample. This is due to the curing stress induced microcracks, which resulted in UCS reduction and permeability increases.

## **7.2. Recommendations for future work**

While significant advancements in the understanding of THMC performance of mine backfill have been made in this thesis, there are still some areas that need further research. The following is a summary of the research recommendations that are related to CPB.

- Cell pressure experiments can be performed with simulated evolution of temperature in CPB samples. Typical temperature increases with time are applied to the samples, while different THMC behaviours at the early ages (up to 7 days) are investigated. Different in-situ monitoring and

numerical data are available in the literature to establish a typical evolution of temperature with time for simulation purposes.

- Cell pressure experiments can be performed with different cement contents (e.g., 3%, 4.5% and 7%) and cement types (e.g., ordinary Portland cement, fly ash and cement, slag and cement, etc.) to understand the effects of cement content and type on the THMC performance of backfill.

- The cell pressure experiments in this research are performed in undrained conditions with few tests in drained condition. The same experimental program (testing and monitoring) can be conducted in drained conditions. Backfill in reality behaves between fully drained and fully undrained conditions based on its physical properties and drainage conditions of the mine stope. Some preliminary work has been done in this research to study the effects of drainage on the UCS, shear strength properties and suction up to 7 days. However, more work is needed to address the effect of drainage on the THMC properties of CPB and long-term curing time.

- Natural tailings, such sulfide-rich tailings, can be used in column experiments. This is to understand the effect of the chemical characteristics and mineralogy of the tailings on the THMC performance of CPB.

- The development of a theoretical relationship between THMC processes is still necessary to more accurately predict the behaviour of CPB.

- A numerical THMC model can be developed to provide a better understanding of coupled THMC processes. Then, the model can be inputted into a geotechnical open source finite element software program to model mine stopes with actual size and geometry.

- Unsaturated behaviour, including self-desiccation induced desaturation and water retention capacity (i.e., SWCC) of CPB can be investigated. CPB samples sealed in a curing chamber can be cured in different temperatures (e.g., 5°C, 15°C, 35°C and 55°C). Then, the unsaturated properties (suction, moisture, index properties) are monitored and measured while the early age strength, such as UCS is measured too. The finding will help to establish the effect of suction as a result of self-desiccation on the mechanical strength improvement of CPB. An analytical solution can be developed to predict the unsaturated behaviour of CPB.

## **APPENDIX A**

### **TEST SET-UP AND EQUIPMENT USED IN THE RESEARCH**



**Figure A-1. Tailings and cement used in experiments**



**Figure A-2. (Right) Food mixer for preparing small volume batches of CPB used in pressure cell experiments; and (Left) Concrete mixer for preparing large volume batches of CPB used in column experiments.**

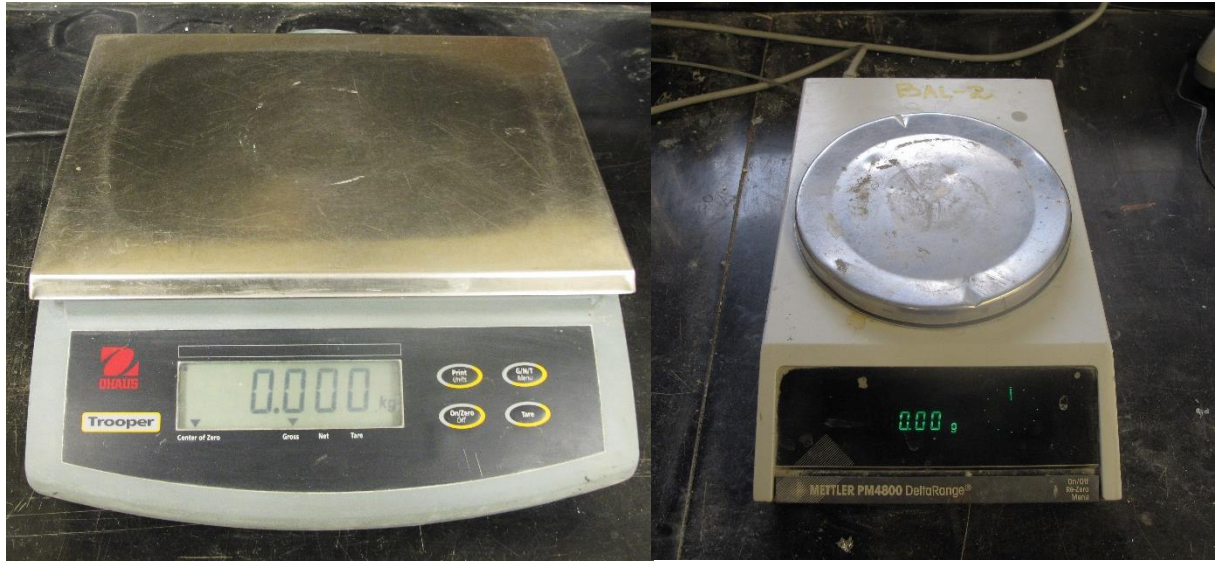


**Figure A-3. Trooper Ohaus TR15RS (15 kg×5g) balance (left) and Mettler PM4800 (4100×0.01g) used in experiments**

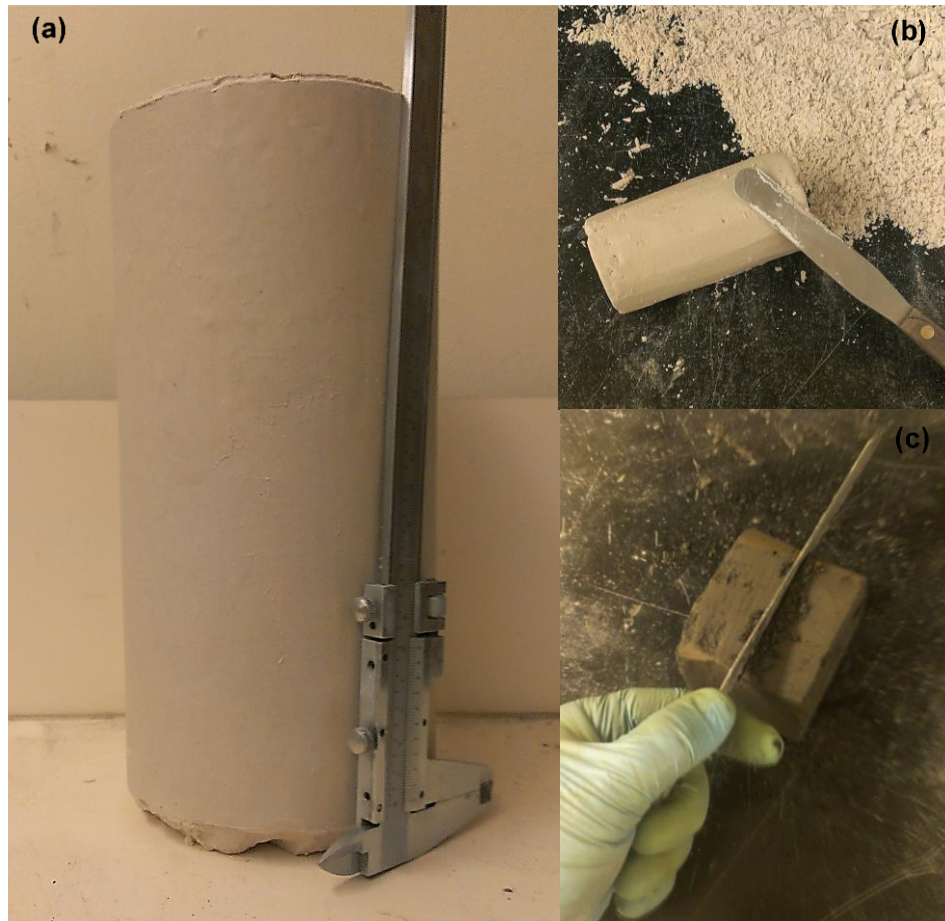


**Figure A-4. (a) Extracted CPB sample from load cell (10×20 cm); (b) Sample trimmed to size for UCS test (5×10 cm); (c) Sample trimmed to size for direct shear test (5×5× 2.5 cm)**

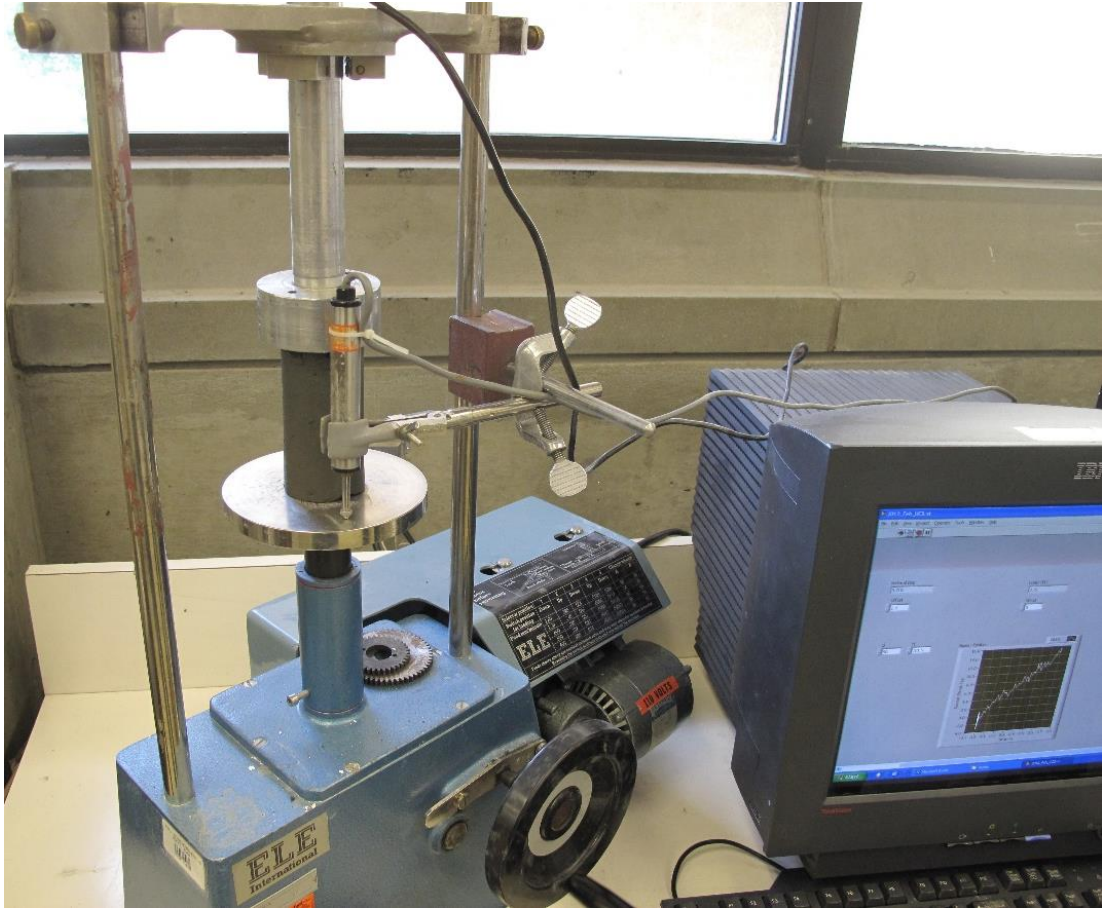


**Figure A-5. Unconfined compressive strength (UCS) machine used to determine  $q_u$  of samples**



**Figure A-6. Direct Shear test machine used to determine shear strength properties of CPB samples**



**Figure A-7. ELE hydraulic conductivity apparatus used to measure saturated hydraulic conductivity of CPB samples**



**Figure A-8. Performing UCS test on CPB sample prepared with zinc tailings**



**Figure A-9.** After performing direct shear test on the cured under stress sample (Silica tailings, 0.31m/h, undrained and 150 days).

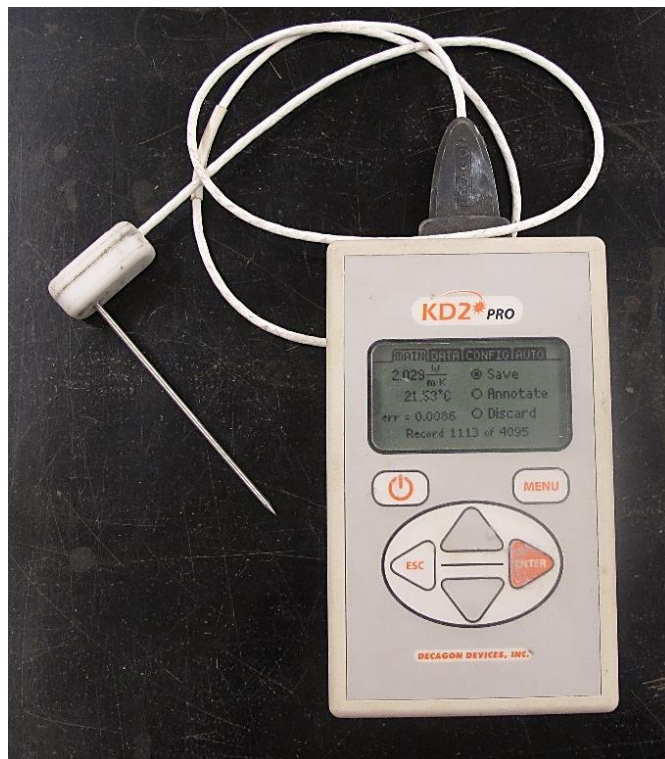


**Figure A-10.** KD2 thermal conductivity probe used to determine thermal conductivity of samples.

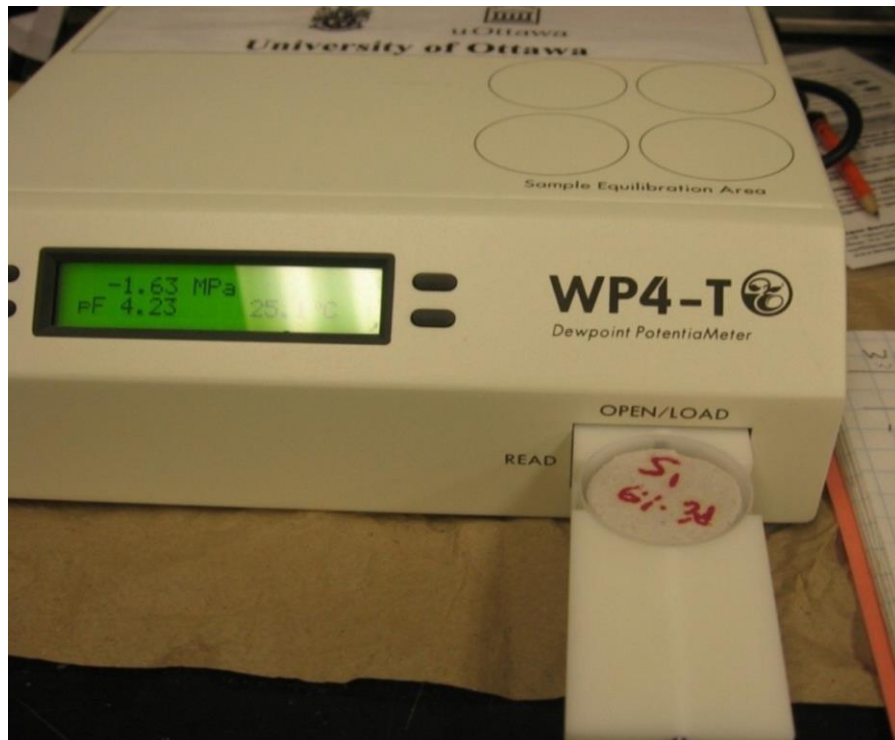


Figure A-11. WP4-T dewpoint potentiometer used to construct WCC of samples

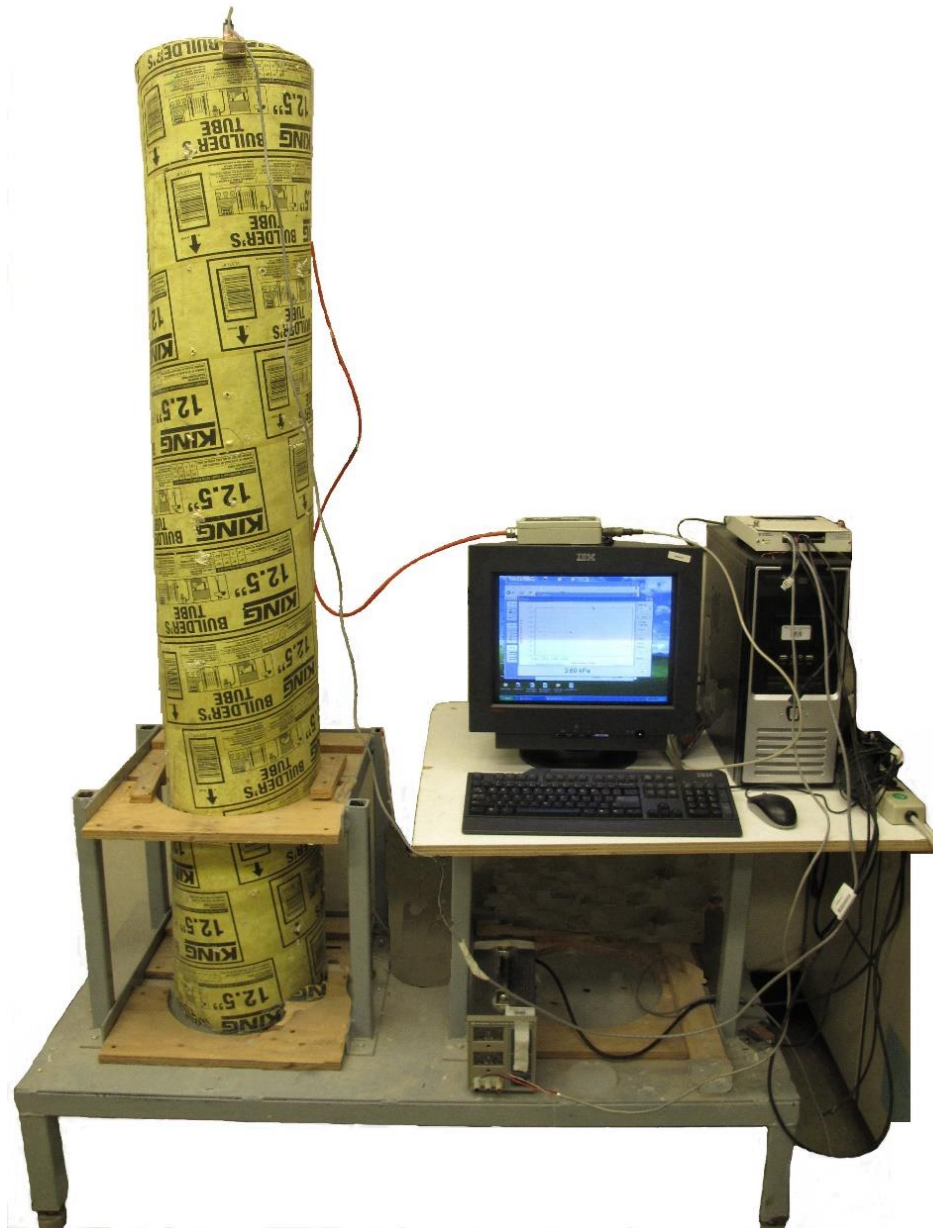


**Figure A-12. Developed column experiment set-up and instrumentations used in monitoring**

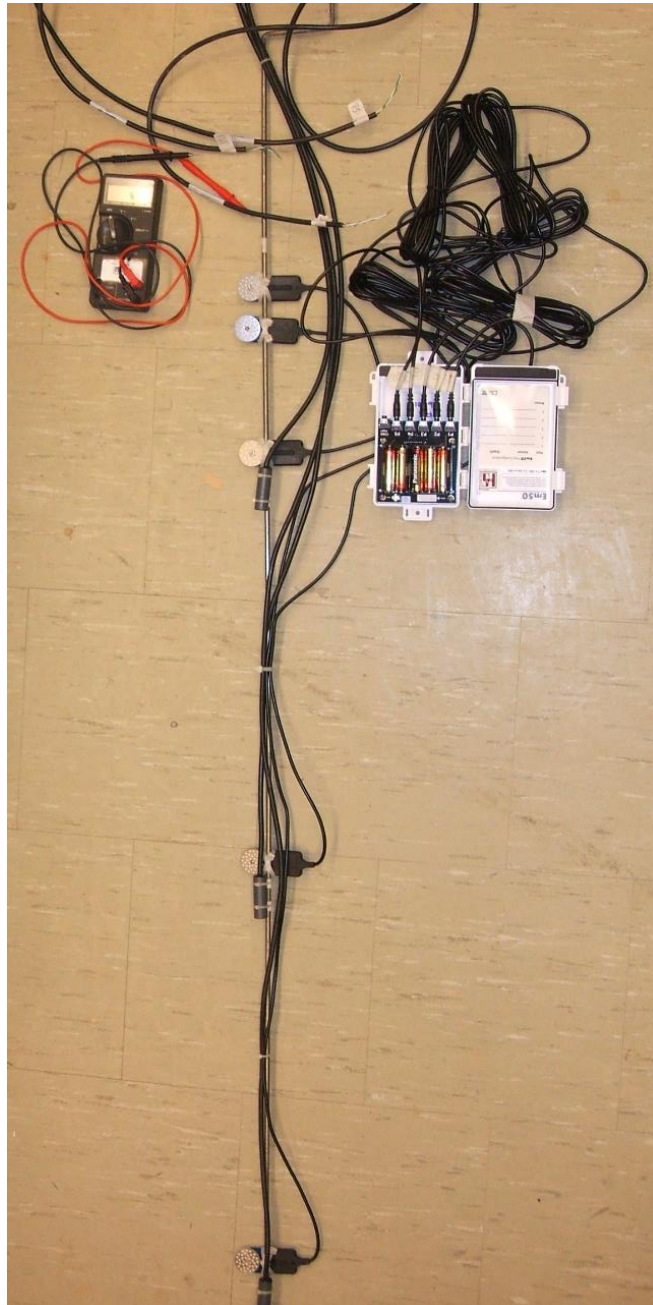


**Figure A-13. Different instrumentation used in high column experiments (suction meters and temperature sensors arrangements)**



**Figure A-14. Temperature sensor (model: TH-T, Roctest) and suction meter (model: MPS-1, Decagon) used in column experiment**



**Figure A-15. Standard vibrating wire piezometer model WP2100, RST, 70 kPa capacity used in high column experiments**

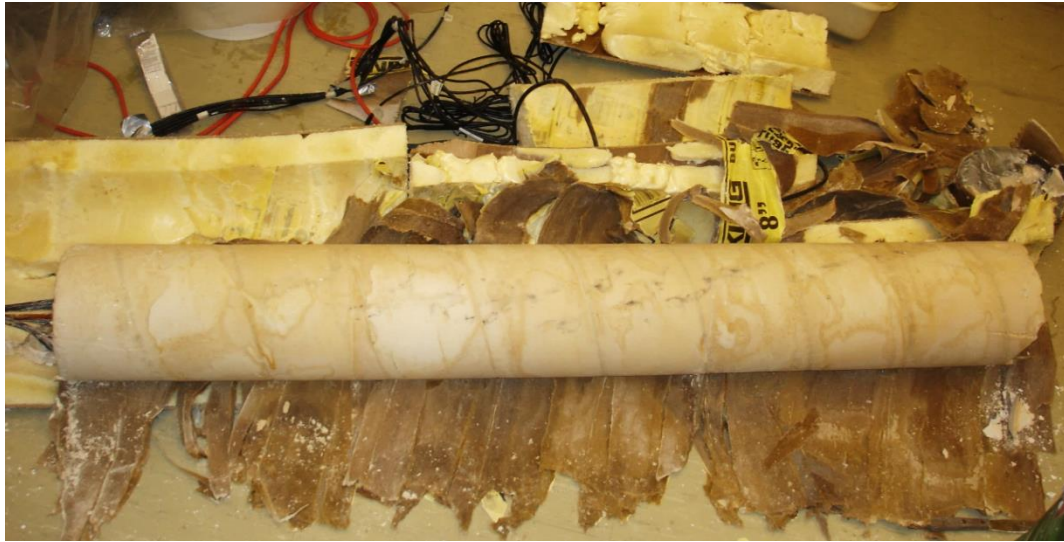


**Figure A-16. CPB removed from column after 150 days curing.**



**Figure A-17. Curing under stress load cell used in monitoring programs**

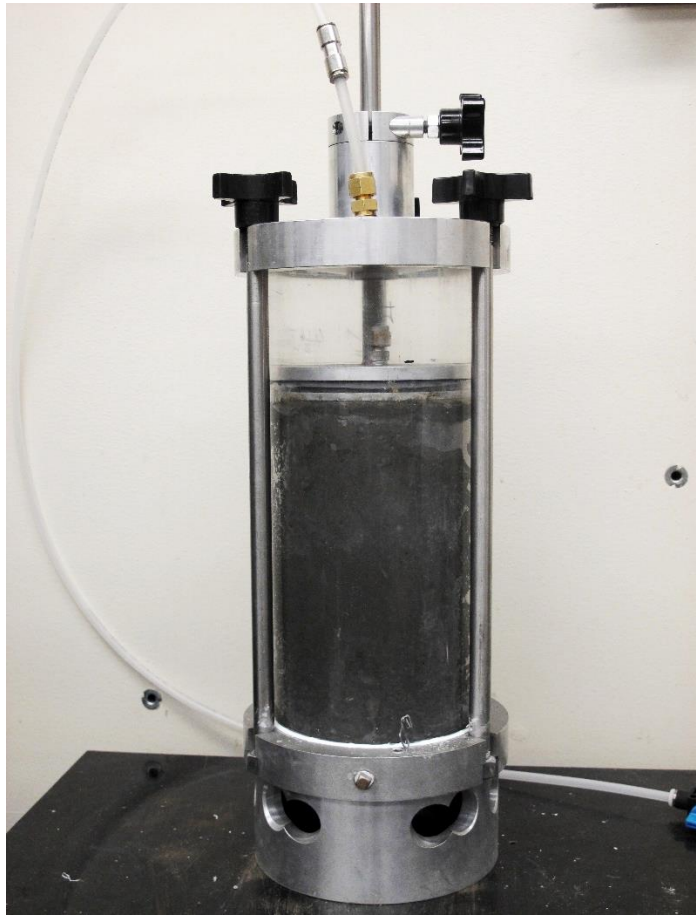


**Figure A-18. Curing under stress load cell used for curing samples**



**Figure A-19. Regulator (600 kPa), pressure gauge and valve used for pressure control and load application in load cell experiments**

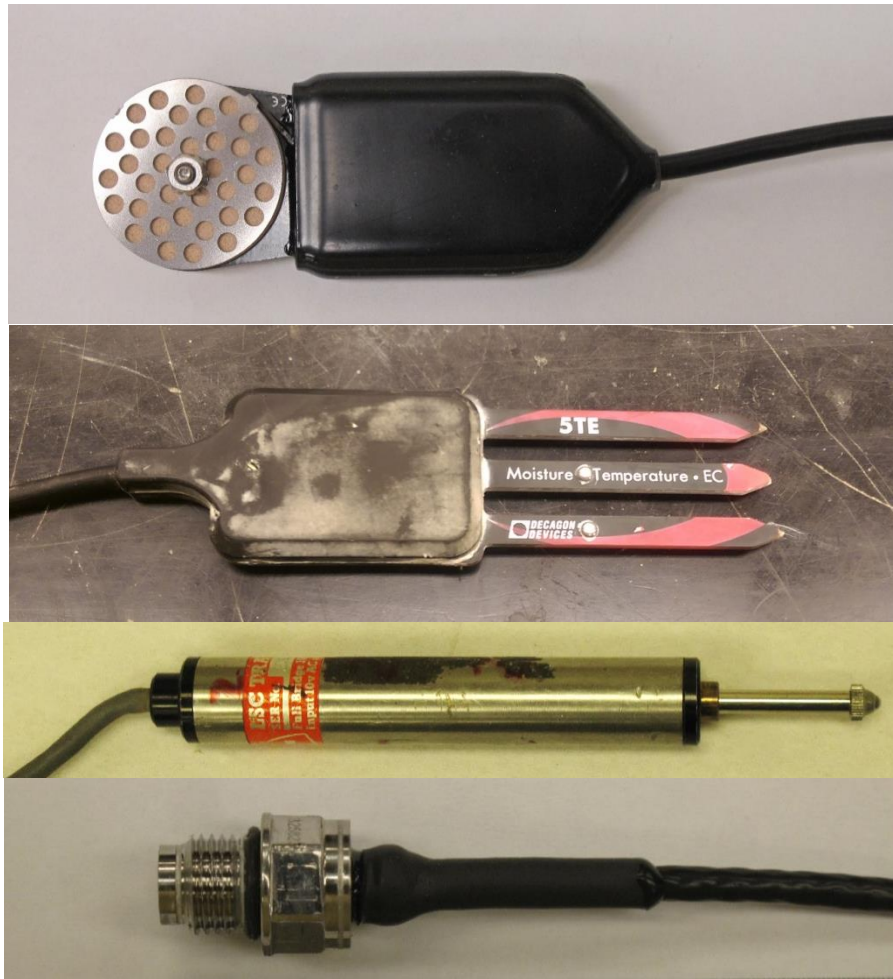


**Figure A-20. From top to bottom: Decagon MPS-2 water potential (or suction meter); Decagon 5TE (temperature, moisture and electrical conductivity) sensors; LVD; and Pressure transducer (1 MPa) used in load cell experiments**

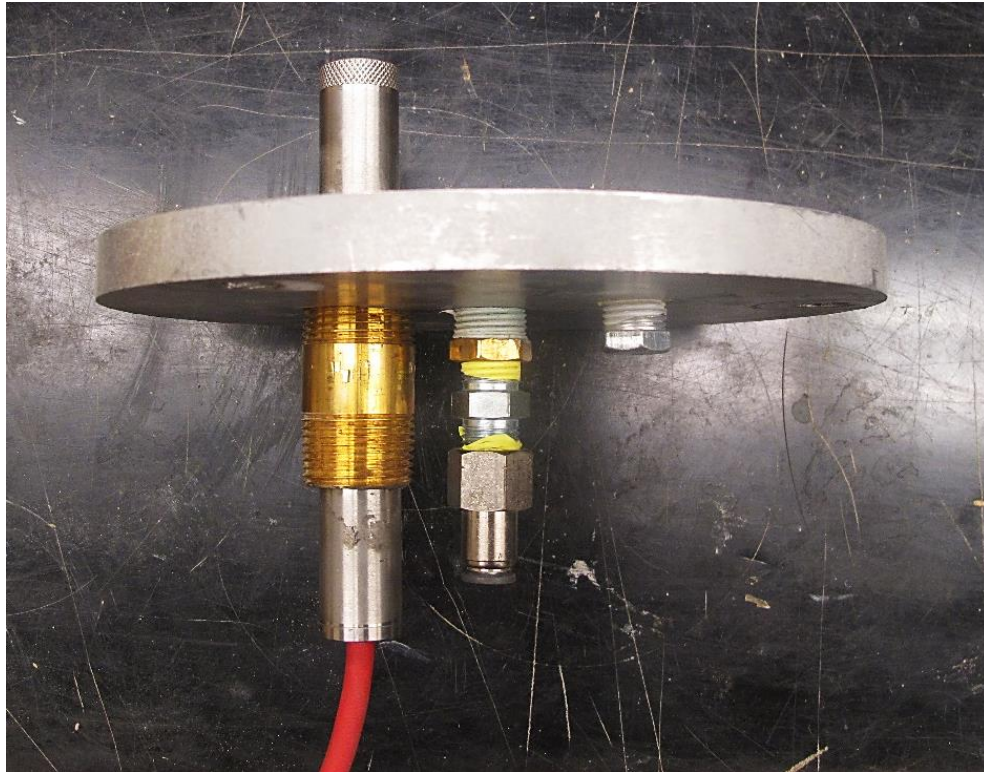


Figure A-20. Standard vibrating wire piezometer model RST VW2100 with 1 MPa capacity used in pressure cell experiments

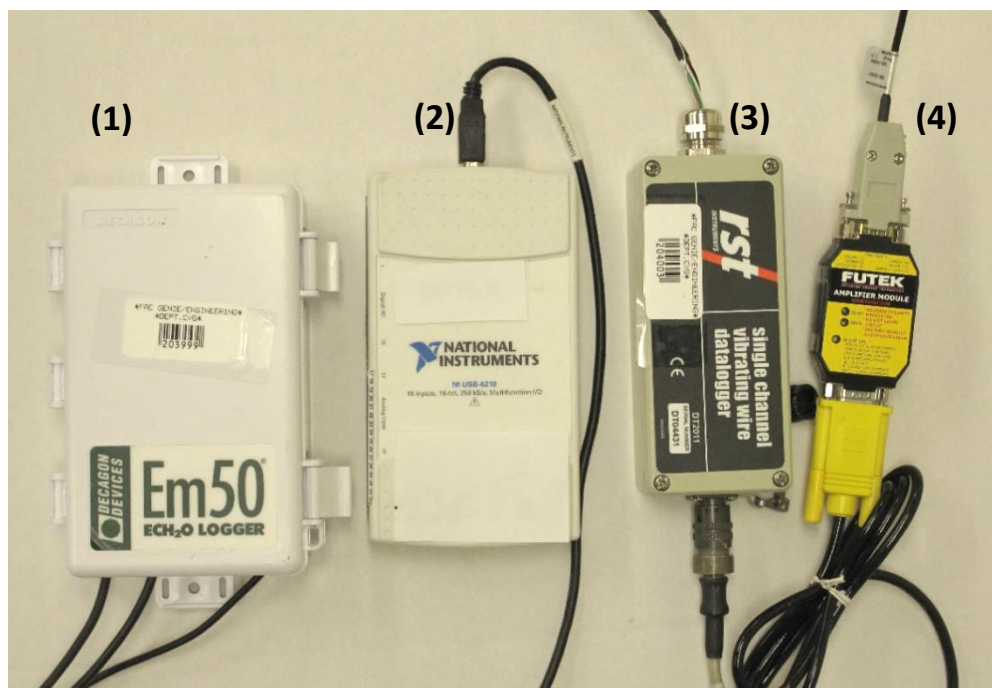


Figure A-21. Different data loggers connected to the sensors: (1) MPS-2 & 5TE; (2) LVDT; (3) Vibrating wire piezometer VW2100 & WP2100; (4) Pressure transducer.



**Figure A-22. CPB pore water squeezer designed and manufactured at the University of Ottawa (top); and squeezer apparatus under hydraulic pressure jack during the pore water extraction (bottom)**

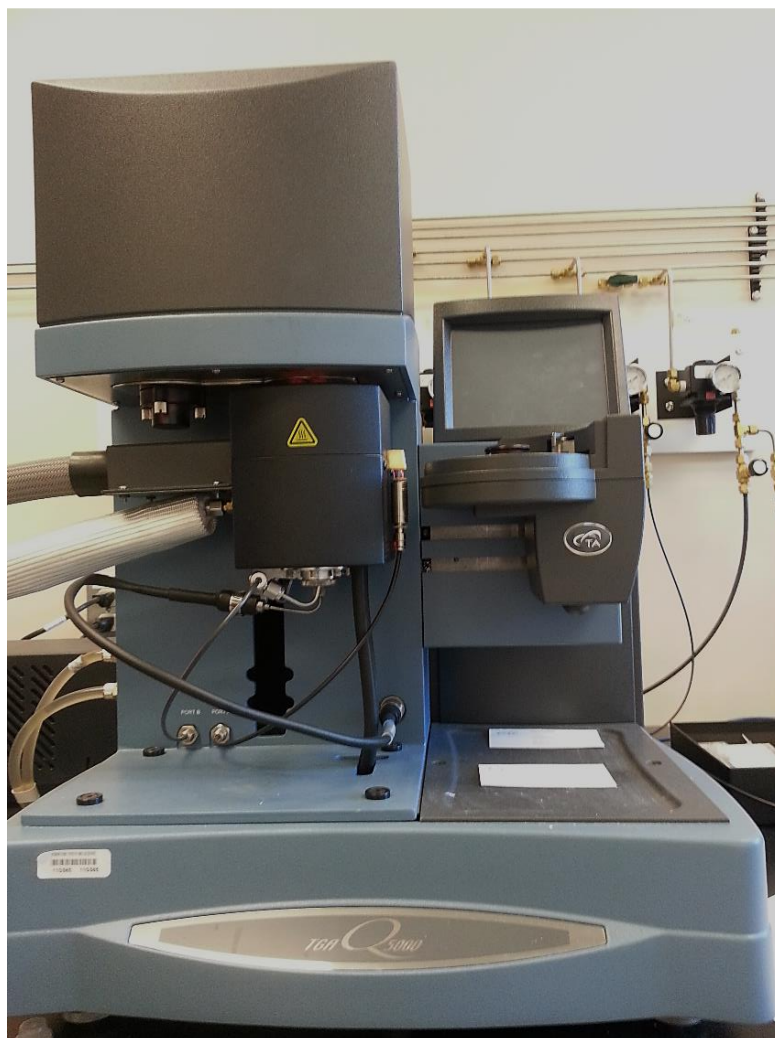


**Figure A-23. Thermogravimetric analysis (TGA) equipment (Q 5000 IR instrument) used to perform thermal analysis on samples**



**Figure A-24. SEM equipment (Hitachi S4800) at National Research Council of Canada (NRC) used to perform SEM analysis on samples in column experiments**

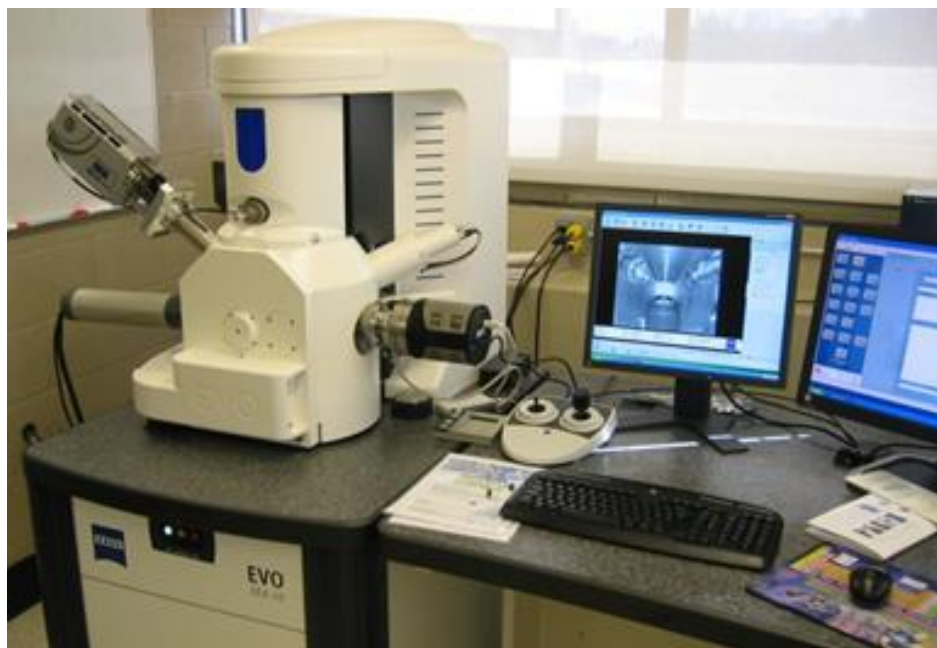


**Figure A-25. SEM equipment (EVO-MA10 from Zeiss, Germany) at the mechanical department of University of Ottawa used to perform SEM analysis on samples in load cell experiments**



**Figure A-26. PMI Mercury/Nonmercury Intrusion Porosimeter instrument used to determine pore size distribution, total pore volume and surface area of the samples**