

Multiphysics investigation of the geotechnical behaviour of cemented paste backfill with superplasticizer

Zubaida Al-Moselly

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Dr. Mamadou Fall

Department of Civil Engineering
Faculty of Engineering
University of Ottawa

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Abstract

The cemented paste backfill (CPB) method finds extensive application in the mining industry as an effective technique to manage mining wastes (tailings) and support underground mine excavations. In this technique, substantial quantities of tailings are repurposed and transformed into a cemented construction material suitable to manage mine wastes, provide structural stability, and diminish the environmental issues associated with the disposal of such waste on the ground surface. CPB comprises of a blend of tailings, a binding agent, water, and, when necessary, additional additives. CPB is usually prepared at a mixing facility (plant) and subsequently, transported into underground mine voids or stopes through pipelines, either via gravity or with the assistance of pumps. To improve the flowability of the freshly mixed CPB through the pipeline system and to prevent the occurrence of pipe blockages, which could lead to unwarranted delays and decreased productivity, high range water-reducing admixtures, commonly referred to as superplasticizers, are often added to the CPB mixture during the mixing process. Once the CPB is transported into the stope as well as throughout its functional service, the CPB structure is subjected to various internal and external factors that affect its engineering behaviour or properties, including thermal (T), hydraulic (H), mechanical (M), and chemical (C) coupled processes. Therefore, multiphysics curing and laboratory testing procedures were conducted to assess the critical engineering design properties (mechanical strength and pore water pressure development) of CPB materials with superplasticizer under several mix components (tailings, dosages of superplasticizer, water chemistry) and various, individually or coupled, THMC field loading conditions close to those encountered in the field using a THMC pressure cell apparatus, specifically modified for the objectives of this study.

Several monitoring tests were implemented in this study to comprehensively understand the mechanisms responsible for the observed geotechnical behaviour, such as electrical conductivity, volumetric water content (VWC), suction, and pore water pressure, which were monitored for various curing times using different sensors. Microstructural analyses such as thermal gravity (TG), differential thermal gravity (DTG), X-ray diffraction (XRD), scanning electron microscopy (SEM) observation, and mercury intrusion porosimetry (MIP) tests were conducted on the CPB with polycarboxylate ether-based superplasticizers specimens to provide a rational elucidation regarding the impact of the field THMC factors and their coupling effects. Moreover, the pore structure (e.g., void ratio, porosity, density) of CPB mixtures was examined to assess the impact of the THMC field curing conditions on the CPB structure.

The obtained results reveal that the mechanical strength and overall performance of the CPB structure with polycarboxylate ether-based superplasticizers are greatly affected by the THMC factors and their interactions. An accounting for field THMC factors and their coupling effect on the strength development, rate of change of positive pore water pressure and suction within the CPB is vital for the optimal design of safer and more economical CPB structures.

Dedication

To my children and my mother

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List of symbols and abbreviations

γ : Unit weight
 σ_v : Vertical Stress
C: Chemical
CPB: Cemented Paste Backfill
CT: Coarse tailings
CUS: Curing Under Stress
DTG: Differential Thermal Gravity
DW: Distilled Water
EC: Electrical Conductivity
FT: Fine Tailings
g: Ground Acceleration (9.81 m/ sec²)
Gs: Specific Gravity
GT: Gold Tailings
H HOURS
h: height
H: Hydraulic
LVDT: Linear Variable Differential Transformer
M: Mechanical
MIP: Mercury Intrusion Porosimetry
MT: Medium Tailings
PCI: Portland Cement type I
PES: Polycarboxylate Ether-based Superplasticizers
PWP: positive Pore Water Pressure
SEM: Scanning Electron Microscopy (SEM) Observation,
SMF: Sulphonated melamine formaldehyde
SNF: Sulphonated naphthalene formaldehyde
ST: Silica Tailings
T: Thermal
TG: Thermal Gravity
TW: Tap Water
UCS: Unconfined Compressive Strength
VMC: Volumetric Water Content
VOC: Volatile Organic Chemical, VOC
W/C: Water to Cement
wt.: Weight
X-Ray: Diffraction
XRD: X-Ray Diffraction (XRD)

Chapter 1: Introduction

1.1 Background

Underground mining is essential for extracting valuable resources from the earth's crust in many countries worldwide. Blasting, crushing, milling ore rocks, and metal extraction make underground mining operations the main activities that generate substantial amounts of mine wastes (tailings), waste rocks, and water treatment sludge (Lottermoser 2010). The disposal of the aforementioned wastes on the ground surface can create serious geotechnical and environmental issues, such as tailings dam failure, heavy metal leaching, and acid mine drainage (AMD), which is very toxic to aquatic life and thus has an adverse impact on human health (Yilmaz et al. 2003). In addition, the formation of large underground voids (stopes) by ore extraction can cause severe geotechnical hazards, such as ground subsidence and regional instability (Fall et al. 2010). For these reasons, mine waste management is vitally necessary to minimize the risk associated with mine waste disposal and strengthen the underground mine structures and stability in the surrounding area, as well as to ameliorate the cost-effectiveness of mining (i.e., increase mine production rate) (Belem et al. 2000; Blight 2010).

Mine waste management techniques consist of surface tailings facilities and underground tailings disposal. The surface tailings disposal techniques include tailings impoundment (tailings dam), densified tailings methods (e.g., thickened tailings disposal, surface paste tailing, and filtered tailing), and co-disposal technique (mixing of waste rock and tailings) (Mark 2006). The accumulation of waste tailings at the surface may cause geotechnical and/or environmental issues, such as tailings dam failures, liquefaction problems of thickened tailings, and acid mine drainage (Archibald et al. 2000; Ercikdi et al. 2009). Underground tailings disposal involves refilling the underground voids (stopes) with the disposal of mine waste by recycling it to backfill the stopes. Backfilling of stopes technologies may be divided into three methods according to the consistency of the backfill material, namely the hydraulic backfill, dry backfill or rockfill, and cemented paste backfill (CPB). The hydraulic backfill method consists of 60-75% solids by weight of mill tailings and/or alluvial sand mixed with a small percentage of cement, whereas the dry backfill or rock fill method consists of waste rock mixed with tailings, water, and cement (Nasir and Fall 2010). However, due to multiple incidents of barricade failure imposed by hydraulic backfill, this method is relatively restricted and nearing extinction (Fall et al. 2007).

The cemented paste backfill method (CPB) is the most common technique in underground mine backfill operations in Canada and worldwide (Fall et al. 2009). In this method, substantial quantities of mine wastes are recycled to backfill the stopes and thus manage the geotechnical and

environmental issues related to the disposal of tailings on the surface (Ercikdi et al. 2009; Fang and Fall 2021). In addition, backfilling the stopes with CPB can provide the required support to the underground mine stopes from collapse and surface subsidence, thus enhancing mining operations' productivity (Yilmaz and Fall, 2017; Cui and Fall, 2017a,b). CPB is a designed plant mixture of milled tailings (70-85 wt.%), hydraulic binder (often 3-7 wt.%), water (fresh and/or mine processed), and additives (Yilmaz et al. 2003; Wu et al. 2014; Haruna and Fall 2020). The mixing of the CPB components can take place at a specialized backfill plant on the ground surface (Haruna and Fall 2020). This process involves blending the hydraulic binder or cement, water, and other additives with mine tailings to generate a homogenous mixture (Helinski 2007). Once the CPB backfill mixture is prepared, it is transported to the underground mine stopes by either gravity and/or a pumping system using a pipelines system (Fall et al. 2010).

Once the CPB is delivered and placed into the underground stope as well as throughout its functional service, the CPB structure is exposed to various internal and external factors, including thermal (T) (e.g., heat generated from binder hydration, self-heating of the surrounding rocks in deep mines, geographical area of the mine (cold/warm region), mine temperature), hydraulic (H) (e.g., drained/partial drained/undrained conditions, negative and positive pore water pressure (PWP), self-desiccation), mechanical (M) (stress induced by the backfill self-weight, filling rate), and chemical (C) (e.g., binder reactions, mixing water chemistry, presences of sulphate, chemical interaction between CPB components and chemical additives).

Like any cementitious materials, the effectiveness of delivering the CPB technique through the pipeline system to stopes without pipeline blockages is greatly related to the flowability of the CPB materials (Wu et al. 2013; Ercikdi et al. 2017). The flowability of the high-density CPB materials can be improved by adding high range water-reducing admixtures, also known as superplasticizers, to the CPB mixture. The addition of superplasticizers into the CPB mix enhances the rheological properties of cementitious mixtures (i.e., enhances their flowability), allows easy mixing, minimizes the potential for segregation of the backfill, and improves the mechanical strength (Ercikdi et al. 2010; Ferrari et al. 2012; Haruna and Fall 2019). It is crucial for a stable and feasible design of CPB mixture to understand the interactions of the superplasticizers with the other CPB components (tailings, cement, and water) under various mine conditions at early ages and long-term performance, as well as their impact on the mechanical strength and pore water pressure development of the CPB. To our knowledge, no attention has been given in the literature to the effect of adding superplasticizer with many other internal and external factors that affect a CPB mixture subjected to the coupled multiphysics THMC factors mentioned above once placed into the stope and during its operational lifespans, such as cement content, temperatures, pressure application, sulphate content, and drainage conditions.

1.2 Problem statement

The short- and long-term stability of the CPB structure is significantly governed by the coupling or interaction effect between the multiphysics THMC factors or processes (Cui and Fall 2017). Therefore, the design of a CPB structure requires extensive consideration of a representative field or underground stope conditions. The quality and reliability of data obtained from common laboratory conditions used to design a CPB structure can have crucial implications in the design of a safe and economically feasible CPB structure.

The literature on the impact of the multiphysics THMC factors on the strength and pore water pressure development of CPB with time is limited. The available published studies (e.g., Yilmaz et al. 2004; Klein and Simon 2006; Fall et al. 2007; Fall and Samb 2009; Yilmaz et al. 2009; Fall et al. 2010; Fall and Pokharel 2010; Ercikdi et al. 2013; Ghirian and Fall 2013, 2014, 2015, 2016a, 2016b; Cui and Fall 2016; Wang et al. 2016) have examined the strength development of the CPB structure with time cured under common laboratory conditions and disregarded the impact of the THMC factors mentioned above together, such as the effect of one or two factors. Some of the main differences between the laboratory test conditions versus those in the field are the non-isothermal temperatures and pressure application. Most of the unconfined compressive strength (UCS) tests on the CPB materials have been conducted using room or constant temperatures and stress-free conditions, which are less severe than those expected under field conditions. In the field, temperatures considerably fluctuate due to weather and the geographical area of the mine, from below 0° C in some regions to over 40° C in others (Fall et al. 2010). Also, the amount of heat generated from binder hydration can cause a significant elevation in the backfill temperatures (Fall and Pokharel 2010; Fall et al. 2010; Ghirian and Fall 2013; Cui and Fall 2016; Wang et al. 2016). Undoubtedly, the in-situ pressure or stress applied to the CPB structure is a unique value for each stope and considerably varies based on the stope depth and geometry, adopted filling rate, and cement content (Thompson et al. 2009).

Moreover, the use of superplasticizers in the CPB mixture is becoming increasingly common in backfill operations to improve the flowability of CPB. It has been widely recognized that the addition of superplasticizers to cementitious mixtures can reduce the mixing water by 12%-30% (Ercikdi et al. 2010; Haruna and Fall 2019). Another important aspect of using superplasticizers is their ability to preserve the designed mechanical strength of the CPB mixture (Huynh et al. 2006, Ercikdi et al. 2010, Simon et al. 2011, Ouattara et al. 2017, Ouattara et al. 2018, Mangane et al. 2018, Haruna and Fall 2020). Therefore, there is a need to understand the impact of adding superplasticizers to the CPB mixture on the geotechnical performance of the CPB structure. However, to date, none of these studies address the short- and long-term influence of adding superplasticizers to the CPB mixture subjected to the coupled multiphysics THMC factors.

1.3 Objectives of the research

The main objective of this research is to investigate the geotechnical performance of the CPB materials containing superplasticizers subjected to various coupled multiphysics THMC factors. The key aspects of this investigation aim to:

- i. Investigate the mechanical strength of CPB made with different mix components (tailings, dosages of superplasticizer, cement and solids contents, tailings fineness, and water chemistry) subjected to various curing conditions (stress-free, under stress, constant temperature, and non-isothermal curing temperatures).
- ii. Experimentally investigate and understand the strength development of CPB materials with superplasticizers subjected to various coupled THMC factors.
- iii. Study the positive and negative pore water pressure development in CPB materials with superplasticizers subjected to various coupled THMC factors.
- iv. Investigate the strength development of CPB materials with superplasticizers subjected to various coupled THMC factors with specific consideration to the sulphate effect.
- v. Study the influence of the initial sulphate content on the development of pore water pressure (PWP) of CPB materials with superplasticizers subjected to various coupled THMC factors.

1.4 Research approaches and methods

The research approaches and methods implemented in this study are illustrated schematically in Figure 1.1. To accomplish the above-listed objectives of this study, multiphysical curing and laboratory testing procedures for CPB materials with superplasticizer have been utilized to assess its critical engineering design properties (mechanical strength) under several mix components (tailings, dosages of superplasticizer, water chemistry), and various THMC curing conditions close to those encountered in the field. Natural and non-reactive artificial silica tailings were used to prepare the CPB mixtures. The use of non-reactive synthetic silica tailings can generally provide a certain level of confidence in the obtained results by controlling the effects of various reactive minerals that can be found in the natural tailings, which may alter the cement hydration process. The hydraulic binder used in the study to prepare the CPB mixtures was Portland cement type I (PCI), which is the most common type of binder used in CPB technology. Polycarboxylate ether-based superplasticizers are used as a water-reducing admixture. Moreover, three types of mixing water (tap water, distilled water, and distilled water containing a specific amount of sulphate) are used in this study. The desired amount of ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), which is the most

common sulphate found in natural CPB, was added to the distilled water to obtain mixing water with sulphate. The geotechnical behaviour and the short- and long-term performance of the prepared CPB materials with polycarboxylate ether-based superplasticizer type were investigated under various laboratory and individually and coupled THMC field loading conditions by using a THMC pressure cell apparatus, specifically modified for the purpose of this study. The main geotechnical properties investigated were the unconfined compressive strength (UCS) and the pore water pressure development.

Several microstructural techniques and monitoring tests were implemented in this study on selected specimens to thoroughly understand the mechanisms responsible for the observed geotechnical behaviour. Electrical conductivity monitoring experiments were done to evaluate the progression of the cement hydration process and to monitor the variation of temperatures in the CPB mixtures. Volumetric water content (VWC) monitoring experiments were carried out to examine water consumption. The evolution of suction and pore water pressure was monitored using different sensors for various curing times. Moreover, the pore structure (e.g., void ratio, porosity, density) of CPB mixtures was examined to assess the effect of the THMC field curing conditions on the CPB structure. The microstructural properties of the CPB with polycarboxylate ether-based superplasticizers specimens were investigated by conducting thermal gravity (TG), differential thermal gravity (DTG), X-ray diffraction (XRD), scanning electron microscopy (SEM) observation, and mercury intrusion porosimetry (MIP) tests. The obtained experimental results provide a supportive reasoning and an explanation about the impact of considering the field THMC factors and their coupling effects on the strength development of CPB with polycarboxylate ether-based superplasticizers for the optimal design of safer and more economical CPB structures as well as for the early opening of barricades (i.e., barriers or retaining structures constructed to constrained the backfill within the stope), which is crucial for improving mine productivity and safety.

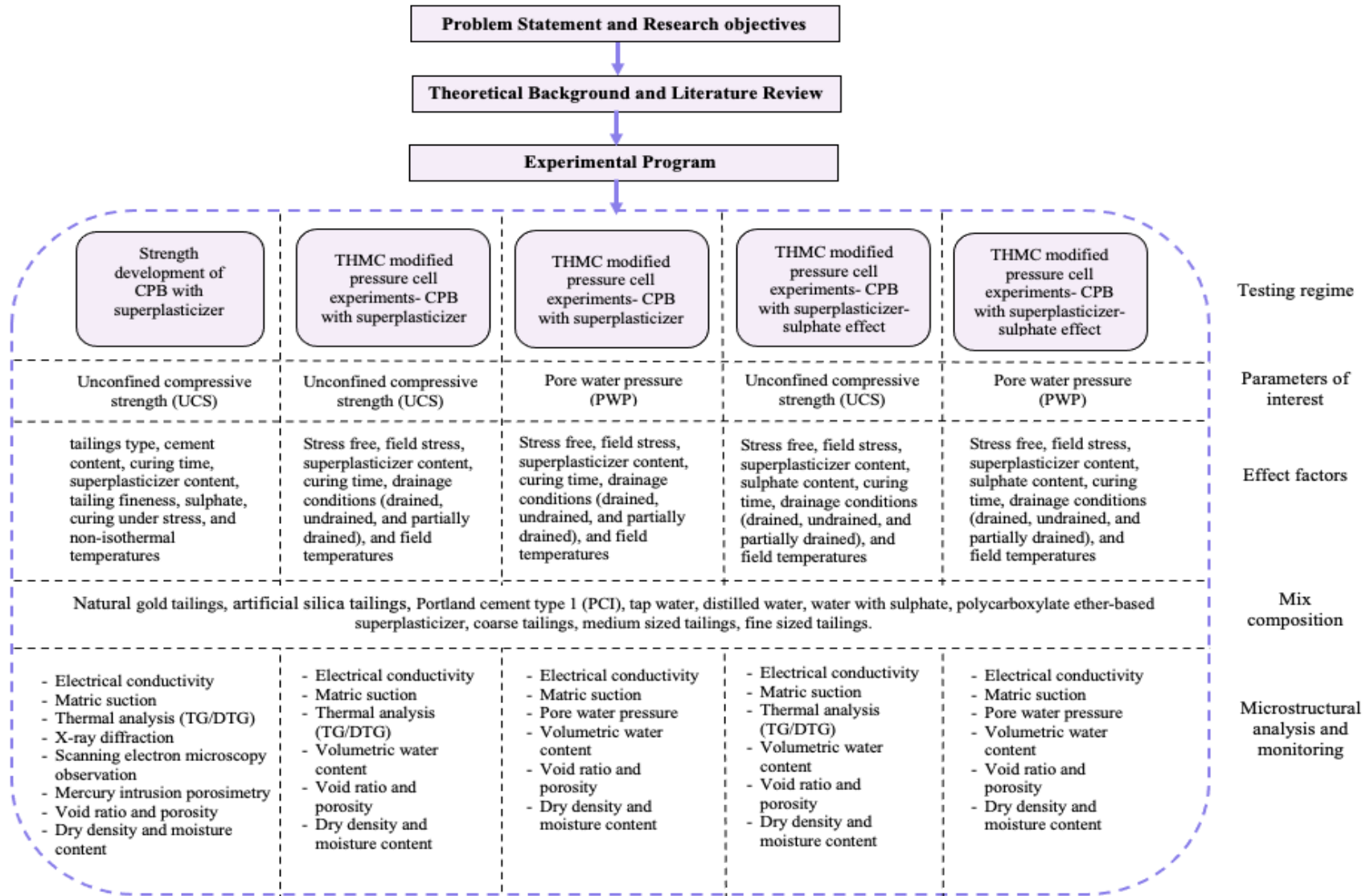


Figure 1.1 Research and study approach

1.5 Tasks and organization of the thesis

This Ph.D. manuscript is structured into nine chapters, which comprise the different research objectives, as presented in Figure 1.2. **Chapter One** is an introduction to the study, which includes background information, an explanation of the problem statement, and the description of the research objectives. **Chapter Two** is a comprehensive literature review on the CPB techniques, binder hydration, use of chemical additives performance, and the behaviour of the CPB materials under coupled THMC factors or processes. Chapters **Three to seven** are organized into a technical paper format, with five manuscripts. Each manuscript includes an introduction, materials and methods, results and discussion, as well as a summary and conclusions. Therefore, some information in these manuscripts may be repeated as each paper is independently written following the manuscript preparation instructions of the corresponding publication journal. **Chapter Three** discusses the effect of mixed components (tailings, dosages of superplasticizer, cement and solids contents, tailings fineness, and water chemistry) on the mechanical strength of CPB subjected to various curing conditions (stress-free, under stress, constant temperature, and non-isothermal curing temperatures). **Chapter Four** presents the strength development of CPB materials with superplasticizers subjected to various coupled THMC factors. **Chapter Five** studies the positive and negative pore water pressure development of CPB materials with superplasticizers subjected to various coupled THMC factors. **Chapter six** presents the strength development of CPB materials with superplasticizers subjected to various coupled THMC factors with specific consideration to the sulphate effect. **Chapter seven** examines the impact of the initial sulphate content on the development of pore water pressure (PWP) of CPB materials with superplasticizers subjected to various coupled THMC factors. **Chapter eight** synthesizes the overall results obtained from this thesis. **Finally, chapter nine** presents the summary and conclusions obtained from this thesis.

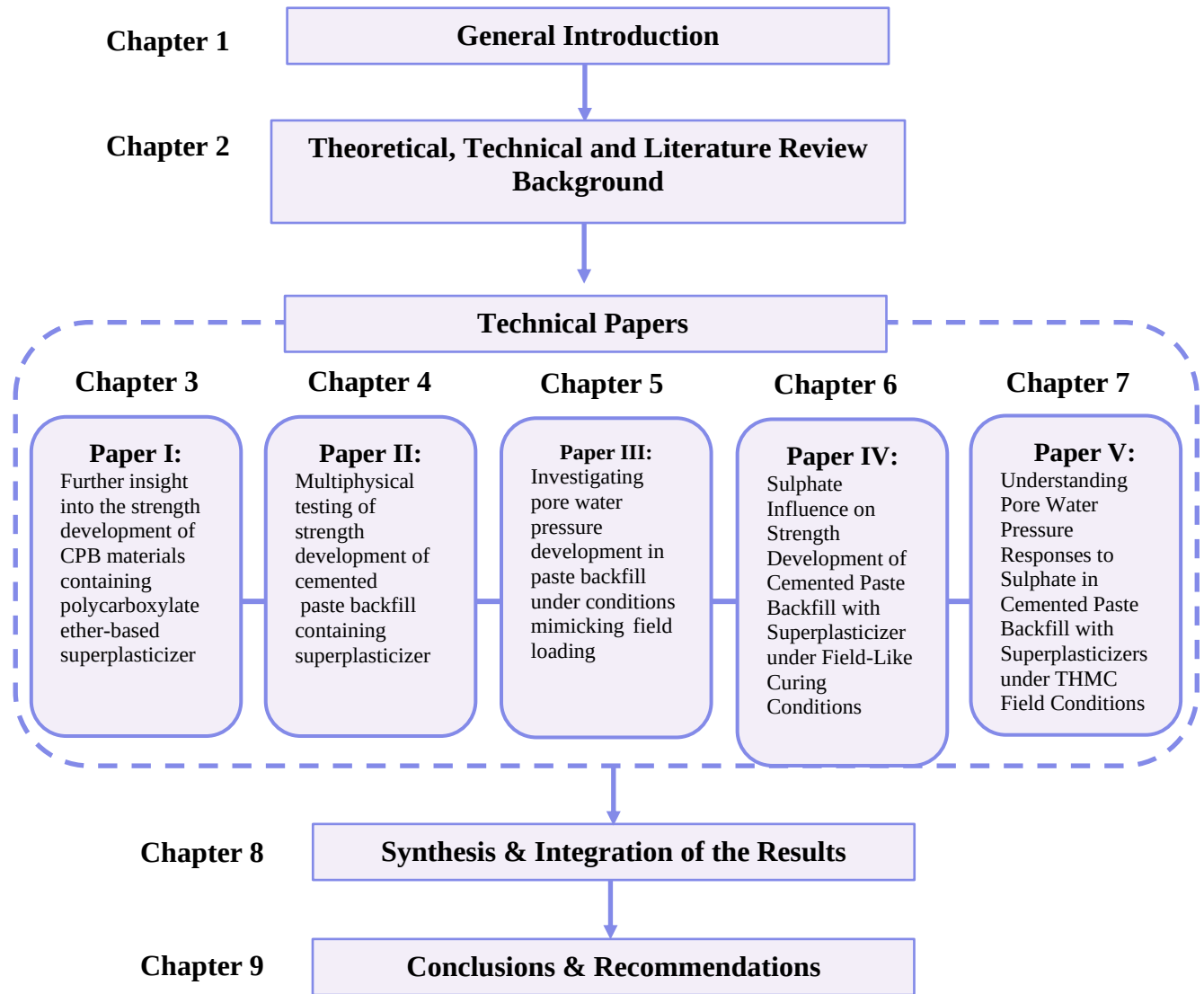


Figure 1.2 Thesis organization

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Chapter 2: Theoretical, Technical and Literature Review Background

2.1 Introduction

This chapter presents a comprehensive review of the fundamental theoretical, technical and literature background aspects regarding mine backfill techniques. A clear understanding of this background information facilitates the understanding of the findings presented in this manuscript, but it is essential to understand the rapid development of new processes and equipment utilized for many years to optimize mine backfilling processes, reduce mine wastes, and increase ore recovery. This chapter is structured as follows: Section 2.1 serves as an introduction, setting the context for the subsequent sections. Section 2.2 provides detailed information about mine backfill methods and cemented paste backfill (CPB) technology, including mix design and preparation, transportation methods of CPB, and backfill strategy and rate. In Section 2.3, background information is provided on the cement hydration process, which plays a vital role in imparting mechanical strength to CPB as well as the influential factors that affect it. The hydration of the binder is a crucial factor that significantly influences the behaviour of CPB. Afterwards, a review is presented in section 2.4 of the current knowledge on various chemical admixtures that are added to CPB materials to enhance their essential properties, and more information is provided on the effects of admixtures on the main properties of the CPB materials. Moving on to Section 2.5, a thorough review is provided of CPB's main processes or factors that affect its engineering performance and behaviour. These processes encompass thermal, hydraulic, mechanical, and chemical aspects, along with the influence of considering field underground stope conditions in designing CPB. In addition, background information on the coupled THMC processes in CPB is also discussed and presented in Section 2.5, contributing to a better comprehension of the research results presented here.

2.2 Background information on mine backfill methods – Cemented Paste Backfill

Underground mining operations often produce significant quantities of mine waste (tailings) on the ground surface. Additionally, the creation of extensive underground voids known as “stopes” creates serious geotechnical engineering challenges, such as ground subsidence and instability in the mine and its surroundings (Nasir and Fall 2009). Traditional surface waste disposal methods like tailings ponds and surface impoundments are environmentally hazardous due to issues such as acid mine drainage (AMD). They are also costly and geotechnically hazardous, as with the issue of tailings dam failures (Landriault 2001; Wu et al. 2013). To tackle these issues, various mining backfill methods have been introduced to manage and control the amount of solid mine waste

(tailings), mitigate ground subsidence and improve overall mining efficiency and safety. Based on the consistency of the backfill materials, mine backfill techniques can be classified into three main methods: dry backfill, hydraulic fill or slurry fill and paste backfill (Nasir and Fall 2010).

The dry backfill or rock fill method involves placing dry, granular material such as sand and crushed waste rocks from underground or open pits into underground voids or stopes to provide support and reduce the collapse of mines during mine operations (Potvin et al. 2005). This technique was effectively introduced several decades ago to support and reduce the collapse of mines during mine operations (Potvin et al. 2005). While the rock fill technique stands out as one of the most economical backfilling methods, it is not without its formidable challenges, particularly concerning rock crushing and the transportation and placement of rock backfill in underground mines (Belem and Benzaazoua 2004). On the other hand, it is difficult to control rock segregation during the placement without the need to use the proper amount of fine materials, which, in turn increases the cost of this method (Belem and Benzaazoua 2008).

The hydraulic backfill method has been developed to tackle the issue associated with the transportation and placement of rock fill into stopes. The hydraulic backfill method has been used in several countries around the world, such as Australia, Canada, China, and Poland (Dalce et al. 2019). The hydraulic backfill method comprises 60-75% solids by weight of mill tailings and/or alluvial sand, which should not contain more than 10% of particles smaller than 10 μm . This is mixed with a lot of water and with or without a small percentage of binder (Dalce et al. 2019). While hydraulic backfill offers the advantage of being a convenient and efficient method regarding the transportation of fill to underground stopes, the deployment of hydraulic backfill in mining industries is subject to rigorous considerations and cautious application. For instance, this method requires considerable operational work to pump out large volumes of water after the solid particles settle to prevent excessive water from bonding within stopes, which may cause excessive loads to barricades and cause the erosion of pipes (Grice 1998). Also, this method requires permeable barricades for proper drainage, as neglecting proper drainage or dewatering measures could result in liquefaction, which may pose significant risks to the safety of miners (Grice 1998). Therefore, the implementation of the hydraulic backfill method in mining industries tends to vanish due to the serious dangers and multiple barricade failure incidents caused by the improper application of this method (Fall et al. 2007).

As a result, researchers developed the cemented paste backfill (CPB) technique to reclaim a considerable percentage of tailings to backfill underground mines or stopes and, thus, provide substantial economic and environmental benefits (Ercikdi et al. 2017; Fang and Fall 2021). The application of CPB has become used extensively worldwide and considerably superior to other techniques for underground mine backfill, particularly in Canada and Australia (Fall et al. 2007). CPB technology allows the return of large portions of the tailings into stopes, eliminates the issue

of segregation of using rock backfill method during transportation and placement of fill into stopes and minimizes many geotechnical and environmental problems, such as shortening mining cycle periods by its ability to harden and gaining the required strength in a short period of time. CPB technology also reduces the formation of acid mine drainage (AMD) by inhibiting the diffusion of oxygen and maximizes the recovery of the processed water via thickening and filtration processes prior to backfill into stopes (Fall et al. 2007; Ercikdi et al. 2017; Cui and Fall 2017). However, despite the ever-increasing and demanding implementation of the CPB technique in backfilling operations, there are some problems associated with its used, such as the high costs related to the transportation of such high-density backfill material through the pipeline system to underground stopes (e.g., energy costs and pumping maintenance) (Ercikdi et al. 2017; Haruna and Fall 2019).

The rational design of the CPB mixture is crucial to achieving the ultimate objectives of providing the required mechanical strength for underground support and reducing costs, which are mainly related to cement consumption rate and transportation. Various cement content, water-to-cement ratio content, tailings fineness, tailings density, chemical compounds and other factors associated with the natural conditions that the CPB mixture is subjected to in the field can considerably affect the long-term performance and mechanical stability of the CPB mixture during its placement and throughout its functional service (Ghirian and Fall 2013a). Therefore, there is significant room for optimization of the CPB mixture in the design process, which is the main target of this research and many studies around the world to obtain a safer and most economical design of CPB mixture.

2.2.1 CPB mix design and preparation

CPB mixture is comprised of 70-85% by weight of tailings, 3-7% (often) by weight of hydraulic binders or cement, water (fresh and/or mine processed), and chemical additives (Yilmaz et al. 2003; Benzaazoua et al. 2004; Fall et al. 2005; Ercikdi et al. 2010; Wu et al. 2014; Fang and Fall 2020; Haruna and Fall 2022). The production of a homogenous CPB mixture involves several processes or stages, starting from milling ores (waste rocks) after extracting all the valuable minerals. The crushed ores, known as tailings, have a solid concentration that varies between 35% and 60% (Belem and Benzaazoua 2008). Then, in order to increase the solid percentage of tailings to up to more than 75%, the excess water is separated and removed. This process or stage is called the thickening stage or the concentrator process (Helinski 2007). In the next stage, the design percentage of cement, water, and chemical additives is added to the thickened tailings and is thoroughly mixed to achieve a homogenous CPB mixture. The percentages of these ingredients are carefully selected and controlled to achieve the desired strength and consistency of the CPB mixture (Alainachi 2020). After the mixing process is complete, the CPB mixture is transported to the underground mine stopes either via gravity and/or a pumping system (Haruna and Fall 2020).

A schematic overview of underground mining operations is shown in Figure 2.1. This figure features the different activities of a typical underground mining operation starting from (i) stope blasting, (ii) ore extraction from stope, (iii) the concentrator process, where ore is processed (crushed and the valuable minerals are extracted), (iv) the backfill plant, in which the generated waste rock and tailings from the concentrator process are mixed with the desired amount of cement, water, and additives to produce the cemented backfilling product, (v) the pipelines transportation system of the CPB from the backfill plant to the stope, and to (vi) the deposit of the CPB slurry into the stope.

2.2.2 Transportation and delivery methods

Once the CPB is prepared at the surface mixing plant, it needs to be transported to the underground mine stopes by gravity and/or through pumping (Roshani and Fall 2020). Several methods can be employed for delivering the CPB, such as pipeline systems, trucks, or railcars (Helinski 2007; Yilmaz and Fall 2017). The pipeline system involves reticulating boreholes, pipelines, pumps, and a cleaning system (Yilmaz and Fall 2017; Aldhafeeri and Fall 2017; Cui 2017; Aldhafeeri 2018). The pipeline system is very efficient for delivering the CPB over long distances and multiple stopes (Yilmaz and Fall 2017).

The transportation of CPB to underground stopes plays a crucial role in the backfilling process and is greatly affected by the rheological properties of the CPB (Ghirian 2016). Clogging in the pipeline system may cause delays and interruptions in the overall backfilling operations of CPB, which leads to considerable financial losses and may require the costly replacement of pipelines (Alainachi 2020).

The flowability of the fresh CPB during its transportation should be maintained by controlling the yield stress of the CPB mixture (Haruna and Fall 2019). The yield stress is the minimum force required to initiate flow in a material (Ali et al. 2021). Therefore, to sustain suitable flowability in fresh CPB, it is essential to ensure that the pumping pressure is larger than the yield stress of the produced CPB (Cui 2017; Alainachi 2020). This approach ensures that the CPB mixture remains in a flowable state and can flow smoothly through the pipelines without clogs or blockages. Various methods and tests can be used to measure the flowability of the fresh CPB, such as rheological measurements (i.e., yield stress and viscosity), slump flow tests, and vane shear tests (Cui 2017; Haruna and Fall 2019). In addition, the pumping pressure of the CPB mixture should be regularly monitored to achieve consistent and optimal flowability during CPB production (Cui 2017; Alainachi 2020).

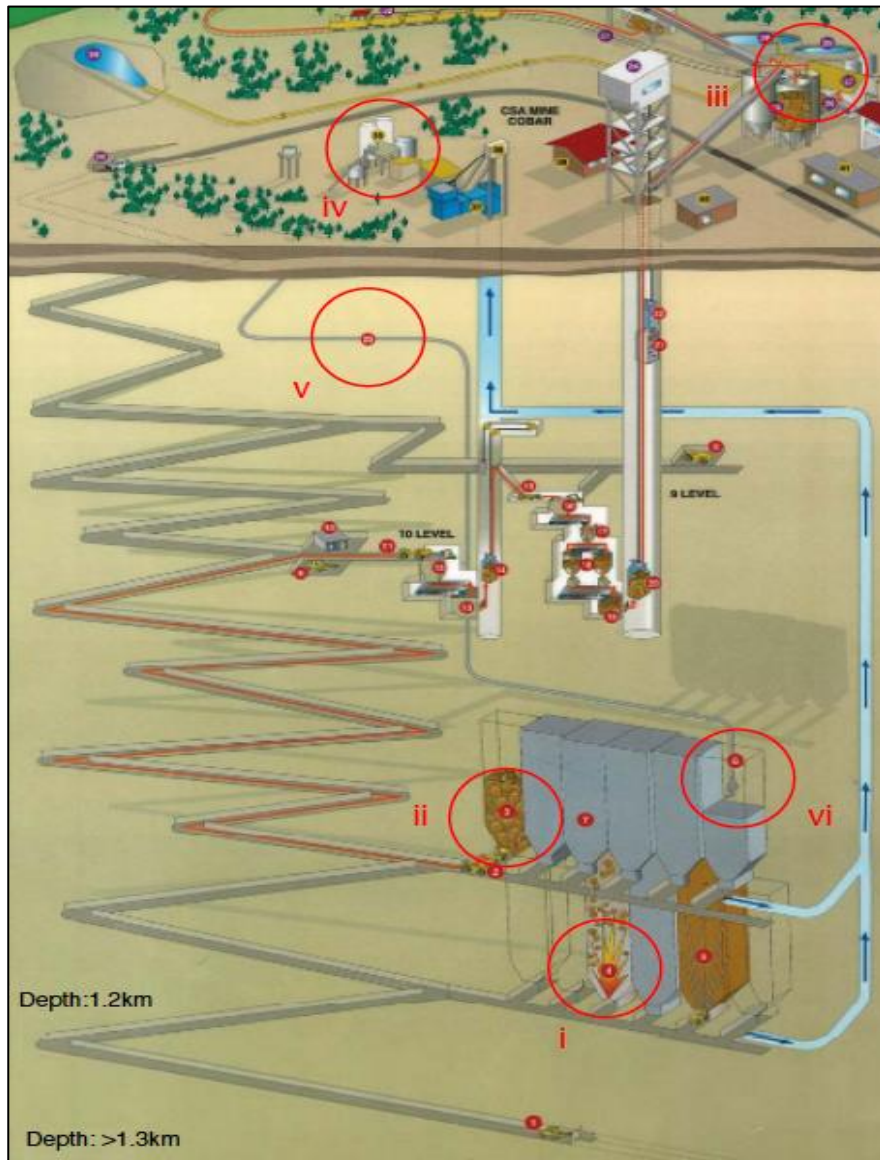


Figure 2.1 Illustration of a typical mine operation with the use of CPB techniques: (i) stope blasting, (ii) ore extraction from stope, (iii) the concentrator process, (iv) the backfill plant, (v) the transportation system, (vi) the deposit of the CPB into the stope (Modified from Helinski 2007)

2.2.3 Backfilling strategy and rate

Mine backfilling strategy and rate should be planned and executed carefully to enhance the safety of mine workings and the overall efficiency of mining processes. The backfilling approach and rate vary from mine to mine and even from one stope to another and can be expressed by the volume (m^3/h) or height of the stope (m/h) (Nasir and Fall 2010). The backfilling strategy and rate generally depend on the geometry of the stope, the design bearing pressure of the barricade (barrier

or retaining wall constructed at the draw points of stopes to confine and support backfill materials), binder setting time (hydration process), binder content, and arching effect (Thompson et al. 2009; Ghirian 2016). Allowing the underground stopes to be backfilled at a faster rate and lower binder contents with one pour or stage will increase the applied pressure on the barricade and may lead to barricade failure (Yilmaz et al. 2014; Ghirian and Fall 2015). Therefore, subsequent or staged backfilling strategy is considered a typical mine standard for backfilling to eliminate the hazards of barricade failure, especially when there is a lack of data on the behaviour of CPB in the field (Thompson et al. 2009). The staged backfill involves pouring an initial plug of 2m to 3m in height and allowing it to cure for at least 24 hours to plug the barricade; then, the main volume of the CPB can be poured (Thompson et al. 2009).

2.2.4 Design criteria of CPB structures

The cemented paste backfill (CPB) design aims to develop a cost-effective CPB structure that addresses mine-specific performance, stability, sustainability, and safety requirements. It requires understanding the physical properties of each component in the CPB materials (i.e., tailings, cement, water, and the chemical additives), mechanical, hydraulic, thermal, chemical, and microstructural aspects (Ghirian and Fall 2017). Many variables influence CPB performance, making the criteria for designing the CPB structures complex. For example, cement reaction and the heat generated by binder hydration (Further explained in Section 2.3), self-desiccation of the CPB materials and their changes with curing time are all factors that are implicated in CPB performance. Moreover, chemical or environmental considerations, such as the presence of sulphate ions in the backfill mixture and temperature variation (e.g., temperature of the rock mass, self-heating of the rocks), can significantly affect the design aspects of CPB structures and alter the output or target results (Fall et al. 2010; Ghirian and Fall 2017).

In general, mechanical stability, which mainly depends on the CPB strength, is one of the most important design criteria of CPB structures (Fall et al. 2007). Understanding the strength development of the CPB materials is paramount in optimizing CPB performance and ensuring safe and sustainable mining operations. The mechanical strength of the CPB structure is driven by the hydration reactions of cementitious materials within the mixture, self-desiccation (suction), and consolidation pressure caused by the self-weight of the backfill mass (Ghirian and Fall 2017; Alainachi 2020). As CPB is placed in underground voids, the CPB interacts with the surrounding rock mass and creates an internal rock mass/backfill interface structure that can sustain the weight of the overlying materials (i.e., part of the stress inside the backfill is transferred to the adjacent rock walls and develops shear stresses) (Cui 2017). This rock mass/backfill interface structural arrangement reduces the pressure on the lower layers of the backfill ($\sigma_v < \gamma h$), known as the arching

effect (Figure 2.2) (Li et al. 2003). Therefore, to ensure a safe work platform for all mine workers and enable an early opening of barricades (i.e., financial benefit), the CPB structure must meet a specific mechanical strength, usually evaluated using the uniaxial compressive strength (UCS), which is the most important mechanical parameter used to assess mechanical strength of the CPB structure (Fall and Pokharel 2010). For instance, CPB employed for void filling usually entails minimal compressive strength of 150 to 300 kPa, whereas CPB utilized for roof support backfill necessitates a significantly higher compressive strength ranging from 1 to 4 MPa (Fall et al. 2005). Moreover, other techniques or tests, such as direct shear and triaxial tests, can be carried out to assess the shear strength characteristics and criteria for failure of CPB (Le Roux et al. 2005, Fall et al. 2007).

In addition, previous studies (Fall et al. 2010; Fall and Pokharel 2010; Ghirian and Fall 2013a, 2013b, 2014, 2015, 2016; Cui and Fall 2017) have revealed that the safety, efficiency, and environmental performance of the CPB structure is significantly influenced by the various conditions that the CPB is subjected to in the field, which should be carefully considered in designing the CPB structure. These conditions or factors include: (i) temperature variations that can significantly influence the properties and characteristics of CPB, which in turn impact its mechanical stability. Elevated temperatures can accelerate the hydration process of the binder present in CPB (Fall et al. 2010). This acceleration can lead to faster setting times and faster development of strength, which can be beneficial in scenarios where rapid support is needed. However, higher temperatures can also cause excessive evaporation of water from the mixture, potentially altering its consistency and flowability (Haruna and Fall 2020); (ii) hydraulic conditions, such as drainage conditions (drained or undrained), self-desiccation, suction, pore water pressure; (iii) mechanical conditions, such as self-weight pressure, filling rate, and external loading; and (iv) chemical conditions, such as the effect of the binder hydration, chemical interactions between CPB components and additives, and presence of sulphate ions. Therefore, a comprehensive understanding of how these factors or conditions influence CPB ensures that its engineering properties remain intact, contributing to the safety and stability of CPB design.

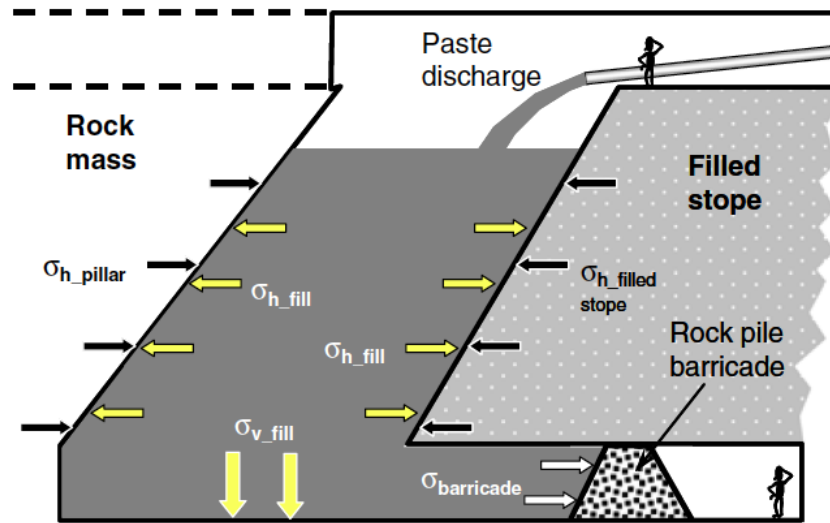


Figure 2.2 Schematic view of backfill in stopes and stress distribution (Belem and Benzaazoua 2008)

2.3 Background information on binder hydration processes and main influential factors

CPB technique typically involves the use of cement as a hydraulic binder. The binder hydration process plays a pivotal role in the short and long-term performance of CPB materials. The development of the required mechanical strength and durability is significantly dependent on the cement hydration process (Fall et al. 2010). Generally, Ordinary Portland Cement - Type I (PCI) finds widespread use as the hydraulic binder in CPB formulation due to its common availability across various regions worldwide (Belem and Benzaazoua 2004). After mixing with water, PCI constituents undergo a complex reaction called the cement hydration process (Alainachi 2020). The subsequent subsections briefly discuss PCI properties, the fundamental hydration reactions, and the main influential factors.

2.3.1 Ordinary Portland Cement

Ordinary Portland Cement – Type 1 (PCI) is one of the most widely used types of hydraulic cement in the preparation of CPB (Belem and Benzaazoua 2004). It is primarily composed of crushed limestone (CaCO_3) mixed with Silica (SiO_2), which is usually sourced from materials like sand or shale, alumina (Al_2O_3) and iron oxide (Fe_2O_3) in addition to the minor oxides (Aldhafeeri 2018). Various crystal phases, including alite (C_3S), belite (C_2S), aluminate (C_3A) and ferrite (C_2AF) are formed due to the oxidation of cement at high temperatures (Aldhafeeri 2018). Upon mixing and reacting with water, it set and hardened to form three main types of cement hydration products, including calcium silicate hydrate (C-S-H), calcium hydroxide or portlandite ($\text{Ca}(\text{OH})$ or CH),

and a calcium sulphoaluminate known as ettringite ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O}$) (Alainachi 2020). The calcium silicate hydrate (C-S-H) gel is formed by the hydration of (C_3S) and (C_2S) at different rates. The C-S-H component makes up approximately 60% (by volume) of the total cement hydration products in hardened cement, and it is characterized by its amorphous, poorly crystalline nature (Ghirian 2016). The calcium hydroxide (CH) component occupies about 20% (by volume) of the total hydration products, and it is characterized by its thin to large hexagonal crystal structure. The remainder of the cement hydration products are mainly comprised of ettringite ($3\text{CaO} \cdot \text{Al}_2\text{O}_3 \cdot 3\text{CaSO}_4 \cdot 31\text{H}_2\text{O}$), which is a type of needle-like crystalline structure. Ettringite is formed by hydrating the aluminate phases and gypsum (Ghirian 2016; Alainachi 2020).

2.3.2 Cement hydration process

The cement hydration process is a series of complex chemical reactions that occur when water (liquid phase) is mixed with cementitious materials (solid compounds), such as Portland cement (Ghirian 2016). Several researchers have elucidated the cement hydration process (e.g., Bullard et al. 2011, Scrivener et al. 2015). They have highlighted that the evolution of cement hydration with time can be divided into four distinct phases, including the initial reaction, the slow reaction, acceleration (or sitting), and the deceleration (or hardening) stage, as shown in Figure 2.3 (Bullard et al. 2011). These stages are summarized as follows:

- (a) Initial reaction (0 to 30 min.): This stage is characterized by the rapid reaction between the C_3S gel component and water, which commences immediately after being exposed to the mixing water (Bullard et al. 2011; Alainachi 2020). Also, this stage is characterized by the significant amount of heat generated by the rapid dissolution of the aluminite and gypsum and the dissolution of C_3S (Bullard et al. 2011).
- (b) Slow reaction (30 min. to 3 hrs): known as the dormant period or the introduction period, which immediately follows the initial contact between calcium silicates (C_2S and C_3S) with water (Ghirian 2016). During this stage, chemical reactions that lead to the formation of hydration products are in their early stages and occur relatively at a slow rate, resulting in the release of ions from cement particles into the pore solution, such as Na, K, Ca, OH, and SO_4 (Ghirian 2016). In this stage, the cement starts to thicken but does not exhibit hardening or setting properties and no significant heat generation (Bullard et al. 2011; Ghirian 2016; Alainachi 2020).
- (c) Acceleration stage (3 to 17 hrs after mixing): The cement setting and hardening processes increase significantly in this stage (Bullard et al. 2011). This stage is characterized by the rapid increase in the hydration rate and the generation of a

significant amount of heat, which results in the refinement of the pore spaces, thus resulting in the setting of the cement paste (Ghirian 2016; Cui 2017).

- (d) Deceleration stage (17 to 48 hrs after mixing): It is characterized by the slowing down of the rate of chemical reactions (i.e., the formation of C-S-H and CH) and a decrease in the rate of heat generation (Ghirian 2016; Cui 2017).

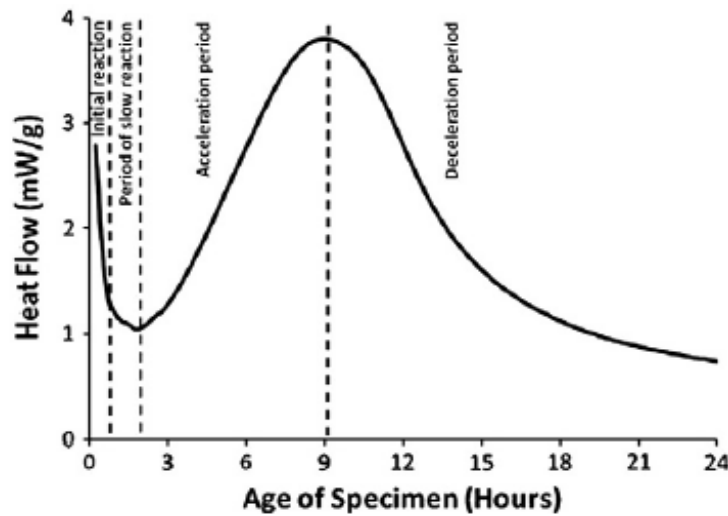


Figure 2.3 Rate of hydration with curing time (Bullard et al. 2011)

2.3.3 Factors that affect the cement hydration process

The cement hydration process is a complex chemical reaction that can be affected by various factors, such as water-cement (w/c) ratio, curing temperature and pressure, cement fineness, chemistry of mixing water, and admixtures (Ghirian 2016). The w/c ratio is one of the most critical factors affecting the cement hydration process (Ghirian and Fall 2017). The rate of cement hydration is inversely affected by the w/c ratio (Alainachi 2020). When the w/c ratio is decreased, it decreases the porosity and void ratio of the cementitious materials, thus increasing the mechanical strength of these materials (Bentz 2006).

Curing temperature has a profound impact on the rate of cement hydration. Previous studies (Bentz 2006; Lin and Meyer 2009; Fall et al. 2010) have demonstrated that higher curing temperatures accelerate the cement hydration process, resulting in the refinement of pore structure, thus densifying the cementitious material. Subjecting cementitious materials to higher temperatures of over 85°C can reduce mechanical strength as they age due to the less uniform microstructure and a coarser pore structure (Cui 2017). In contrast, lower curing temperatures slow down the cement hydration process (Haruna and Fall 2020). Moreover, a higher curing pressure

generally increases the hydration rate and, therefore, helps in densifying the cementitious matrix (i.e., decreasing the porosity) by promoting the dissolution of cement particles and enhancing chemical reactions, which can result in higher early strength development (Roy et al. 1972; Zhou and Beaudoin 2003).

Finer cement particles generally hydrate more rapidly than coarser particles due to the higher surface area of the finer cement, which in turn can reduce the setting time and increase the mechanical strength of cementitious materials (Lin and Meyer 2009; Ghirian 2016). Also, the chemistry of the mixing water (i.e., the presence of some chemical compounds in the mixing water) can react with cementitious compounds and influence the hydration process (Alainachi 2020). For instance, the presence of the sulphate anions can inhibit the cement hydration process by the interaction of sulphate anions and C_3A compounds within the cement, which results in the formation of a thin coating around the C_3A grains, which acts as a barrier, preventing the C_3A grains from reacting with water and delaying the setting time and strength development of cementitious mixtures (Alainachi 2020; Li and Fall 2016). The sources of sulphate in the CPB and their presence effect are further discussed in Section 2.5.4.

Moreover, the addition of chemical admixtures, such as accelerators, retarders, plasticizers, and superplasticizers, significantly impacts the hydration process (as explained in Section 2.4) (Ercikdi et al. 2010). These chemical admixtures can improve cementitious materials' performance and sustainability (Yang et al. 2018; Haruna 2022).

2.4 Chemical admixture used in CPB

Like any hydraulic-cement mixtures, CPB materials can be treated with several chemical additives to improve their engineering properties. In general, chemical additives are used to improve the CPB's rheological properties (flowability) (i.e., sitting time) and enhance their mechanical strength. The chemical admixtures must be carefully selected and dosed with the CPB mixture. The main chemical additives used in CPB are as follows:

2.4.1 Accelerators and retarders

Accelerators and retarders are chemical additives commonly added to cementitious materials (Liu et al. 2020). Accelerators, such as sodium sulphate (Na_2SO_4), expedite the reaction rates of cement hydration, thereby reducing the sitting time and increasing the rate of early-age strength development of CPB (Liu et al. 2020; Wu 2020; ASTM 2022). Conversely, retarders, like lignosulfonates, extend the sitting time of the backfill mixture, which is beneficial when longer transportation and placements are necessary (Bratty 1991; ASTM 2022).

2.4.2 Plasticizers

Plasticizers, also known as low range water-reducing admixtures, are chemical compounds of organic molecules used to reduce the quantity of mixing water needed to produce concrete of a given slump to 5 to 12% (ASTM 2022; Haruna 2022). The main purpose of using plasticizers is to preserve the workability of cementitious materials while simultaneously maintaining their essential engineering properties, such as mechanical strength (Haruna 2022). The molecules of plasticizers insert themselves between the polymer chains (i.e., the cementitious materials that the plasticizers are added to them). Therefore, creating more space and retarding the hydration process (Bhatty 1991).

2.4.3 Superplasticizers

Superplasticizers, also known as high range water-reducing admixtures, are added to the backfill mix to reduce the mixing water demands by 30%, thereby producing a higher solid content without jeopardizing the consistency of the mixture (Ercikdi et al. 2010; Yang et al. 2018; Haruna 2022). Superplasticizers are organic polymer molecules that can adsorb on the surface of cementitious materials and develop electrostatic repulsive forces and steric hindrance forces that disperse the solid particles (Mangane et al. 2018; Ouattara et al. 2018; Yang et al. 2018). Figure 2.4 illustrates the mechanism of action of superplasticizers and its interactions with solid particles (i.e., tailings and cement).

The rheology of cementitious materials (i.e., flowability) significantly depends on the type and dosage of superplasticizers, and the flowability rate may vary from one mixture to another (Benaicha 2015; Haruna 2022). This depends on the percentage of solid content, tailings compositions, as well as cement type and content (Mangane et al. 2018, Ouattara et al. 2018; Yang et al. 2018; Haruna and Fall 2019). Superplasticizers can be classified into three main groups according to their dispersing functionality, namely lignosulfonate-based, sulphonated-based (further subdivided into sulphonated naphthalene formaldehyde and sulphonated melamine formaldehyde) and polycarboxylate- based superplasticizers (Ramachandran et al.1998).

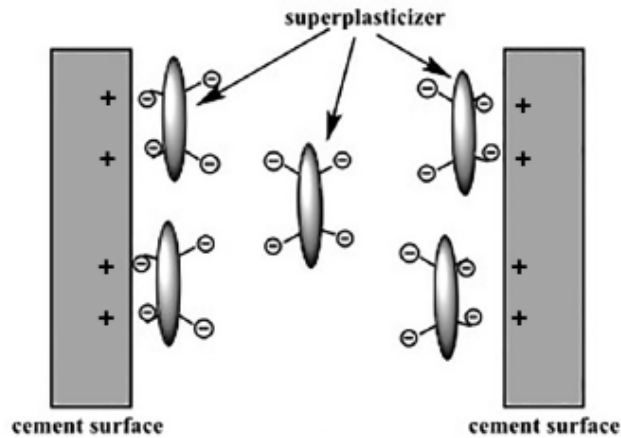


Figure 2.4 Typical adsorption of superplasticizers on the surface of cement particles (modified from Breilly et al. 2021)

2.4.3.1 Lignosulfonate-based

Lignosulfonate-based superplasticizers are derived from lignin, a natural polymer extracted from wood (Breilly et al. 2021). They are considered to be the first-generation superplasticizers and are typically in the form of sodium, calcium, or ammonium salts of lignosulfonates (Ramachandran et al.1998). The simplified molecular structure of lignosulfonate-based superplasticizers is shown in Figure 2.5. Lignosulfonate-based superplasticizers are relatively economical but have limitations in terms of their water-reducing abilities compared to newer generations of superplasticizers (Ramachandran et al.1998; Nagaraj and Jeyakumar 2018).

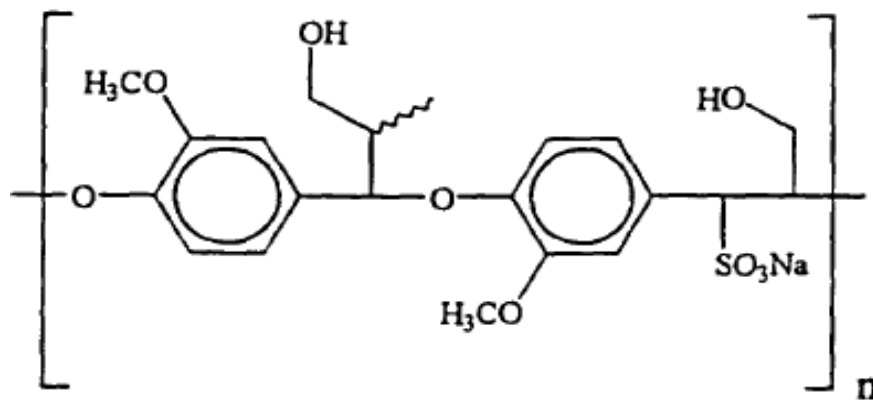


Figure 2.5 The structural formula of lignosulfonate-based superplasticizers (Ramachandran et al.1998)

2.4.3.2 Sulphonate-based superplasticizers

Sulphonate-based superplasticizers are considered to be the second generation of superplasticizers and one of the most effective groups of high range water reducing admixtures (Ramachandran et al.1998). Sulphonate-based superplasticizers are subdivided into two family groups, namely sulphonated naphthalene formaldehyde and sulphonated melamine formaldehyde.

2.4.3.2.1 Sulphonated naphthalene formaldehyde

Sulphonated naphthalene formaldehyde (SNF) superplasticizers are chemically synthesized from sulfonated naphthalene formaldehyde condensates (Ramachandran et al.1998; Haruna 2022). Following its extraction from petroleum, coal or tar, naphthalene (which is composed of two fused benzene rings) undergoes a process of sulphonation and subsequent polymerization until it achieves its final molecular structure, as shown in Figure 2.6 (Harkouss and Hamad 2015). SNF superplasticizers are available as sodium, calcium, or potassium salts and are widely used in North America due to their excellent advantage of not altering the stability of pore network in an air-entrained concrete with freeze-thaw resistance (Breilly et al. 2021; Haruna 2022).

Figure 2.7 illustrates the electrostatic dispersing mechanism of SNF. As the SNF superplasticizers are added to the cementitious mixture, the positively charged particles of SNF superplasticizers (e.g., Na^+) will separate from the negatively charged particles (e.g., SO_3^-), which will adsorb onto the positively charged cement particles. The negative charge carried by the admixture serves a dual purpose: part of it is utilized to bond with the superplasticizer on the cement, while the remaining unoccupied negative charges work to push away adjacent particles of the same charge, thereby guaranteeing by this process the effective dispersion of the cement (Harkouss and Hamad 2015).

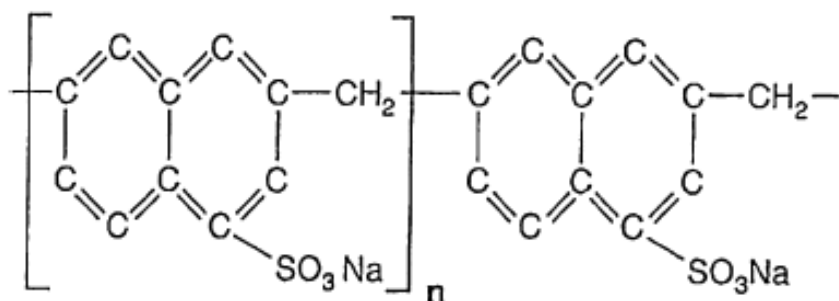


Figure 2.6 The structural formula of sulphonated naphthalene formaldehyde superplasticizers (Harkouss and Hamad 2015)

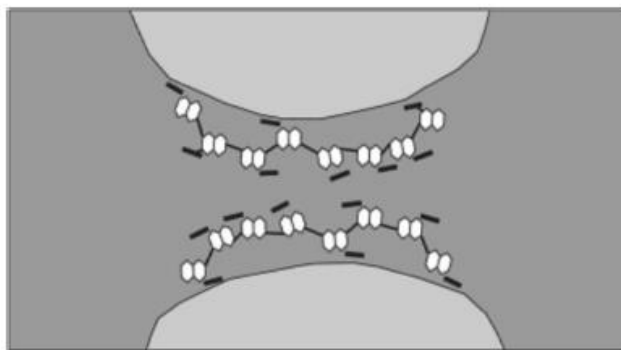


Figure 2.7 The electrostatic dispersing mechanism of sulphonated naphthalene formaldehyde superplasticizers (Harkouss and Hamad 2015)

2.4.3.2.2 Sulphonated melamine formaldehyde

Sulphonated melamine formaldehyde (SMF), also known as polymelamine sulphonates (PMS), is the second family of sulphonated-based superplasticizers. SMF superplasticizers are synthesized from melamine formaldehyde condensates, and they are available as sodium or calcium salts, as shown in Figure 2.8 (Ramachandran et al.1998). Although SMF superplasticizers are known for their high water-reduction capabilities and excellent workability enhancement, this synthetic polymer has been substituted due to the environmental concerns arising from the release of residual formaldehyde (a Volatile Organic Chemical, VOC) during the hardening process, coupled with limitations in the variety and types of molecules (monomers) utilized (Breilly et al. 2021).

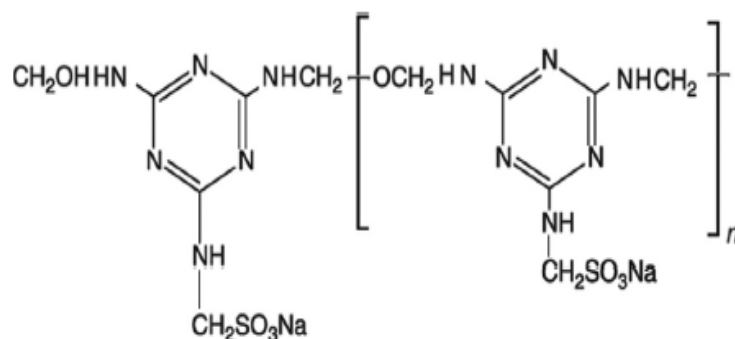


Figure 2.8 The structural formula of sulphonated melamine formaldehyde superplasticizers (Aicha 2020)

2.4.3.3 Polycarboxylate-based

Polycarboxylate-based superplasticizers represent the third and most recent generation of superplasticizers (Aicha 2020). Polycarboxylate-based superplasticizers are synthesized from complex polymeric or comp-like structures containing carboxylate functional groups (Aicha 2020). The structural formula of polycarboxylate-based superplasticizers is shown in Figure 2.9. Polycarboxylate-based superplasticizers provide excellent water reduction and dispersing properties compared to the first and second generation of superplasticizers, and they are available in various forms, including liquid and powder (Haruna 2022). The main reason this superplasticizer provides excellent dispersing properties over other types of superplasticizers is that the polycarboxylate-based superplasticizers disperse the solid particles through two mechanisms or dispersing forces, including electrostatic repulsive forces and steric hindrance forces (Ouattara et al. 2017). Steric hindrance is more effective than electrostatic repulsion (Ouattara et al. 2017). The steric repulsion mechanism offered by this type of superplasticizer is associated with the long polymer chain structures of these additives (Ouattara et al. 2017). When the comp-like structures of the polymer molecules adhere to the surface of cementitious materials, they bridge or link the molecules to the neighbouring particles and prevent particle agglomerations, as shown in Figure 2.10 (Ramachandran et al.1998; Harkouss and Hamad 2015; Ouattara et al. 2017).

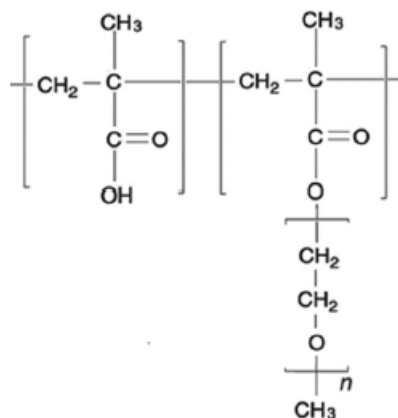


Figure 2.9 The structural formula of polycarboxylate-based superplasticizers (Aicha 2020)

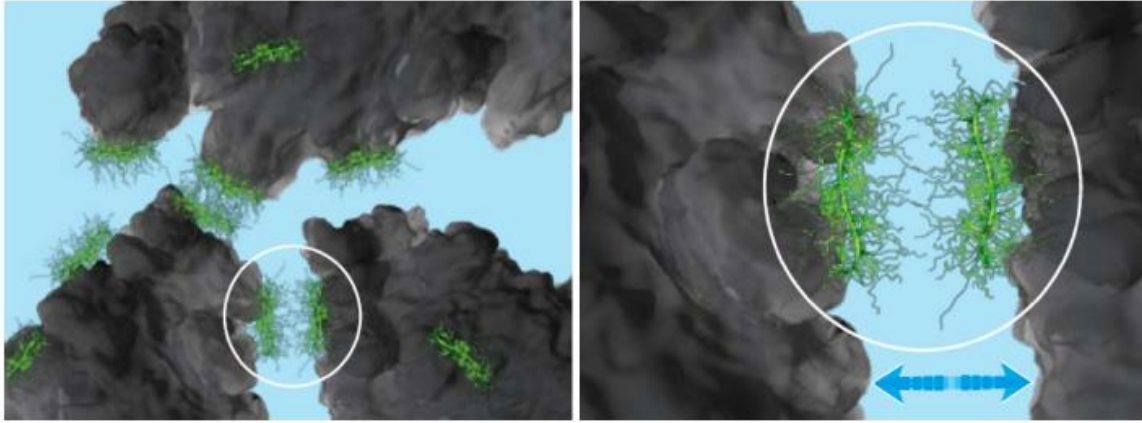


Figure 2.10 Steric hindrance dispersing mechanism of Polycarboxylate-based superplasticizers (Harkouss and Hamad 2015)

2.4.4 Effects of superplasticizers on the properties of CPB

Several studies have been conducted in recent years to understand the effects of the inclusion of different types of superplasticizers on the properties of CPB materials. These studies investigate the effect of different types and dosages of superplasticizers on the rheological and mechanical properties of CPB materials, which consist of various binder types and content, various tailings characteristics, sulphate content, and cured under various curing conditions.

Huynh et al. (2006) investigated the effect of polyphosphate and naphthalene sulfonate formaldehyde condensate (NSF) on the yield stress of two types of tailings (original plant tailings (with a solid content of 66 wt.%) and $< 38\mu\text{m}$ fraction of tailings samples prepared from wet screening the original plant tailings through $38\mu\text{m}$ sieve then drying them). They found that the polyphosphate superplasticizer type is less effective in lowering the yield stress of the CPB than the NSF superplasticizer type when used at the same concentration. This occurs due to the interaction between cement particles and polyphosphate superplasticizer, which diminishes the dispersing capability of polyphosphate. When cement is mixed with water, it undergoes hydration and releases calcium ions into the solution. These calcium ions then react with the polyphosphate superplasticizer, causing it to lose its dispersing effectiveness.

Klein and Simon (2006) studied the effect of various superplasticizer types (NSF and polycarboxylate-based superplasticizer (PCA)) on the setting time and unconfined compressive strength (UCS) of CPB materials. They observed that the influence of incorporating superplasticizers into the CPB mixture varies significantly depending on the type of superplasticizer used. Their findings demonstrated that the CPB mixture containing polycarboxylate-based superplasticizers achieved the highest UCS values during a one-year curing period compared to the other types utilized, as shown in Figure 2.11.

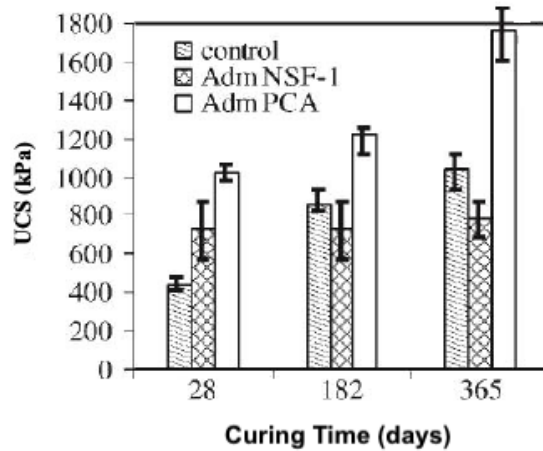


Figure 2.11 Influence of superplasticizers type on the mechanical strength of CPB with time (Klein and Simon 2006)

Ercikdi et al. (2010) investigated the influence of the addition of three types of water-reducing admixtures (Lignin (P1), polynaphthalene sulfonate (SP1), and polycarboxylate-based (SP2) on the rheological and mechanical properties of CPB produced from sulphide-rich tailings. They found that adding these superplasticizers noticeably enhances CPB's consistency and mechanical strength. Also, they reported that only the CPB samples containing polycarboxylate-base superplasticizers achieved and maintained the desired 28-day mechanical strength compared to the other samples, as shown in Figure 2.12.

Simon et al. (2011) illustrated the effect of polycarboxylate-based superplasticizers type on CPB materials' yield stress and mechanical strength. They stated that adding 0.185% by wt. of solid polycarboxylate-based superplasticizers increases the 28-day UCS values from around 450 kPa to approximately 1000 kPa, as illustrated in Figure 2.13.

Similar studies were conducted in the past five years to determine the effect of various types and dosages of superplasticizers on the workability and mechanical strength of CPB materials under different curing conditions (Mangane et al. 2018; Ouattara et al. 2018; Yang et al. 2018; Haruna and Fall 2020a; Liu et al. 2020; Cavusoglu and Fall 2022). Their results demonstrate that the superplasticizer's effect on the CPB performances depends on the type and dosage of the admixtures. Their studies have shown that incorporating superplasticizers into the CPB mixture not only enhances the flowability of CPB materials but can also significantly improve their mechanical strength. Furthermore, their findings indicate that polycarboxylate superplasticizers outperform the other types in achieving the desired consistency without compromising the mechanical strength of the CPB.

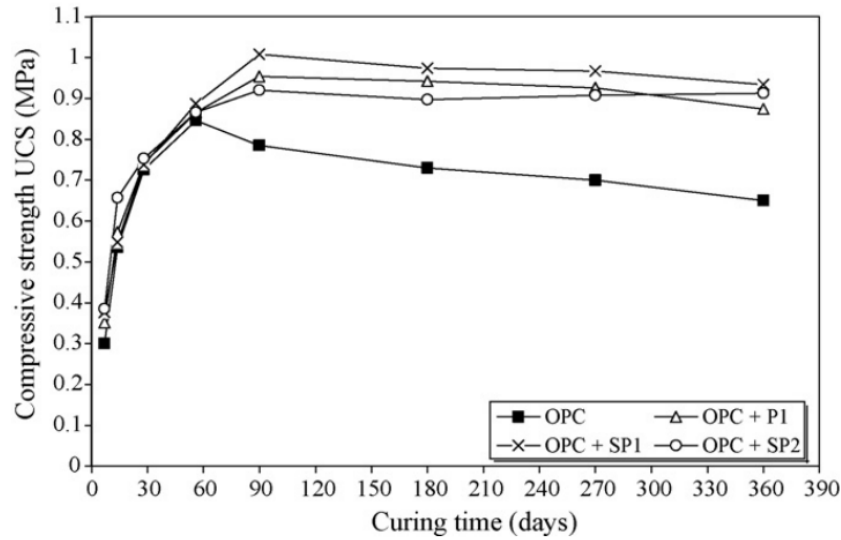


Figure 2.12 The effect of superplasticizers type on the mechanical strength of CPB produced from sulphide-rich tailings with time (Ercikdi et al. 2010)

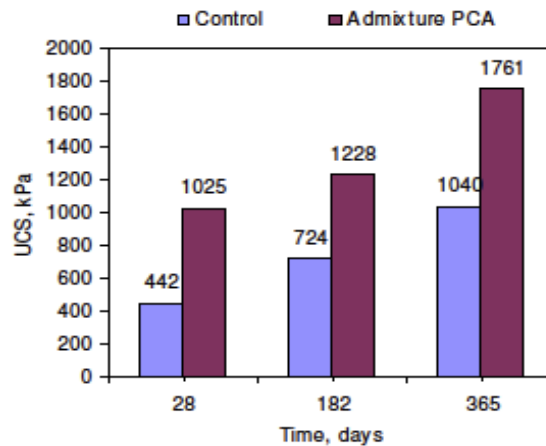


Figure 2.13 The effect of polycarboxylate-based superplasticizers on the UCS of CPB with time (Simon et al. 2011)

2.5 Thermal-hydraulic-mechanical-chemical factors or processes of CPB

In the field, CPB structure is subjected to various multiphysics internal and external factors, including (i) Thermal factors (T) which are related to the variation in temperatures, such as temperatures induced by the generated heat from binder hydration, high rock temperature in deep mines, geographical area of the mine (cold/warm region), and mine temperatures; (ii) Hydraulic factors (H) which include the variation in drainage conditions (i.e., drained, partially drained, and undrained conditions), positive pore water pressure (PWP), and negative pore water pressure (suction); (iii) Mechanical factors (M), which are affected by the variation in stresses (i.e., backfill

self-weight pressure, filling rate, and external loading); and (iv) Chemical factors (C) which are controlled by the chemistry and mineralogy of CPB components (i.e., tailings, cement, water, and additives) such as tailings type, tailings fineness, cement content, the chemistry of the mixing water (i.e., the presence of sulphate in the mixing water), and dosages and types of chemical admixtures. In addition, the coupled THMC processes significantly impact the short- and long-term performance, transportation, and placement of CPB materials, as shown in Figure 2.14 (Ghirian and Fall 2017).

Understanding the THMC processes and their coupled effects is paramount for the cost-effective, safe, and sustainable design of CPB structures. Previous authors have investigated and assessed the impact of THMC processes on the mechanical strength development of CPB with time under common laboratory conditions (i.e., in stress-free, room temperature or constant temperature conditions) and considered the effect of one or two factors and disregarded the impact of the THMC factors altogether. This primarily results from on-site sampling and testing challenges, including limited accessibility to filled stopes and safety concerns (le Roux et al. 2002). This section provides an inclusive literature review of the current knowledge of the THMC processes in CPB and their coupled effects.

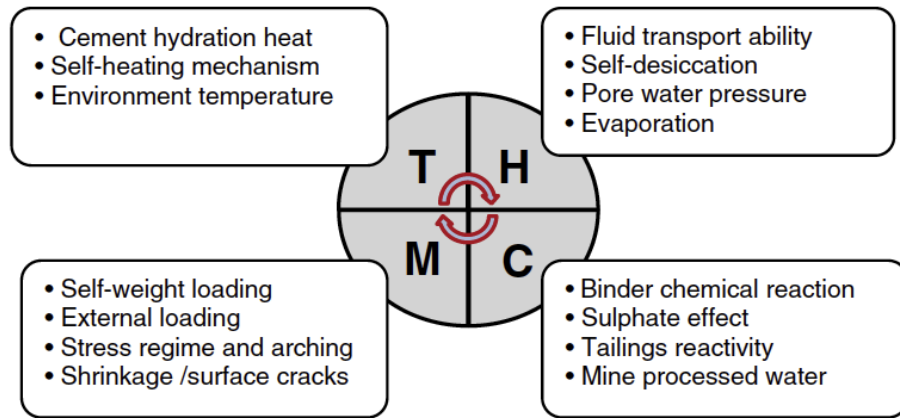


Figure 2.14 The coupled multiphysics THMC factors that affect the strength of CPB structures (Ghirian and Fall 2013a)

2.5.1 Thermal processes of CPB and influence factors

The thermal (or temperature) processes of CPB vary significantly from mine to mine and even from stope to stope, as well as during curing time. There are different sources of heat in mine backfilling operations, such as heat generated from the exothermic binder hydration reaction, host rock temperatures in deep mines, self-heating of sulfidic rock (and tailings) and the geographical area of the mine (cold/warm region), and mine temperatures (Fall et al. 2010; Ghirian 2016; Bull

and Fall 2020). The temperature fluctuations have been substantiated via on-site measurements (Thompson et al. 2009). These temperature changes largely depend on stope size, filling rate, binder type and content, w/c ratio, and mixing water chemistry (Nasir and Fall 2009).

Several studies (e.g., Fall and Samb 2009; Fall and Pokharel 2010; Fall et al. 2010; Wang et al. 2016; Cui and Fall 2016; Haruna and Fall 2020; Tian and Fall 2021) have been conducted to investigate the effect of the thermal process on the short- and long-term performance of CPB under various conditions. For example, Fall and Samb (2009) investigated the effect of isothermal curing temperatures (100°C, 200°C, 400°C, and 600°C) on the strength and microstructure (e.g., pore structure, porosity) of CPB with time using different types of tailings, tailing fineness, various w/c ratio, and through a laboratory setup designed to simulate the different high-temperature conditions. They observed that increasing temperatures up to 200°C generally enhances the strength of most studied hardened CPB types, as shown in Figure 2.15. Nevertheless, it is noteworthy that a significant strength reduction occurs, accompanied by changes in the CPB's microstructure when temperatures exceed 400°C. This reduction in strength can be attributed to several factors, including the thermal decomposition of hydrates and the development of microcracks at the interfaces between the tailings and cement.

Other studies (e.g., Fall et al. 2010; Wang et al. 2016) investigated the effect of different isothermal curing temperatures (2°C, 20°C, 35°C, and 50°C) and curing times on the mechanical strength of different types of hardening CPB samples. They found that the curing temperatures significantly influence the UCS values of CPB, and its effect largely depends on the binder type, w/c ratio, tailings type and curing time.

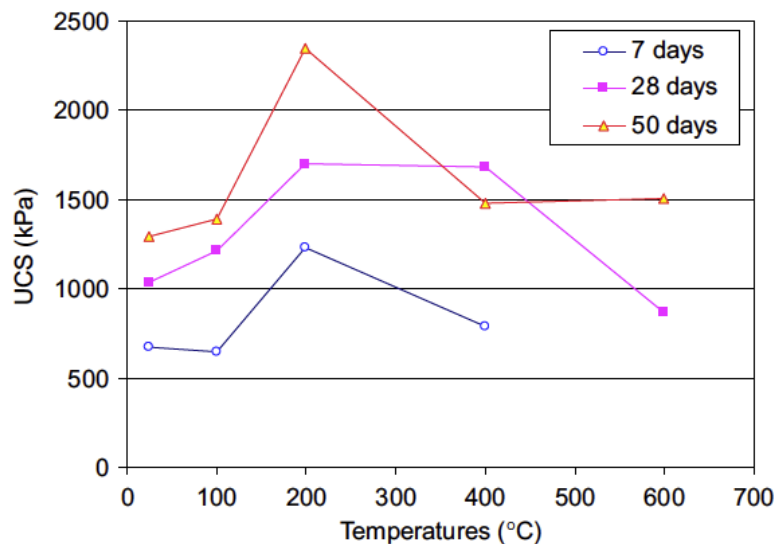


Figure 2.15 Effect of isothermal curing temperatures on the strength of CPB with various curing times (Fall and Samb 2009)

Fall and Pokharel (2010) studied the coupled effects of various sulphate contents (0, 5000, 15000, and 25000 ppm) and various isothermal curing temperatures (0°C, 20°C, 25°C, 35°C, and 50°C) on the strength development of CPB at different curing times (28, 90, and 150 days). They demonstrated that the influence of sulphate on the mechanical strength of the CPB is greatly affected by the curing temperature and time, as shown in Figure 2.16. They indicated that at curing temperatures of 20°C or lower, sulphate concentrations of up to 15,000 ppm positively influence the strength development of the CPB materials studied across all curing times. However, for CPBs with an initial sulphate content of 25,000 ppm, their strength tends to be lower, particularly at high curing temperatures of 50°C, irrespective of the curing period.

Cui and Fall (2016) designed an experimental setup to investigate the influence of various initial curing temperatures (5°C, 20°C, and 35°C) on the strength of CPB cured under elevated stress and various drainage conditions (drained and undrained). Their results reveal that the mechanical strength of CPB is greatly affected by the initial backfill temperatures, curing under stress, and drainage conditions, as shown in Figure 2.17.

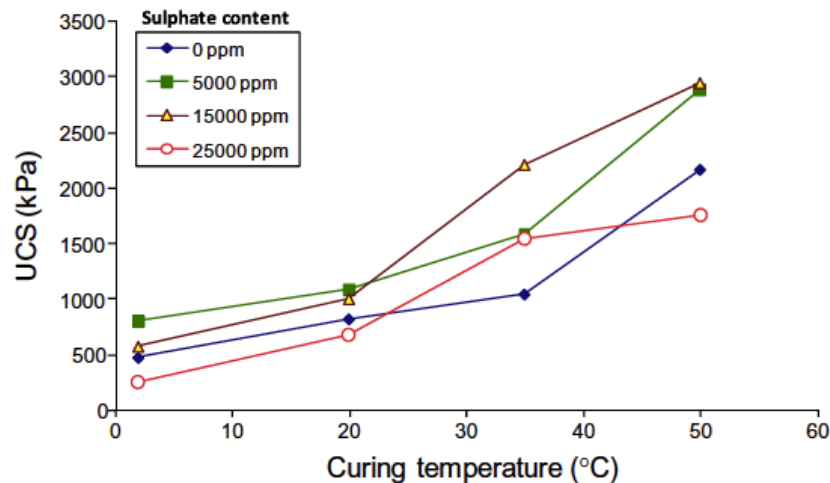


Figure 2.16 Coupled effect of isothermal curing temperatures and sulphate content on the strength of CPB with time (Fall and Pokharel 2010)

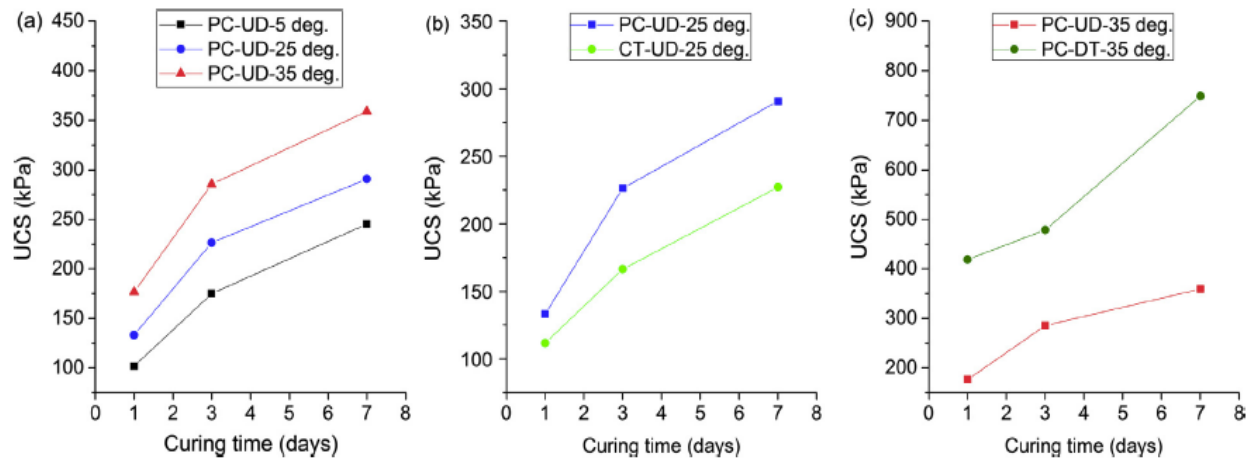


Figure 2.17 Effect of (a) different isothermal curing temperatures, (b) curing stress, and (c) drainage conditions on the evolution of UCS (PC: cured under pressure, CT: control test without pressure, UD: undrained test, and DT: drained test) (Cui and Fall 2016)

Haruna and Fall (2020) studied the influence of various constant temperatures (2°C, 20°C, and 35°C) on the strength development of CPB with superplasticizer mixtures at different curing times. They found that the UCS values significantly increase as the curing temperature increases, and it is more noticeable in the CPB samples containing superplasticizers. Moreover, Tian and Fall (2021) investigated the effect of field non-isothermal curing temperatures on the strength development of CPB with time using different tailing types and cement content. Their study concluded that field non-isothermal curing temperatures significantly increase the strength of CPB with time.

In general, all the previous studies obtained valuable information about the impact of curing temperatures on the performance of CPB, particularly the mechanical strength. However, while isothermal curing conditions (constant temperatures) were mostly considered in their studies, such conditions are not representative of CPB thermal curing conditions. In the field, CPB structure is subjected to non-isothermal curing conditions, which need to be considered for a more economical and reliable design of CPB structure.

2.5.2 Hydraulic processes of CPB and influence factors

The main hydraulic processes of CPB include positive pore water pressure, negative pore water pressure (suction), and self-desiccation (i.e., the reduction in the excess pore water pressure mainly caused by cement hydration in cementitious materials) (Li and Fall 2016). A grasp of how positive pore water pressures and suction evolve and progress within CPB is vital for evaluating CPB's short- and long-term mechanical performance. It is also crucial for assessing the stability of

barricades during the backfilling process of CPB. Barricade failure has terrible effects on mine operations, posing serious social and financial risks to mining workers' lives and increasing costs due to production delays (Shahsavari and Grabinsky 2016; Fang and Fall 2020). A barricade is constructed to withstand a specified pressure capable of supporting the weight of an extended column of freshly poured CPB material (Helinski et al. 2007; Helinski et al. 2011). This helps prevent the flow of CPB into adjacent stopes or active mining operations until the CPB has achieved its desired strength. When the CPB mixture is deposited into the stope, it applies hydrostatic pressures on the barricade equivalent to the CPB's unit weight times its height (Shahsavari and Grabinsky 2016). The positive pore water pressure within the CPB starts to develop and subsequently reduces the effective stresses of CPB materials. The primary engineering concern leading to barricade failure arises when the pressure generated by the CPB materials exceeds the designed pressure capacity of the barricades (Cui and Fall 2017). However, as the pore water pressure gradually dissipates over time and the negative pore water pressure (suction) within the CPB begins to develop, the effective stress of the CPB gradually increases. The excess positive pore water pressure within the CPB can be dissipated through pore water drainage and by self-desiccation through the cement hydration process. This development of effective stresses is pivotal for CPB to transition from a fluid-like state to a hardened state (Shahsavari and Grabinsky 2016; Ghirian and Fall 2015). Therefore, it is necessary to understand the development of positive pore water pressure and suction to ensure the stability of underground structures and barricades, as they need to withstand the evolving pressures applied by the CPB materials.

Several studies have been conducted in the past to evaluate the positive pore water pressure (PWP) and negative pore water pressure (suction) development within the CPB under different curing conditions (e.g., Abdul-Hussain and Fall, 2011; Helinski et al. 2007; Shahsavari and Grabinsky 2015, 2016; Wang et al. 2016; Ghirian and Fall 2013, 2015). For instance, Helinski et al. (2007) studied the reduction in pore water pressure (i.e., self-desiccation) due to the cement hydration process through an analytical model, and they experimentally verified it using two different types of tailings. They stated that the volume changes resulting from the cement hydration process led to significant changes in the pore water pressure. The reduction in pore water pressure is significantly influenced by factors such as the type of tailings and the cement used, the quantity of water consumed during cement hydration, material stiffness, and material porosity, as shown in Figure 2.18.

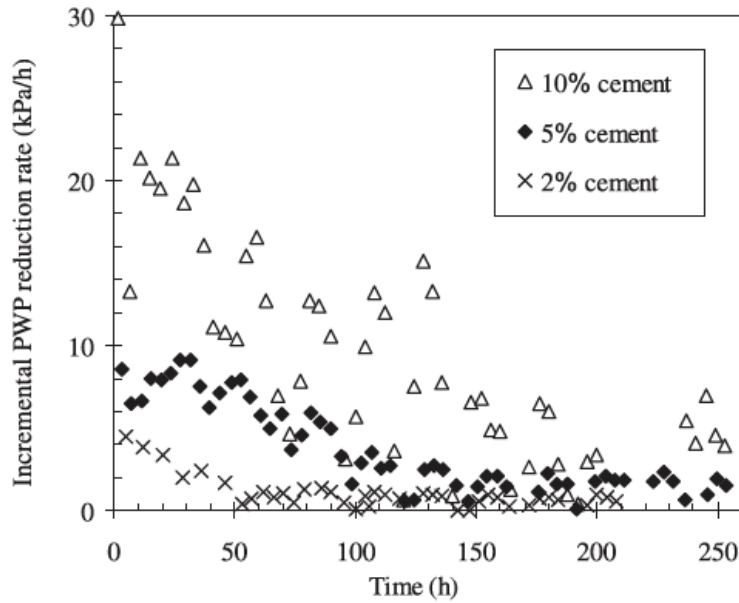


Figure 2.18 Rate of pore water pressure reduction with time for various cement content (Helinski et al. 2007)

Shahsavari and Grabinsky (2015 and 2016) modified a numerical model to predict the pore water pressure variation within the backfill stope under various material properties, backfill depth and weight. Ghirian and Fall (2013 and 2015) experimentally investigated the effect of drainage conditions and filling rate on the development of positive pore water pressure (PWP) and negative pore water pressure (suction) within the CPB materials with time. They established that the pore water pressure significantly increases at an early age as the filling rate increases, and the application of both drainage and curing under stress on the CPB materials at the early hours of curing causes a quick development of suction.

However, to date, there is a lack of knowledge on the impact of coupled (Thermal-Hydraulic-Mechanical-Chemical) THMC factors on pore water pressure development within the CPB, such as the impact of variations in temperatures in the field, the impact of pressure applied to the CPB materials (e.g., overburden pressure), drainage conditions (drained, partially drained, and undrained), and the effect of additives (i.e., superplasticizer). Therefore, it is important to address the development of positive and negative pore water pressure within CPB materials containing superplasticizers under simulated field conditions, encompassing various coupled THMC processes.

2.5.3 Mechanical processes of CPB and influence factors

Mechanical strength is one of the most important design criteria for a cost-effective and stable CPB structure (Fall et al. 2007). In underground mine operations, CPB must meet specific mechanical compressive strength requirements to ensure the safety of all mining personnel and a secure underground working environment (Fall et al. 2010). For instance, in cut and fill mining, the 28-day compressive strength necessary to ensure backfill stability typically falls below 1 MPa (Fall et al. 2010). In contrast, when CPB serves as roof support, the strength requirement rises to over 4 MPa (Fall et al. 2010). Nevertheless, when CPB is used for void filling or underground disposal, the desired compressive strength typically ranges from 150 kPa to 300 kPa (Fall et al. 2010). The mechanical compressive strength of CPB is usually assessed or measured using the uniaxial compressive strength (UCS) test (Belem et al. 2000). The UCS is a reliable, quick, and relatively inexpensive test, which makes it easy to incorporate into routine quality check procedures at mining operations (Vergne 1996). Other tests or methods, such as direct shear and triaxial tests, can be used to evaluate the shear strength parameters and stress-strain relationship (Ghirian 2016). Indirect test methods, such as ultrasonic wave measurements, thermal profiling, and shear wave velocity, can also be used to evaluate the mechanical strength of CPB structures (Ercikdi et al. 2014; Ghirian 2016).

Many factors influence the mechanical strength of CPB structure, such as tailings mineralogy and fineness, curing conditions (including curing time and curing under stress), curing temperature, solid content, cement content, cement type, w/c ratio, dosage and type of admixtures, and presence of sulphate (Fall et al. 2005; Kesimal et al. 2005). These factors can significantly affect the design compressive strength of CPB structures and change the output or intended designed strength (Fall et al. 2010; Ghirian and Fall 2017).

Several studies have been conducted in past years to assess the UCS development of CPB (Yilmaz et al. 2004; Klein and Simon 2006; Fall et al. 2007; Yilmaz, Belem et al. 2009; Yilmaz, Benzaazoua et al. 2009; Fall et al. 2010; Fall and Pokharel 2010; Ercikdi et al. 2014; Ghirian and Fall 2013; Cui and Fall 2016; Wang et al. 2016, Haruna and Fall 2020, Chen et al. 2022). These studies have considerably contributed to a better understanding of the strength of CPB and its evolution with the curing time. Nevertheless, there is limited understanding of the development of the mechanical strength of CPB structure in real-world conditions (in-situ conditions), and most of these assessments are conducted under standard laboratory curing conditions (i.e., in stress-free, room temperatures or constant temperature conditions). For example, Yilmaz et al. (2004) investigated the effect of binder type and tailings chemistry on the long-term strength development of CPB samples using two types of sulphur-rich tailings and various types of cement. Their results indicated that the physical, chemical, and mineralogical compositions are important criteria that

affect the performance of CPB, and ordinary Portland cement is not an appropriate binder for sulphur-rich tailings to provide long-term strength due to sulphate attack and the subsequent deterioration in the strength of CPB.

Klein and Simon (2006) studied the effect of CPB composition, including binder type and content, chemical admixtures (superplasticizers), mineral additive (fly ash), and pore fluid chemistry on the strength development of CPB. They found that the mechanical strength of CPB is sensitive to paste composition, and CPB's mechanical strength is highest when the paste contains superplasticizers. Yilmaz et al. (2009) designed a curing under applied pressure system (named CUAPS), as shown in Figure 2.19, to mimic the in-situ curing conditions of CPB under self-weight consolidation settlement and/or geostatic stress. The designed CUAPS provides effective curing conditions (curing under stress and drainage port to allow water to drain) at a laboratory scale. They investigated the hydro-mechanical performance of CPB samples prepared from sulphide-rich mine tailings, two types of binder, and cured the CPB samples under two various pressure application scenarios (up to 500 kPa) and drainage conditions (drained and undrained). Their results highlighted the differences in the CPB strength obtained between laboratory and simulated in-situ conditions samples. They indicated that the compressive strength values of the CPB samples increase with increasing vertical stress, and the drainage rate increases with increasing pressure, as shown in Figure 2.20.

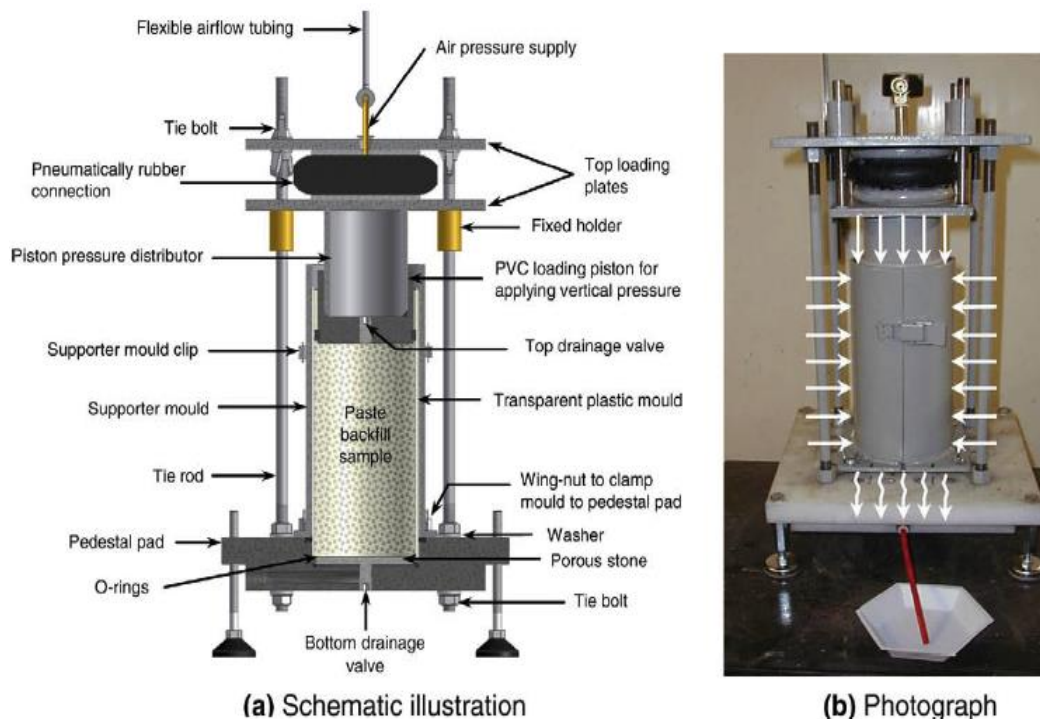


Figure 2.19 Curing under applied pressure system (CUAPS) apparatus to assess the hydro-mechanical performance of CPB (Yilmaz et al. 2009)

Yilmaz et al. (2009) conducted a similar study to examine the influence of curing under stress on the hydro-mechanical and geo-mechanical properties of CPB with time using different binder contents (3, 4.5, and 7 wt.%). Their results demonstrated the importance of considering the in-situ stress conditions in evaluating the mechanical performance of CPB. Also, they found that the UCS values significantly increase with the increase in the binder content, as shown in Figure 2.21.

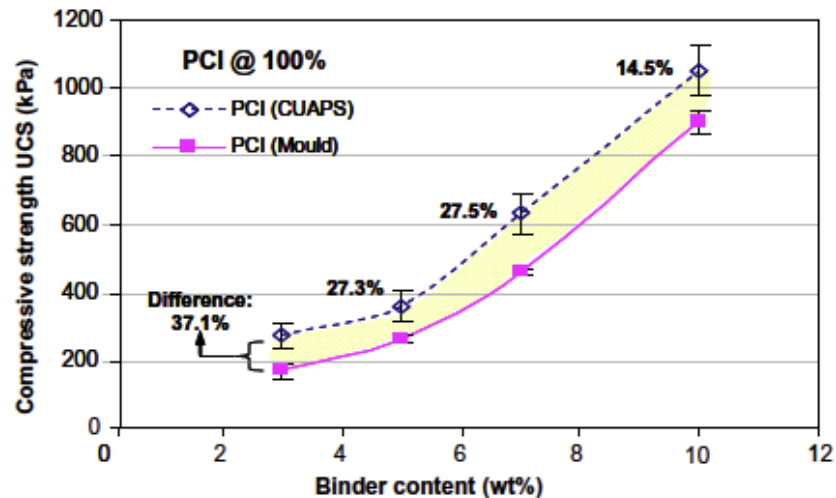


Figure 2.20 Effects of curing under applied pressure on the mechanical strength of CPB (Yilmaz et al. 2009)

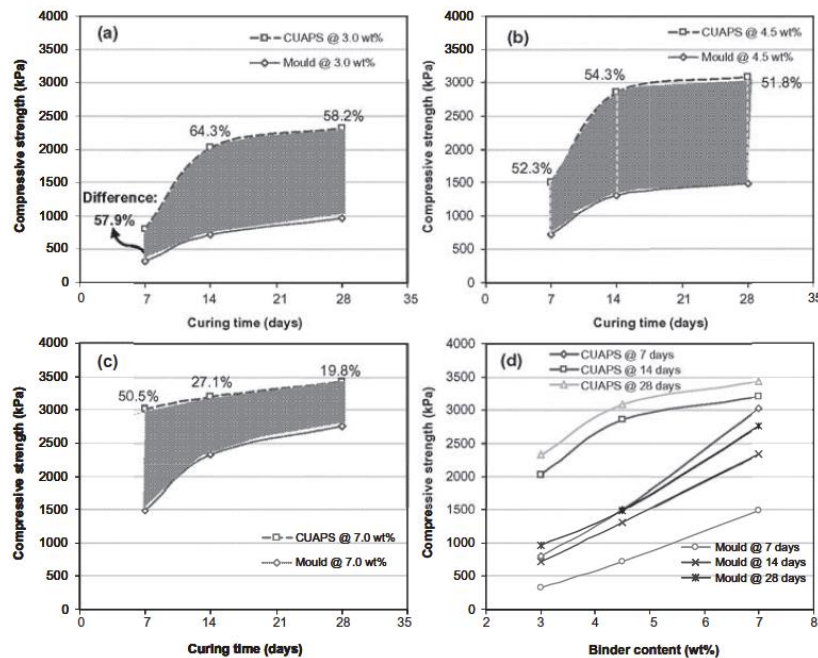


Figure 2.21 Effects of curing under applied pressure on the mechanical strength of CPB using different binder contents (Yilmaz et al. 2009)

Ghirian and Fall (2013) developed a pressure cell apparatus, as presented in Figure 2.22, to study the effect of curing under stress, filling strategy, and drainage conditions on the strength development of CPB with time. They adopted different loading conditions under different curing scenarios, including various filling rates and filling sequences (0.155 m/hrs, 0.31 m/hrs, and 0.62 m/hrs), as well as drained and undrained drainage conditions. They found that the mechanical strength of the drained CPB samples cured under a faster filling rate is significantly higher than the undrained CPB samples cured under lower filling rates, as shown in Figure 2.23. Also, they recorded excessive positive pore water pressure development at the early hours of curing within the undrained CPB samples caused by the application of pressure and drainage conditions, which resulted in lower UCS values during the early hours of curing compared to the control sample, as presented in Figure 2.24.

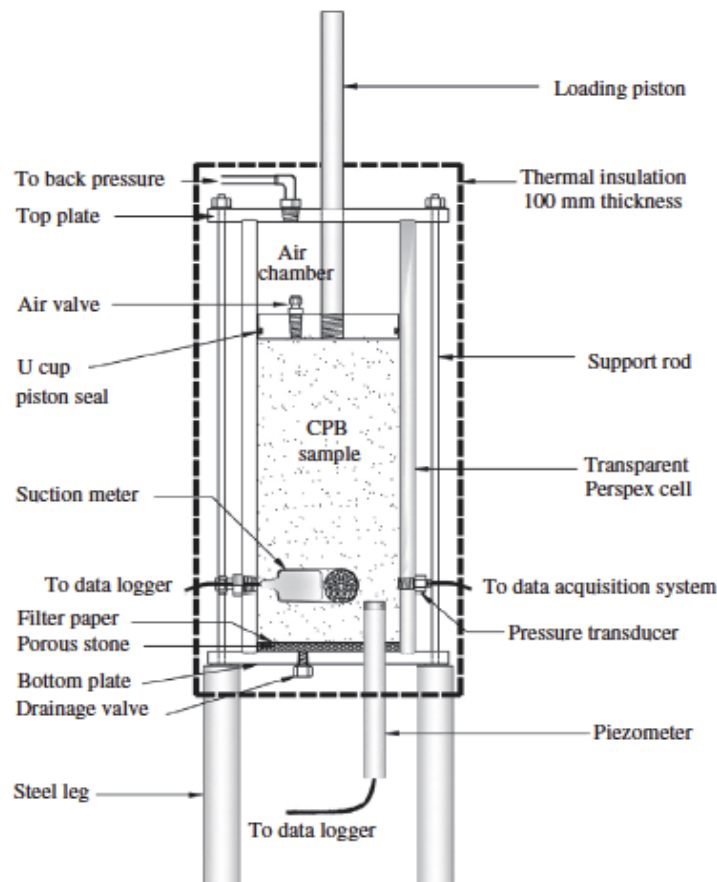


Figure 2.22 A pressure cell apparatus for assessing the mechanical strength of CPB (Ghirian and Fall 2013)

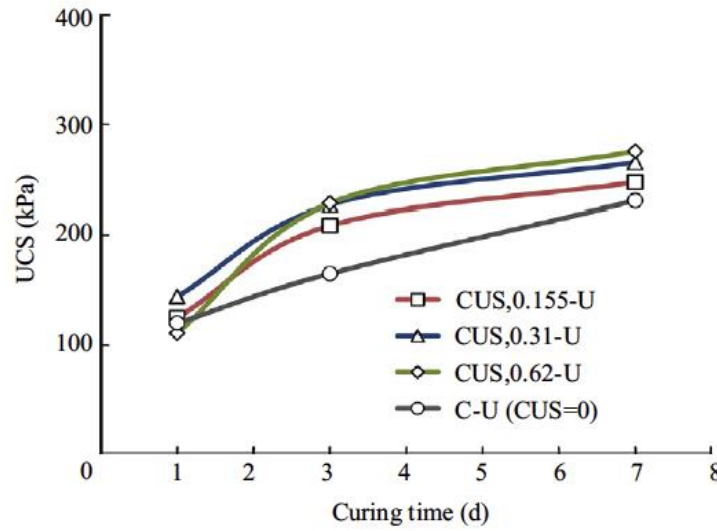


Figure 2.23 Effect of filling rate on the early age mechanical strength of CPB (Ghirian and Fall 2013)

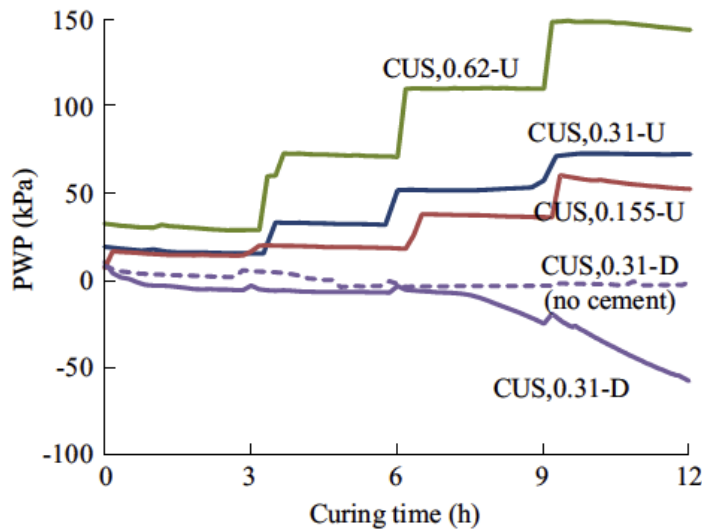


Figure 2.24 Pore water pressure development of CPB samples cured under different loading conditions (Ghirian and Fall 2013)

Chen et al. 2022 studied the physical-mechanical behaviour of CPB samples subjected to various curing stresses (0 kPa, 180 kPa, 360 kPa, and 540 kPa) using an apparatus designed to cure the CPB samples under stress, as shown in Figure 2.25. They conducted several mechanical tests, microstructural analyses, and electrical conductivity monitoring to demonstrate the impact of high-

pressure application on the CPB. They concluded that applying the pressure during the early curing periods increases the mechanical strength of the CPB, as presented in Figure 2.26.



Figure 2.25 Curing under-stress apparatus for assessing the mechanical strength of CPB (Chen et al. 2022)

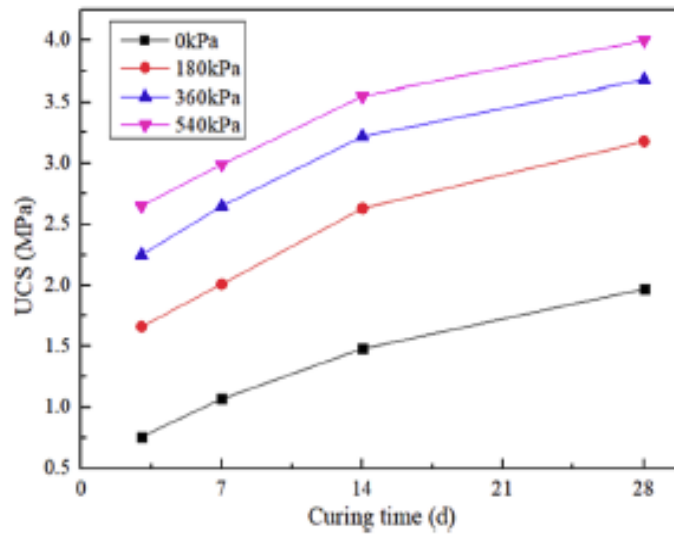


Figure 2.26 Effects of curing under stress on the mechanical strength of CPB with time (Chen et al. 2022)

Most of the literature review presented above shows the impact of one or two factors on the mechanical strength of the CPB. The impact of the combined THMC processes on the strength of CPBs with superplasticizer addition has not been investigated using curing conditions close to those encountered in the field. In other words, there is a complete lack of scientific information on the impact of the combined THMC factors on the UCS development of CPB with superplasticizer. For the reasons mentioned previously, it is necessary to remedy these knowledge gaps.

2.5.4 Chemical processes of CPB and influence factors

The chemical processes or factors of CPB are contingent on the chemical and mineralogical characteristics of its components, including the chemical composition and mineralogy of tailings, the chemical composition and reaction of binders used, the chemistry of mixing water, and the chemistry of the admixtures used. These chemical factors can significantly impact the short and long-term mechanical performance of CPB structure (Kesimal et al. 2005, Fang and Fall 2019). One of the most frequently established factors that affect the strength of CPB is its initial sulphate content (Li and Fall 2016). The content of sulphates (or sulfates) in CPB may range widely, from as low as 5,000 ppm to as high as 25,000 ppm and may come from various sources (Fall and Pokharel 2010). Sulphates can be found in CPB from various sources or ways: (i) the oxidation of sulphide minerals present in tailings. CPB made with sulphide-rich tailings (e.g., pyrite) can undergo oxidation when exposed to oxygen, a process known as weathering (Ghirian 2016). The extent of oxidation primarily depends on the pyrite content and degree of saturation. This weathering results in the release of metal ions and the generation of acid mine drainage, which can impact the environment (Ghirian 2016); (ii) The sulfur dioxide/air method utilized in gold mining; (iii) the addition of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or anhydrite (CaSO_4) to the cement; and (iv) the usage of mine processing water, typically rich in sulphate, during CPB preparation (Li and Fall 2016; Alainachi 2020).

The initial sulphate contents (i.e., sulphides and sulfates) present in the CPB components (i.e., tailings, binder, and mixing water) can adversely affect the development of CPB strength due to sulfate attacks. The presence of sulphate anions in the CPB inhibits cement hydration (Alainachi 2020). The reason for inhibition of cement hydration is due to the chemical interactions of sulphate anions with the C_3A compounds within the cement, which results in the forming of a thin coating around the C_3A compounds, which will act as a barrier, preventing the C_3A compounds from reacting with water and delaying the setting time, thus impacting strength development of cementitious mixtures (Li and Fall 2016). Many previous studies (Fall and Benzaazoua 2005; Ercikdi et al. 2009; Fall and Pokharel 2010; Pokharel and Fall 2013; Li and Fall 2016) have

investigated the impact of sulphate on the strength of CPB. These studies have established that the impact of sulphate on the strength is greatly contingent on the initial sulphate content and curing time. For example, Li and Fall (2016) investigated the impact of various initial sulphate contents (0 ppm, 5000 ppm, 15000 ppm, and 25000 ppm) on the mechanical strength of CPB samples cured at room temperature at early ages (1, 3, 7, 28 days). They stated that the initial sulphate content is a determinant of whether sulphate has a positive or negative impact on the strength of CPB at early ages. They found that low sulphate content (5000 ppm) has a negative effect on the strength at early ages (1 and 3 days) and a positive effect after 7 and 28 days of curing. In contrast, high sulphate concentrations (15,000 and 25,000 ppm) result in strength reduction at all early ages and the magnitude of the negative effect is increased with increases in the sulphate concentration, as presented in Figure 2.27. High sulphate concentrations result in strong inhibition of the binder hydration and produce excess formation of ettringite, sulphate absorption by C-S-H and coarsening of the pore structure of CPB, thus decreasing CPB's mechanical strength with time.

Moreover, as discussed earlier in Section 2.4.4, adding chemical admixtures, such as superplasticizers, significantly impacts the rheological and mechanical properties of CPB materials with time. Our understanding of the effect of sulphate content and other chemical admixtures, such as superplasticizers, on CPB's short- and long-term mechanical strength under coupled THMC loading conditions is still limited and needs to be addressed in this research.

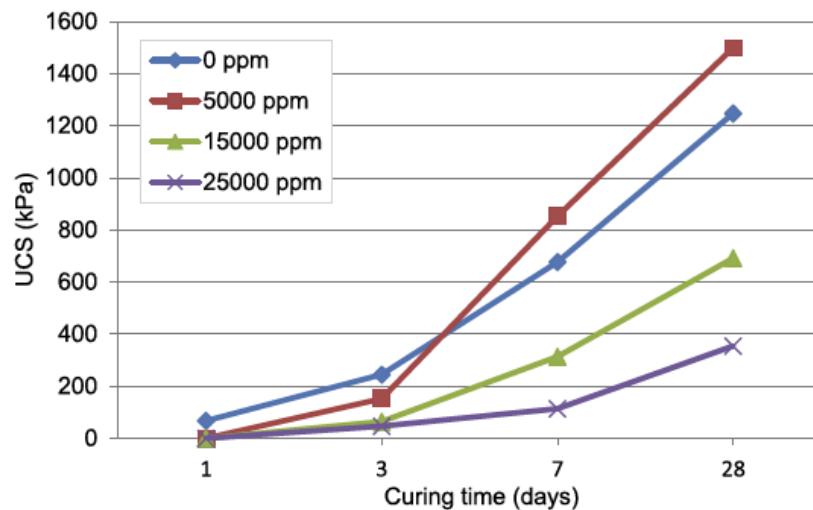


Figure 2.27 Effects of various initial sulphate content on the mechanical strength of CPB with time (Li and Fall 2016)

2.5.5 Coupled THMC processes of CPB

The short and long-term performance and stability of CPB structure are significantly governed by the four multiphysics THMC (thermal, T, hydraulic, H, mechanical, M, chemical, C) processes or factors. These factors are related and coupled (i.e., interact with each other). The extent to which one process or factor influences another may vary, creating weak or strong interactions among them (Ghirian and Fall 2017), as shown in Figure 2.28.

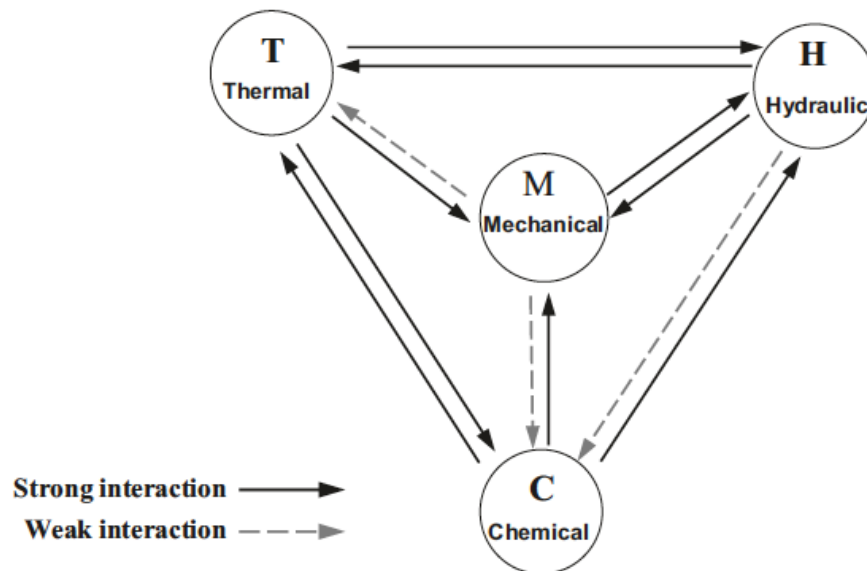


Figure 2.28 The multiphysics THMC processes or factors in CPB materials and their interactions (Ghirian and Fall 2017)

Understanding the complex interactions or the coupling of these THMC factors is vital for a cost-effective, safe, and sustainable design of CPB structures. In a coupled geotechnical system involving CPB structure, the individual factors exert influence on each other, impacting their initiation as well as their development (i.e., it is insufficient to predict the entire process by examining each factor individually as this could lead to a misunderstanding of the phenomena under study) (Jing and Feng 2003). Therefore, it is essential to investigate the related interactions between individual processes in a two-way manner (Ghirian and Fall 2017). For example, in processes that involve thermal and mechanical factors, a coupling may constitute a TM process, in which the thermal factor (T) may influence the mechanical factor (M). Conversely, in MT process, the mechanical factor (M) can impact the thermal factor (T) at different rates (Ghirian and

Fall 2017). This complex interplay among processes underscores the need for a comprehensive understanding of their interactions in THMC studies.

Previous authors (e.g., Nasir and Fall 2010; Abdul-Hussain and Fall 2012; Ghirian and Fall 2013, 2014, 2015, 2017; Wang et al. 2013; Haruna and Fall 2022) have investigated and assessed the coupled THMC processes or factors that affect CPB materials with time either partially or in combination. For instance, Wang et al. (2016) investigated the coupled THMC processes of CPB materials that contain sodium-silicate as an admixture with time. Their study examined the coupled evolution of thermal factors by adopting various initial temperatures (2°C, 20°C, 35°C, and 50°C), hydraulic factor by examining the evolution of self-desiccation (measured by volumetric water content and suction monitoring tests), mechanical factors assessed by the compressive strength tests (UCS), and chemical factors by studying the cement hydration process and the use of sodium-silicate as an admixture. They found that as the curing temperature increases, the cement hydration process (measured by the electrical conductivity test) accelerates in a rate proportionate to the increase in temperature. These thermo-chemical interactions then trigger the evolution of hydraulic factors (i.e., the suction starts to develop and increase with time), which directly affects the strength gain of CPB, as presented in Figure 2.29. They conclude that a consideration of the Effect of the coupled thermal-hydraulic-mechanical-chemical factors on the mechanical strength development of CPB at early ages (up to 28 days) played a crucial role in the design of stable and economical CPB structures.

Haruna and Fall (2020) investigated the coupled thermal (various isothermal temperatures (2°C, 20°C, and 35°C)), chemical (cement hydration process, use of superplasticizer as an admixture), and hydraulic (suction) on the strength development of CPB cured under common laboratory conditions (i.e., in stress-free). They found that the coupled THMC factors significantly affect the mechanical strength (i.e., USC) gain of CPB, and it is more manifest in the CPB samples containing superplasticizers.

From the reviewed studies, the importance of considering the THMC processes in the design of CPB structure can be observed. However, to date, no experimental studies have been conducted to investigate the effect of these coupled THMC processes on the strength of CPBs with the addition of superplasticizers considering curing conditions that resembling those encountered in real-world field scenarios.

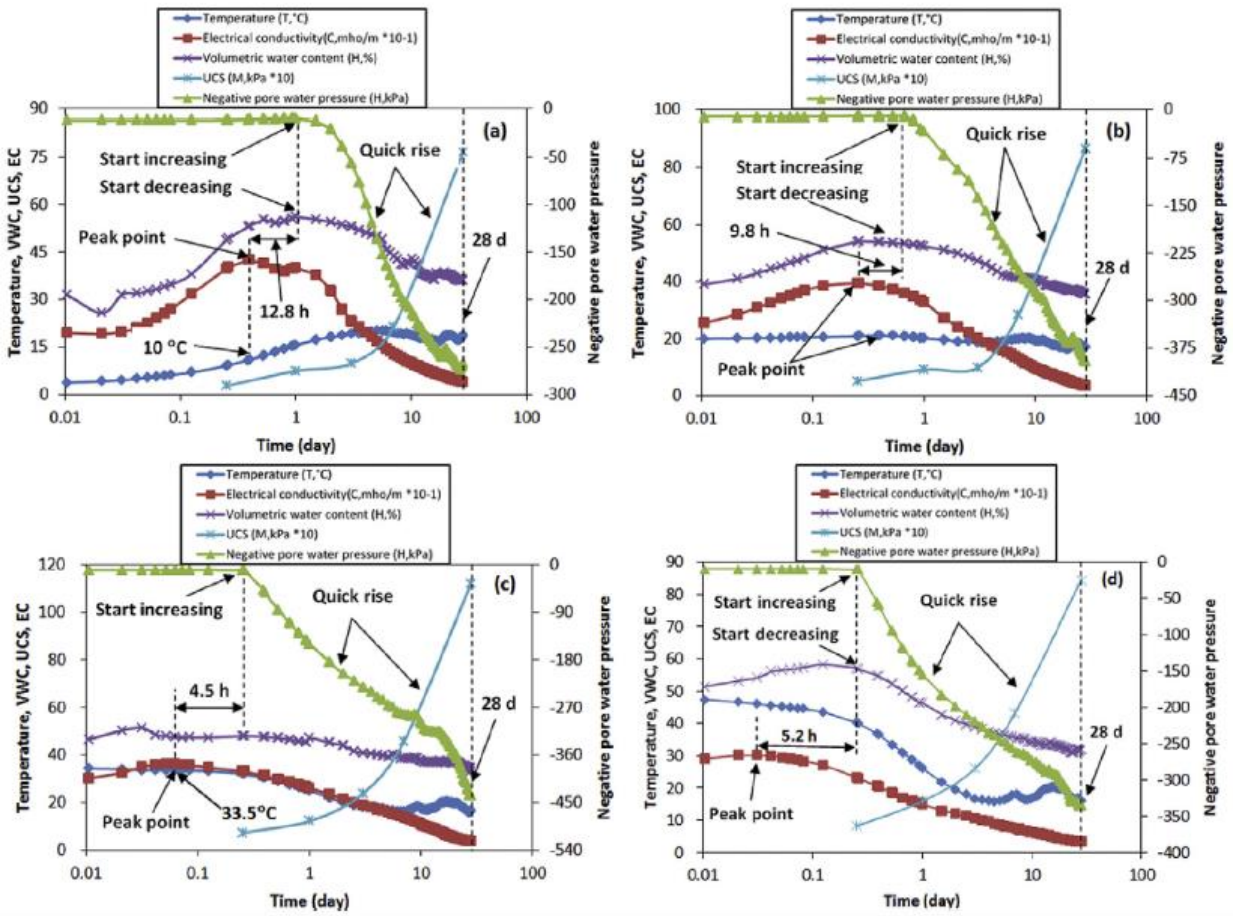


Figure 2.29 The coupled evolution of the THMC process and their effect on the strength of the CPB for various initial temperatures (a) 2 °C, (b) 20 °C, (c) 35 °C and (d) 50 °C (Wang et al. 2016)

2.6 Conclusion

Cemented Paste Backfill (CPB) technology is an innovative and vital component of modern mining and geotechnical engineering backfilling practices. CPB involves creating a cementitious mixture using more than 60% of hazardous mine wastes tailings, cement binders, water (fresh or mine processed), and chemical admixture or additives. This resulting paste is purposefully placed underground to provide structural support and safely dispose of mining waste materials. Understanding and optimizing the complex interaction of factors, including the thermal, hydraulic, mechanical, and chemical processes within CPB, are essential for ensuring its long-term stability and performance. From the reviewed literature, it can be observed that researchers investigated the multiphysics THMC (thermal, T, hydraulic, H, mechanical, M, chemical, C) processes or factors that affect the CPB individually or coupled under common laboratory conditions (room or constant temperatures and stress-free conditions) which are much lower than those expected under field conditions. The quality and reliability of data obtained from standard laboratory conditions used to design a CPB structure can hold significant consequences for the design of a safe and economically feasible CPB structure. Also, from the reviewed literature, the mining industries and several researchers have recognized and considered the benefits of adding superplasticizers to the CPB mixture on the mechanical performance of the CPB structure. However, the available literature on the inclusion of superplasticizers into CPB is still very limited, and to date, none of these studies address the short- and long-term impact of adding superplasticizers to the CPB mixture subjected to the coupled multiphysics THMC factors mentioned above. Therefore, there is a great need to investigate the impact of the coupled multiphysics THMC of CPB with superplasticizers cured simulated from a representative field or underground stope conditions.

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Chapter 3: Further insight into the Strength Development of Cemented Paste Backfill Materials Containing Polycarboxylate ether-based Superplasticizer - Technical Paper 1

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Zubaida Al-Moselly, Mamadou Fall, Sada Haruna

Abstract:

The utilization of water-reducing admixtures has become immensely popular in underground mine backfilling operations not only to enhance the workability of cemented paste backfill (CPB, a mine construction material), but also for their ability to enhance the mechanical strength and long-term durability of CPB. This study aims to evaluate the effect of a polycarboxylate ether-based superplasticizer (PES) on the mechanical strength of CPB made with different mix components (tailings, dosages of PES, cement and solids contents, tailings fineness, and water chemistry), and subjected to various curing conditions (stress-free, under stress, constant temperature, and non-isothermal temperatures). An extensive experimental program has been conducted to investigate the uniaxial compressive strength development, hydraulic (positive pore pressure, suction) and microstructural properties of CPB with PES. The results show that including PES in CPB mixtures significantly increases the unconfined compressive strength (UCS) as well as affects the microstructure and hydraulic properties of CPB. This UCS increase depends on the amount of PES added, type and fineness of the tailings, sulphate content, and curing time. After 7 days of curing, the UCS of the CPB increases as the dosage of the PES is increased. The CPB that contain PES and cured under stress exhibit a higher compressive strength after just 3 days of curing as compared to that without PES and cured under similar stress conditions. It is also found that curing CPB under non-isothermal conditions considerably increases the compressive strength, and this increase is more significant with the presence of PES. These findings have significant impacts on the short- and long-term performances of CPB structures with PES and their associated economic implications for underground mine backfilling operations.

Keywords: Superplasticizer, cemented paste backfill, tailings, pore pressure, mine, curing under stress, cement.

3.1 Introduction

One of the widely accepted remedies to preserve the natural environment, strengthen underground mine structures and increase regional stability is the use of cemented paste backfill (CPB) technology (Kesimal et al. 2005; Orejarena and Fall 2008; Cihangir et al. 2012; Wu et al. 2013; Yilmaz et al. 2014; Cao et al. 2018; Li et al. 2018). CPB, a backfilling material, is a mix of dewatered tailings from the milling or processing operations (70-85 wt.%), binders (usually 3-7 wt.%), and fresh and/or mine processed water (Yilmaz et al. 2003; Fall and Benzaazoua 2005; Abdul-Hussain and Fall 2011; Li and Fall 2018). CPB has an appearance and consistency close to those of fresh hydraulic cement concrete. The consistency of CPB as well as its flowability have significant implications for its transport from the paste plant to a stope (Ercikdi et al. 2010). This flowability of CPB is tremendously affected by each of its key components (tailings, binder, and water) (Benzaazoua et al. 2004; Nasir and Fall 2010). Successful application of CPB technology however requires preparing CPB mixtures with suitable or optimal flowability.

In response to a large number of demands to optimize the transport of high-density CPB mixtures to stopes and avoid any clogging of the pipelines systems induced by CPB with poor flowability, as well as minimize the costs associated with its transport into underground voids without jeopardizing the strength gain (Wu et al. 2013; Jung and Biswas 2002; Ercikdi et al. 2017), various investigations have been recently carried out to enhance the flowability of CPB by adding chemical compounds, such as superplasticizers. Superplasticizers are a high range water-reducing admixture used in the construction industry to improve the rheological properties of cementitious mixtures (i.e., enhance their flowability) while preserving the other required performance properties, such as the mechanical strength (Ercikdi et al. 2010; Ferrari et al. 2012; Haruna and Fall 2019). The main property of superplasticizer responsible for its beneficial effects on the rheological properties is its tendency to adsorb on the surface of cementitious mixtures and develop repulsive forces that disperse the particles (Ouattara et al. 2018; Yang et al. 2018; Haruna and Fall 2019). Several studies have demonstrated that the addition of superplasticizer to CPB can significantly improve its rheological properties, thereby enhancing its flowability (Ercikdi et al. 2010; Haruna and Fall 2019; Aiad 2003; Huynh et al. 2006; Ercikdi et al. 2010; Simon et al. 2011; Ouattara et al. 2017; Koohestani et al. 2018; Mangane et al. 2018; Haruna and Fall 2019; Guo et al. 2021). Applying superplasticizers to CPB mixtures can significantly reduce up to 30% of the mixing water content (Ercikdi et al. 2010; Haruna and Fall 2019).

Moreover, numerous previous studies have concluded that the addition of superplasticizer to CPB can increase its uniaxial compressive strength (UCS). The UCS is the key mechanical parameter needed to evaluate the mechanical stability of CPB. Ercikdi et al. (2010) reported a 20-50% improvement in the mechanical properties of CPB with a large amount of sulphate by adding

different types of superplasticizers (lignosulphonate, naphthalene sulfonate and polycarboxylate-based). Similar studies have been conducted to examine the effect of adding different types and/or dosages of superplasticizers on the compressive strength of CPB mixtures at various curing periods, with a focus on assessing the flowability of the CPB mixtures (Mangane et al., 2018; Ouattara et al., 2018; Yang et al. 2018; Zhang et al. 2018; Haruna and Fall 2021). The main outcomes of these studies are that workability, flowability and the mechanical strength can be significantly improved with an increase in the superplasticizer content, especially after 28 days of curing.

However, all of the previous studies on the UCS of CPB that contains superplasticizer are based on CPB cylinders cured under usual laboratory conditions (i.e., in stress-free, room temperature or constant temperature conditions). Consequently, the aforementioned results related to the UCS of CPB with superplasticizer are not representative of the in-situ mechanical strength of CPB with superplasticizer. This might lead to conservative (costly) and/or unsafe CPB and barricade designs. This is because during its curing in the field, the CPB is exposed to complex mechanical (e.g., stress induced by self-weight, filling rate), thermal (e.g., heat generated during cement hydration) and hydraulic (e.g., drainage) loading conditions (Le Roux et al. 2005; Yilmaz et al. 2009; Ghirian and Fall 2013, 2014). These conditions were not reflected or considered in the aforementioned previous studies. This means many fundamental questions about the strength development of CPB with superplasticizer are still unanswered. For example, what are the effects of curing stress, drainage, and field curing temperature on the strength development of CPB with superplasticizer? To date, there is no investigation tackling these important design issues. Moreover, no previous studies have examined the effect of sulphate on the strength of CPB with superplasticizer.

Haruna and Fall (2020) investigated the influence of various constant temperatures on the strength development of CPB with superplasticizer mixtures at different curing times. They obtained valuable information about the impact of curing temperature. However, while isothermal curing conditions (constant temperatures) were considered in their study, such conditions are not representative of CPB thermal curing conditions in the field. CPB masses are subjected to non-isothermal curing conditions in the field. Indeed, the heat source can significantly vary during mine backfilling operations or curing due to binder hydration and its transport through pipelines, self-heating of the surrounding rocks in deep mines, initial temperatures of the CPB mix constituents, depth and geographical area around the mine (cold/warm region) as well as the temperature of the mine (Fall and Pokharel 2010; Fall et al. 2010; Cui and Fall 2016; Wang et al. 2016). However, no studies have addressed the effect of non-isothermal curing conditions on the strength and deformation behaviour of CPB with superplasticizer. As such, there is a need to address the research and knowledge gaps mentioned above.

Moreover, it is well-known that changes in suction and pore water pressure (PWP) within the CPB significantly affect the strength of CPB (Abdul-Hussain and Fall 2011; Wang et al. 2016; Ghirian and Fall 2017). However, no studies have been performed on PWP or suction development in CPB with superplasticizer. Finally, the development of the CPB microstructure during binder hydration plays a significant role in its strength acquisition (Fall et al. 2010; Haruna and Fall 2021). Nevertheless, our understanding of the influence of adding different dosages of superplasticizer, and curing temperature, stress and time on the microstructure of CPB and the impact of the change in microstructure on the strength of CPB is still limited which requires further investigation for a better understanding of the behaviour.

Thus, the objective of this manuscript is to discuss the outcomes of an experimental study conducted: (i) to assess the effect of mix components (tailings; dosages of superplasticizer, water chemistry), curing time and stress, and non-isothermal curing conditions on the strength of CPB with polycarboxylate ether-based superplasticizer (PES); (ii) to gain insight into the PWP or suction development in CPB with PES and the effect on its strength; and (iii) to understand the changes in the microstructure of CPB with PES and the impact on its strength development.

3.2 Experimental program

3.2.1 Materials

3.2.1.1 Tailings

Natural gold tailings (GT), and synthetic silica tailings (ST) are utilized to prepare the fresh CPB in this study. The GT used are retrieved from a mine situated in eastern Canada. The ST were made with non-reactive ground silica powder which contains 99.8% silicon dioxide (SiO_2). The main reason behind using ST is to minimize the uncertainties in the study results. The chemical and mineralogical compositions of the reactive minerals found in natural tailings may alter the cement hydration process, and thus influence the analysis of the experimental results. The mineralogical compositions of both types of tailings that were obtained from an X-ray diffraction (XRD) analysis are presented in Table 3.1. The GT contain a wide range of reactive chemical elements (such as albite, chlorite, and pyrite), which may interact with the cement binder in the CPB. ST are essentially made of quartz. The physical characteristics of both types of tailings are presented in Table 3.2. The ST contain about 43 wt.% of fines, so that it can be classified as medium sized tailings (35-60 wt.% of 20 μm particles). Figure 3.1 shows that the ST have a grain size distribution that approximate the average particle size distribution of tailings in nine Canadian mines.

Table 3.1 Mineralogical composition of the tailings in this study

Tailings (wt.%)	Mineral										
	Quartz	Albite	Dolomite	Calcite	Chlorite	Magnetite	Pyrite	Talc	Pyrrhotite	Spinel	Others
ST	99.8	-	-	-	-	-	-	-	-	-	0.2
GT	15	32.8	15	4.2	16.1	2.4	1	7	1.8	1.8	2.9

ST: silica tailings; GT: gold tailings; wt.: weight.

Table 3.2 Physical properties of the tailings used in this study.

Element	G _s	D ₁₀	D ₃₀	D ₅₀	D ₆₀
Unit	-	μm	μm	μm	μm
ST	2.7	1.9	9.0	22.5	31.5
GT	3.1	3.2	15.8	35.5	49.5
Average of 9 types of tailing	-	1.8	9.1	20.0	30.8

G_s: specific gravity

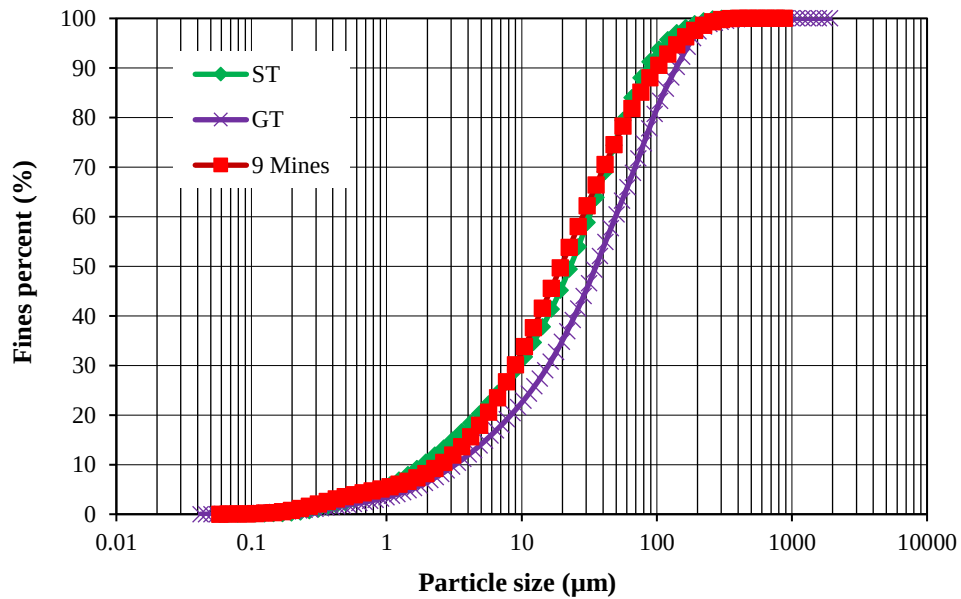


Figure 3.1 Particle size distribution of the tailing's material used and the average particle size distribution of tailings from nine mines in Canada

3.2.1.2 Cement and Mixing Water

Portland cement type 1 (PCI) was used (PCI is the most common type of binder used in CPB technology), and its chemical and physical properties are listed in Table 3.3. Ordinary tap water (TW) and distilled water (DW) were used to mix the binder and tailings. The purpose of using distilled water is to obtain an accurate sulphate concentration. The most common sulphate found in natural CPB is ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$), which was added to the distilled water in specific amounts to obtain mixing water with a sulphate concentration of 25,000 ppm.

Table 3.3 Chemical and physical properties of binder used.

Element (%)	SO ₃	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	CaO	MgO	Relative density	Specific surface (m ² /g)
PCI	3.82	2.70	4.53	18.03	62.82	2.65	3.20	1.30

3.2.1.3 Chemical Admixture

A polycarboxylate ether-based superplasticizer (PES) commercially known as MasterGlenium 7500 (Badische Anilin und Soda Fabrik or BASF SE, Germany) was employed as the admixture to prepare the CPB. The PES is a full-range water-reducing admixture used in the construction industry to improve the workability as well as increase the early age strength of concrete. The PES meets the ASTM C 494/C 499M requirements for Type A water-reducing and Type F high-range water-reducing admixtures (BASF 2015).

3.2.2 Specimen Preparation, Mix Proportions, and Stress-free Curing Conditions

The influence of the curing time, dosage of PES, and cement, solids, and sulphate contents on the strength of the CPB materials that contain superplasticizer (CPB-PES) was investigated by preparing different CPB-PES specimens with the use of different tailings (ST and GT), cement contents (3%, 4.5%, and 6% by weight), percentages of PES (0%, 0.125%, 0.25%, and 1% by weight), solids content (69% and 82%), and water (distilled, contains sulphate). The water to cement ratio (w/c) used is equal to 7.35. A summary of the mix composition of the prepared CPB-PES specimens is presented in Table 3.4.

First, the tailings and cement powder were mixed for about 2 minutes in a mechanical mixer. Then, the measured amount of water with the required percentage of PES was added to the CPB and thoroughly mixed and homogenized for 7 minutes. The freshly mixed CPB-PES was poured into plastic curing cylinders that are 5 cm in diameter and 10 cm in height and manually

vibrated to ensure that any entrapped air is removed. The yield stress and viscosity values of the prepared fresh CPB-PES varied between 30 and 190 Pa, 0.7 and 2.3 Pa.s, respectively, which is favourable to the transportability of the backfill in the field (Fall et al. 2010). To study the effect of tailings fineness on the strength of the CPB-PES system, fine, medium and coarse tailings were prepared. Fines (% of 20 μm particles $> 60\%$ by weight) were prepared by sieving the ST to remove the required amount of particles that are $> 20 \mu\text{m}$ until achieving % of 20 μm particles $> 60\%$ by weight, whereas the coarse tailings (% of 20 μm particles $\leq 35\%$ by weight) were prepared by mixing an appropriate amount of ST with sand to produce tailings with 20 μm particles $\leq 35\%$ by weight. The above-prepared molds were cured at a temperature of 20°C for 0.5, 1, 3, 7, and 28 days.

To assess the influence of sulphate in the CPB system on the strength of the CPB-PES samples, a total of 32 specimens were prepared with different percentages of PES (0% and 0.125% by weight) and mixing waters with two different initial sulphate contents (0 and 25,000 ppm), then cured at a temperature of 20°C for 7, 28, 90, 250, and 300 days.

To study the effect of the non-isothermal curing temperature on the strength of the CPB-PES system and simulate the temperature variations in mine backfill structures, five sets of CPB specimens with 0% and 0.125% by weight of PES were examined. Each set of specimens was cured under different temperature histories (H1, H2, and 20°C; see Figure 3.2) in a temperature-controlled chamber. H1 and H2 represent the temperature readings with time at a point located 2.5 m above the bottom of the two CPB stopes with a height and width of 20 m x 10 m and 5 m x 2.5 m, respectively, based on Nasir and Fall (2009). The CPB-PES specimens were cured for 0.5, 1, 3, 7, and 28 days.

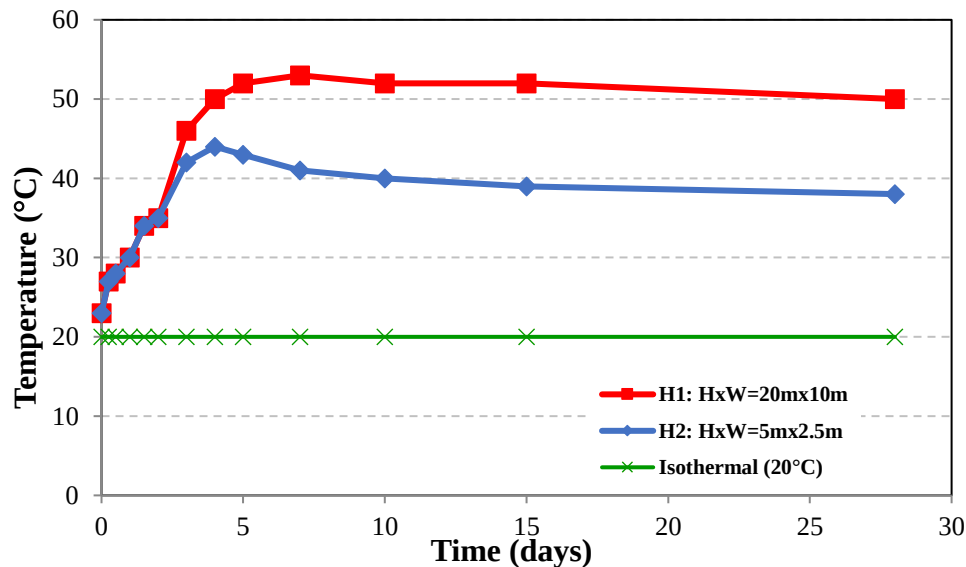


Figure 3.2 Temperature histories of CPB for different stope sizes (modified from: Nasir and Fall 2009). (H: stope height; W: stope width)

3.2.3 Pressure Cell Experiment Set-up, Instrumentation, and Pressure Application

In addition to the above-mentioned CPB-PES specimens, two sets of CPB-PES samples with different percentages of PES (0% and 0.125% by weight) at an initial temperature of 20°C were used to demonstrate the effect of curing stress on the CPB-PES system. The CPB-PES specimens were prepared in the same manner as described above, and cured under stress for 0.5, 1, 3, 7, and 28 days.

A pressure cell apparatus developed in Ghirian and Fall (2015, 2016) at the University of Ottawa was used to replicate the actual field conditions and investigate the influence of self-weight (overburden pressure) or curing stress produced by mine stope filling processes on the engineering properties of the CPB-PES. The main parts of the pressure cell comprised a Perspex (acrylic plastic) mold with a diameter of 101.6 mm (4 inches) and a height of 304.8 mm (12 inches), an axial loading piston located on the top base end of the mold, and a layer of glass wool blanket with a thickness of 100 mm for thermal insulation and slowing down the heat transfer between the CPB-PES and surrounding environment as shown in Figure 3.3. The purpose of the thermal insulation is to simulate the relatively slow heat transfer between a narrow CPB stope and the surrounding rock mass in the field, as well as study the effect of the heat generated by CPB hydration during curing on the strength of the CPB-PES system (Ghirian and Fall 2015; Wang et al. 2016).

Moreover, different sensors were installed in one of the four cells assigned for each curing time to monitor the behaviour of the CPB-PES samples and measure the different CPB-PES properties, such as electrical conductivity (EC), suction and temperature changes during the specified curing time. In addition, the changes in the PWP were measured with Omega PX309 pressure transducers at a range of -15 to +15 PSI and $\pm 0.25\%$ accuracy, and a LVDT was connected to the loading piston rod to record any deformations caused by the applied load and/or binder hydration. All of these sensors were attached to a Decagon Em50 data logger to record the experiment data with time.

Undrained CPB-PES conditions are adopted in this study, which take into consideration the worst-case scenarios in the field, thus representing a conservative approach in analyzing the mechanical stability of CPB-PES structures. Several studies have shown that the CPB strength in undrained backfilled conditions is lower than in drained backfilled conditions (Le Roux et al. 2005; Nasir and Fall 2010; Cui and Fall 2016). Fresh CPB-PES was cast into the pressure cell up to a height of 200 mm (length-to-diameter ratio of 2). An initial set pressure of 20 kPa was immediately applied onto the CPB-PES specimen through the piston to ensure full contact between the specimen and the vertical piston. Then, air pressures of 35, 55, 75, and 150 kPa were gradually applied at intervals of 3 h. Afterwards, air pressures of 300, 450, and a maximum of 600 kPa (for lab safety regulations) were applied every 24 h, which represented an equivalent filling rate of 0.48

m/h. The maximum pressure of 600 kPa represents the CPB pressure at 34.9 m deep (assuming that the initial density of the CPB is 1.72 g/cm^3 and neglecting the arching effects).

3.2.4 Mechanical Tests

UCS tests were carried out in accordance with the procedure in ASTM C39 on the CPB-PES specimens at various early and long-term ages (0.5, 1, 3, 7, 28, 90, 250, and 300 days). To ensure the repeatability of the test results, a minimum of two samples were used for each curing time. A computer data acquisition system with a constant deformation rate of 1 mm/min was utilized.

3.2.5 Microstructural Analysis

Several microstructural techniques are implemented in this study to examine the effect of the PES, curing time, temperature and stresses on the cement hydration process or pore structure of the CPB-PES. After the specified curing time, all of the samples used for the microstructural analysis were oven-dried at 45°C until mass stabilization to remove the free water. The microstructural properties of the CPB-PES samples were analyzed by conducting thermal gravity (TG), differential thermal gravity (DTG), X-ray diffraction (XRD), scanning electron microscopy (SEM) observation, and mercury intrusion porosimetry (MIP) tests.

The TG and DTG analyses were done on the cured samples ($w/c = 1$; to simulate the high-water content of CPB) prepared in the same manner as the CPB-PES samples. The tests were conducted by using a thermogravimetric analyzer, which involves continuous measurements and recordings of the weight loss, heat flow, and temperature transitions in the sample at a rate of 10°C per minute up to 1000°C .

XRD tests were performed to study the mineralogical composition of the hydration products of the CPB-PES. The XRD tests were conducted on the cured cemented paste samples with a Scintag XDS2000 powder diffractometer. SEM observation tests were performed to examine the texture of the CPB-PES with a Hitachi S4800 field emission scanning electron microscope.

The MIP tests were done on the CPB-PES samples by using a Micromeritics AutoPore III 9420 mercury porosimeter to assess the pore size distribution and total porosity of the CPB-PES system. Moreover, the microstructural properties of the CPB-PES samples were also studied by conducting void ratio (e) and porosity (n) tests on the CPB-PES specimens.

3.2.6 Electrical Conductivity and Temperature Monitoring

In order to evaluate the progression of cement hydration, temperature changes, and structural variations that commence within the hydration of cementitious materials, a 5TE temperature sensor was used to measure the electrical conductivity (EC) and monitor the temperature of the CPB-PES samples for various curing times (0.5, 1, 3, 7, and 28 days). The EC can measure the change in ion concentration in the pore fluid of the CPB as a result of cement hydration reactions (Ghirian and Fall 2017). The 5TE temperature sensor can measure the EC with an accuracy of ± 0.1 in the range of 0-23 dS/m, as well as measure and monitor the changes of temperature with an accuracy of $\pm 1^\circ\text{C}$ and a temperature range of -40°C to 60°C . The 5TE temperature sensor was attached to the Decagon Em50 data logger to record the experimental data with time.

3.2.7 Volumetric Water Content and Suction Monitoring

The volumetric water content (VWC) monitoring tests were carried out to examine water consumption of the CPB-PES samples from the cement hydration process for various curing times (0.5, 1, 3, 7, and 28 days). VWC monitoring was performed with the 5TE sensor (also used to monitor the EC), which can measure the VWC in a range of percentage from 0 to 100% with an accuracy of $\pm 15\%$ from 40-80. Likewise, suction monitoring was performed on the CPB-PES samples cured under stress for various curing times (0.5, 1, 3, 7, and 28 days). The development of suction was done by using an MPS-6 dielectric water potential sensor at a range of -9 to $-100,000$ kPa and an accuracy of $\pm 10\%$ of reading $+2$ kPa from -9 to 100 kPa.

Table 3.4 Summary of mix composition of specimens used

Sample Name	Tail-ings type	Binder content (%)	W/C ratio	Mixing water	PES content (%)	Solid content (%)	Curing stress	Curing temperature (°C)
<i>Effect of tailings type and curing time on the UCS of CPB-PES</i>								
ST-0.0%	ST	4.5	7.35	TW	0	75	0	20
ST-0.125%	ST	4.5	7.35	TW	0.125	75	0	20
GT-0.0%	GT	4.5	7.35	TW	0	75	0	20
GT-0.125%	GT	4.5	7.35	TW	0.125	75	0	20
<i>Effect of curing time and PES content on the UCS of CPB-PES</i>								
ST-0.0%	ST	4.5	7.35	TW	0	75	0	20
ST-0.125%	ST	4.5	7.35	TW	0.125	75	0	20
ST-0.25%	ST	4.5	7.35	TW	0.25	75	0	20
ST-1.00%	ST	4.5	7.35	TW	1.00	75	0	20
<i>Effect of cement content on the UCS of CPB-PES</i>								
ST-3.0%	ST	3.0	7.35	TW	0.125	82	0	20
ST-4.5%	ST	4.5	7.35	TW	0.125	82	0	20
ST-6.0%	ST	4.5	7.35	TW	0.125	82	0	20
ST-6.0%	ST	6.0	7.35	TW	0.125	69	0	20
<i>Effect of tailings fineness on the UCS of CPB-PES</i>								
CT-0.125%	CT	4.5	7.35	TW	0.125	75	0	20
MT-0.125%	ST	4.5	7.35	TW	0.125	75	0	20
FT-0.0%	FT	4.5	7.35	TW	0	75	0	20
FT-0.125%	FT	4.5	7.35	TW	0.125	75	0	20
<i>Effect of mixing water chemistry (sulphate) on the UCS of CPB-PES</i>								
ST-0.0%-0.0 ppm	ST	4.5	7.35	DW	0	75	0	20
ST-0.125%-0.0 ppm	ST	4.5	7.35	DW	0.125	75	0	20
ST-0.0%-25,000 ppm	ST	4.5	7.35	SW	0	75	0	20
ST-0.125%-25,000 ppm	ST	4.5	7.35	SW	0.125	75	0	20
<i>Effect of curing under stress on the UCS of CPB-PES</i>								
ST-CUS-0.0%	ST	4.5	7.35	TW	0	75	CUS	20
ST-CUS-0.125%	ST	4.5	7.35	TW	0.125	75	CUS	20
<i>Effect of non-isothermal curing temperature on the UCS of CPB-PES</i>								
ST-H1-0.0%	ST	6.5	7.35	TW	0	75	0	H1
ST-H1-0.125%	ST	6.5	7.35	TW	0.125	75	0	H1
ST-H2-0.125%	ST	6.5	7.35	TW	0.125	75	0	H2
ST-20 °C-0.0%	ST	6.5	7.35	TW	0	75	0	20
ST-20 °C-0.125%	ST	6.5	7.35	TW	0.125	75	0	20

Notes: ST: silica tailings; GT: gold tailings; W/C ratio: the ratio of the mass of water to the mass of the binder; PES: polycarboxylate ether-based superplasticizer; TW: tap water; DW: distilled water; SW: water with sulphate; CT: coarse tailings; MT: medium sized tailings; FT: fines; CUS: curing under stress; H1: Temperature History 1; and H2: Temperature History 2.

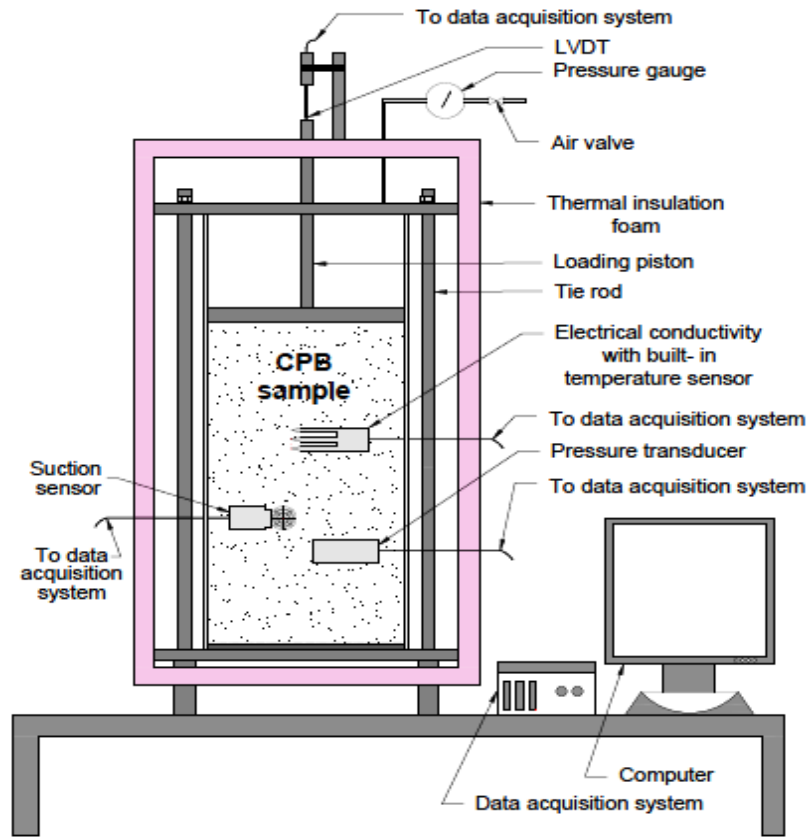


Figure 3.3 Illustrative diagram of the pressure cell set-up and sensor arrangement (modified from: Ghirian and Fall 2015)

3.3 Results and discussion

3.3.1 Effect of curing time on the strength development of CPB-PES

Figures 3.4 and 3.5 depict the evolution of the mechanical strength of the CPB samples made, respectively, with ST and GT with different amounts of PES. It can be seen that irrespective of the tailings type, the mechanical strength of the CPB increases as the curing time is increased. This increase can be mainly attributed to the strength hardening process of the CPB owing to the precipitation of a large volume of cement hydration products, such as C-S-H, CH, and ettringite (Benzaazoua et al. 2004; and Fall et al. 2010). The C-S-H is the main bonding phase in the cement hardening process (Taylor 1993; Gan 1997). Indeed, the large quantity of cement hydration products significantly contributes to the strength gain of CPB over time due to increased cohesion and the pore refinement (decrease in porosity) of the pore structure (Fall et al. 2010). This increase in cement hydration products is congruent with the results of the TG/DTG analysis conducted on the CPB-PES cement paste samples with PES dosages of 0% and 0.125% that were cured for 7 days; see Figure 3.6. In this figure, the first peak (between 100°C and 200°C) represents the

immediate drop in weight due to the dehydration of water molecules in the hydration products – the ettringite, gypsum and C-S-H (Fall et al. 2010). Furthermore, the second peak (400°C - 500°C) comes from the de-hydroxylation of CH, and the third peak or the weight loss (650°C - 750°C) represents the calcite decomposition (Fall et al. 2010).

Similarly, for both the GT and ST, the CPB samples that contain 0.125% PES exhibit considerably higher compressive strength than those that contain no PES after 3 days of curing. For example, the UCS values of the CPB made with ST and cured for 28 days increase from 534 kPa to 706 kPa with an increase in the dosage of PES from 0% to 0.125% as shown in Figure 3.4. This increase in the strength is attributed to the dispersion effect of the PES in the CPB mix. Repulsive forces between the solid particles form when superplasticizers adsorb on the surface of CPB mixtures which prevent the particles from flocculating (Klein and Simon 2006; Ercikdi et al. 2010). This process of dispersing the cement particles inhibits their hydration at an early age (Siler et al. 2014; Haruna and Fall 2020). Indeed, Figures 3.4 and 3.5 reveal that the compressive strength of CPB specimens that contain ST and GT with 0.125% PES cured for less than 7 days is lower than that of the samples with no PES. For example, the UCS of a 12 h GT-CPB sample without PES is 80 kPa, whereas with the addition of 0.125% PES, the UCS decreases to 55 kPa. Furthermore, the UCS of the GT samples is a lower value in comparison to that of the ST samples. This can be ascribed to several reasons associated with the physical properties and mineralogy of GT, such as specific gravity and grain size distribution (see Tables 3.1 and 3.2). This finding is supported by a number of other studies on the mechanical strength of CPB (Yilmaz et al. 2014; Ghirian and Fall 2015; Wang et al. 2016; Haruna and Fall 2020).

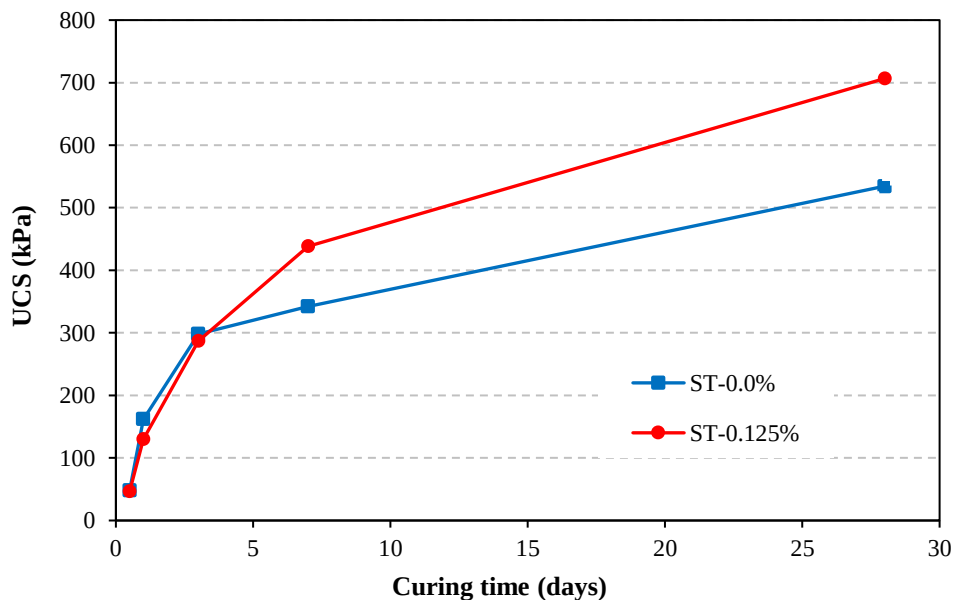


Figure 3.4 Strength (UCS) of ST-CPB with different dosages of PES

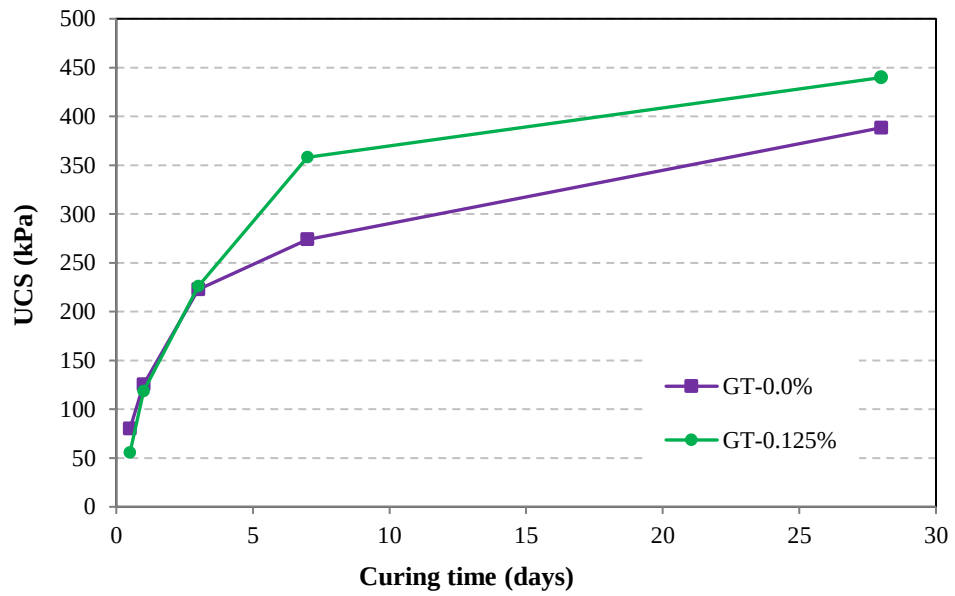


Figure 3.5 Strength (UCS) of GT-CPB with different dosages of PES

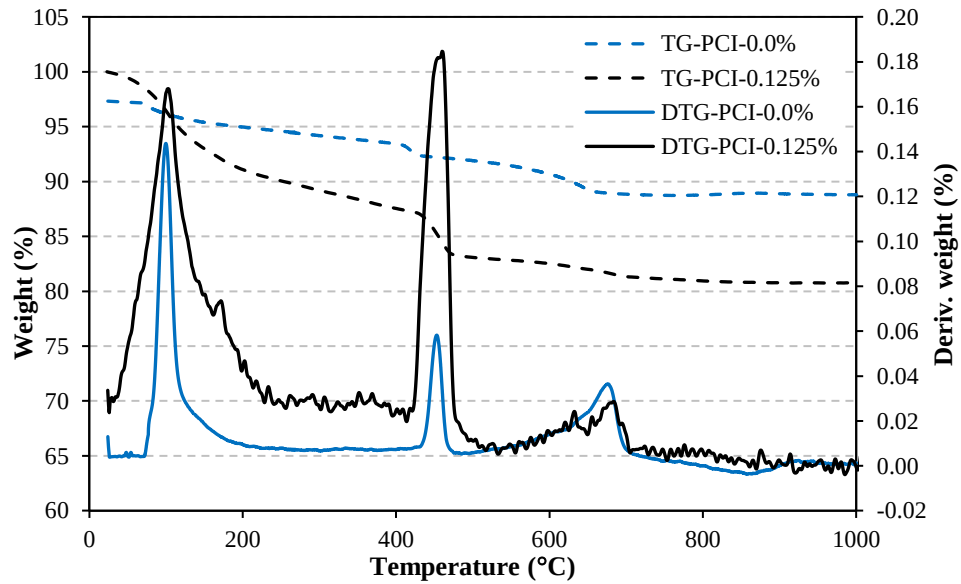


Figure 3.6. Effect of PES content on the TG/DTG diagrams for cement paste cured for 7 days

3.3.2 Effect of curing time and PES content on the strength development of CPB-PES

The UCS test results for the CPB-PES samples with various dosages of PES and different curing times are presented in Figure 3.7. It can be clearly observed that the strength of the CPB samples depends on both the dosage of the PES added to the CPB mixture and the curing time. The addition of PES to the CPB mixtures creates a significant improvement in the strength of the CPB. The CPB-PES samples that contain 0.125%, 0.25%, and 1.00% PES (ST-0.125%, ST-0.25% and ST-1.00% respectively) exhibit a higher compressive strength than the CPB without PES (ST-0.0%) after 7 days of curing. Also, the UCS values increase as the dosage of PES increases (except for the 7-day ST-1.00%), which will be discussed later). For example, increasing the dosage of PES from 0% to 1.00% results in an increase in the UCS from 534 kPa to 930 kPa after 28 days of curing. The reason for this increase in the strength of the CPB-PES specimens with 7 days of curing is mainly due to the increase in the rate of binder hydration with time, and thus the generation of a higher volume of binder hydration products, such as C-S-H and CH, which is favourable for CPB strength acquisition (Benzaazoua et al. 2004; Fall and Pokharel 2010). This higher volume of cement hydration products with time is demonstrated by the results of the TG/DTG analysis conducted on ST-0.0% and ST-0.25% and cured for 28 days as shown in Figure 3.8. A comparison of the TG/DTG diagrams of the cemented paste reveals that the second peak, which is between 400°C and 500°C, (due to the dehydroxylation of CH (Fall et al. 2010)) is higher for ST-0.25%.

Furthermore, the reason for the rise in the mechanical strength can be ascribed to the binder hydration process with time and the related refinement of the pore structure, which result from the precipitation of a large volume of cement hydration products, which is useful for strength development (Ghirian and Fall 2016; Fall et al. 2010). The results of the evolution of the physical properties (porosity, void ratio, dry density, and gravimetric water content) of the CPB with various dosages of PES (shown in Figure 3.9) demonstrate the refinement of pore structure and its contribution to the hardening and mechanical strength gain with time. It can be seen that the porosity and void ratio of CPB decrease as the dosage of PES increases after a curing time of 7 days. This is because of the continuing binder hydration process and thus the generation of a larger quantity of hydration products, and as a result, pore structure refinement occurs over time (Fall and Samb 2008; Fall and Pokharel 2010). This is also experimentally confirmed by the MIP test results performed on the 7- and 28-day CPB-PES samples presented in Figure 3.10. It can be observed that ST-0.125% has a denser microstructure and fewer pores (i.e., finer porosity) compared to ST-0.0% for both curing times. Ouellet et al. (2007) reported that the mechanical strength of CPB samples increases when porosity decreases over time. Indeed, the UCS of ST-0.125% that has been cured for 7 days is greater than that of ST-0.0%. This result agrees with those

in previous research work (Ouellet et al. 2007; Fall et al. 2010; Zheng et al. 2016; Haruna and Fall 2020).

Figures 3.9c and 3.9d also show that as the PES content and curing time are both increased, the gravimetric water content decreases while the dry density increases. This can be attributed to the ongoing cement hydration process and self-weight consolidation of the solid particles (Ouattara et al. 2018; Haruna and Fall 2020).

The extent of the above-mentioned improvement of the mechanical strength of CPB-PES depends on the curing time and the dosage of PES added to the CPB mix. It is evident in Figure 3.7 that the compressive strength of the CPB samples with PES and cured for 3 days or less is lower than that of ST-0.0%. This phenomenon can be explained by the impact of PES on the cement hydration process over time. The steric repulsion of PES increases particle-particle repulsion and delays their interactions, which will slow the cement hydration process (delay in setting time) at the early ages (Klein and Simon 2006). This reduction in particle-particle contact causes the decrease of the mechanical strength of the CPB-PES samples at the early ages of curing. The effect of adding PES to the CPB mixture on the CPB setting time (i.e., the delay in setting time at the early ages) is dependent on the dosage of PES added to the CPB mixture. An excessively large dosage could increase the delay in the setting time (Mangane et al. 2018). Indeed, the UCS results of ST-1.00% that has been cured for 7 days are lower than that of ST-0.25% (see Figure 3.7). This process of dispersing the cement particles and the associated delay in setting time at the early ages is supported by the results of TG/DTG diagram performed on ST-0.0% and ST-1.00% and cured for 1 day as shown in Figure 3.11. According to the TG/DTG results (Figure 3.11), the second peak, which is found between 400°C and 500°C, is lower for ST-1.00%. This is because a higher dosage of PES inhibits the cement hydration process at the early ages, thereby resulting in lower amounts of CH in the CPB samples at the early ages (the first 7 days of curing in this study).

Moreover, to understand the impact of adding PES on the binder hydration process and precisely on the pore structure of CPB materials over time, SEM analyses were conducted for the CPB samples with and without PES after 28 days of curing as shown in Figure 3.12. Large, connected capillary pores between the solid particles can be seen in the CPB sample without PES, compared to the smaller pores in the CPB sample with 0.25% PES. The tailings and cement particles are more connected and bonded in the CPB sample with 0.25% PES, which produce a denser and more compacted CPB structure.

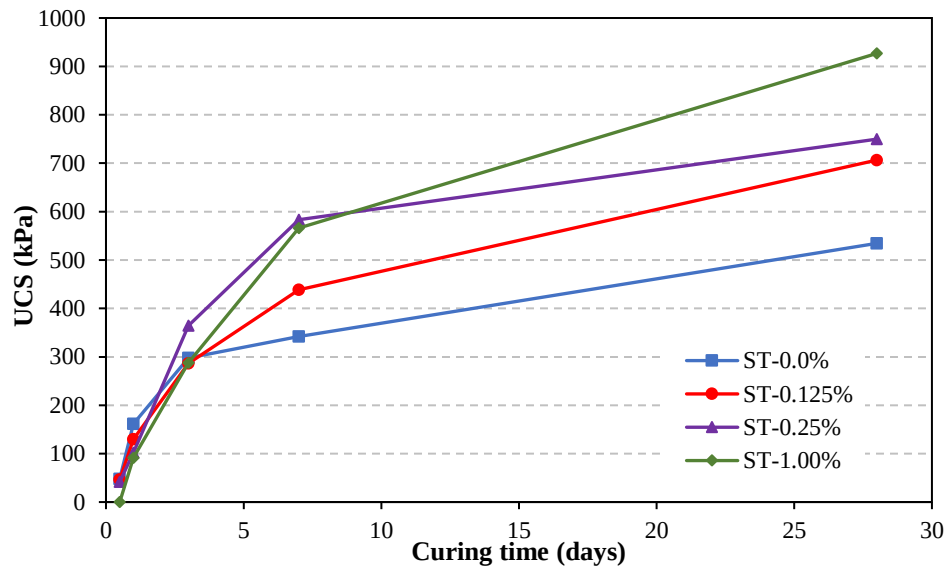


Figure 3.7 Effect of PES content on the strength development of CPB-PES

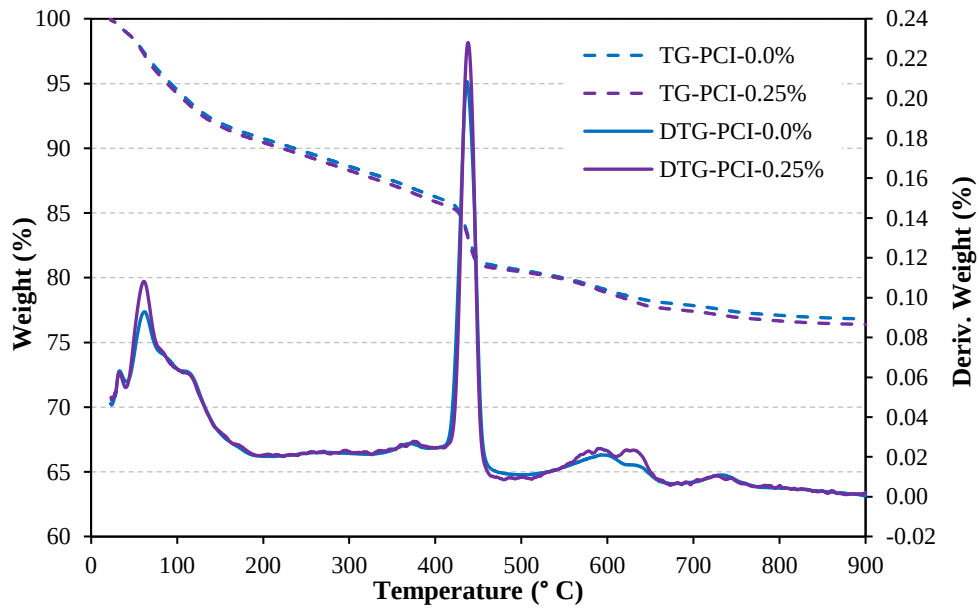


Figure 3.8 TG/DTG diagrams of effect of PES content in cement paste cured for 28 days

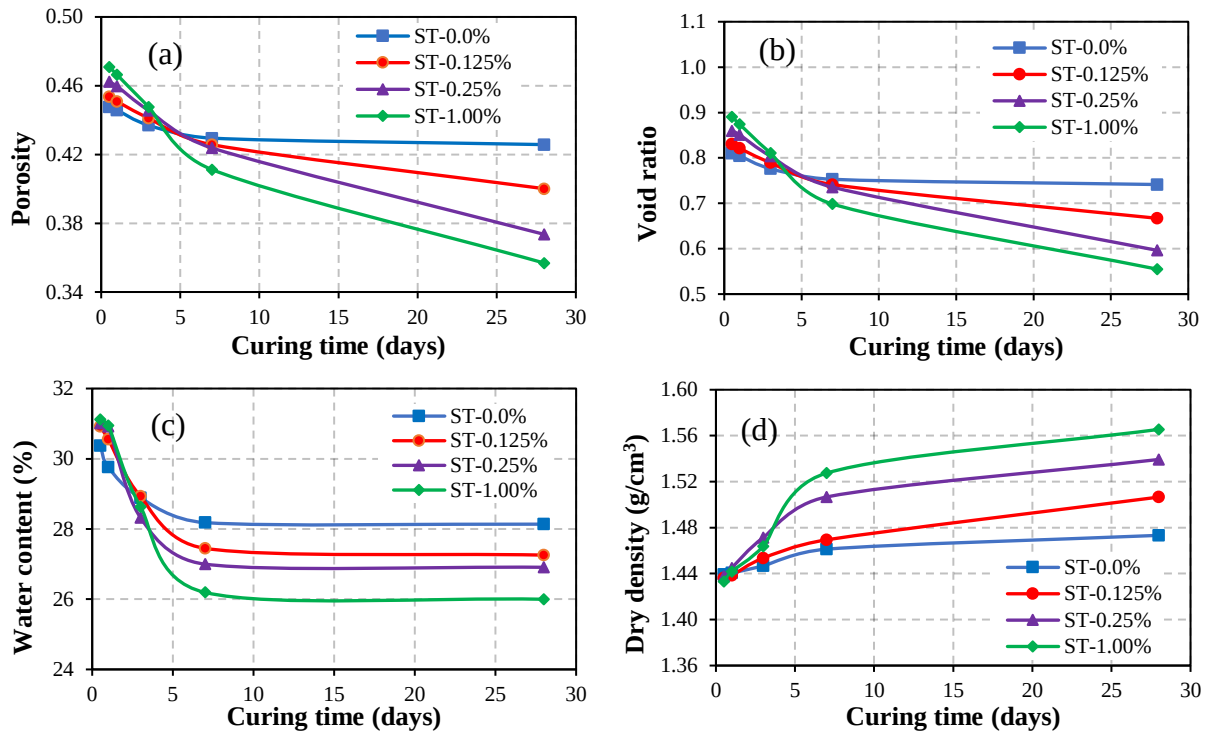
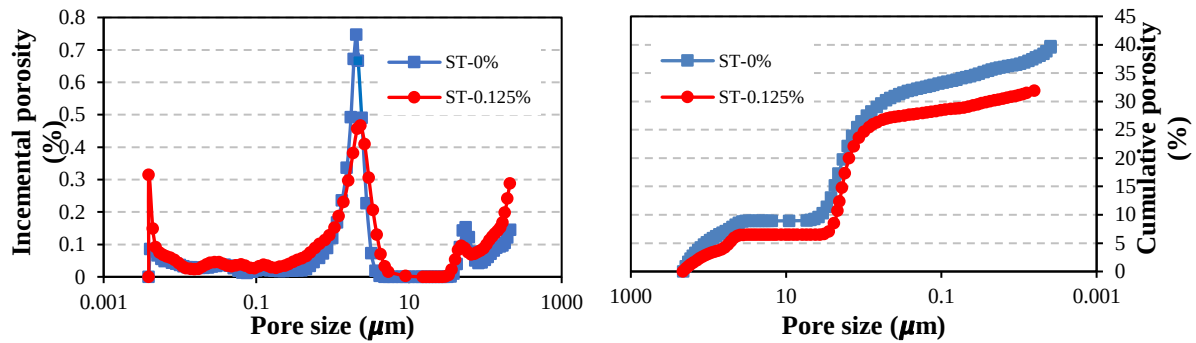
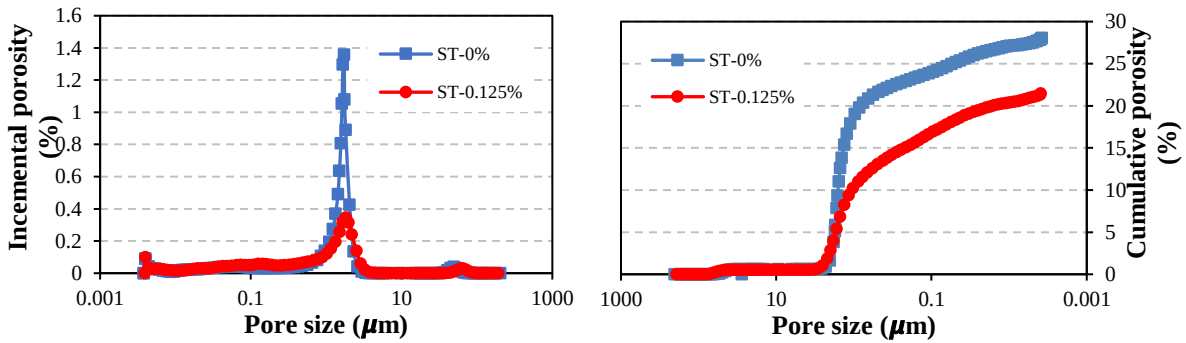


Figure 3.9 Changes in physical properties of CPB with different amounts of PES: (a) porosity; (b) void ratio; (c) water content; and (d) dry density



(a) 7 days of curing



(b) 28 days of curing

Figure 3.10 MIP pore size distribution of CPB with different amounts of PES after (a) 7 days, and (b) 28 days of curing

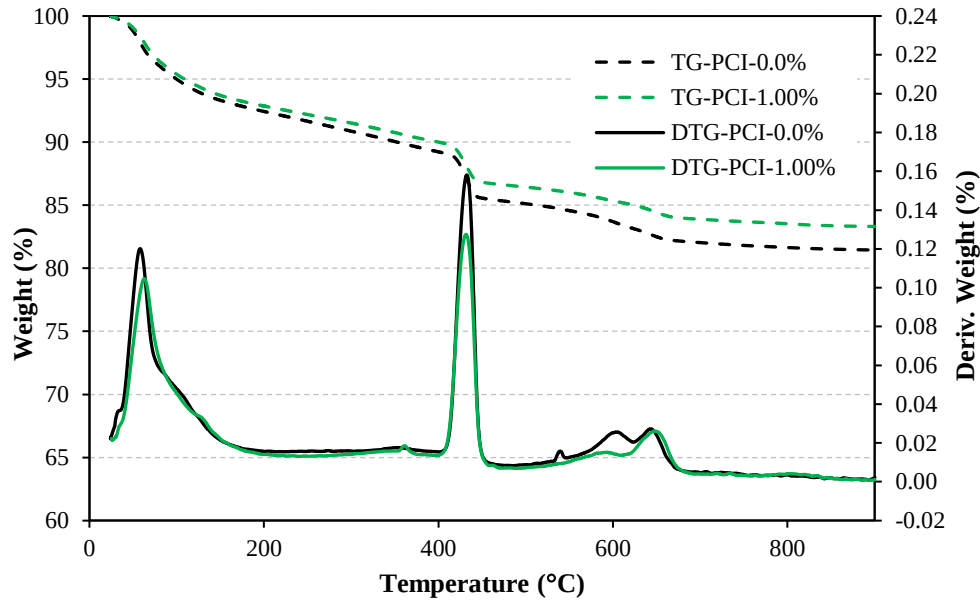


Figure 3.11 TG/DTG diagrams of 1-day cement paste with different amounts of PES

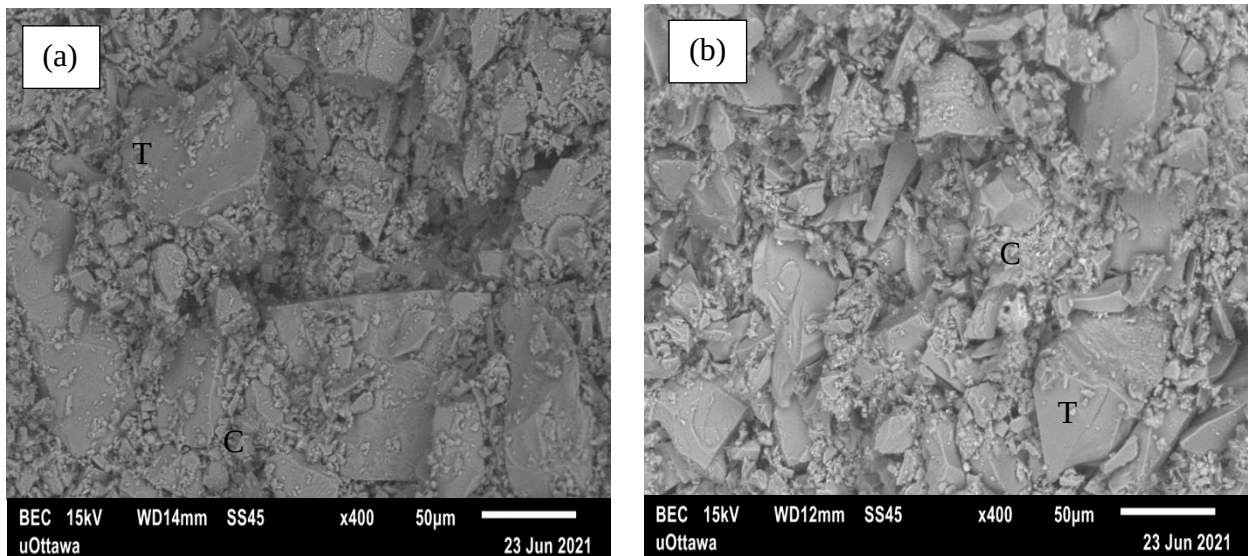


Figure 3.12 SEM images of the effect of adding PES on CPB microstructure after curing for 28 days: (a) without PES; (b) with 0.25% PES (T: tailings particles; C: cement hydration products)

3.3.3 Effect of cement content on the strength development of CPB-PES

The influence of the cement content on the compressive strength of the CPB-PES samples over time with three different percentages of cement (3.0%, 4.5%, and 6.0%), a PES dosage of 0.125% and two solid percentages (69% and 82%) is presented in Figures 3.13 and 3.14. The UCS test results of the CPB with a fixed solid content (82%) as shown in Figure 3.13, indicate that the

compressive strength of the CPBs increases as the cement content increases over the curing periods. For example, the increase in the UCS value from 785 kPa to 1490 kPa results from the cement content increase of 3% to 6% for a 7-day curing period. This is related to the fact that increasing the cement content leads to increased precipitation of hydration products in the CPB matrix over time such as C-S-H, C-H, and ettringite, as well as the associated refinement of the pore structure and thus porosity decrease of the CPB (Taylor 1993; Fall et al. 2008). However, this increase in the compressive strength of the CPB-PES greatly depends on the solids content. As shown in Figure 3.14, an increase in the percentage of solids content in the CPB mixture significantly increases the compressive strength regardless of cement content. This is due to the fact that the total porosity of the CPB decreases with increasing solids content and curing time, which results in a denser mixture, and thus higher strength (Fall et al. 2008; Zheng et al. 2016; Yang et al. 2018). Moreover, incorporating 0.125% of PES into the CPB mixture enhances the CPB microstructure (Mangane et al. 2018). These findings are in good agreement with earlier experimental investigations conducted by other researchers (e.g., Ouattara et al. 2018; Yang et al. 2018).

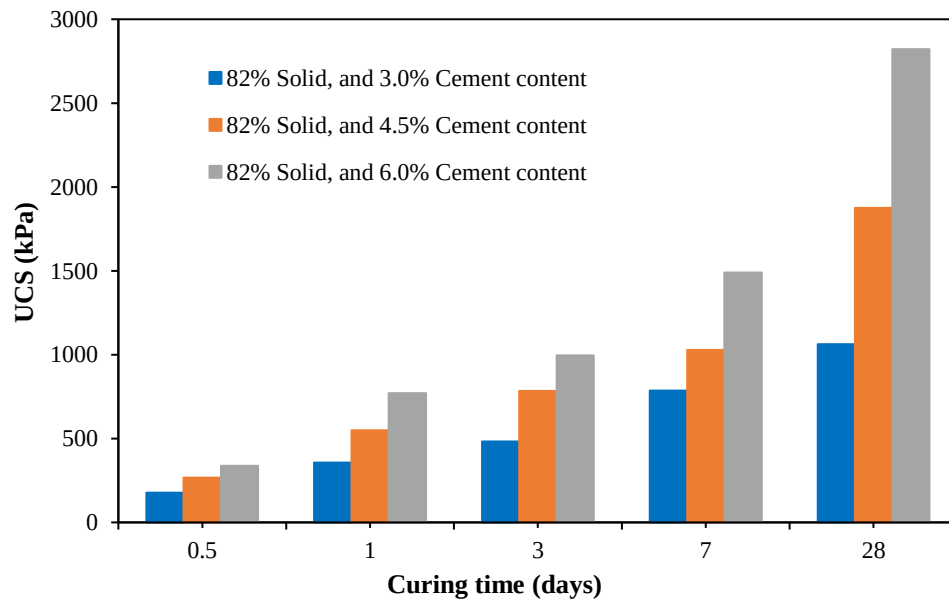


Figure 3.13 Effect of cement content (3%, 4.5%, and 6%) on the strength of CPB-PES with 82% solids content and 0.125% PES

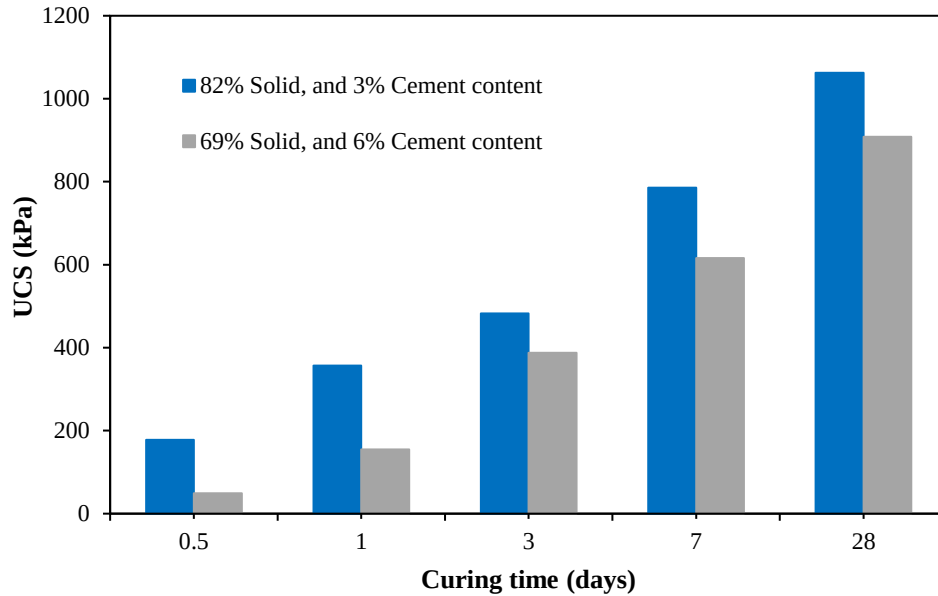


Figure 3.14 Effect of solids contents (69% and 82%), and cement content (3% and 6%) on strength of CPB with 0.125% PES

3.3.4 Effect of tailings fineness on the strength development of CPB-PES

The impact of tailings fineness (tailings grain size) and the incorporation of PES on the strength of the CPB-PES samples over time are illustrated in Figures 3.15 and 3.16. It is evident that the proportion of fines particles (20 μm particles >60% by weight) affects the strength development of the CPB-PES samples, as expected, and the effect is based on the percentage of fines, and the added dosage of PES. Figure 3.15 shows that the UCS of the CPB-PES increases as the grain fineness increases until approximately 45-55% of the fine percentage is attained. Following that, as the grain fineness increases, the UCS gradually decreases. The CPB samples made with medium sized tailings (35-60% by weight of 20 μm particles) are more beneficial for strength acquisition over time (Fall et al. 2008). These observations can be explained by the fact that an increase in the tailings fineness increases the overall porosity and void ratio of the CPB-PES samples. This is confirmed by the results of the porosity and void ratio tests of the CPB samples with 0.125% PES as shown in Figure 3.17. The obtained results show that the porosity and void ratio of CPB-PES made with fines are higher than those of the samples made with medium sized and coarse tailings. It can be clearly observed that when the utilized tailings contain 45-55% fines by weight, the lowest porosity and smallest void ratio are obtained, which in turn would lead to an increase in the compressive strength. The observed reduction in the compressive strength of the CPB-PES as the tailings fineness increases (i.e., 20 μm particles >60% by weight) can be attributed to the poor grain size distribution of the tailings resultant of more fines. Higher porosity and larger void ratio

create lower packing density of the cemented material and a higher volume of void spaces (Fall et al. 2005, 2008). It can be also observed in Figures 3.17c and 3.17d that the CPB-PES samples made with fines exhibit higher water content and lower dry density for all curing times compared to the CPB-PES samples made with medium sized and coarse tailings. This increase in water content is attributable to the larger surface area associated with higher percentages of fines, which indicates that there is a greater yield with higher water content and lower density (Fall et al. 2005).

Figure 3.16 demonstrates the influence of PES on the strength of the CPBs made with fines. The results indicate higher compressive strength of the CPB made with fines and contains PES compared to the control sample after 3 days of curing. Incorporating PES into the CPB mixtures significantly contributes to the enhancement of the microstructure of the material and self-consolidation of the solid particles (Ercikdi et al. 2010; Yang et al. 2018). The dispersion of the cement and tailings particles caused by the addition of PES resulted in a higher precipitation rate of the cement hydration products, and thus reduced the porosity and increased the packing density. It can be observed that compared to 7- and 28-day cured samples with 0.125% PES, the UCS values of the CPB without PES at the early ages (12 h, 1 day, and 3 days) are higher. This is due to the delay of cement hydration caused by the PES. This is also experimentally supported by the results of the porosity and void ratio tests of CPB samples with no PES and 0.125% PES as shown in Figure 3.18. The results indicate that the porosity and void ratio of the CPB made with fines and containing 0.125% PES are lower than those of the CPB without PES after 7 days of curing, whereas at the early ages (less than 7 days), the obtained results show the reverse. It can also be observed in Figures 3.18c and 3.18d that the water content and dry density decreases and increases, respectively, as the PES content increases with curing time due to the ongoing cement hydration, which results in higher consumption of water and more pore voids that are filled with hydration products. This indicates that the pore structures of the CPB samples become finer with the inclusion of PES and increased curing time. Therefore, this microstructure enhancement densifies the CPB and thus increases its mechanical strength over time.

Moreover, the results of the EC and matric suction monitoring presented in Figures 3.19 and 3.20, respectively, illustrate the delay of cement hydration (i.e., longer setting time) at the early ages (less than 7 days). Figure 3.19 shows that the EC of the CPB without PES peaks at 4.8 mS/cm after only 4 h, whereas the highest EC for CPB with 0.125% PES is 4.6 mS/cm, about 6 h after mixing. This indicates a reduction in the rate of cement hydration of the CPB samples with 0.125% PES at an early age. The results of the matric suction monitoring (Figure 3.20) are in agreement with the EC results. It can be noticed that the delay of cement hydration creates lower matric suction of the CPB samples with 0.125% PES at an early age. However, after 3 days of curing, a continuous increase in the matric suction is found, due to the continuous cement hydration

and the associated chemical reactions which lead to further consumption of free water in the CPB samples with 0.125% PES.

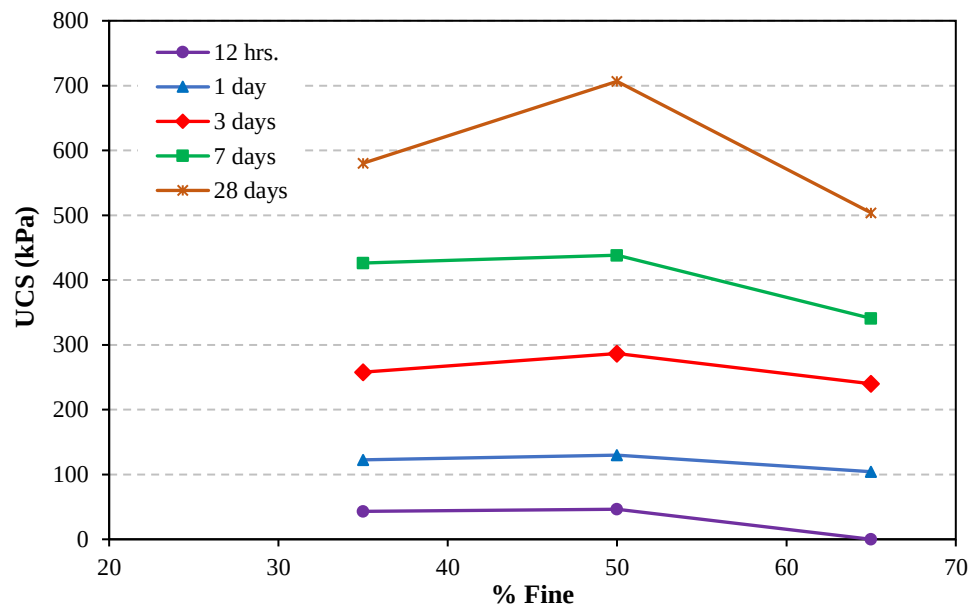


Figure 3.15 Effect of tailings fineness on the strength of the CPB-PES samples with 0.125% PES

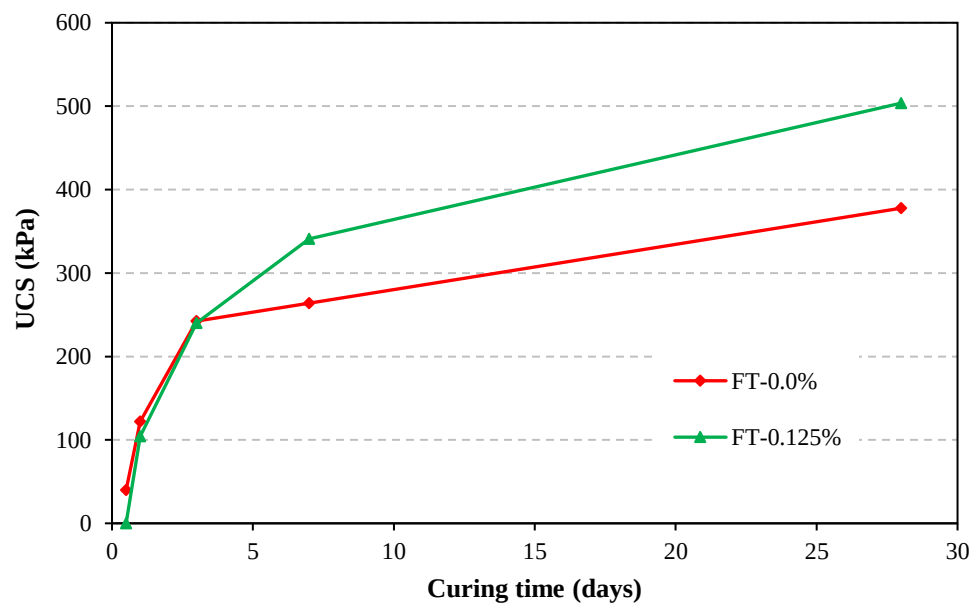


Figure 3.16 Effect of PES content on the strength of cemented paste backfill specimens made with fines.

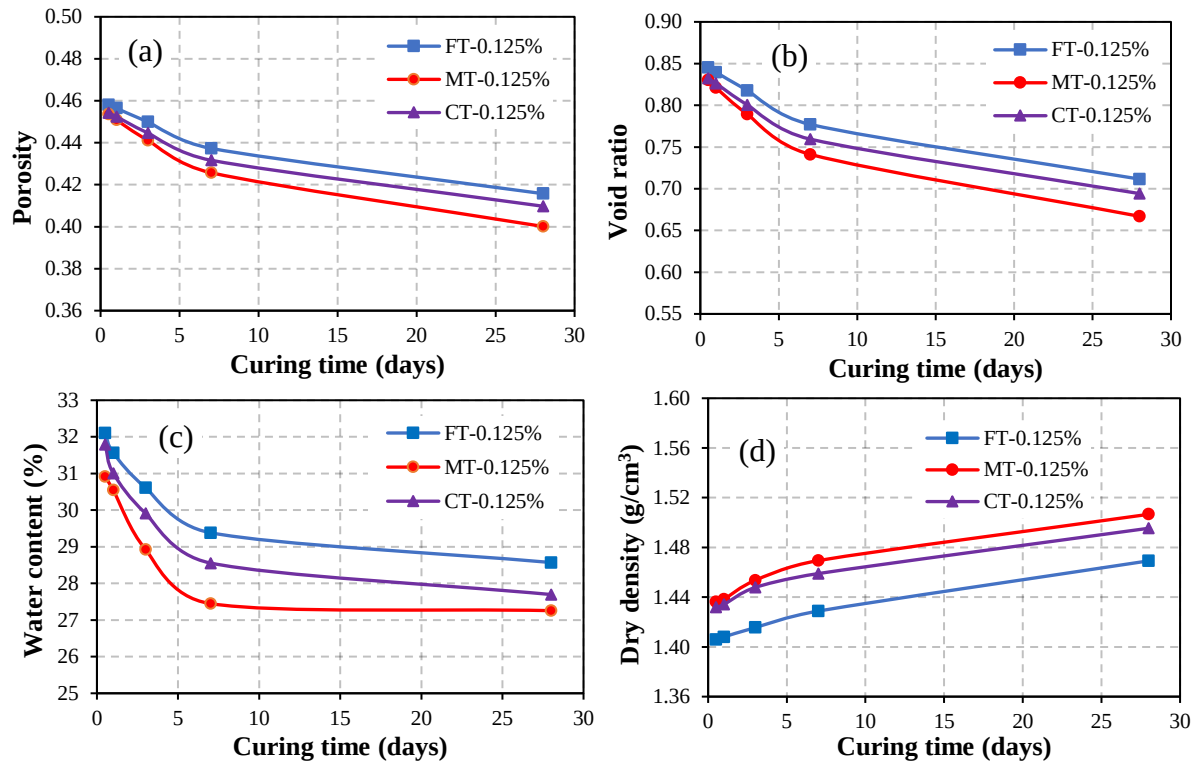


Figure 3.17 Changes in the physical properties of CPB-PES with different fineness contents: (a) porosity; (b) void ratio; (c) water content; and (d) dry density

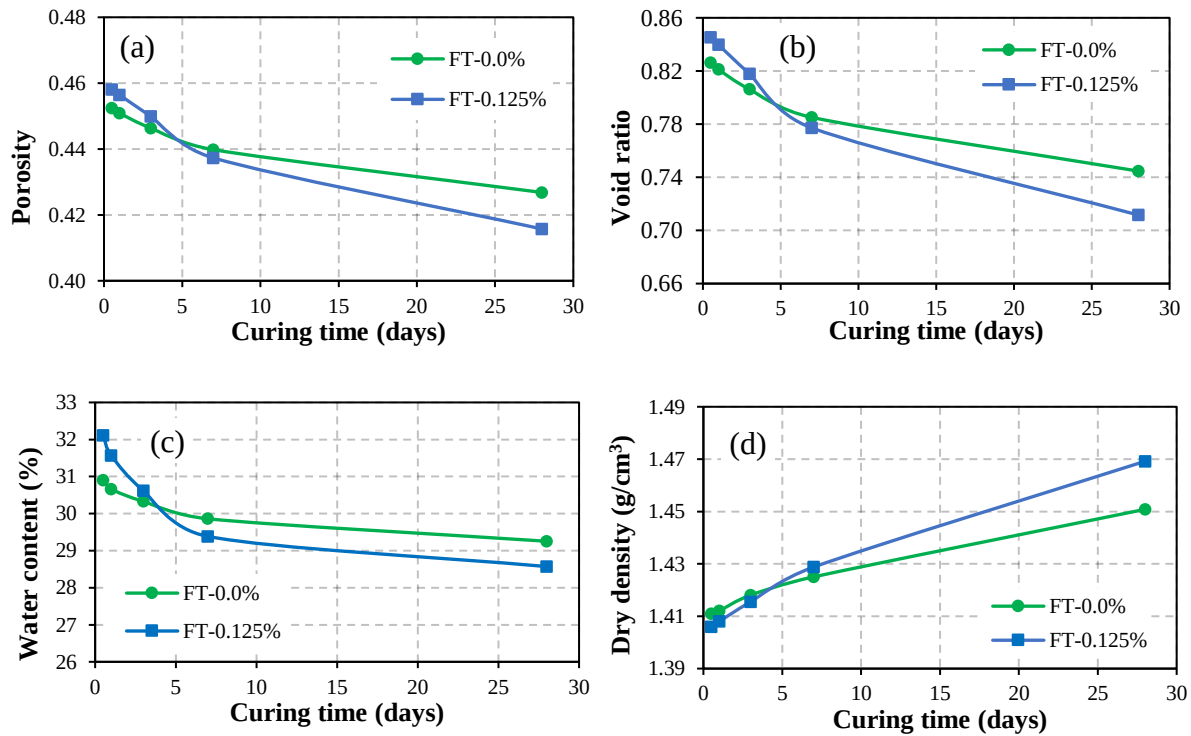


Figure 3.18 Changes in the physical properties: (a) porosity; (b) void ratio; (c) water content; and (d) dry density of CPB with fines and different amounts of PES

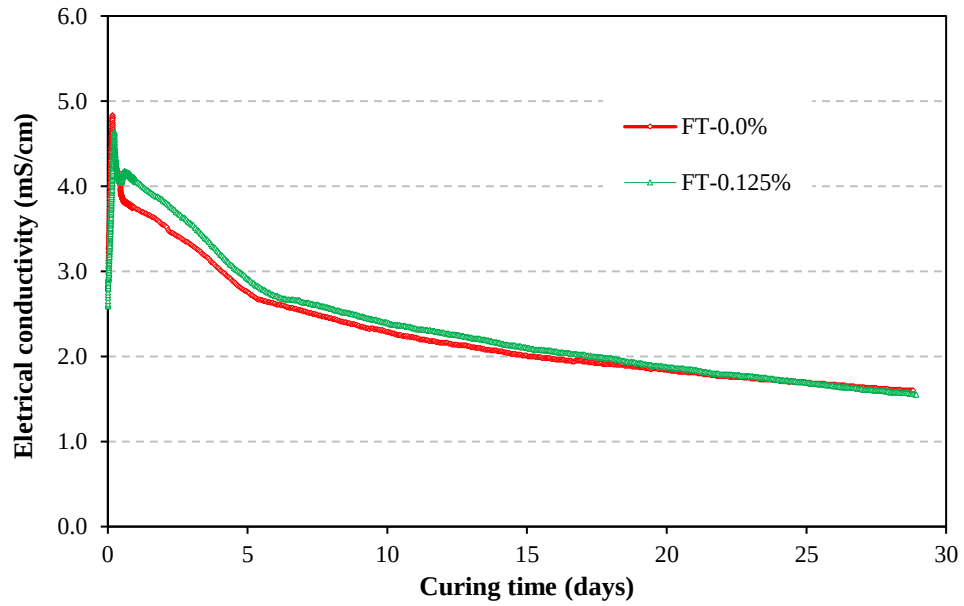


Figure 3.19 Variation in electrical conductivity of CPB samples made with fines and different PES contents.

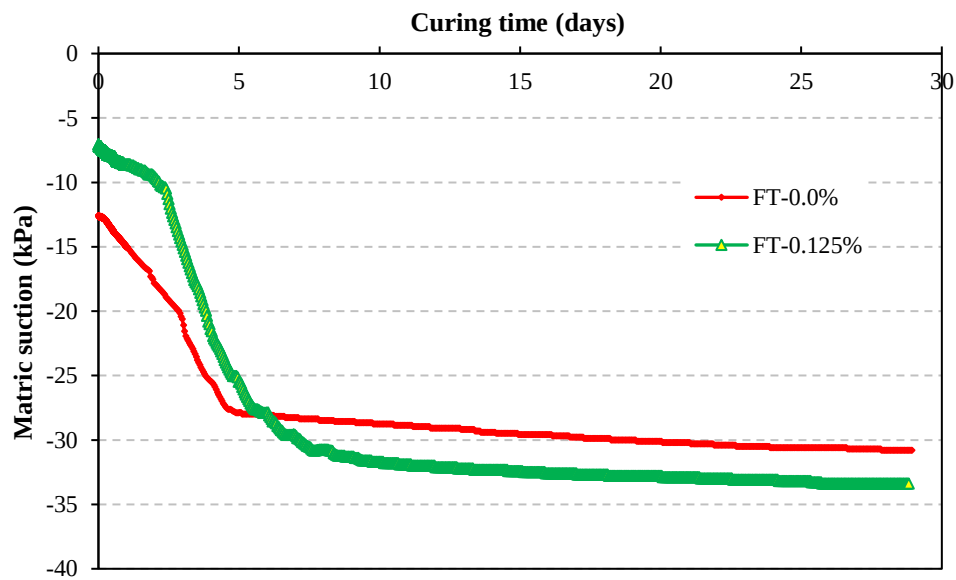


Figure 3.20 Variation of matric suction in CPB samples made with fines and different PES contents.

3.3.5 Effect of sulphate on the strength development of CPB-PES

The compressive strength acquisition and the short- and long-term mechanical performances of the CPB-PES materials are greatly affected by the amount of sulphate in the mixing water. Figure 3.21 illustrates the effect of sulphate on the strength of CPB samples with PES over a curing period of 300 days. It can be observed that regardless of the PES content, the CPB samples with sulphate show lower strength than the sulphate-free CPB at an early age (7 days). This is attributed to the action mechanism of both the superplasticizer and sulphate ions, which inhibit and delay cement hydration reactions at the early ages, and thus affect the CPB strength (Fall and Benzaazoua 2005; Fall and Pokharel 2010; Ercikdi et al. 2010). The inhibition of cement hydration by the sulphate ions is experimentally demonstrated by the EC monitoring results of the CPB-PES samples with 0.125% PES and two initial sulphate contents – no sulphate and 25,000 ppm as presented in Figure 3.22. It can be observed that the EC of the CPB-PES sample with 25,000 ppm of sulphate reaches the peak value of 2.56 mS/cm after 1.25 days, whereas the sample without sulphate reaches the peak value of 4.66 mS/cm after only 6 hours. These results show that the EC of CPB-PES sample with 25,000 ppm of sulphate requires a longer time to peak, thus demonstrating delayed cement hydration.

Additionally, the inhibition of cement hydration due to the presence of sulphate reduces the volume of hydration products (Taylor 1993; Gan 1997; Fall and Pokharel 2010) and inhibits the self-desiccation of CPB-PES. The former is experimentally supported by the results of the TG/DTG analyses performed on the cemented paste samples cured for 60 days as shown in Figure 3.23. The second peak (between 400°C and 500°C) is higher for the cemented paste with 0.125% PES because there are more cement hydration products or a larger volume of CH (Fall et al. 2010).

This inhibition of self-desiccation at an early age is experimentally supported by the results of the suction monitoring presented in Figure 3.24. Note that a high initial sulphate content considerably affects the self-desiccation and the suction value of the CPB-PES sample with 25,000 ppm of sulphate is lower. This sample requires a longer curing time, which indicates delay of self-desiccation or suction within the CPB-PES at an early age (7 days), and thus has lower compressive strength. This phenomenon is attributed to the reduction of water consumption at the early ages resultant of the sulphate ion induced inhibition of cement hydration, which is consistent with the results in previous studies (Fall and Pokharel 2010; Li and Fall 2016, 2018).

On the other hand, adding PES to the CPB mixture causes further delay of cement hydration and subsequently, the loss of suction, and thus further inhibits the early-age strength development of CPB-PES. Yamada et al. (2001) reported that the adsorption of superplasticizer on the surface of cement particles is reduced as the volume of sulphate ions increase in the aqueous phase since

they and the superplasticizer are adsorbed on the cement particles competitively, which declines with further consumption of the sulphate.

After 7 days of curing, the strength of the CPB-PES samples starts to increase with time regardless of the amount of sulphate, see Figure 3.19. Figure 3.21 also shows that the UCS of the CPB samples with 25,000 ppm of sulphate and 0.125% PES have a higher strength than both the samples with and without sulphate without any PES. For example, the 28-day strength of the sample with 0.125% PES and 25,000 ppm of sulphate is 975 kPa, whereas that of the samples with 25,000 ppm sulphate and without sulphate as well as no PES is 624 kPa and 679 kPa respectively. This is attributed to the greater ability of the PES to disperse the solids particles (cement and tailings) of CPB-PES samples with sulphate after 7 days. Incorporating PES reduces the adsorbed water that surrounds the tailing particles, which leads to increased friction of the particles and subsequently increased interparticle contact, and thus an increase in the strength of the CPB-PES samples over time (Simon et al. 2011; Zheng et al. 2016; Mangane et al. 2018).

Furthermore, note in Figure 3.21 that the curves of the strength acquisition of all of the CPB-PES samples from the addition of PES are similar in that the strength tends to increase when cured over a period of 250 days. Afterwards, the strength tends to slightly decrease or increase. Many studies (Kesimal et al. 2005; Fall et al. 2007; Ercikdi et al. 2009) have made similar observations, and reported a deterioration of the strength of CPB samples that contain sulphate over a long period of curing with the exception of Simon et al. (2011) who reported a continuous increase in the strength of CPB samples that contain sulphate with time.

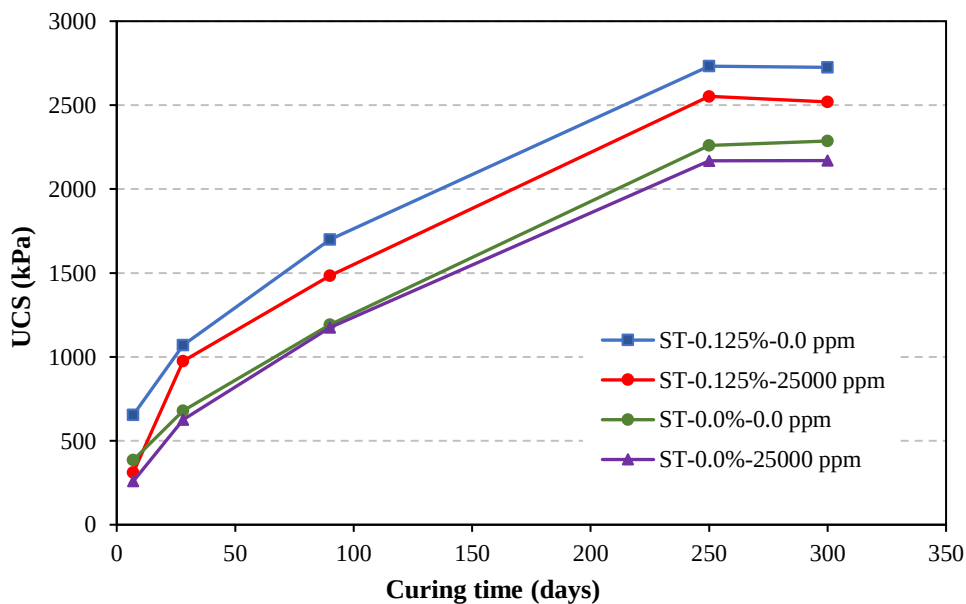


Figure 3.21 Effect of initial sulphate content on the strength of the CPB samples with different amounts of PES

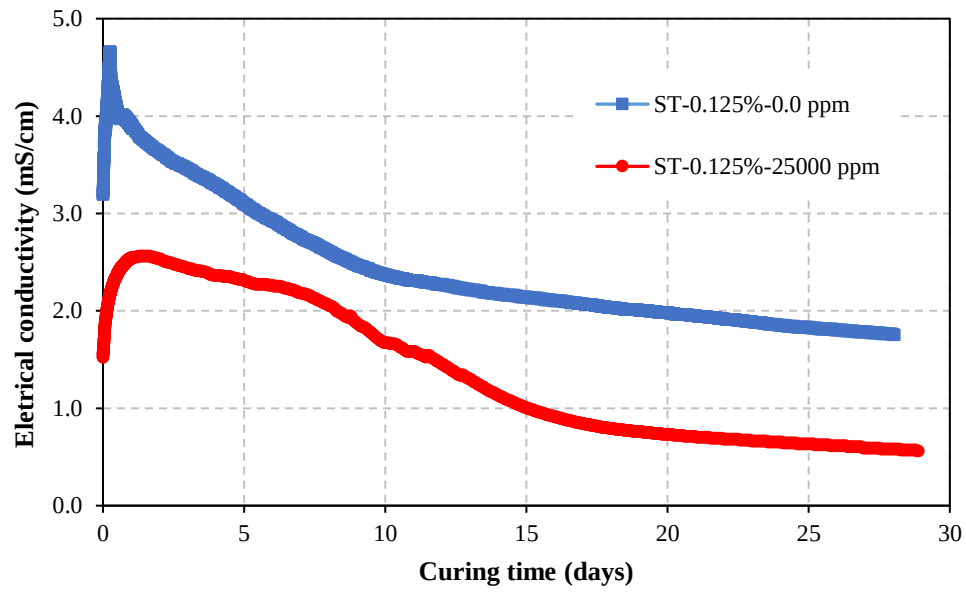


Figure 3.22 Electrical conductivity monitoring of CPB-PES samples with different initial sulphate contents

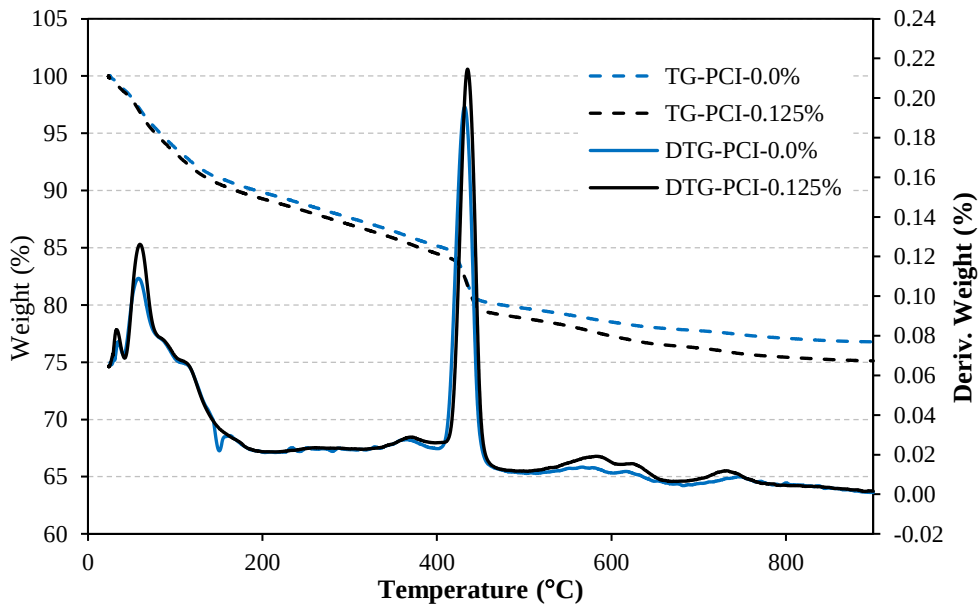


Figure 3.23 TG/DTG diagrams for 60 day cemented paste with different amounts of PES.

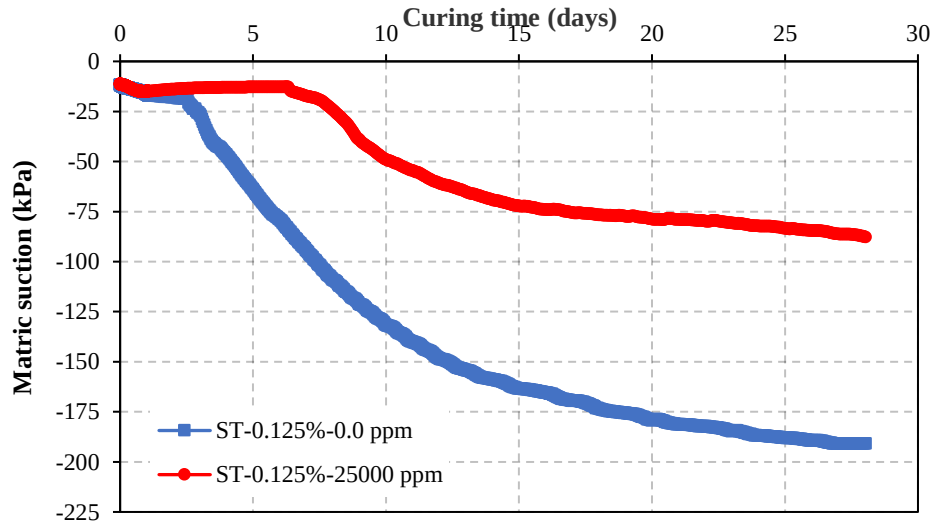


Figure 3.24 Results of matric suction monitoring of CPB-PES samples with different initial sulphate contents

3.3.6 Effect of curing under stress on the strength development of CPB-PES

The changes in the UCS of the CPB-PES samples with curing time under different curing conditions and different dosages of PES are plotted in Figure 3.25. The latter shows that the strength values for all of the samples increase with curing time. This is attributed to the rise in the degree of binder hydration with time and the subsequent increased refinement of the pore structure of the CPB because of the precipitation of large volumes of cement hydration products (Figure 3.26), as well as suction increases within the CPB due to self-desiccation (Figure 3.27). Note in Figure 3.25 that the UCS of the CPB-PES samples cured under stress (ST-CUS) is higher than that of the samples cured without stress, which is the effect of applying pressure onto the CPB-PES samples. Curing under stress creates a significant increase in the packing density of the material, which results in a reduction in porosity and void ratio (Ghirian and Fall 2015). Figure 3.26 demonstrates the reduction in porosity and void ratio, as well as the increase in dry density with time, which result in a denser pore structure and higher compressive strength. This correlation between strength acquisition and porosity reduction can be explained by the filling of the capillary pores in the CPB matrix with cement hydration products with time (Fall et al. 2008).

Moreover, it can also be observed that the samples with PES and cured under stress exhibit higher compressive strength compared to those without PES starting after just 3 days of curing. The reason can be traced back to the role of PES in the cement hydration process. Due to the dispersing effect of PES, the cement particles in the CPB-PES become dispersed, which inhibits cement hydration at an early age. The addition of PES, on the other hand, accelerates cement hydration by favouring ionic diffusion at a later age (Haruna and Fall 2000). This is consistent

with the matric suction results shown in Fig 3.27 for the CPB-PES sample with 0.125% PES and cured under stress (ST-CUS-0.125%). A higher consumption of free water (suction) in ST-CUS-0.125% occurs as a result of the higher chemical reaction caused by cement hydration at a later age. Figure 3.27 shows that the initial increase in suction commences at different curing times between the two samples. For instance, the suction in ST-CUS-0.0% starts to develop after about 12 h, but changes to 24 h with ST-CUS-0.125%. This observed delay of suction changes for both samples at the early hours of curing can be generally attributed to the development of PWP due to the application of pressure which will be discussed later. Further, the additional delay in the ST-CUS-0.125% can also be attributed to the previously discussed effect of the addition of PES. After that, rapid changes in the suction can be seen from 12 to 48 h and 24 to 72 h for ST-CUS-0.0% and ST-CUS-0.125%, respectively. This is followed with very little change in suction for both samples mainly due to the declining rate of cement hydration in conjunction with a slower rate of pore refinement during this time frame (Ghirian and Fall 2015).

Figure 3.28 illustrates the changes in the PWP of ST-CUS-0.0% and ST-CUS-0.125% with curing time measured by the installed sensors for 28 days. The PWP of both samples is greatly affected by the increase in pressure. In the early hours of curing, the PWP is noticeably high, which can be attributed to the weak microstructure of the CPB sample due to high pressure which causes the sample to behave like a fluid in the early hours of curing (Ghirian and Fall 2015). The application of stress to fresh CPB results in the development of microcracks within the CPB (Ghirian and Fall 2016), thus resulting in a mechanically damaged CPB structure, which is a significant contributor to loss of the mechanical strength of CPB at the early hours of curing (see Figure 3.25). Previous studies show that a higher PWP caused by the application of pressure leads to a reduction in the effective stress (zero effective stress) at an early age (Ghirian and Fall 2015, 2016, 2017). It can also be observed in Figure 28 that the PWP developed at the early hours of curing starts to gradually dissipate after the rapid development of a negative PWP (suction) within the CPB samples (see Figure 3.27). Moreover, the results presented in Figure 28 also show that the PWP developed in ST-CUS-0.125% is higher than that in ST-CUS-0.0%. This is due to the effectiveness of PES in dispersing the solid particles (cement and tailings) at the early ages and inhibiting interparticle contact, which allow the trapped water between the tailing particles and cement to escape (Mangane et al. 2018). This results in an increase in the water content in ST-CUS-0.125% (Figure 3.26c), and consequently a higher PWP compared to ST-CUS-0.0% at the early ages.

Furthermore, the observed high PWP in the early hours of curing is in agreement with the results of the EC for both samples as shown in Figure 3.29. When comparing the CPB sample cured without stress to that cured under stress, the results show that a longer time is required to reach the peak maximum of the EC for the latter in comparison to the former. For example, ST-

CUS-0.0% and ST-CUS-0.125% peak after around 10 h and 20 h, respectively, as opposed to just 4 h for the CPB samples cured without stress (ST-0.0%). This indicates that in the early hours of curing, samples cured under stress have a relatively high PWP, and thus require additional time for setting to occur (Ghirian and Fall 2015). Furthermore, it is clear that ST-CUS-0.125% shows a lower EC value after about 2.5 days compared to ST-CUS-0.0% which shows that incorporating PES leads to an increase in cement hydration products, which in turn, refines the pore structure and thus, reduces the porosity and void ratio (Figures 3.26a and 3.26b) of the CPB matrix (Fall et al. 2005). Accordingly, this increase in packing density leads to a reduction in the interconnected capillary pores and thus an increase in tortuosity and a longer flow channel for ions, which cause a reduction in the EC (Ghirian and Fall 2015).

The results of the vertical deformation of the studied CPB-PES samples for a curing time of 28 days are presented in Figure 3.30. As expected, during the early hours of curing, both samples become more vertically deformed. ST-CUS-0.125% shows more deformation compared to ST-CUS-0.0%. After that, a lower rate of increase in deformation can be observed and eventually becomes nearly linear with time. A 1.59 mm vertical deformation was recorded for ST-CUS-0.0% during the first 12 h, followed by a slower rate of increase from the 12th to 24th hour of curing. This is mainly attributed to the combined effects of: (i) curing under stress which causes rearrangement of the tailing particles at the early hours of curing, and can result in large deformations, and (ii) the self-desiccation of the CPB-PES samples which is caused by cement hydration (Ghirian and Fall 2015). A larger deformation can be observed for ST-CUS-0.125% compared to ST-CUS-0.0% due to the dispersion influence of PES on the cement and tailing particles in the CPB mixture, and thus, an associated reduction in water content (Figure 3.26c). Indeed, the accumulated bleed water on the top of the sample is evidence of the water content reduction (Outattara et al. 2018).

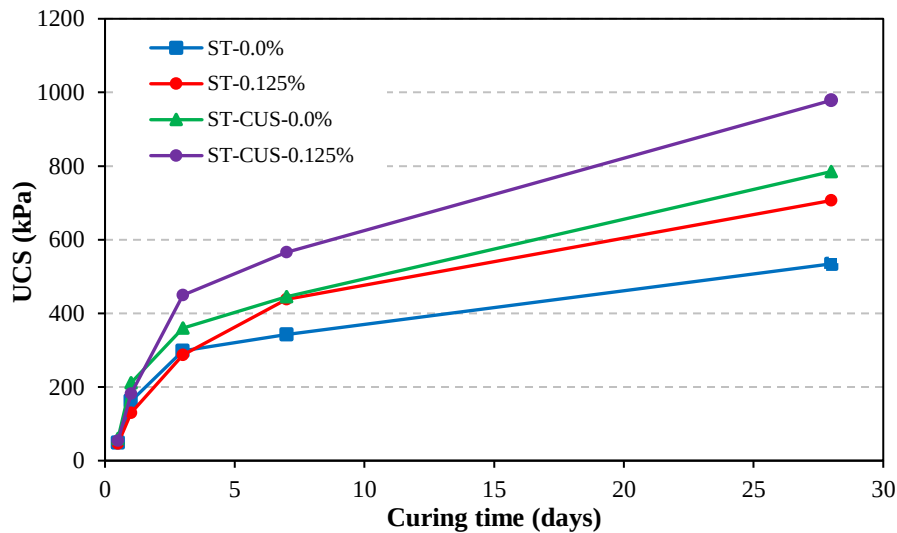


Figure 3.25 Effect of curing under stress on the UCS of CPB-PES with different amounts of PES

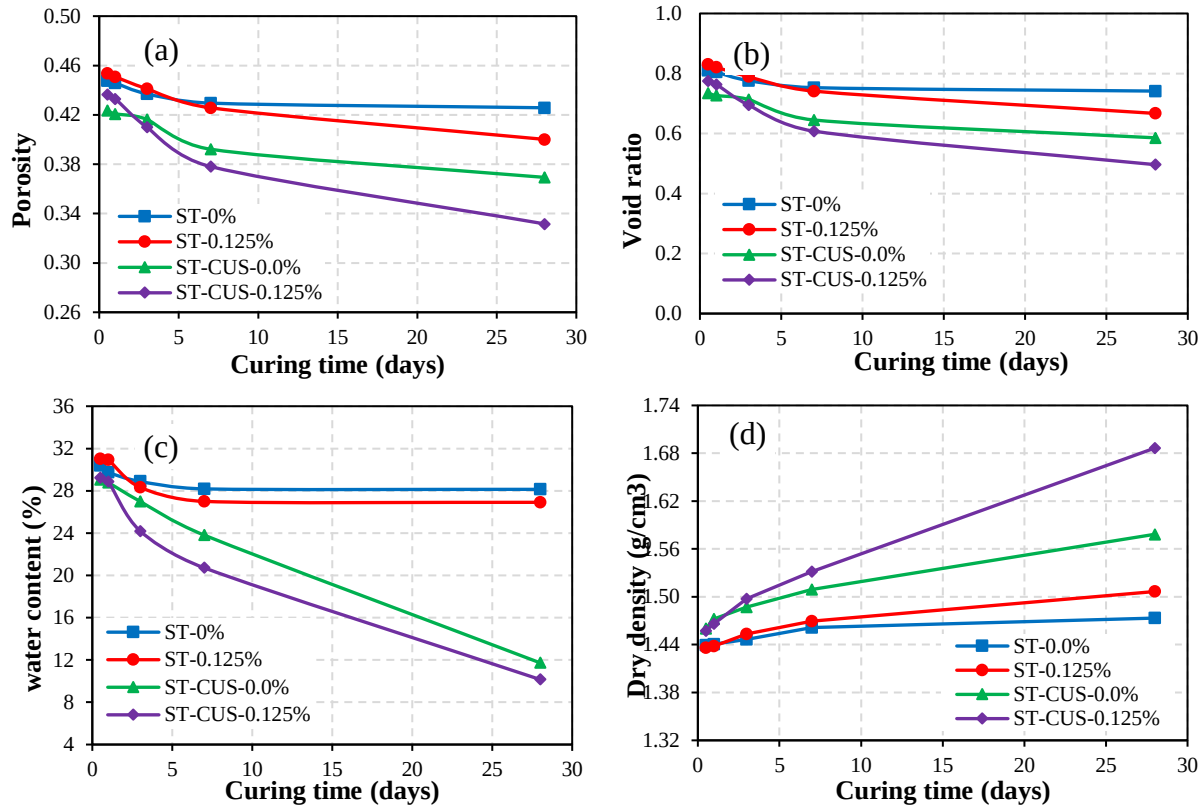


Figure 3.26 Changes in the physical properties of CPB-PES with different amounts of PES under different stress conditions: (a) porosity; (b) void ratio; (c) water content; and (d) dry density

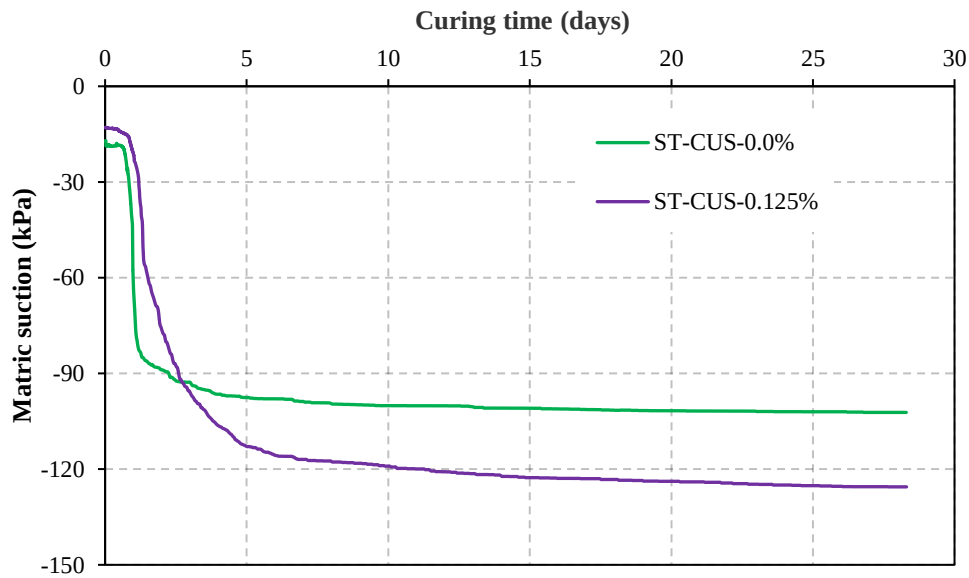


Figure 3.27 Changes in matric suction of CPB-PES samples with different amounts of PES cured under stress.

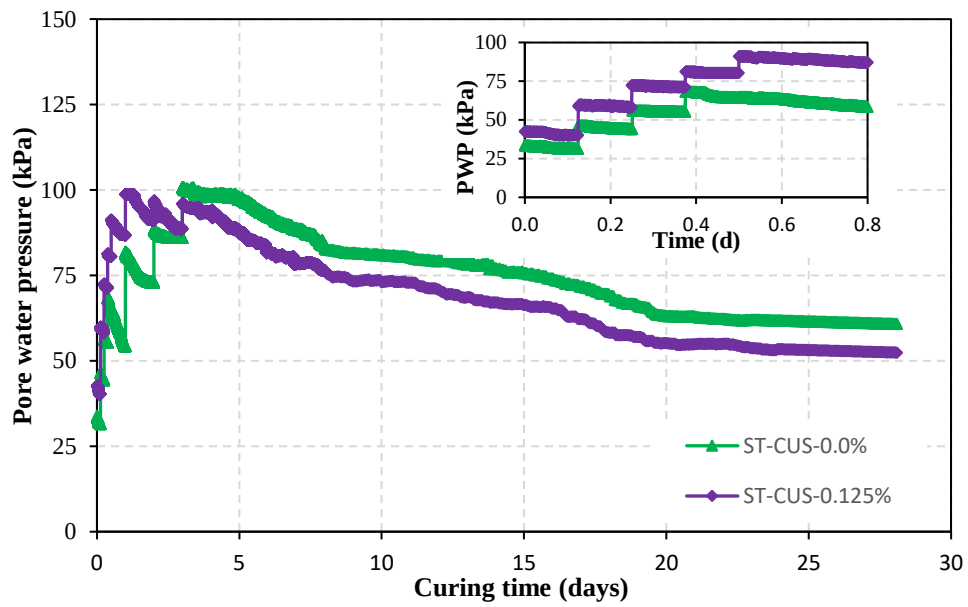


Figure 3.28 Changes in pore-water pressure of CPB-PES samples with curing time

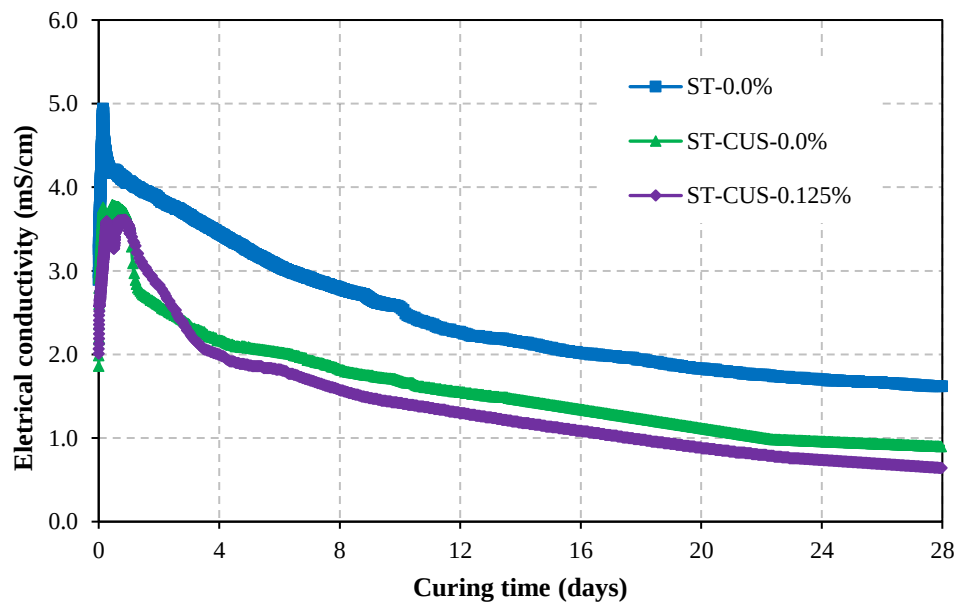


Figure 3.29 Changes in electrical conductivity of CPB-PES samples with curing time

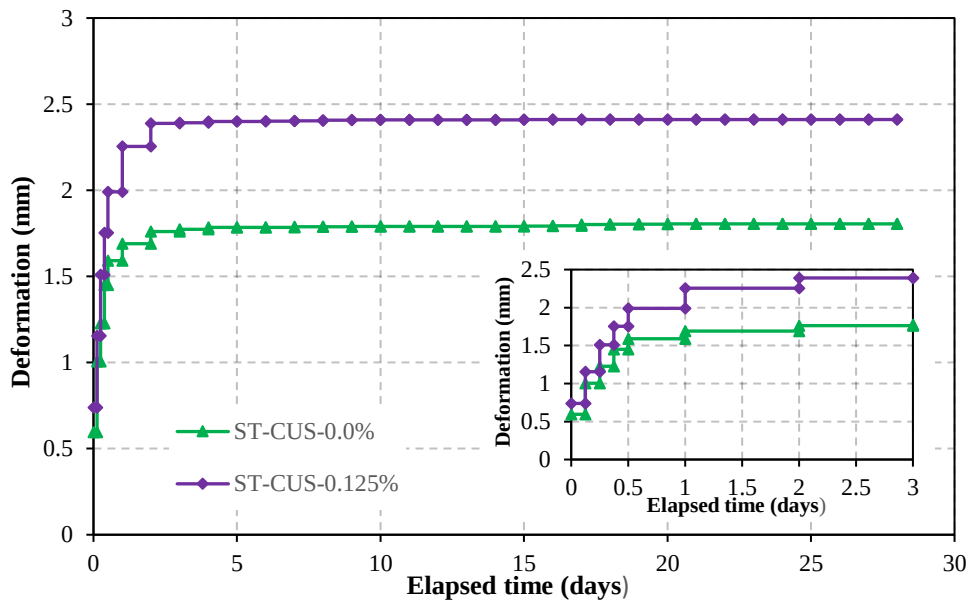


Figure 3.30 Effect of curing under stress on the deformation of CPB-PES samples with curing time

3.3.7 Effect of non-isothermal curing temperature on the strength development of CPB-PES

The influence of non-isothermal curing temperatures on the UCS of the CPB-PES samples with different dosages of PES and cured for 0.5, 1, 3, 7, and 28 days is presented in Figures 3.31 and 3.32. It can be seen that the UCS development of the CPB-PES samples is significantly affected by the curing temperature. Figure 3.31 shows the impact of H1 (see Figure 3.2) on the strength acquisition of the CPB with different dosages of PES (0% and 0.125%). From this figure, it can be observed that starting from 12 h of curing time, the CPB samples cured at H1 and containing 0.125% PES (ST-H1-0.125%) exhibit higher UCS values compared to all the studied CPB samples. This increase in mechanical strength can be attributed to the combined influence of PES and non-isothermal curing conditions on the strength gain of the CPB. Previous studies (Fall et al. 2010; Cui and Fall 2016; Wang et al. 2016) demonstrate that higher curing temperature accelerates the cement hydration process thereby resulting in the refinement of the pore structure of the CPB at the early ages due to the precipitation of a greater volume of cement hydration products, and this results in higher compressive strength. The dispersing influence of PES to the CPB particles at the early ages, as discussed earlier, and the subsequent delay of cement hydration are counterweighed by the accelerated cement hydration caused by the elevated curing temperature (Haruna and Fall 2020). The increase in the amount of cement hydration products formed with the addition of 0.125% PES and higher curing temperature is experimentally demonstrated by the

results of XRD of 28-day cemented paste samples cured at H1 with 0.0% and 0.125% of PES (ST-H1-0.0% and ST-H1-0.125%) as shown in Figure 3.33. The results confirm the presence of higher volumes of cement hydration products in ST-H1-0.125% (Figure 3.33b) compared to ST-H1-0.0% (Figure 3.33a). The intensity of CH at 18° 2-theta is 1399 CPS in ST-H1-0.125% but about 1232 CPS in ST-H1-0.0%). In a similar way, the intensity of CH at 34, 47, and 51° 2-theta in ST-H1-0.125% is slightly higher than ST-H1-0.0%.

Moreover, the aforementioned refinement of the pore structure of the CPB at the early ages is experimentally demonstrated by EC results in Figure 3.34. The EC of ST-H1-0.125% is considerably lower after 12 h of curing compared to ST-H1-0.0%. Previous studies (Fall et al. 2005; Fall et al. 2010) have found that an increased volume of cement hydration products result in a denser microstructure and finer distribution of pores. This causes less pore connectivity which in turn leads to an increase in the flow paths for ions, and thus decreases the EC.

The experimental results presented in Figure 3.32 show that the mechanical strength of the CPB-PES samples cured at H1 and H2 is significantly higher than the UCS of the CPB-PES samples cured at 20°C (ST- 20°C -0.125%). As discussed earlier, higher curing temperatures increase the volume of cement hydration products, which in turn leads to an increase in the mechanical strength of the CPB-PES samples over time. It can be also observed that after 7 days of curing and beyond, the UCS of the CPB-PES samples cured at H1 is significantly higher than that of the samples cured at H2 and 20°C . This is due to the rapid increase with H1 after 7 days (see Figure 3.2).

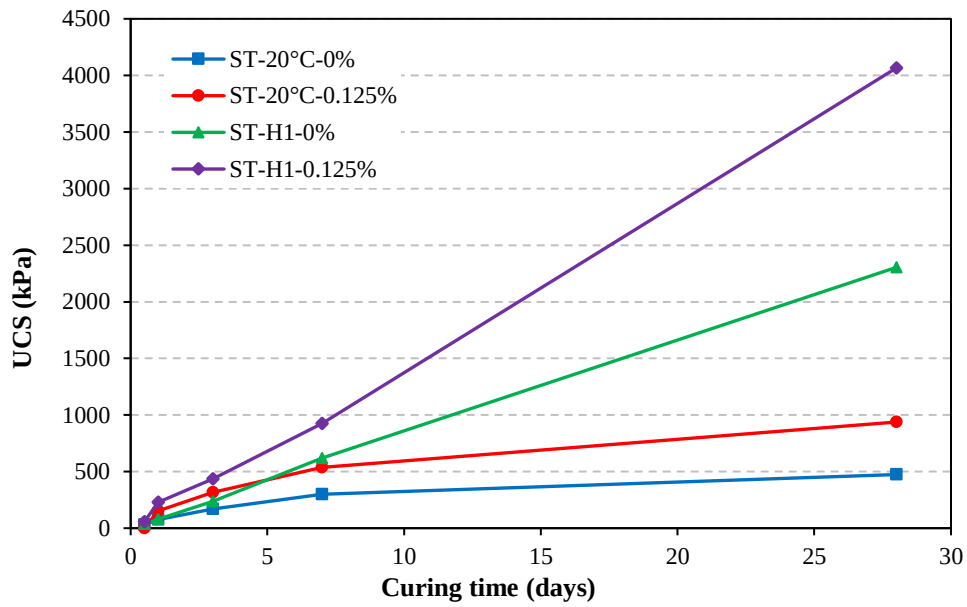


Figure 3.31 Effect of non-isothermal curing temperature on the strength of CPB samples with different amounts of PES and different curing time

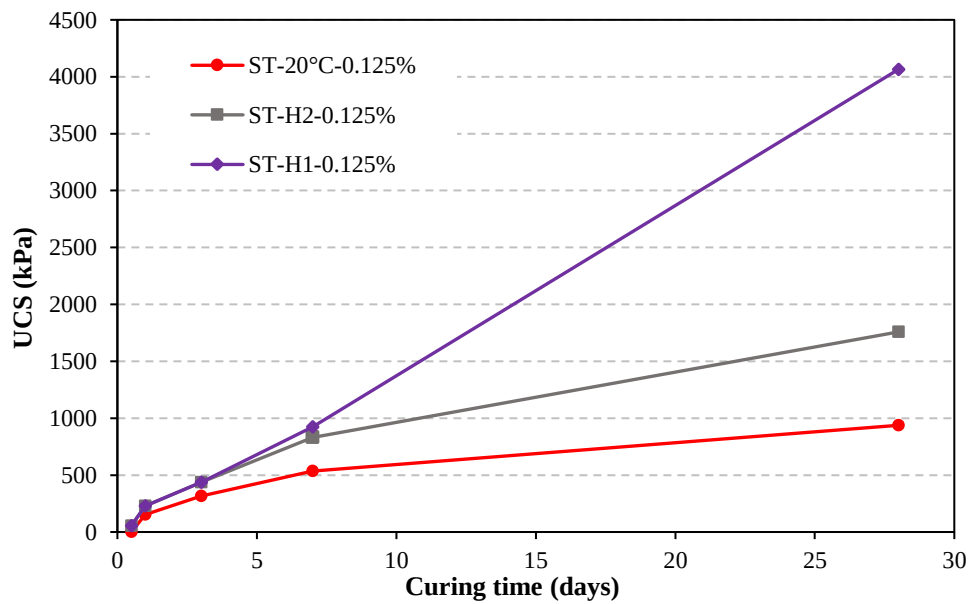
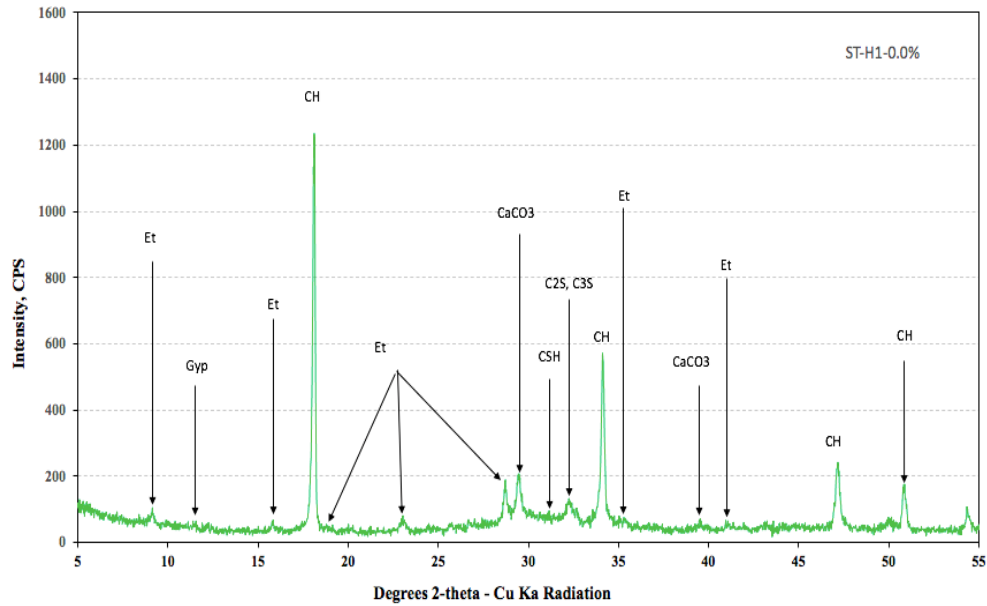
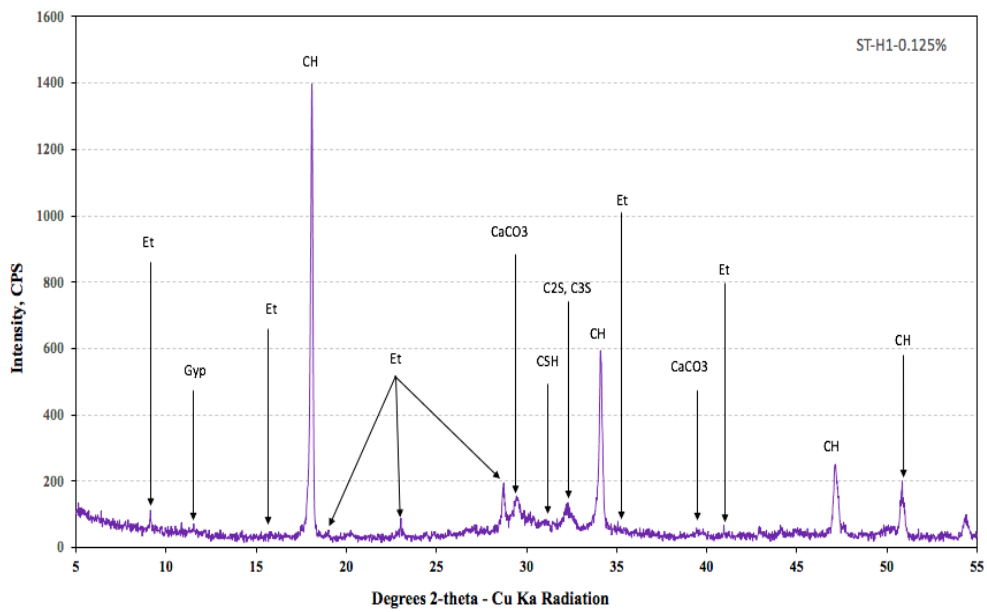


Figure 3.32 Effect of non-isothermal curing temperature on the strength of CPB-PES samples with curing time



a) Cured at H1 with 0.0% PES



b) Cured at H1 with 0.125% PES

Figure 3.33 XRD results of 28 day cemented paste cured at H1 and a) 0.0% PES and b) 0.125% PES

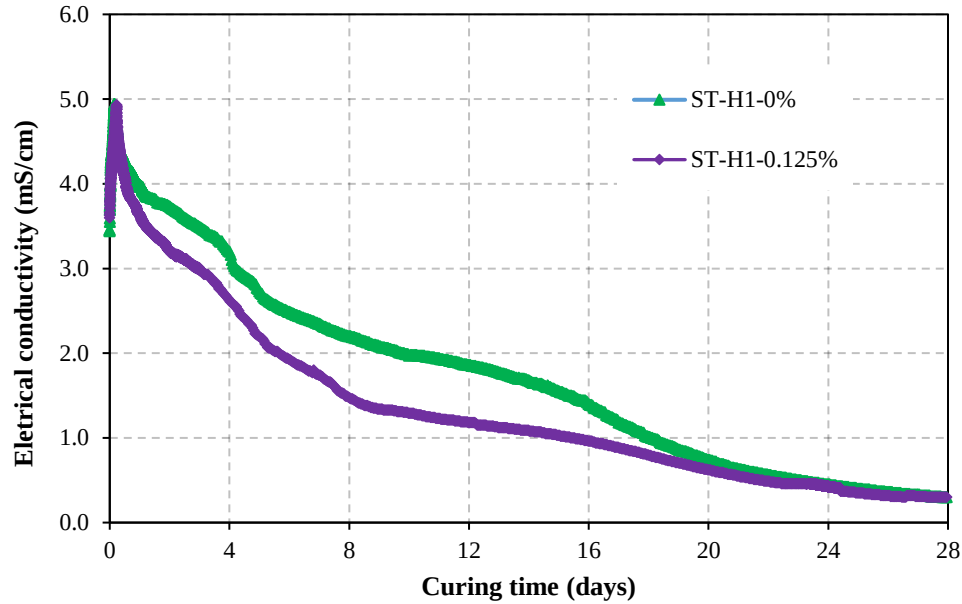


Figure 3.34 Changes in electrical conductivity of CPB-PES samples cured at H1 with different amounts of PES

3.4 Summary and conclusions

The experimental results in this investigation contribute to a better understanding of the effectiveness of PES as a chemical admixture for CPB. Based on the results, the following conclusions can be made:

- The addition of PES to the CPB mixture has a significant effect on the mechanical strength of CPB, but depends on the amount of PES added, type of tailings used and length of curing time. After 7 days of curing, the UCS of the CPB increases as the dosage of the PES is increased.
- The cement and solids contents play an important role in the strength development of CPB-PES.
- The obtained results demonstrate that fines particles (20 μm particles >60% by weight) significantly affect the strength acquisition of CPB-PES, and this effect depends on the percentage of fines, and the dosage of PES added.
- The short- and long-term strengths of CPB-PES are significantly affected by the amount of sulphate found in the mixing water. However, regardless of the amount of PES, after 7 days of curing, the CPB with sulphate is lower in strength than the sulphate-free CPB. Nevertheless, the strength of the CPB-PES samples increases with time regardless of the sulphate content, and the UCS of the CPB with sulphate and 0.125% PES has higher strength than both the samples with and without sulphate and

without any PES. Moreover, after 250 days of curing, the strength of all the CPB-PES samples tends to slightly decrease or increase.

- The CPB with PES and cured under stress has a higher strength after just 3 days of curing in comparison to the CPB without PES. Curing under stress rearranges the tailings particles and increases the packing density, which in turn reduces the void ratio and porosity, and thus increases the compressive strength of the CPB-PES samples.
- The CPB made with PES and cured under stress shows a high PWP during the early hours of curing, which in turn reduces its strength compared to the sample without PES.
- The CPB made with PES and cured in non-isothermal curing conditions has a significantly higher strength than the CPB without PES. The results show that the inhibition of cement hydration caused by the addition of PES at the early ages is compensated by the acceleration in cement hydration induced by elevated temperatures.

Despite the results obtained, the strength development of CPB with PES under multiphysics curing conditions was not considered or assessed in this study. There is a need to address this knowledge gap in future studies because the CPB is subjected to multiphysics curing conditions in the field.

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Chapter 4: Multiphysical Testing of Strength Development of Cemented Paste Backfill Containing Superplasticizer - Technical Paper 2

(Submitted)

Zubaida Al-Moselly, Mamadou Fall

Abstract:

Current laboratory curing and testing procedures for cemented paste backfill (CPB) to determine its critical engineering design property (mechanical strength) do not take into account the multiphysics (thermal, T, hydraulic, H, mechanical, M, chemical, C) processes or factors and their interactions to which CPB structures are subjected in the field. Inappropriate laboratory curing and strength testing procedures for CPBs can lead to unreliable measurements of the compressive strength of the CPB, and thus to improper design of CPB structures, which could lead to safety problems in the field and/or undesirable financial consequences. In this study, a multiphysical curing and testing procedures for CPB with superplasticizer has been developed to evaluate its strength development under THMC curing conditions close to those encountered in the field. The individual and coupled effects of thermal (e.g., field curing temperature), hydraulic (drainage conditions in the field), mechanical (field overburden pressure and pressure increase rate) and chemical (polycarboxylate ether-based superplasticizer and cement hydration) factors on the CPB strength were evaluated. The obtained results revealed that the mechanical strength and overall performance of the CPB-PES structure are greatly affected by the THMC factors and their interactions. A fundamental conclusion of this study is that accounting for field THMC factors and their coupling effect on the strength development of CPB is vital for the optimal design of safer and more economical CPB structures as well as for the early opening of barricades, which is crucial for improving mine productivity and safety.

Key words: Cemented paste backfill, tailings, superplasticizers, in-situ conditions, THMC.

4.1 Introduction

Cemented paste backfill (CPB) has been introduced as a best practice method for underground mine support and mine waste (tailings) management in mining industries around the world (Fall et al. 2004; Yilmaz et al. 2004; Fall and Samb 2009; Fall and Pokharel 2010). This technology ameliorates the mine production rate (i.e., increase ore recovery) and minimizes the environmental problems associated with mine waste disposal (Archibald et al. 2000; Ercikdi et al. 2009). CPB is a mixture of dewatered tailings from the milling or processing operations of mines (70-85 wt.%), hydraulic binders (3-7 wt.%, often), and fresh and/or mine processed water (Fall and Benzaazoua 2005; Fall et al. 2008; Célestin and Fall 2009). A key objective in CPB design is to produce a mix with acceptable flowability, which can result in a CPB structure with satisfactory mechanical stability in the field (Kesimal et al. 2003; Ghirian and Fall 2013).

The flowability of CPB (defined by its rheological properties) plays an essential role in its transport through pipelines (by pumping and/or gravity) from the CPB plant to the underground cavity or stope (Ercikdi et al. 2010). Any deficiencies in the transportation process (e.g., pipeline blockages) caused by poor flowability of CPB can have severe consequences for the CPB production and transportation costs (e.g., pumping maintenance and energy costs) as well as the productivity of the mine (Wu et al. 2013; Ercikdi et al. 2017; Haruna and Fall 2019). The rheological properties of CPB can be enhanced by adding high range water-reducing admixtures, also known as superplasticizers, that are efficient in reducing the mixing water content up to 30%, while maintaining the design mechanical properties (Ercikdi et al. 2010; Haruna and Fall 2019; Huynh et al. 2006; Simon et al. 2011; Ouattara et al. 2017; Ouattara et al. 2018; Ouattara et al. 2018b; Mangane et al. 2018). The main feature of the superplasticizer is its capability to adsorb and generate repulsive forces on the surface of cementitious mixtures that disperse the particles and enhance the rheological properties of the admixtures (Ouattara et al. 2018b; Yang et al. 2018).

Mechanical stability at a given time is a critical design criterion for a CPB structure. Once deposited in the underground mine cavity or stope, CPB must meet specific mechanical load resistance requirements to ensure safe working conditions for all mining workers. Moreover, these requirements should be satisfied as fast as possible to enable an early opening of the barricades (retaining wall built at the bottom of the stope to keep the fresh fluidic CPB from flowing into the working areas) (Fall and Pokharel 2010). CPB structure failures often lead to fatalities and/or injuries and have considerable financial consequences for a mine. Moreover, the early opening of the barricades allows to reduce the mining cycle time, thereby increasing the mining productivity or efficiency, which is associated with a substantial financial benefit for the mine (Cui and Fall 2017; Li and Fall 2018).

The uniaxial compressive strength (UCS) is the most important mechanical parameter used to assess the mechanical performance and stability of CPB (Fall and Samb 2009; Fall and Pokharel 2010). This is because testing of UCS is reliable, quick, and relatively cheap and can be integrated into routine quality control programs at the mine (Vergne 1996). Therefore, understanding and assessing the UCS development of CPB in the field is essential for the design of cost-effective CPB structures. However, the UCS development of the CPB in the field is poorly understood. Moreover, the laboratory testing method of the UCS of CPB currently used in engineering practices does not consider the interacting multiphysical processes to which the CPB is subjected during its curing in the field. Consequently, the UCS values of the CPB assessed according to this current method are not representative of the UCS of CPB in the field. An understanding and assessment of the UCS of CPB in the field require integrating into the assessment and testing of the UCS the relevant multiphysics or coupled processes to which the CPB structure is exposed in the field during its curing, as briefly discussed below.

Following placement of the CPB into the underground stopes, the behaviour and strength development of CPB structures are simultaneously influenced by thermal (T) (e.g., exothermic binder hydration, mine temperature), hydraulic (H) (e.g., drainage conditions, self-desiccation, suction, pore pressure), mechanical (M) (e.g., stress induced by the backfill self-weight, filling rate), and chemical (C) (e.g., binder hydration, chemical interactions between CPB components and additives) processes or factors as illustrated in Figure 4.1. The interactions or coupling between these THMC factors govern the behaviour and the mechanical properties of CPB, such as strength (Ghirian and Fall 2013, 2014, 2015, 2016; Cui and Fall 2017). As an example, the temperature can fluctuate considerably inside the CPB structure due to the large amount of heat generated by binder hydration, the initial temperatures of the CPB mix components, the surrounding conditions of the mine (external source of heat), as well as due to the intrinsic characteristics of CPB materials such as specific heat capacity and thermal conductivity (Fall et al. 2010; Fall and Pokharel 2010; Ghirian and Fall 2013; Wang et al. 2016; Cui and Fall 2015, 2016). These temperature variations will directly influence the binder hydration rate and, subsequently, the strength evolution of CPB (Cui and Fall 2015, 2016). Moreover, the development of the negative pore water pressure (suction) is also affected by the binder hydration reaction (Simms and Grabinsky 2009; Abdul-Hussain and Fall 2012). As cement hydration proceeds, pore-water pressure will be dissipated within the CPB due to the consumption of pore water by cement hydration reactions. As a result, self-desiccation will be generated, and the negative pore-water pressure (suction) can be gradually developed in the hydrating CPB structure. Suction development is one of the most important factors that affect the early strength gain (i.e., increase in the effective stress) of CPB (Rankine et al. 2001; Helinski et al. 2006, 2007; Grabinsky and Simms 2006). Furthermore, susceptibility to mechanical deformation or consolidation under

backfill self-weight pressure also affects CPB behaviour and strength (Yilmaz et al. 2009; Ghirian and Fall 2015, 2016). Furthermore, the accumulation of cement hydration reaction products in the pores of CPB contribute to pore refinement and porosity reduction of the CPB as well as creates and enhances the cementation between tailings particles (Fall et al. 2009).

Extensive research has been conducted in past years to assess the UCS development of CPB (Yilmaz et al. 2004; Klein and Simon 2006; Fall et al. 2007; Fall and Samb 2009; Yilmaz et al. 2009; Fall et al. 2010; Fall and Pokharel 2010; Ercikdi et al. 2013; Ghirian and Fall 2013, 2014, 2015, 2016; Cui and Fall 2016; Wang et al. 2016). These studies have considerably contributed to a better understanding of the strength of CPB and its evolution with the curing time. However, the transferability of the results from these previous studies to the field conditions remains limited because all these previous studies did not consider the aforementioned THMC factors in evaluating the UCS of CPB. Most of the studies included only the impact of one factor, such as temperature (e.g., Fall and Samb 2009; Fall et al. 2010; Wang et al. 2016; Cui and Fall 2016), cement hydration progress (e.g., Yilmaz et al. 2004; Kesimal et al. 2005; Fall et al. 2009; Ghirian and Fall 2014; Li and Fall 2018) and stress (e.g., Fall et al. 2007; Yilmaz et al. 2009; Ghirian and Fall 2015, 2016; Cui and Fall 2016) or two factors, such as temperature and chemical composition of the mixing water (Fall and Pokharel 2010), on the UCS development of CPB. No experimental studies have been conducted to investigate the effect of these coupled THMC processes on the strength of CPBs with the addition of superplasticizers. In other words, technical data on the influence of the coupled THMC factors on the UCS development of CPB and CPB with superplasticizer is inexistent. Therefore, there is a need to address knowledge deficiency for the reasons discussed earlier.

The objective of this paper is to experimentally investigate and understand the strength (UCS) development of CPB with superplasticizers subjected to various coupled THMC curing conditions.

4.2 Experimental Programs

4.2.1 Materials

4.2.1.1 Tailings

Synthetic silica tailings (ST) were used in this study. Synthetic silica tailing is a non-reactive silica powder which comprises 99.8% quartz (SiO_2) and has a grain size distribution close to the average of nine Canadian mine tailings (Figure 4.2). Quartz is the dominant mineral in tailings from Canadian hard rock mines. The purpose of using the silica tailings is to control the chemical and mineralogical compositions of the tailings accurately and to minimize the influence of reactive chemical elements that may be found in natural tailings, which can interact with cement, and

accordingly may affect the analysis and the interpretation of the results. Table 4.1 provides the chemical composition of the used silica tailings.

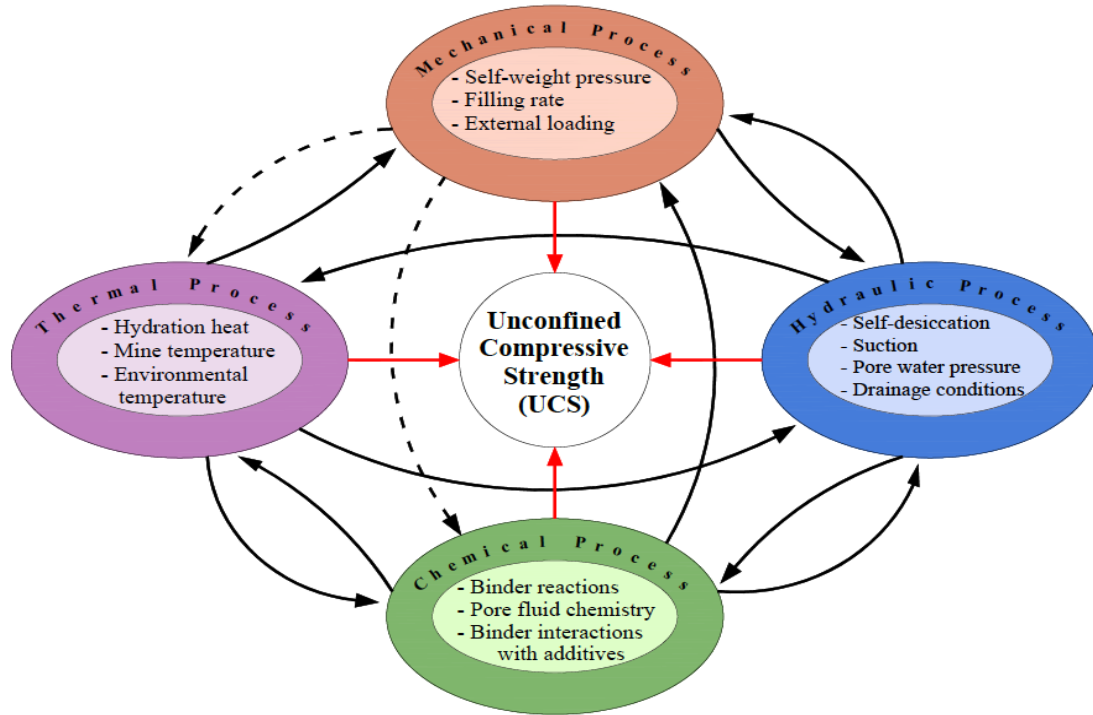


Figure 4.1 Multiphysics processes or factors that affect the strength of CPB structures (dashed arrow = weak couplings)

4.2.1.2 Binder and mixing water

Portland cement type 1 (PCI) was used in this study as the binder. The chemical and physical properties of the PCI are given in Table 4.2. Tap water was used for mixing the binder and tailings.

4.2.1.3 Chemical admixture

A polycarboxylate ether-based superplasticizer type was used as a water-reducing admixture in this study. The dispersing mechanism of the polycarboxylate ether-based superplasticizer is steric hindrance forces. The polycarboxylate ether-based superplasticizer (PES) is a commercial product supplied by Badische Anilin und Soda Fabrik BASF SE, Germany. It meets the ASTM C 494/C 499M requirements for Type A water-reducing and Type F high-range water-reducing admixtures (BASF, 2015).

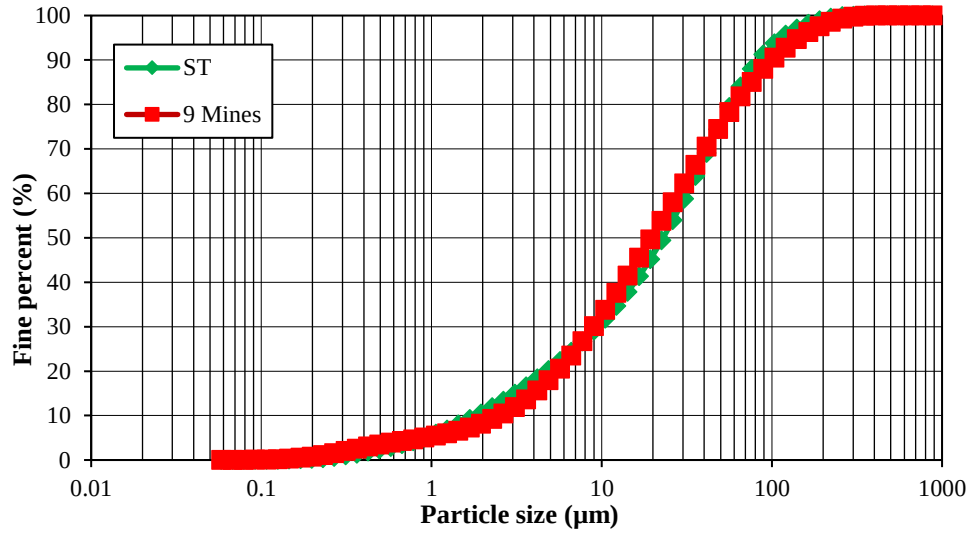


Figure 4.2 Grain size distribution of the silica tailings used and that of the average of nine natural mine tailings in Eastern Canada

Table 4.1 Chemical composition of the silica tailings.

Mineral Composition (wt.%)	Mineral (symbol)								Loss on ignition
	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O	
	99.8	0.035	0.05	0.02	0.01	<0.01	<0.01	0.02	

Table 4.2 Chemical and physical properties of binder used.

Element (%)	SO ₃	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	CaO	MgO	Relative density	Specific surface (m ² /g)
PCI	3.82	2.70	4.53	18.03	62.82	2.65	3.20	1.30

4.2.2 Sample preparation

The CPB with polycarboxylate ether-based superplasticizer (CPB-PES) samples were prepared using a weight proportion of 4.5% PCI and a water-to-cement ratio (w/c) of 7.35. Two percentages of PES (0% and 0.125%) were used. The w/c ratio and cement proportions remained constant in all prepared mixes. The tailings material, cement, water, and the specified percentage of the PES were mixed and homogenized in a mechanical mixer for about 7 min to make the desired CPB-

PES mixture. After that, the freshly prepared CPB-PES mixtures were poured into the pressure cells described below and cured under various THMC conditions for specific curing times, as summarized in Table 4.3 and discussed below.

4.2.3 Description of the THMC backfill curing system

The complexity of coupling the most important processes (THMC) in designing the CPB-PES structure should be appropriately reflected in the designing of the curing system in a laboratory setting. The curing system is required to determine the influence of various THMC factors, such as self-weight (overburden pressure) caused by mine stope filling processes, the evolution of cement hydration, pore water pressure, suction, temperature, deformation, and drainage conditions that may affect the strength and performance of the CPB-PES structure. For these purposes, a pressure cell apparatus originally developed at the University of Ottawa by Ghirian and Fall (2013, 2015) was additionally altered and used in this study. A schematic diagram of the modified pressure cells set-up for both drained and undrained conditions is shown in Figure 4.3. The CPB-PES specimen is contained in a Perspex (acrylic plastic) mould with a diameter of 101.6 mm (4 inches) and a height of 304.8 mm (12 inches), that is attached to an axial loading piston located on the top base end of the mould. Two cover plates were placed at the top and bottom of the mould, with three stainless steel tie rods to hold the mould and cover plates together. The purpose of the axial loading piston is to mimic the backfilling processes of the mine stope and the stope filling rate by applying compressed air pressure into the CPB-PES specimen. A series of pressure gauges and pressure regulators were used to control the gradual application of the air pressure on the cured samples. The non-isothermal curing conditions were simulated by enclosing the pressure cell moulds in a temperature-controlled chamber.

Furthermore, to incorporate the drainage conditions, a drainage hole at the bottom cover plate is attached to a water tube to collect the expelled water, which may represent water drained through the barricades and/or the fractured rock mass adjacent to the backfill structure. A drainage valve is attached to the bottom drainage hole to control the water flow. The volume of excess pore water drains from the base plate is measured through a digital scale.

Moreover, the pressure cells were equipped with various sensors to monitor the evolution of suction, temperature, volumetric water content, and electrical conductivity (EC), as shown in Figure 4.3. A 5TE temperature sensor was installed in the pressure cell to measure the electrical conductivity with an accuracy of ± 0.1 from 0 to 23 dS/m, and monitor the evolution of temperature within the CPB-PES samples with an accuracy of $\pm 1^\circ\text{C}$ and a range of -40°C to 60°C . Monitoring the electrical conductivity is an effective way of assessing the progress of cement hydration since the electrical conductivity reflects the ion concentration and ion mobility changes in the CPB

specimen (Li and Fall 2016). The evolution of negative pore water pressure (PWP) or suction was recorded using the MPS-6 dielectric water potential sensor with a range of -9 to $-100,000$ kPa and an accuracy of $\pm 10\%$ of reading $+2$ kPa from -9 to 100 kPa. Monitoring volumetric water content and suction is an excellent way to gain insight into the development and intensity of self-desiccation of the backfill material due to water consumed by cement hydration. A linear variable differential transformer (LVDT) was attached to the axial loading piston rod to measure the deformations produced by the application of load and/or binder hydration of the CPB-PES specimen. All the above-installed sensors were attached to the applicable data loggers to record the test data with time.

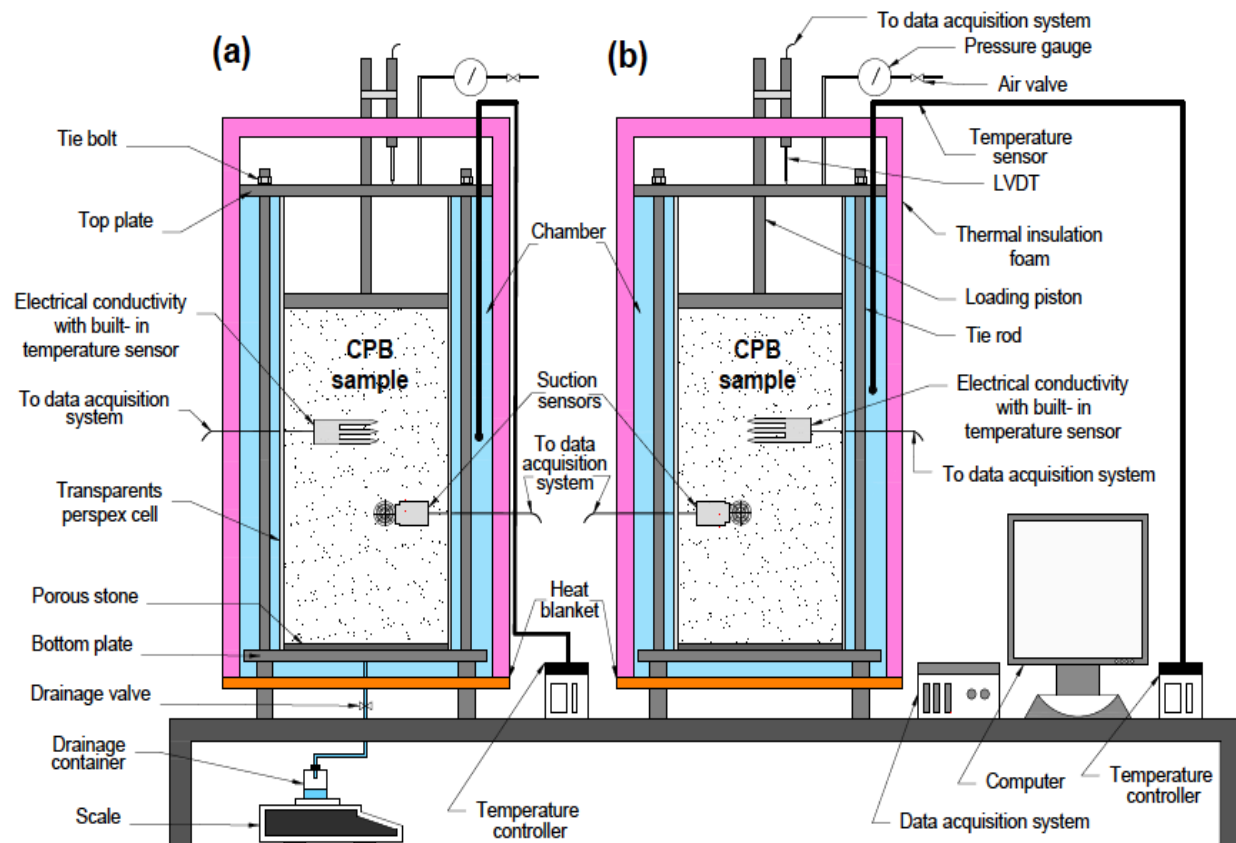


Figure 4.3 Schematic diagram of pressure cells set-up: (a) drained condition, and (b) undrained condition (modified from Ghirian and Fall 2015)

4.2.4 Applied THMC curing conditions and monitoring program

The CPB-PES samples with different initial compositions prepared according to the procedures described above were cured under the conditions described below and summarized in Table 4.3.

4.2.4.1 Mechanical curing conditions (curing under applied pressure)

The in-situ vertical pressures applied to the CPB structure are significantly varied from mine to mine and further in from stope to stope and greatly depend on the stope geometry, stope depth, backfilling rate, cement content, barricade and the related design pressure on the initial plug (Al-Moselly and Fall 2022). To address the critical importance and complexity of the mechanical behaviour of in-situ backfilling processes and to understand the coupled effect with the other THC processes over time on the strength development of CPB samples, stress-curing conditions with other THC factors were applied to the CPB-PES samples and compared it to that of CPB samples under standard laboratory conditions. The in-situ pressure field measurements data for a long hole stope of 32 m height presented in Thompson et al. (2009) were adopted in this study. Table 4.4 shows the vertical pressure and the equivalent backfill rate and height applied to the CPB-PES specimens in this study. For the first 2 hours, no pressure was applied to the sample, followed by a gradual air pressure increase up to 600 kPa with an average filling rate of 0.26 m/h after 3 m height.

Table 4.3 Summary of specimens mixing composition and curing conditions.

Sample Name	Tailings type	Binder type (C)	PES content (%) (C)	Curing stress (M)	Drainage condition (H)	Curing temperature (T)	Curing time (day)
Control-UD-0.0% PES	ST	PCI	0	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
Control-UD-0.125% PES	ST	PCI	0.125	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
THMC-D-0.125% PES	ST	PCI	0.125	Field stress ^a	D	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-PD-0.125% PES	ST	PCI	0.125	Field stress ^a	PD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-UD-0.0% PES	ST	PCI	0	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-UD-0.125% PES	ST	PCI	0.125	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
HMC-UD-0.125% PES	ST	PCI	0.125	Field stress ^a	UD	20°C	0.5, 1, 3, 7, 28
THC-UD-0.125% PES	ST	PCI	0.125	Stress-free	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THC-D-0.125% PES	ST	PCI	0.125	Stress-free	D	Field temp. ^b	0.5, 1, 3, 7, 28

ST: silica tailings; PES: polycarboxylate ether-based superplasticizer; ^a simulated field curing stress (vertical pressure); ^b simulated field curing temperature; D: drained; PD: partially drained; UD: undrained conditions; PCI: Portland cement type I. C: chemical factor; M: mechanical factor; H: hydraulic factor; and T: thermal factor

Table 4.4 Pressure application scheme and the corresponding equivalent CPB height.

Elapsed time	Applied vertical pressure (kPa)	Equivalent height (m)	Equivalent filling rate (m/h)
start	-	-	-
2 h	20	1.00	0.50
4 h	35	2.00	0.50
6 h	55	3.00	0.50
8 h	60	3.20	0.40
10 h	80	4.30	0.43
12 h	90	4.80	0.40
1 d	100	5.38	0.22
1.5 d	125	6.66	0.19
2 d	150	7.92	0.17
3 d	250	13.25	0.18
4 d	400	21.41	0.22
5 d	450	24.00	0.20
6 d	600	32.00	0.22

4.2.4.2 Hydraulic curing conditions

The drainage condition significantly affects the unconfined compressive strength of the CPB-PES and, thus the mechanical stability of the underground mine. The selection of the drainage condition is based on many factors, such as the geological conditions of the mine, groundwater conditions, and the permeability of the CPB material used. In the field, if the fresh CPB has very low permeability (for example, if fine tailings and high cement content are used) and the surrounding rock mass is not fractured, CPB mass may not drain any water out; thus, the CPB mass will be in almost undrained conditions during its curing. Drained (D) conditions can theoretically happen if the CPB is highly permeable (coarse tailings used), the surrounding rock mass is highly fractured to let water flow away from the CPB mass, and drainage conditions at the barricade are highly favourable. However, in many field cases, the drainage conditions of the CPB mass are between UD and D, i.e., the CPB mass is partially drained. To simulate different drainage conditions, three drainage conditions are considered in this study: (1) undrained condition (UD), (2) drained condition (D), and (3) partially drained conditions (PD). The partial drainage conditions are obtained by closing the drainage valve after approximately 1.5 days of curing (i.e., about 50% of the water that can be drained will be drained out of the CPB structure).

4.2.4.3 Thermal curing conditions

Incorporating temperature variation in the underground mine backfill process in the curing process of CPB-PES materials is of paramount significance to assess the mechanical strength of

the CPB-PES structure and, thus the overall stability of the underground mine stopes and barricade, as it is well documented and established that significant heat can develop in the backfill mass in the field (Fall et al. 2010). Therefore, isothermal (temperature of 20°C) and non-isothermal curing temperatures (field temperature) curing conditions were considered in this study. The considered field temperature–time history was determined by Nasir and Fall (2009) and Wu et al. (2012) using a numerical tool for a stope height of 30 m, which was backfilled with CPB material containing a binder content of 4.5% as shown in Figure 4.4.

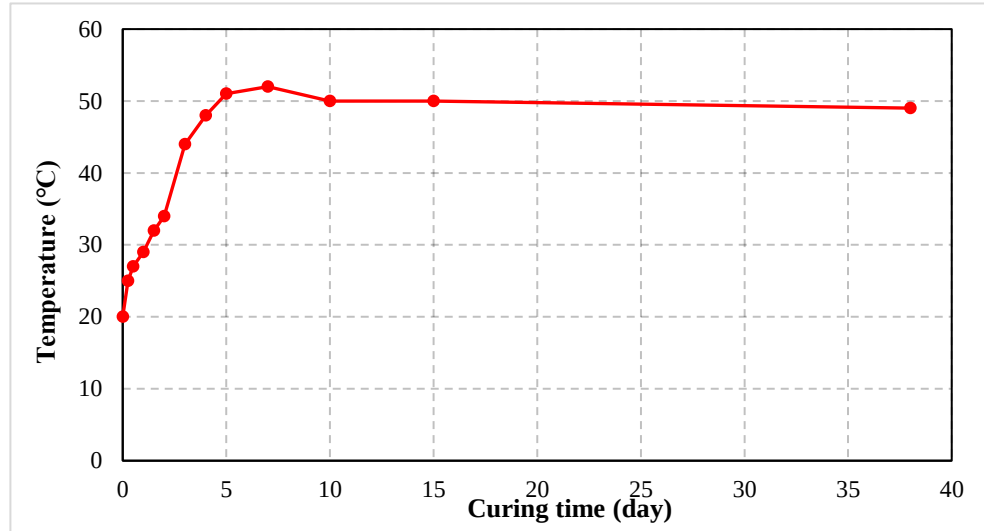


Figure 4.4 Predicted field temperature history for a stope size of 30 m height (from Nasir and Fall 2009 and Wu et al. 2012)

4.2.4.4 Chemical curing conditions

The chemical evolution of CPB-PES and its relationship to the other THM process or factors were investigated with time to study the effect of the chemical composition (particularly the effect of PES) of the CPB-PES mixture on the strength development cured under isothermal and non-isothermal, various drainage conditions (drained, undrained, and partially drained), free and field curing stress. The chemical processes of CPB-PES are mainly caused by the binder or cement reactions and the chemical interactions between the CPB components, including tailings, binder, mixing water, and additives (i.e., polycarboxylate ether-based superplasticizer). This study focuses primarily on the effect of the presence PES and its interactions with other components (e.g., cement) on the response of CPB under Multiphysics curing conditions. Therefore, the preparation of specimens with different PES contents under various curing conditions would capture the evolution of cement hydration and its interaction with the superplasticizer.

4.2.5 Testing programs

4.2.5.1 Mechanical test

Uniaxial compressive strength (UCS) tests were conducted according to the ASTM C39 procedure on the CPB-PES samples at various curing times (0.5, 1, 3, 7, and 28 days). The displacement rate of the press machine is 1 mm/min. For each curing time, a minimum of two samples were tested to ensure the repeatability of the results and the average value was considered as the strength of the tested sample. Following the proposed curing time, the UCS cells were disassembled, and the CPB-PES samples were trimmed within the standard cylindrical specimens' measurement of length-to-diameter ratio (H/D) of two. The UCS test results data were recorded using a computer data acquisition system.

4.2.5.2 Determination of physical properties and microstructure

To assess the effect of the THMC curing conditions on the pore structure (e.g., void ratio, porosity, density) and formation of cement hydration products, multiple physical property and microstructure testing techniques were employed in this study. The gravimetric water content (ω %) and bulk density (γ) tests were conducted on the prepared and cured CPB-PES samples according to ASTM D2216-10 and ASTM D763-09, respectively. In addition, the evolution of index properties and pore structure of the CPB-PES samples, including void ratio (e) and porosity (n), were measured, and assessed with time. Furthermore, thermogravimetric analyses (TG and DTG) were performed on some cement paste samples ($w/c = 1$; to mimic the high-water content of CPB) prepared in the similar way as the CPB specimens to determine the types and relative amount of cement hydration products generated in the samples. The tests were performed using a thermogravimetric analyzer, which implies continuous monitoring and recording of weight loss, heat flow, and temperature changes in the sample at a rate of 10°C per minute up to 1000°C.

4.3 Results and Discussion

4.3.1 Coupled effect of THMC factors on the strength evolution of CPB-PES

Figure 4.5 presents the coupled effect of the thermal (T), hydraulic (H), mechanical (M), and chemical (C) processes or factors on the strength development of CPB with PES cured under simulated field curing conditions (THMC-D-0.125% PES) compared to the strength development of CPB without PES cured under conventional laboratory (Control-UD-0.0% PES) conditions (i.e., stress-free, undrained, and room temperature of 20°C). Figure 4.5 clearly indicates that the THMC factors strongly influence the strength acquisition of the CPB-PES with time. It can be seen that the drained, cured under field stress, cured under non-isothermal field temperatures, and containing

polycarboxylate ether-based superplasticizer (i.e., 0.125% of PES) samples exhibited significantly higher strength compared to the control samples (undrained, cured under zero stress, cured under an isothermal temperature of 20°C, and without polycarboxylate ether-based superplasticizer (0% PES). For the THMC-D-0.125% PES samples, it can be noted that there is a strength improvement of approximately 302%, 229%, 318%, 688%, and 809% on the 12h, 1, 3, 7, and 28 days of curing, respectively, when compared to the control sample.

This significant increase in the UCS values of the drained THMC samples with 0.125% PES (THMC-D-0.125% PES) can be attributed to the following different mechanisms: (i) curing the samples at non-isothermal field curing temperatures accelerates the cement hydration process and thus increases the precipitations of large amounts of cement hydration products, which in turn increase the pore refinement of the CPB material and this results in higher strength (Fall et al. 2010; Wang et al. 2016; Cui and Fall, 2016); (ii) it has been shown that the mechanical strength of a drained backfill is higher than that of an undrained backfill mainly due to higher effective stress in the drained backfill (le Roux et al. 2005; Ghirian and Fall 2015); (iii) curing under stress increases the packing density of the material, which leads to a reduction in the void ratio and higher concentration of solids and thus higher strength (Cayouette 2003; Yilmaz et al. 2009); and (iv) in addition to the strength gain caused by the precipitation of large amounts of cement hydration products over time and the associated refinement of the pore structure, the incorporation of a polycarboxylate ether-based superplasticizer (PES) into the CPB material significantly improves the mechanical strength due to the dispersing effect of PES (Haruna and Fall 2021; Al-Moselly et al. 2022).

The combined effects of the aforementioned THMC factors not only lead to the generation of more cement hydration products (i.e., stronger cementation) in the CPB material, but also result in a refinement of the pore structure and greater densification of the CPB material, as well as a decrease in pore water pressure or an increase in suction (i.e., enhanced self-desiccation) in the CPB. All these factors are known to affect the strength of cementitious materials. This effect of the THMC factors on the pore structure refinement and densification of the CPB material is demonstrated in Figure 4.6. This figure compares the evolution over time of porosity (Figure 4.6a) and dry density (Figure 4.6b) of CPB samples with 0.125% PES exposed to THMC curing conditions with that of control samples without PES. The results indicate lower porosity and greater dry density with time for THMC-samples with 0.125% PES compared to the control samples. Moreover, the intensification of self-desiccation induced by the THMC curing conditions is demonstrated by the suction monitoring results displayed in Figure 4.7. From the results presented in this figure, the suction values for the THMC-D-0.125% PES sample are much higher than those for the control sample. For example, the suction measure for the THMC-D-0.125% is 558 kPa at 28 days compared to 103 kPa for the control sample.

The individual contribution of each of the thermal (T), hydraulic (H), mechanical (M) and chemical (C) factors to the impact of coupled THMC processes on the strength evolution (UCS) of the CPB-PES material is further investigated and discussed in the subsections below.

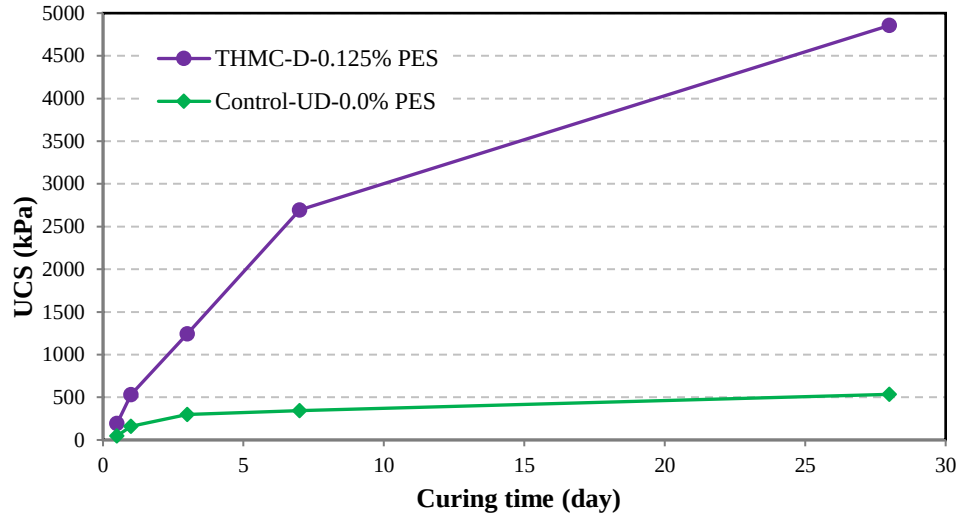


Figure 4.5 Coupled effect of THMC factors on the strength development of CPB-PES with time

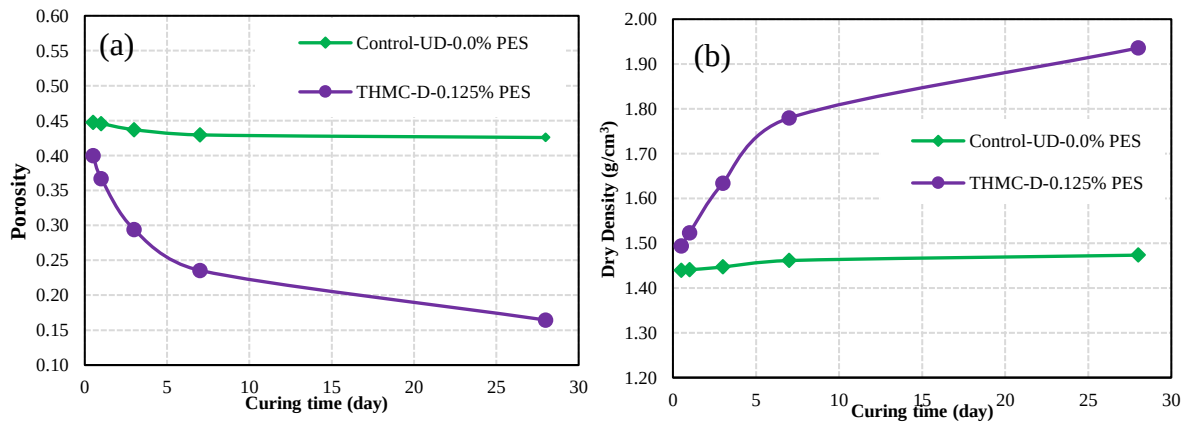


Figure 4.6 Changes in physical properties of CPB-PES under THMC curing conditions and under conventional laboratory curing conditions (control): (a) porosity; and (b) dry density.

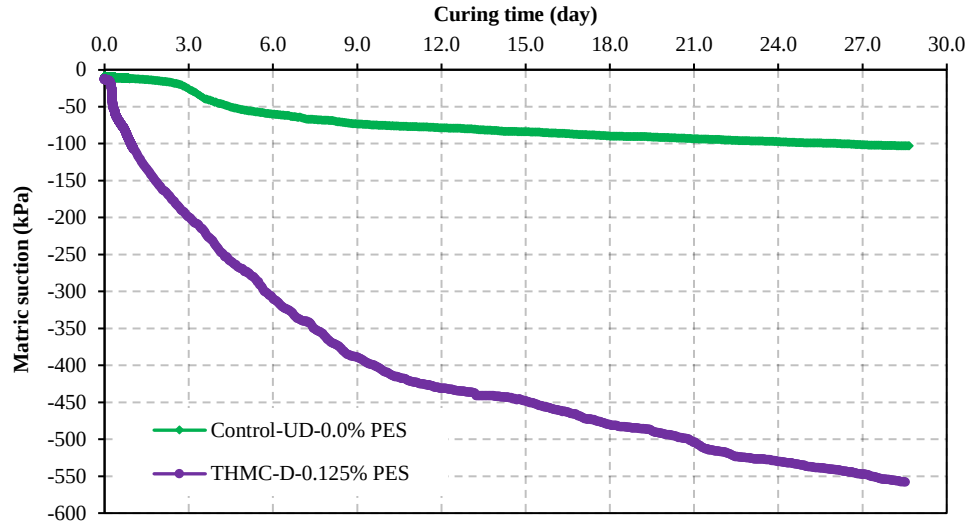


Figure 4.7 Matric suction monitoring results of CPB-PES under THMC curing conditions compared to control CPB.

4.3.1.1 Contribution of the chemical (C) factor (addition of PES) to the UCS development

Figure 4.8 illustrates the influence of polycarboxylate ether-based superplasticizer (PES) addition on the strength acquisition of CPB samples cured under THMC factors. The evolution of the resistance of the control samples with and without PES is also presented for comparison. The CPB samples containing 0.125% of PES and cured under coupled THMC factors (THMC-UD-0.125% PES) exhibited a significant increase in the mechanical strength compared to the CPB samples containing 0.0% PES (THMC-UD-0.0% PES) starting from 1 day of curing. For example, the incorporation of 0.125% of PES allows an increase in the UCS values of approximately 22%, 94%, 93%, and 79% on 1, 3, 7, and 28 days of curing, respectively, when compared to the THMC-UD-CPB samples containing 0.0% PES (THMC-UD-0.0% PES). This significant increase in the UCS values can be attributed to the individual effect of PES on cement hydration in CPB mixtures as well as the combined influence of superplasticizer and high temperature on cement hydration. The addition of polycarboxylate ether-based superplasticizer (PES) allows the solid particles (tailings and cement) in the CPB mixture to disperse and generate repulsive forces between the solid particles, and these inter-particle repulsive forces inhibit the cement hydration process at the early age (Ercikdi et al. 2010; Yang et al. 2018; Haruna and Fall 2019). This justifies the lower strength values at an early age (i.e., 12 h) for the samples with 0.125% PES. However, at later ages, the cement hydration rate increases due to the promotion of ionic diffusion caused by the action of PES (Haruna and Fall 2020), which in turn results in the formation of more cement hydration products. Moreover, the steric repulsion mechanism in the polycarboxylate ether-based superplasticizer and the associated long polymer chains help to link the particles and increase the

contact points between the CPB-PES particles and thus increase the mechanical strength of CPB-PES with time (Ercikdi et al. 2010; Yang et al. 2018). This rise in cement hydration products is consistent with the TG/DTG analysis results of cement paste samples with 0% and 0.125% PES dosages that were cured for 7 days (Figure 4.9). In this figure, the first endothermic peak the DTG curve between 100 °C and 200 °C accounts for the rapid weight loss caused by the evaporation of water and the disintegration of hydration products, e.g., ettringite, gypsum, carboaluminates, and C-S-H (Wang et al. 2016). The peak found at 400 °C to 500 °C is from the dehydroxylation of calcium hydroxide (CH), whereas the third peak at 650 °C to 750 °C is related to the breakdown of calcite (Fall and Pokharel 2010). When comparing the TG/DTG curves of the cement paste with 0% and 0.125% PES, the specimen with 0.125% PES has the greatest loss in the first and second peaks. This indicates that more hydration products are generated in the presence of PES. Moreover, Haruna and Fall (2020) have demonstrated that, the PES-induced increase in cement hydration product or rate is higher in CPB cured at higher temperatures. This conclusion by Haruna and Fall (2020) is also consistent with the results presented in Figure 4.8. This figure shows that the impact of PES on strength increase, and the rate of increase is much higher under high curing temperatures (non-isothermal field curing conditions) than under isothermal laboratory curing conditions (20°C). For example, the 28-day strength of THMC-UD-CPB with and without PES is 4264 kPa and 2380 kPa (a difference of 1884 kPa), while the 28-day strength of the control sample with and without PES is 707 kPa and 534 kPa (a difference of 407 kPa).

This increase in cement hydration products due to the individual effect of PES and the coupled effect of temperature and PES on cement hydration not only leads to the strengthening of CPB cohesion, but also leads to the refinement of its pore structure and the decrease of pore water (intensification of self-desiccation). The refinement of the pore structure and intensification of self-desiccation are experimentally demonstrated by the results of the physical properties test results presented in Figure 4.10. From Figures 4.10a and 4.10b, it can be noticed that the void ratio and porosity of the CPB samples that contain 0.125% of PES and cured under THMC factors (THMC-UD-0.125% PES) are lower compared to the CPB samples containing 0.0% PES (THMC-UD-0.0% PES). Moreover, the THMC-UD-0.125%PES-samples show higher dry density. Many studies reported an increase in the mechanical strength of the CPB materials when the porosity and void ratio decrease, or dry density increases over time (Taylor 1993; Ouellet et al. 2007; Fall and Samb 2008; Ghirian and Fall 2015). Furthermore, Figure 4.10d demonstrates the significant reduction in the water content with time for the CPB samples with 0.125% of PES and cured under THMC factors compared to the other samples due to the utilization of water during the ongoing cement hydration (i.e., reduction of free water). Numerous studies (e.g., Ercikdi et al. 2009; Fall and Samb 2009; Ghirian and Fall 2015) have concluded that the increase in the moisture content

of the CPB materials has an adverse impact on the compressive strength due to the weak microstructure of the CPB materials caused by the increase in the moisture content.

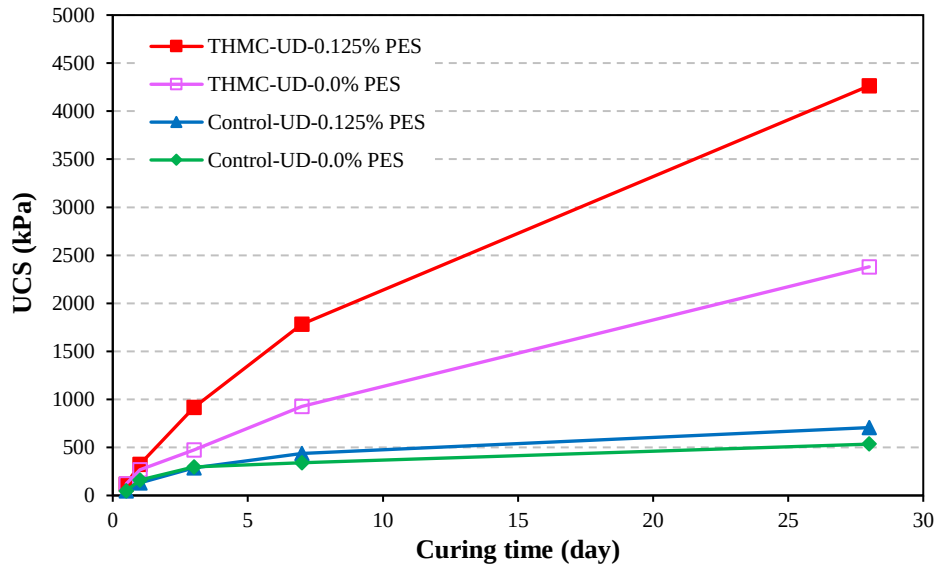


Figure 4.8 Influence of polycarboxylate ether-based superplasticizer (PES) on the strength development of CPB cured under THMC curing conditions.

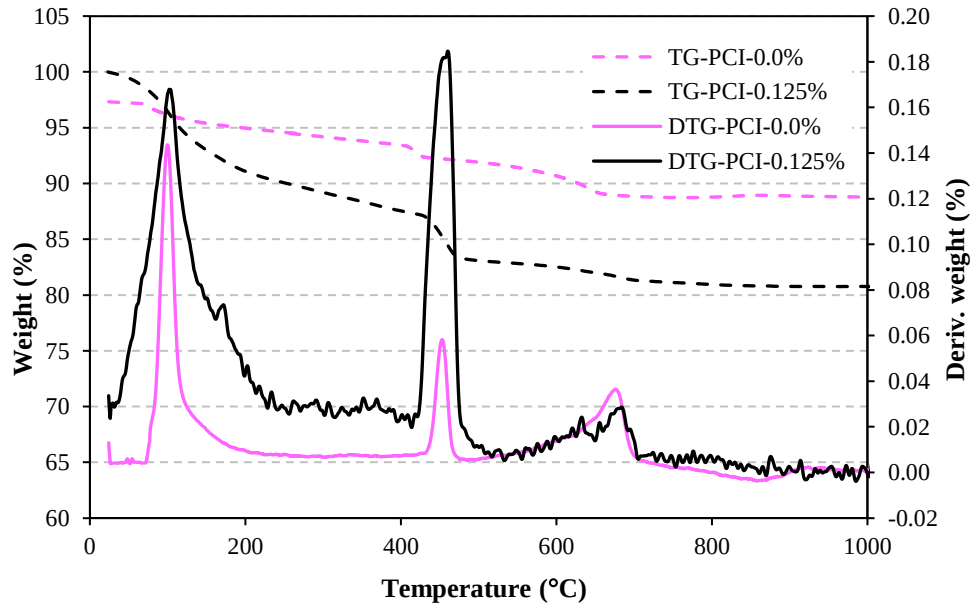


Figure 4.9 TG/DTG diagrams for 7-day old cement paste with 0.125% PES and without PES.

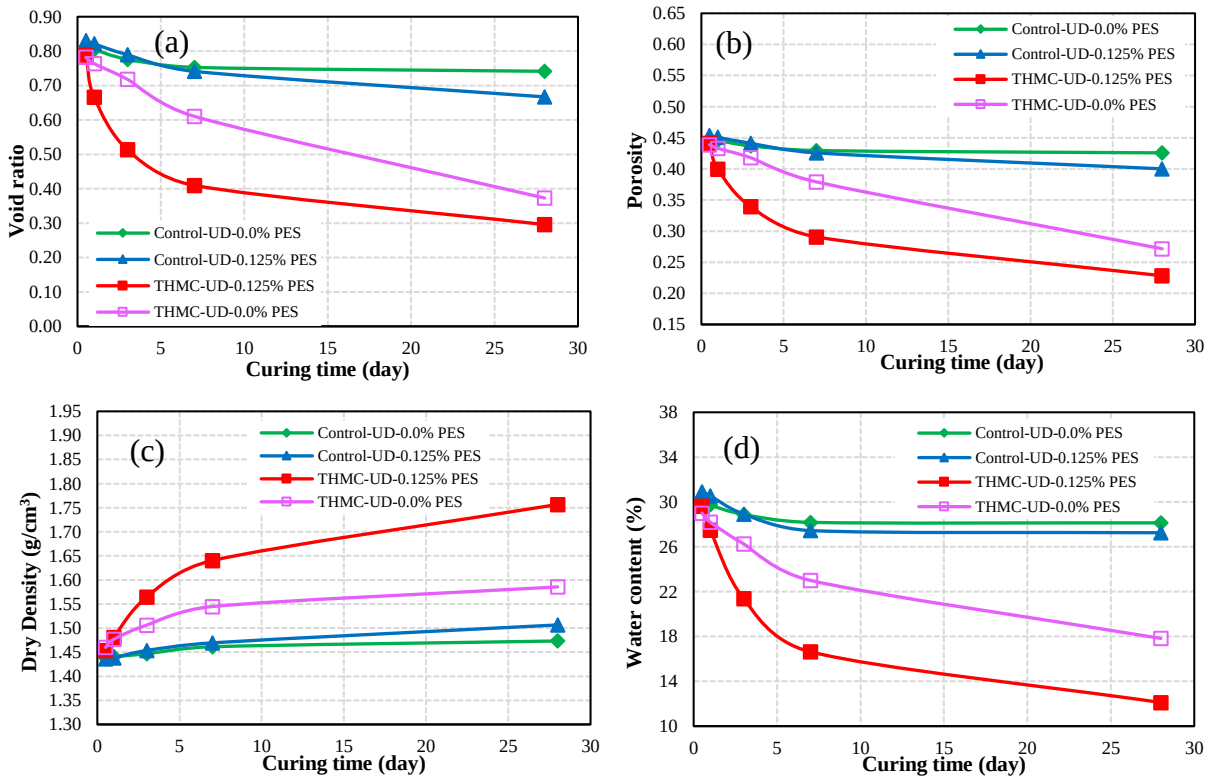


Figure 4.10 Changes in physical properties of CPB-PES under THMC curing conditions, the effect of chemical factor. (a) void ratio; (b) porosity; (c) dry density; and (d) water content.

4.3.1.2 Contribution of the thermal (T) factor (non-isothermal field curing condition) to the UCS development

Figure 4.11 presents the strength acquisition of the CPB-PES samples cured under THMC factors and under only HMC factors (i.e., cured under undrained drainage (H) conditions, under stress (M) and containing 0.125% PES (C), or without the effect of field curing temperature of CPB-PES). From this figure, it can be seen that the CPB samples cured under THMC factors have higher compressive strength compared to the CPB samples cured under HMC factors. When compared to the CPB-PES samples cured under HMC samples, the CPB-PES samples cured under THMC factors provided a compressive strength increase of 28%, 28%, 63%, 127%, and 275% for the 12 h, 1, 2, 3, 7, and 28 days respectively. For a curing period of 28 days, the UCS values increased from 118 kPa to 4264 kPa for the CPB-PES samples cured under THMC factors, whereas the UCS value increased from 92 kPa to 1136 kPa for the CPB-PES samples cured under HMC factors. This significant increase in mechanical strength is attributed to the effect of non-isothermal field curing conditions (i.e., elevated temperatures) on the cement hydration process. Higher curing

temperature accelerates the cement hydration process, which leads to the precipitation of higher amounts of cement hydration products (Fall et al. 2010; Tian and Fall 2021). The generation of higher amounts of cement hydration products enhances the binding forces between the solid particles, increases the self-desiccation of the CPB-PES material, and refines its pore structure, thereby significantly increasing the mechanical strength of the CPB-PES (Haruna and Fall 2020).

The results of the electrical conductivity (EC) monitoring for both CPB-PES samples cured under THMC and HMC factors presented in Figure 4.12 demonstrate the accelerated cement hydration process caused by the increase in curing temperatures. It can be seen from this figure that the EC of the CPB-PES sample cured under THMC factors reached its peak after about 6.5h, whereas the CPB-PES sample cured under HMC factors reached its peak at 9 hours. The earlier EC peak of the CPB-PES sample cured under THMC factors indicates a higher concentration of ions, caused by the intensifying rate of the chemical reactions of the binder (Thottarath 2010; Tian and Fall 2021), in other words, it is indicative of a faster rate of cement hydration. Also, the EC of the CPB-PES samples cured under THMC factors is lower after around 8 hours compared to the CPB-PES samples cured under HMC factors. This can be attributed to the increased flow path of ions in the CPB mixture caused by the reduction of connected pores, therefore, reducing the EC (Al-Moselley et al. 2022).

The results of the evolution of the void ratio and porosity of the CPB-PES samples cured under THMC factors and HMC factors, presented in Figure 4.13, show a significant reduction in the void ratio and porosity for the CPB-PES samples cured under THMC factors, i.e., a refinement of their pore structure, compared to the CPB samples cured under HMC factors. This can be attributed to the generation of higher amounts of cement hydration products and the related pore structure refinement caused by curing CPB samples under higher temperatures (Fall and Pokharell 2010). The finer pore structure of the CPB-PES, produced by pores filled with cement hydration products, leads to a denser connection between the tailing's particles, and thus lower porosity and void ratio can be observed (Ghirian and Fall 2015). Several studies (Fall and Samb 2008, 2009; Fall et al. 2010; Ghirian and Fall 2015, 2016; Cui and Fall 2016) concluded that increased mechanical strength of the CPB materials is linked to a reduction in overall porosity and void ratio of the CPB materials.

Moreover, it can be observed from Figure 4.11 that curing the CPB-PES samples in non-isothermal curing field curing conditions counterposes the early age retardation of cement hydration induced by the addition of polycarboxylate ether-based superplasticizer (PES) in the CPB mixture (Haruna and Fall 2020). Indeed, polycarboxylate-based superplasticizers, such as the one employed in this study, are well documented to retard hydration of PCI cement for the first 30 hours (Lothenbach et al. 2007). However, starting from 12 hours of curing, the UCS value of the

CPB-PES samples cured under THMC factors is higher than that of the CPB-PES samples cured under HMC factors.

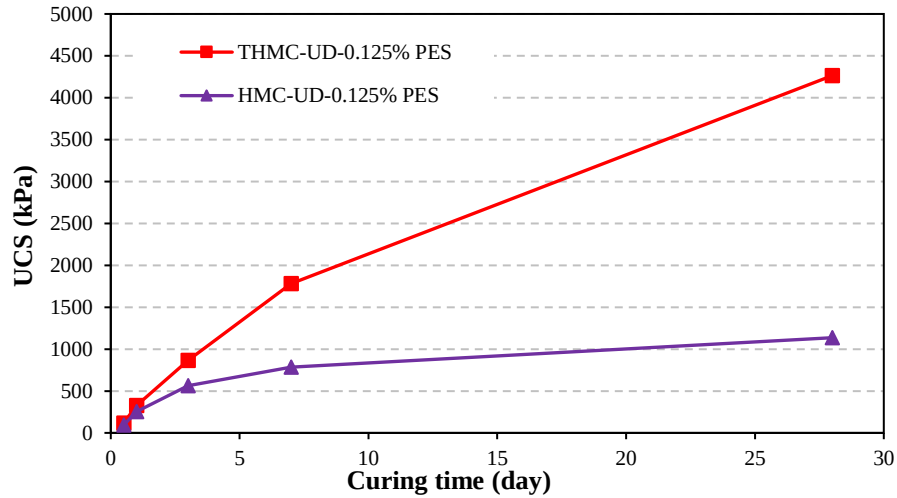


Figure 4.11 Contribution of non-isothermal field curing temperatures to the strength development of CPB-PES.

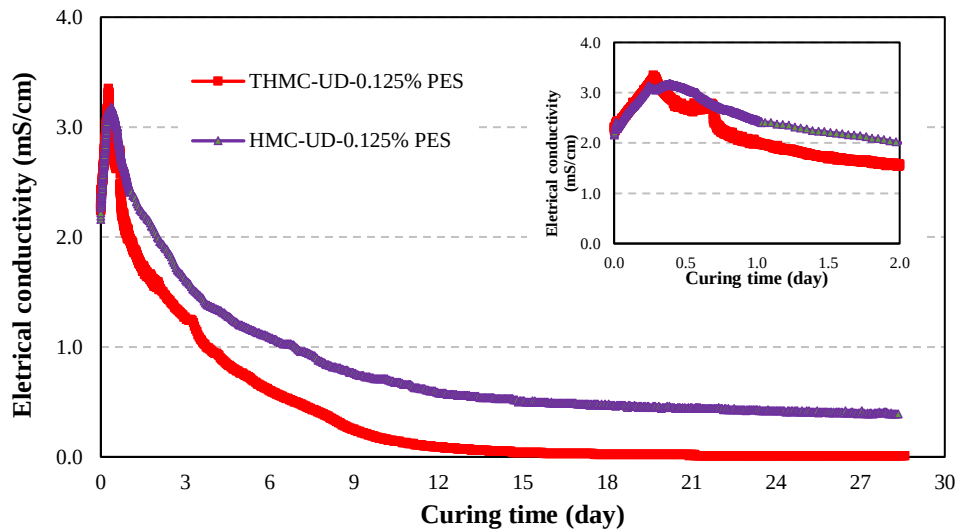


Figure 4.12 The EC evolution of CPB-PES samples cured under THMC and HMC factors with time.

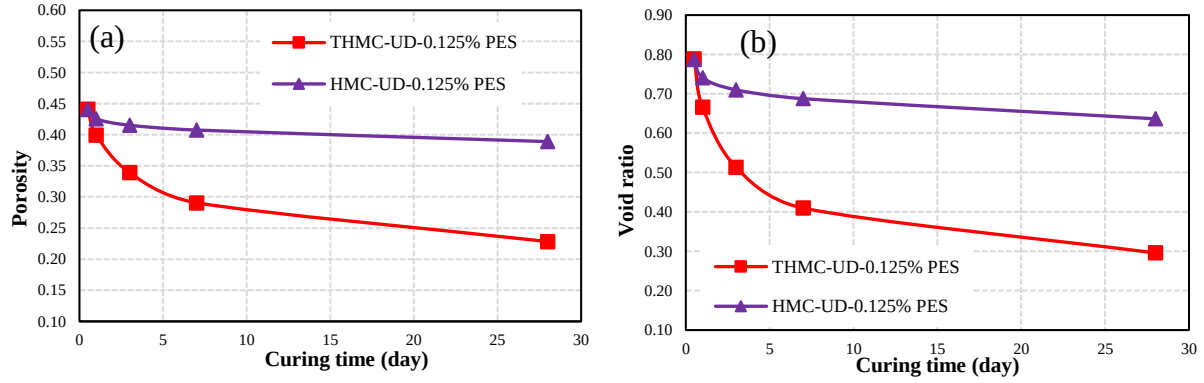


Figure 4.13 Evolution of the porosity (a) and void ratio (b) of CPB-PES samples cured under THMC and HMC curing conditions.

4.3.1.3 Contribution of the Mechanical (M) factor (curing under stress) to the UCS development

The vertical pressure and rate of pressure increase measured in a CPB structure in the field or in-situ (Thompson et al. 2009) were applied to CPB-PES specimens to evaluate the effect of curing stress (M) and other Multiphysics factors (THC) on the strength acquisition of CPB-PES and the results are shown in Figure 4.14. It can be observed from this figure that mechanical strength of the CPB-PES samples cured under THMC factors is considerably higher than that of the CPB-PES samples cured under only THC factors (i.e., cured under non-isothermal curing temperature (T), undrained drainage (H) conditions, and contain 0.125% PES (C)). For example, the UCS values of CPB-PES samples cured under THMC are higher than those under THC curing conditions by 57%, 31%, 54%, 48% and 32% at 12 hours, 1, 3, 7 and 28 days of curing, respectively. The application of stress on the CPB-PES samples at the early hours of curing rearranges the solid particles (i.e., tailings and cement), increases the packing density and accelerates the release of more free water to react with the binder, which will contribute to speeding up the hydration process, and thus more hydration products will be generated and fill the voids between the solid particles (Ghirian and Fall, 2016; Chen et al. 2021). The consumption of water also leads to an increase in the density of the CPB-PES samples and thus improves the mechanical strength of the CPB-PES samples with time (Yilmaz et al. 2009). Also, the increase in the packing density caused by the pressure applied on the CPB-PES samples at the early hours of curing contributes significantly to the refinement of the pore structures of the CPB-PES, which in turn leads to a reduction in the porosity and void ratio, and consequently, an increase in the mechanical strength of the CPB-PES samples (Ghirian and Fall, 2015; Al-Moselly et al. 2022). Figure 4.15 demonstrates the evolution of the physical properties mentioned above for the CPB-PES samples cured under THMC curing conditions compared to the CPB-PES samples cured under THC curing

conditions only with time. From Figures 4.15a and 4.15b, it can be seen that the void ratio and porosity for the CPB-PES samples cured under THMC curing conditions are lower than that of the CPB-PES samples cured under THC curing conditions due to the refinement of the pore structure described above. Also, the results of the moisture content presented in Figure 4.15d indicate the consumption of water (i.e., the reduction of moisture content for the CPB-PES samples cured under THMC curing conditions compared to the CPB-PES samples cured under THC curing conditions) related the accelerated cement hydration process caused by the pressure application (Ghirian and Fall 2015, 2016).

However, it should be emphasized that the level of influence of the mechanical factor (i.e., curing under stress or vertical pressure) on the strength acquisition of the CPB-PES materials is lower compared to the chemical and thermal factors discussed in subsections 4.3.1.1 and 4.3.1.2, respectively. For example, when adding 0.125% of polycarboxylate ether-based superplasticizer (PES) to the CPB mixture, the UCS values increased by 22%, 94%, 93%, and 79% for the 1, 3, 7, and 28 days of curing, respectively. Also, when curing the CPB-PES samples under elevated field temperatures, the UCS values increased by 28%, 63%, 127%, and 275% for the 1, 2, 3, 7, and 28 days respectively. Whereas curing the CPB-PES samples under field vertical stress conditions, the UCS values increased only by 31%, 54%, 48%, and 32% for the 1, 3, 7, and 28 days of curing, respectively. This is in good agreement with interaction or coupling arrows between the THMC factors that govern the behaviour and the mechanical properties of CPB materials sketched in Figure 4.1. These results should have important practical engineering implications for the design and operation of field CPB structures.

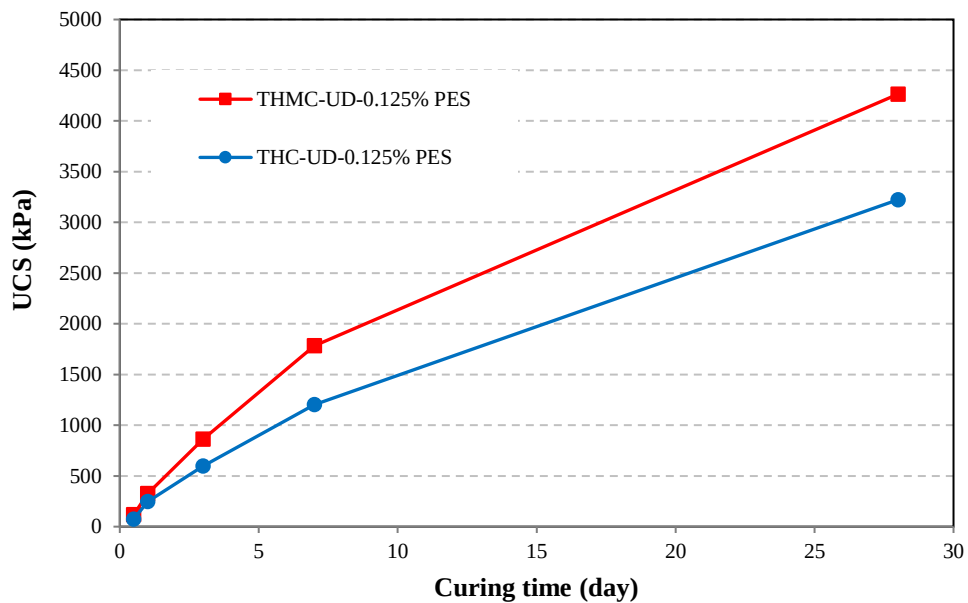


Figure 4.14 Contribution of curing under stress to the strength development of CPB-PES with time.

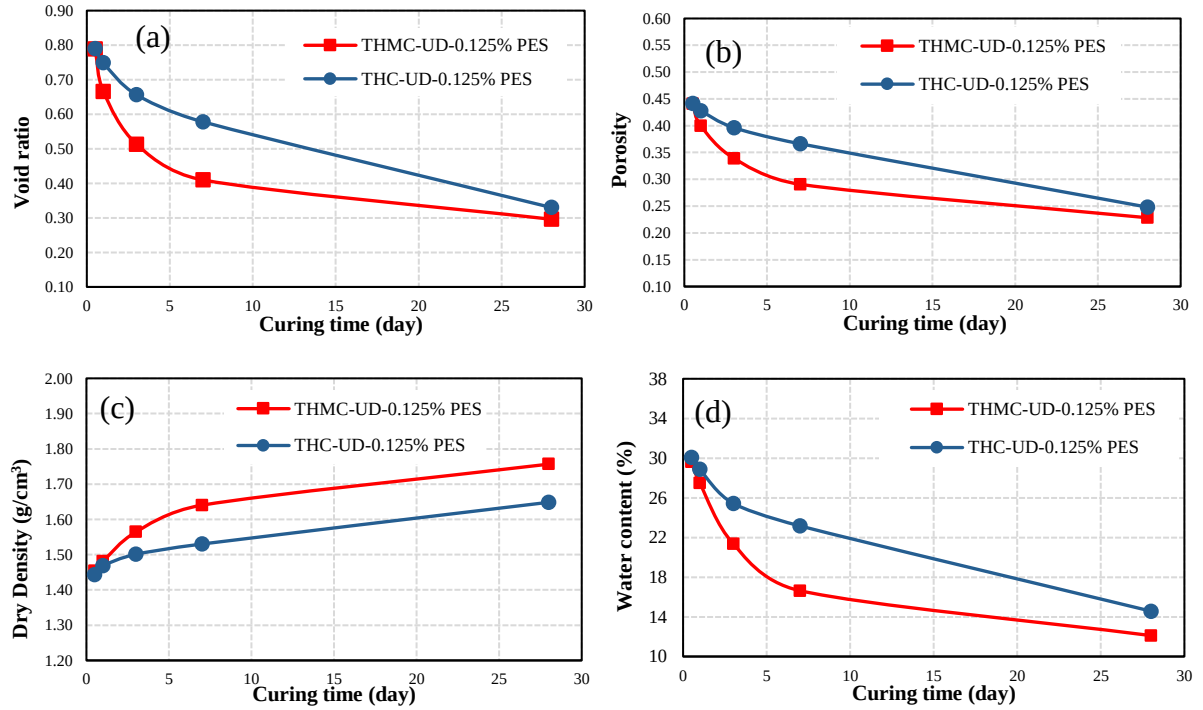


Figure 4.15 The evolution of the physical properties of CPB-PES samples cured under THMC and THC curing conditions. (a) void ratio; (b) porosity; (c) dry density; and (d) water content.

4.3.1.4 Contribution of the hydraulic (H) factor (drainage conditions) to the UCS development

Figure 4.16 illustrates the influence of various drainage curing conditions (drained (D), partially drained (PD), and undrained (UD)) on the strength acquisition of the CPB-PES samples with time. As expected, the mechanical strength for the drained CPB-PES samples cured under THMC factors (THMC-D-0.125% PES) is higher than both the partially drained CPB-PES (THMC-PD-0.125% PES) and the undrained CPB-PES samples (THMC-UD-0.125% PES). The CPB-PES samples cured in undrained curing conditions exhibited lower UCS values than the partially drained CPB-PES samples. It can be observed from Figure 4.16 that the UCS values of the drained CPB-PES samples (THMC-D-0.125% PES) are 193, 532, 1244, 2695, 4856 kPa at 12 hours, 1, 3, 7 and 28 days, respectively. The rate of improvement in the mechanical strength is 64%, 64%, 36%, 51%, and 14% on the 12h, 1, 3, 7, and 28 days of curing, respectively, compared to the undrained CPB-PES samples (THMC-UD-0.125% PES). The UCS values of the partially drained CPB-PES samples (THMC-PD-0.125% PES) are 193, 532, 1113, 2160, and 4347 kPa at 12 hours, 1, 3, 7 and 28 days, respectively. The rate of strength upgrade is 64%, 64%, 21%, 21%, and 2% after 12 hours, 1, 3, 7, and 28 days of curing, respectively, in comparison to the undrained CPB-PES samples (THMC-UD-0.125% PES).

This drainage-induced increase in the mechanical strength can be attributed to different mechanisms: first, the reduction in the volume of water (Figures 4.17, 4.19) in the CPB-PES material caused by the water drainage leads to a lower water-to-cement ratio (w/c) (Figure 18a) of the CPB-PES samples, which results in a denser pore structure (Figure 18b), and thus higher mechanical strength can be attained (Ghirian and Fall 2016, 2017). Previous studies demonstrated that the mechanical strength of the CPB samples significantly increases as the w/c decreases (Fall et al. 2004; Kesimal et al. 2005; Fall et al. 2008). Second, due to the development of negative pore water pressure (PWP) (Figure 4.18) initiated by the reduction of water volume by drainage and the utilization of free water in the ongoing cement hydration process, the strength of the CPB increases (Ghirian and Fall 2016; Al-Moselly and Fall 2022). Indeed, it can be seen from Figure 4.17 that the drainage conditions can significantly affect the development of negative pore water pressure (suction) in the CPB-PES samples at early ages. The monitoring results of the CPB-PES samples cured under similar curing conditions except for drainage conditions show that the drained CPB-PES sample exhibited a significant increase in the negative pore water pressure (PWP) starting from 5 hours of curing time compared to the undrained CPB-PES sample due to water loss through drainage and the self-desiccation of the CPB-PES. In addition, the results of the EC monitoring presented in Figure 4.19 show that the drained CPB-PES sample cured THMC factors peaks at 2.6 mS/cm after 3 hours of curing, while the undrained CPB-PES sample cured under similar curing conditions peaks at 3.35 mS/cm after 6.5 hours of curing. This indicates a higher rate of cement hydration process in the drained CPB-PES sample (Li and Fall 2016).

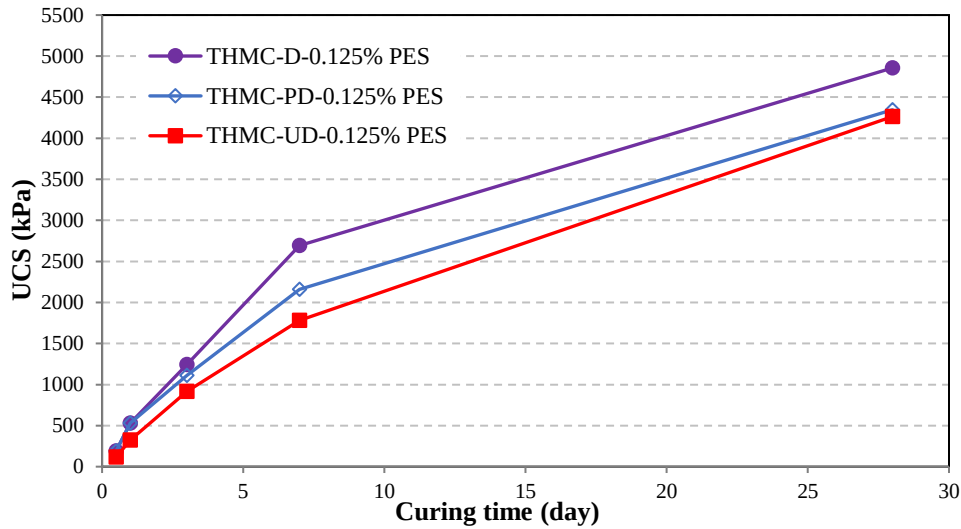


Figure 4.16 Effect of drainage conditions on the strength development of CPB-PES cured under THMC factors with time.

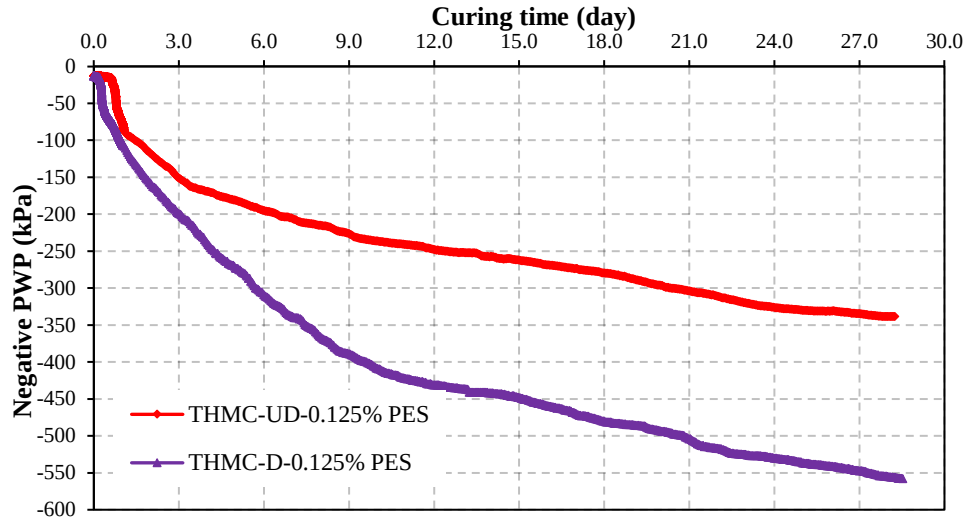


Figure 4.17 Effect of various drainage curing conditions on the development of negative pore water pressure (suction) with curing time of CPB-PES cured under THMC factors.

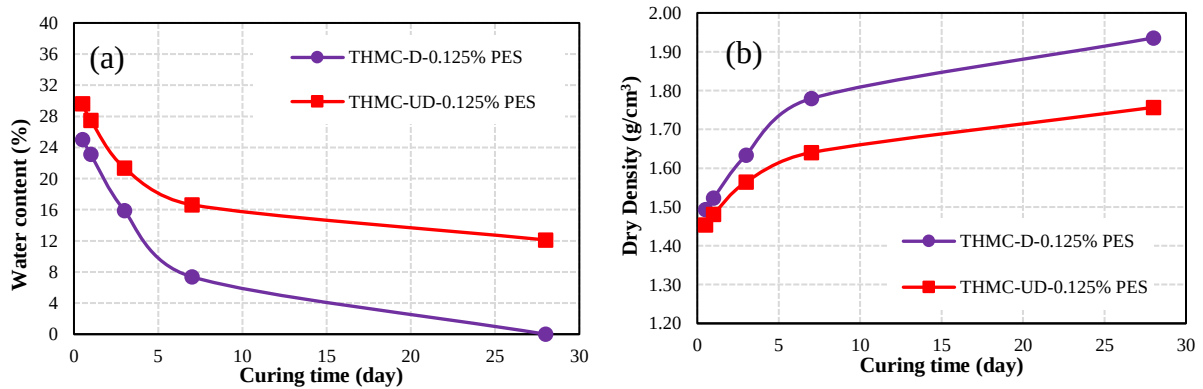


Figure 4.18 The effect of the hydraulic factor (drainage conditions) on the physical properties of CPB-PES samples cured under THMC factors. (a) water content; and (b) dry density.

Moreover, the influence of the drainage state on the mechanical strength of the CPB-PES, without the effect of the pressure application, is investigated and presented in Figure 4.20. It can be seen from this figure that regardless of curing the CPB-PES samples under pressure, the drained CPB-PES samples cured under THC factors only (THC-D-0.125% PES) showed higher strength values compared to the undrained CPB-PES samples cured similar curing conditions (THC-UD-0.125% PES). The mechanisms responsible for this behavior are the same as those responsible for the effect of drainage on samples cured under the THMC curing conditions explained earlier. These obtained results are in good agreement with the findings of several researchers with respect

to the effect of drainage on CPB strength (Yilmaz et al. 2010; Ghirian and Fall 2015, 2016; Al-Moselly and Fall 2022).

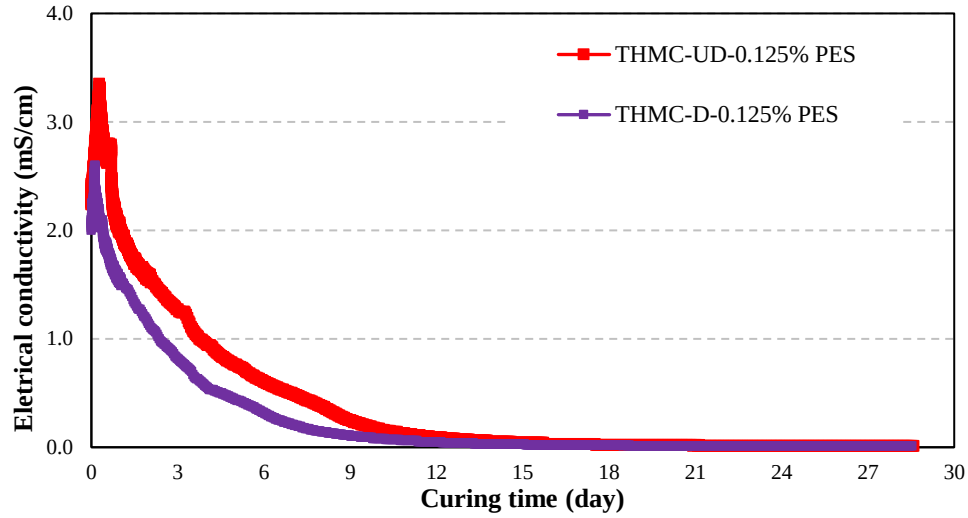


Figure 4.19 The EC evolution of CPB-PES samples cured under various drainage conditions with time.

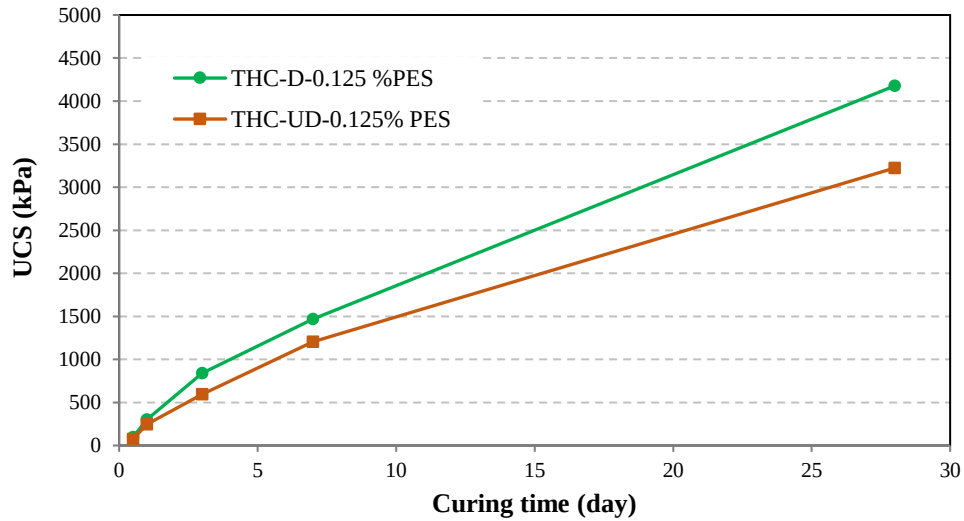


Figure 4.20 Effect of drainage conditions on the strength development of CPB-PES cured under THC factors only with time.

4.3.2 Coupled evolution of the THMC processes

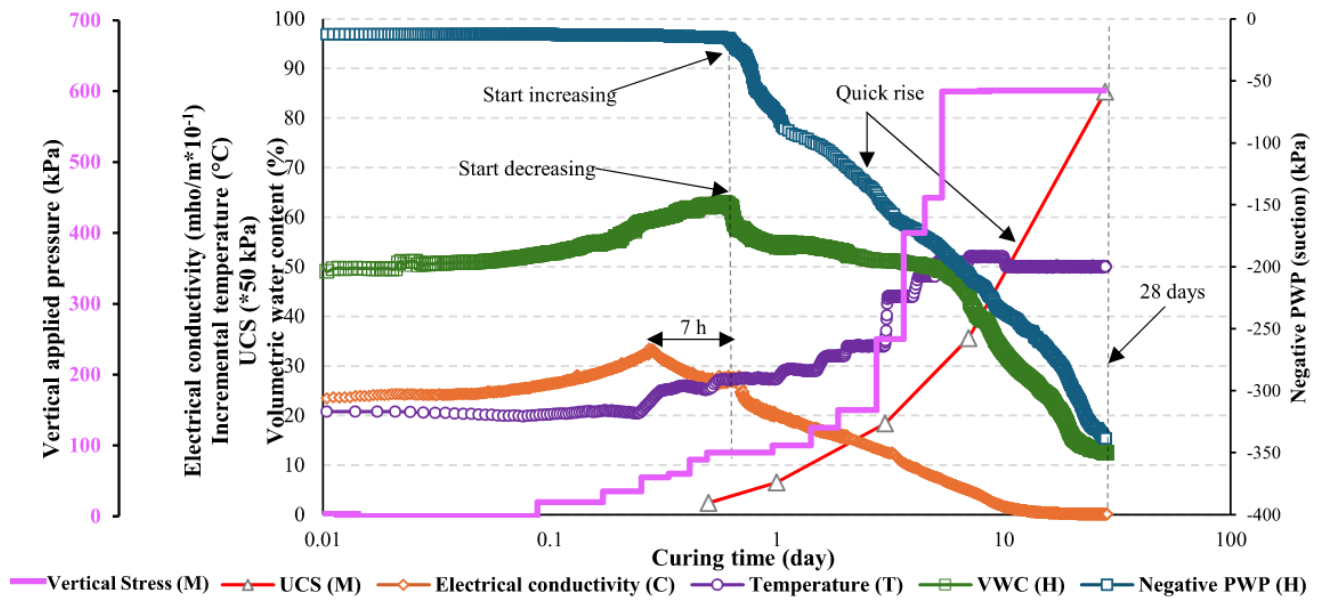
The comprehension of the interrelation between the THMC factors is of significance for making sound decisions regarding the cost-effective design of CPB-PES structures and barricade opening time. To illustrate the evolution of the THMC factors and their interactions in the studied CPB, two examples of results obtained from the monitoring and testing the CPB-PES samples cured in two different drainage conditions (i.e., drained, and undrained drainage conditions) are summarized in Figure 4.21. This figure provides a graphic illustration of the evolution and interaction of these processes. The non-isothermal field curing temperatures (i.e., incremental temperatures) represent the thermal factor (T); negative pore water pressure (suction) and volumetric water content (VWC) are the hydraulic factors (H); the vertical field stress (field backfill overburden pressure) applied to the CPB-PES samples and the UCS test results accounts for the mechanical factors (M); and electrical conductivity (EC), which shows the progress of the cement hydration process, represents the chemical factor (C). Presenting all the monitoring and test results obtained in graphs similar to Figure 4.21 is beyond the scope of this section to keep the length of the manuscript reasonable.

From Figure 4.21, the evolution of THMC processes in CPB appears to interact and be related regardless of whether the undrained CPB-PES samples (Figure 4.21a) or the drained CPB-PES samples (Figure 4.21b) are considered. For example, it can be observed from Figures 4.21a and b that, regardless of the drainage conditions, when the temperature of the backfill (T-factor) begins to increase, the electrical conductivity (EC; C-factor) rapidly increases to its maximum values, indicating an acceleration of the cement hydration process. This peak in EC is shortly followed by a significant decrease in volumetric water content and an increase in suction (H factors) in the CPB as well as a gain in strength (M factors) of the CPB. In other words, the T, C, H and M factors are related.

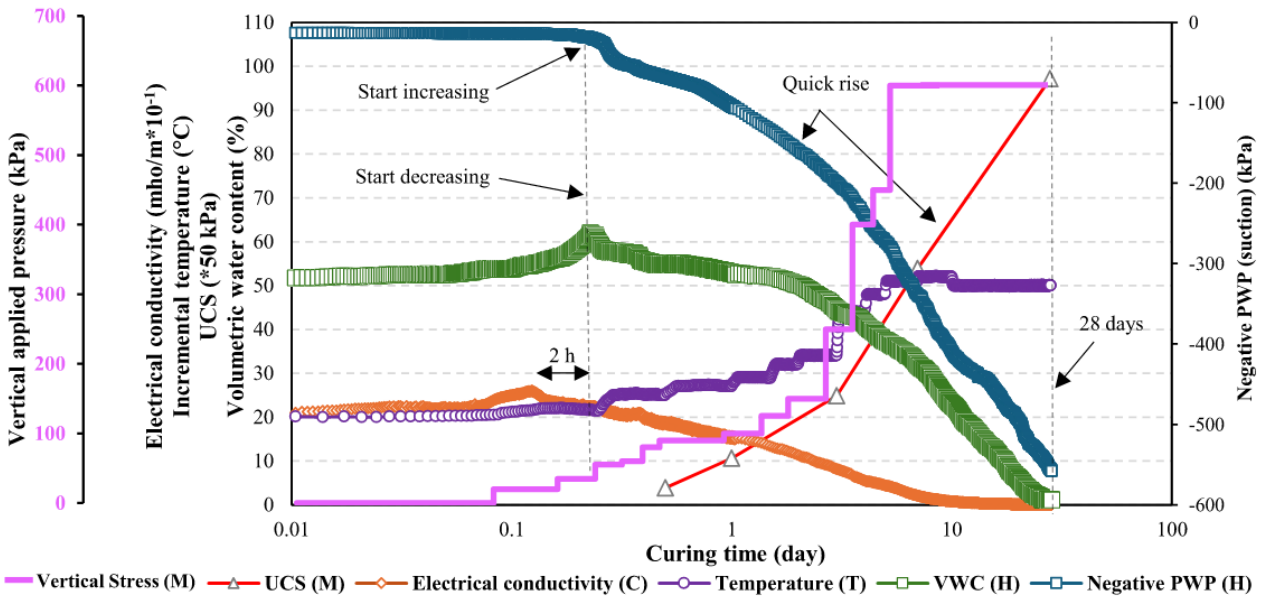
However, comparison of the results presented in Figure 4.21a and 4.21b indicates that the intensity and evolution of the cement hydration process (characterized the EC, factor C), volumetric water content (VWC) and suction (factors H), and as well as the strength (factor M) are function of the drainage conditions. It can be seen that the EC peaks earlier (after 3 hours) in the drained samples than in the undrained samples (6.5 hours of curing), which suggests an enhancement of cement hydration rate in the drained samples. Furthermore, the volumetric water content (VMC), which measures the water consumption in the undrained CPB-PES samples during the cement hydration process, peaks after about 7 hours and 2 hours from the EC maxima for the undrained CPB-PES sample (THMC-UD-0.125% PES) and the drained CPB-PES sample (THMC-D-0.125% PES), respectively. Different mechanisms can explain these behaviours: first, when curing CPB-PES samples under drained conditions, it removes water from the pore structure

of CPB-PES samples and leads to an increase in ion concentration in the pore solution, which in turn leads to higher chemical reactions (Ghirian and Fall 2017). This explains the shorter time to reach the maximum EC value for the drained CPB-PES sample (THMC-D-0.125% PES) compared to the undrained CPB-PES sample (THMC-UD-0.125% PES). Second, the higher rate of cement hydration increases the VWC to the maximum value at the shortest curing time for the THMC-D-0.125% PES sample compared to the THMC-UD-0.125% sample. Then, as the curing time increases, the VMC starts to decrease rapidly for both samples due to the consumption of water in the cement hydration process. The downward slope of the VMC curve for the drained CPB-PES sample (THMC-D-0.125% PES) is faster compared to THMC-UD-0.125% PES. This is mainly due to the reduction of pore water caused by the expulsion of water from the pore structure of CPB-PES due to the drainage process (Tian and Fall 2021).

Figure 4.21a and b also show that, compared to the undrained CPB-PES sample (THMC-UD-0.125% PES), the drained CPB-PES sample (THMC-D-0.125% PES) exhibited higher suction values with time. For example, the 28-day negative pore water pressure of the THMC-D-0.125% PES sample is about -558 kPa, whereas the negative pore water pressure of the THMC-UD-0.125% PES is approximately equal to -338 kPa. These higher suction values in the drained samples can be related to the following mechanisms: (i) water loss through drainage, which is obviously associated with the increase in suction; (ii) the faster cement hydration rate in the undrained samples, as mentioned earlier, results in the consumption of more water during the cement hydration process, which induces a significant increase in suction with time (Chen et al. 2022); (iii) the beneficial effect of adding superplasticizers in the flowability of the CPB materials (Ercikdi et al. 2010; Haruna and Fall 2019) allows more water to drain freely from the CPB material in the case of the drained CPB-PES sample and thus increases the suction value, which indicates a coupling between the hydraulic (H) factor and the chemical (C, superplasticizer) factor. These higher suction values observed for the drained specimens contribute to give the drained specimens a higher strength than the undrained specimens, reflecting a coupling between the hydraulic factor, suction, and the mechanical factor, strength. Several studies (Ghirian and Fall 2014, 2015, & 2016; Yilmaz et al. 2010; Wang et al. 2016; Haruna and Fall 2020; Chen et al. 2022) demonstrated that the negative pore water pressure (suction) significantly contributes to increasing the effective stress and the compressive strength of porous materials.



a) Undrained CPB-PES samples cured under THMC factors (THMC-UD-0.125% PES).



b) Drained CPB-PES samples cured under THMC factors (THMC-D-0.125% PES).

Figure 4.21 Coupled evolution of the temperatures, cement hydration process, volumetric water content, negative pore pressure (suction), and strength of CPB-PES samples.

4.4 Conclusions

This paper investigates the mechanical strength development of CPB materials containing polycarboxylate ether-based superplasticizer (CPB-PES) cured under simulated in-situ thermal (T), hydraulic (H), mechanical (M), and chemical (C) factors. Modified pressure cells were adapted to encompass and monitor the coupled effect of the THMC processes. Based on the obtained results, the following conclusions can be made:

- The THMC factors significantly affect the strength development of the CPB-PES with time, and this effect mainly depends on each one of these factors and the interplay between these factors. It was found that the UCS values for the drained CPB samples containing 0.125% superplasticizer cured under field vertical stress and field elevated temperatures were significantly higher than those for the control samples (0% superplasticizer undrained, cured under free stress and isothermal temperature of 20°C).
- The contributions of each one of the investigated THMC factors on the strength improvement (i.e., the percentage of increase in the UCS values) are not equally similar and greatly depend on the interaction between these factors and curing time.
- An important and new element of this investigation is the addition of polycarboxylate ether-based superplasticizer (PES) to the CPB. It was found that adding 0.125% of PES significantly increased the UCS values of the CPB materials cured under THMC starting from 1 day of curing compared to the CPB samples cured under similar curing conditions but without PES.
- The obtained results indicate a strong coupling effect between the thermal (T) and chemical (C) factors and between the chemical (C) and the mechanical (M) factors. It was found that the effect of the mechanical factor (curing under stress) on the strength development is lower compared to the chemical and thermal factors.
- The UCS values of the CPB-PES materials are greatly affected by the drainage conditions; the UCS values are higher for the drained conditions followed by the partially drained conditions, and the lowest UCS values were obtained from the undrained conditions.

Typically, the compressive strength of the CPB-PES structure is an essential parameter for mine backfill stability assessment and opening the barricades. Designing stable and economical CPB structures and reducing mine cycles are the main projections of underground mining operations. Therefore, a fundamental finding or conclusion of this study is that consideration of the THMC factors and their coupling effect on the evaluation of the strength development of CPB is crucial for the optimal design of safer and more economical CPB structures as well as for the early opening

of barricades. These factors are a function of many parameters and site conditions, such as stope depth and geometry, temperatures of the stope and surrounding areas, heat generated by the cement hydration process, drainage conditions, and the CPB mix components. Any changes in any of these conditions will directly affect the THMC factors and thus the compressive strength of the CPB-PES structure.

4.5 References

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Chapter 5: Investigating pore water pressure development in paste backfill under conditions mimicking field loading - Technical Paper 3

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Zubaida Al-Moselly, Mamadou Fall

Abstract:

This paper presents and discusses the outcomes of an experimental study aimed at investigating changes in pore water pressure (PWP) in cemented paste backfill (CPB) materials incorporating polycarboxylate ether-based superplasticizer (PES). The research mimics real-world backfill field curing conditions, encompassing factors such as thermal (T; field curing temperatures), hydraulic (H; drainage conditions), mechanical (M; field vertical stress), and chemical (C; presence or absence of PES) factors. Utilizing a developed THMC backfill curing system, controlled THMC experiments were conducted to assess the impact of these factors and their interactions on pore water pressure (PWP) in CPB with or without PES. Results reveal that both individual THMC factors and their interactions significantly affect PWP development within CPB. The study also highlights the impact of PES on PWP in CPB, showing that adding 0.125% of PES can lead to a reduction in pore water pressure values by approximately 50% after 28 days of curing. Moreover, the results obtained demonstrated the effectiveness of the experimental THMC test techniques developed in this study in successfully mimicking field-like loading conditions, substantiating their usefulness for subjecting laboratory CPB samples to realistic loading scenarios in the field. These findings are of great importance for the mining industry and backfill designers, providing technical insights into complex THMC interactions affecting PWP in CPB-PES. Understanding these relationships is vital for optimizing CPB and barricade design, ensuring structural integrity, enhancing mine productivity, and guiding future research on numerical models for PWP prediction across all CPB structures.

Keywords: Cemented paste backfill, tailings, superplasticizer, pore water pressure, barricade THMC, in-situ conditions.

5.1 Introduction

An innovative method for managing large quantities of solid mining waste (tailings) and supporting underground mining is to use cement paste backfill (CPB), which is used to backfill underground mine cavities (stopes) to prevent surface subsidence and stope collapse, increase mine productivity and significantly control the environmental challenges that arise from surface tailings disposal, such as acid mine drainage and groundwater contamination (Fall et al. 2010a,b; Wu et al. 2014; Cao et al. 2018; Jiang et al. 2019; Yilmaz et al. 2022; Zhang et al. 2022a, b; Chai et al. 2023; Sari et al. 2023). CPB is an engineered mixture consisting mainly of 70 to 85 wt.% tailings from milling or processing operations, 3 to 7 wt.% hydraulic binder, and fresh and/or mine-processed water (Yilmaz et al. 2003; Belem et al. 2006; Li et al. 2020; Roshani and Fall 2020; Haruna and Fall 2022). CPB is transported from the paste plant to mine stopes through a pipeline system by pumping or gravity (Orejarena and Fall 2008; Ercikdi et al. 2010; Wang et al. 2019; Sari et al. 2022). Mix fluidity is an important factor in the feasibility and the economic efficiency of delivering high-density CPB mix to underground stopes. Consequently, a high-performance water-reducing admixture, also known as a superplasticizer, is often added to the CPB mix to improve its fluidity (i.e., prevent pipe blockages and minimize material segregation) and thus facilitate its transport. In addition, the addition of this admixture can lead to an increase in the mechanical strength of CPB materials (Ercikdi et al. 2010, Ouattara et al. 2017; Haruna and Fall 2020; Al-Moselly et al. 2022).

In mining operations, each stope's footprint is constrained by a designed barricade (retaining structure) usually located at the base of the stope to prevent the long column of fresh CPB materials, over ten vertical meters of continuous CPB pour, from flowing into adjacent stopes or active mining operations until the CPB reached its desirable strength (Helinski et al. 2007; Helinski et al. 2011; Cui and Fall 2018b; Alainachi et al. 2022). Preserving the stability of barricades during the backfilling process is paramount in any paste-fill operations. The disastrous implications of barricade failure have a severe social (i.e., threats to mining personnel lives) and economic impact (i.e., additional cost caused by the delay in production) on mining operations (Shahsavari and Grabinsky 2016; Fang and Fall 2019, 2020, 2021). The primary technical risk causing barricade failure occurs when the developed pressure by the CPB materials is greater than the designed pressure of the barricades (Cui and Fall 2016, 2017a,b). The pressure applied to the designed barricades is greatly dependent on several complex interactions, including the effect of the self-weight of the CPB mass, dissipation of pore water pressure and the related development of the effective stress within the CPB structure (Helinski et al. 2006). The significant increase in the positive pore water pressure of the CPB materials at early ages represents a significant threat to the stability of the barricades (Lu and Fall 2018; Zhao et al. 2020). The dissipation of the excess

positive pore water pressure coupled with the development of negative pore water pressure (suction) or the reduction of water content in the CPB materials leads to a strength gain (i.e., increase in the effective stress) and thus leads to the required hardening stage in the CPB materials and early opening of barricades (Ghirian and Fall 2013a, 2015).

Moreover, in underground stopes, CPB material is also subjected to complex interactions involving the thermal, T , (e.g., variation in mine temperature due to the depth and geological conditions of the mine, self-heating due to the presence of sulphide minerals, heat generated from cement hydration), the hydraulic, H , (e.g., drained conditions, partially drained, undrained conditions), the mechanical, M , (e.g., variation in the stresses applied to the CPB structure which largely depends on the stope geometry, stope depth, self-weight of the CPB, backfilling rate, cement content, designed pressure of the barricades, in situ stress conditions) and the chemical, C , (e.g., cement hydration, superplasticizer) factors (Fall et al. 2010b; Helinski et al. 2011; Ghirian and Fall 2014, 2015; Wu et al. 2019; Al-Moselly and Fall 2022; Yan et al. 2023). Therefore, because of the unique characteristics of each mine operation and stope conditions, it is crucial to understand the development of pore water pressure within the CPB structure under various field conditions for designing a stable and cost-effective CPB structure and reducing mine cycles (i.e., early opening of barricades).

Many studies have been carried out in the past to assess the pore water pressure development within the CPB materials (e.g., Helinski et al. 2007; Shahsavari and Grabinsky 2015, 2016; Ghirian and Fall 2013b, 2015; Al-Moselly and Fall 2022). But, as of now, despite notable advancements in comprehending pore water pressure (PWP) evolution in CPBs, almost all previous studies have focused solely on investigating the individual effects of some influencing factors (e.g. binder hydration, binder type, backfill height) on CPB PWP development. For example, Helinski et al. (2007) investigated the reduction in pore water pressure due to the cement hydration process using an analytical model and was experimentally verified using two different types of tailings. It was observed that the volume changes resulting from cement hydration caused significant changes in the pore water pressure, and the reduction in pore water pressure significantly depends on the cement-tailings mixture, the amount of water consumed during the cement hydration process, material stiffness, and the porosity of the material. Shahsavari and Grabinsky (2015 and 2016) numerically predicted the pore water pressure variation within the backfill stope under various material properties, backfill depth and weight. Ghirian and Fall (2013b and 2015) investigated the effect of drainage conditions and filling rate on the development of positive pore water pressure (PWP) and suction within the CPB materials with time. They found that the pore water pressure significantly increases at an early age as the filling rate increases, and the application of both drainage and curing under stress on the CPB materials at the early hours of curing causes a quick development of suction. Shahsavari et al. (2023) carried out backfill column

experiments and their results indicate that the rapid filling rate of the column has an impact on the development of pore water pressure in the CPB and that the highest pore water pressures occur at the end of filling. Min et al.'s (2023) experimental studies conclusively demonstrate the substantial influence of binder type on suction (negative pore water pressure) development in CPB. Specifically, their findings reveal that CPB incorporating (sulpho)aluminate-based cements exhibited elevated suction levels and more pronounced self-desiccation.

However, to date, no studies have addressed the impact of coupled thermal-hydraulic-mechanical-chemical (THMC) factors on the development of PWP in CPB. Research and knowledge gaps exist regarding the coupled effects of field temperature variations (T factor), pressure or stress applied to CPB (e.g. overburden pressure, backfill rate) (M factor), drainage conditions (drained and undrained) (H factor) and additives used in the preparation of CPB (e.g. superplasticizer) (C factor) on the development of PWP sure in CPB. This gap in knowledge and research needs to be filled given the importance of PWP in the design of backfill and barricade structures, as discussed above. Therefore, the objective of this study is to investigate the development of PWP within CPB materials containing superplasticizer by mimicking real field conditions, encompassing various coupled THMC interactions. By delving into these interconnected factors, this research seeks to shed light on how they collectively impact PWP in the CPB. Comprehending these interconnections is essential to enhance CPB and barricade designs, guarantee structural soundness, improve mining efficiency, and guide upcoming research on numerical models to predict PWP development in CPB structures.

5.2 Experimental Program

5.2.1 Materials

5.2.1.1 Tailings

The tailings used in this experimental investigation were synthetic silica tailings (ST), a non-reactive silica powder of 99.8% quartz (SiO_2). A grain size distribution analysis was carried out, and the obtained grain size distribution curve is presented in Figure 5.1. This figure shows that the grain size distribution curve of the silica tailings is close to the average of nine Canadian mine tailings. Also, from this curve, the values of D_{10} , D_{30} , and D_{60} were 1.9 μm , 9.0 μm , and 31.5 μm , respectively. Therefore, the synthetic silica tailings can be classified as medium-sized tailings (35-60 wt.% of less than 20 μm particles) (Landriault 2001). Synthetic silica tailings were utilized to meticulously regulate the chemical and mineralogical compositions, eliminating uncertainties in the analysis and interpretation of results. This approach ensures precision by avoiding the presence of reactive chemical elements found in natural tailings, which might otherwise interact with

cement and potentially skew the outcomes. Tables 5.1 and 5.2 present the physical properties and the chemical composition of the used synthetic silica tailings, respectively.

5.2.1.2 Binder and water

Portland cement (PC) type 1 (PCI) was utilized in this study as the hydraulic binder. PC is the most common type of binder used in CPB technology, as it is widely available worldwide, making it a practical and accessible option for paste backfill operations worldwide. In addition, PC is compatible with a variety of mineral admixtures and additives, making it possible to tailor the paste backfill mix to specific mine conditions. The chemical and physical properties of the PCI are provided in Table 5.3. Tap water was used in this study for mixing tailings and the binder.

5.2.1.3 Chemical additives

A polycarboxylate ether-based superplasticizer type was chosen in this experimental study as a water-reducing additive. The polycarboxylate ether-based superplasticizer, commonly used in the concrete industry, is characterized as the most effective superplasticizer type for its dispersing mechanism (Ouattara et al. 2017, 2018). Polycarboxylate ether-based superplasticizer exhibit good compatibility with a wide range of cements, including ordinary Portland cement, blended cements, and others (Haruna and Fall, 2022). Polycarboxylate ether-based superplasticizer has steric hindrance forces, which arise from the comb structure of high molecular weight (i.e., the main backbone molecules, produced from the polymerization of carboxylic acid groups (polycarboxylate), are linked to the other polycarboxethylene side chains) to prevent agglomeration of cement particles (Yoshioka et al. 1997; Bjornstrom and Chandra 2003; Papayianni et al. 2005). The polycarboxylate ether-based superplasticizer, denoted by PES, used in this study is a commercial solution that meets ASTM C 494/C 499M requirements for Type A water-reducing and Type F high-range water-reducing admixtures (BASF, 2015).

Table 5.1 Physical properties of the tailings used in this study.

Element	G_s	D₁₀	D₃₀	D₅₀	D₆₀
Unit	-	μm	μm	μm	μm
ST	2.7	1.9	9.0	22.5	31.5
Average of 9 natural Canadian mine tailings	-	1.8	9.1	20.0	30.8

G_s: specific gravity

Table 5.2 Mineralogical composition of the silica tailings.

Concentration (wt.%)	Ingredient (symbol)								Loss on ignition
	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O	
	99.8	0.035	0.05	0.02	0.01	<0.01	<0.01	0.02	0.1

Table 5.3 Chemical and physical properties of binder used.

Element (%)	SO ₃	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	CaO	MgO	Relative density	Specific surface (m ² /g)
PCI	3.8	2.7	4.5	18.0	62.8	2.6	3.2	1.3

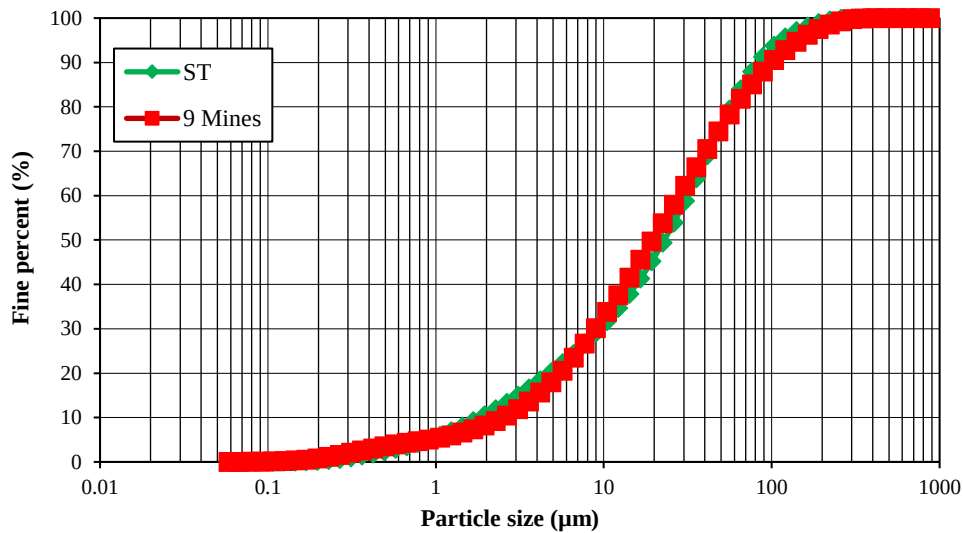


Figure 5.1 Grain size distribution of the silica tailings used and that of the average of nine natural mine tailings in Eastern Canada.

5.2.2 Sample preparation

The CPB with PES (CPB-PES) mixtures were prepared by adding the necessary amounts of tailings to the specified percentage by weight of PCI (4.5%) and mixing them together for about 2 minutes in a mechanical mixer. While continuing the mixing, the specified percentage of polycarboxylate ether-based superplasticizer (PES = 0% and 0.125%) and the measured amount

of tap water were added and thoroughly mixed for 7 minutes to obtain a homogenized CPB-PES material. The measured amount of water was calculated using a water-to-cement ratio (w/c) of 7.35 in all mixes. After mixing, freshly prepared CPB-PES mixtures were poured into the pressure cell cylinders explained below and cured under various field THMC curing conditions for specific curing times. The experimental variables (i.e., mixing composition and curing conditions) are listed in Table 5.4 below.

5.2.3 Description of the THMC backfill curing system

The curing system employed in this study for simulating the influence of various THMC factors that may affect the pore pressure development and dissipation within the CPB-PES structure, originally developed at the Ottawa University by Ghirian and Fall (2013, 2015), is additionally altered and explained in detail in Al-Moselley et al. (2022) and Al-Moselley and Fall (2022), and only a brief summary is given in this section. The curing system is capable of considering the influence of various THMC factors, such as the evolution of positive PWP, negative pore water pressure (suction), cement hydration, self-weight (overburden pressure) caused by mine stope filling processes, temperature variation, and drainage conditions (drained, undrained, and partially drained). The modified pressure cell setup for both drained and undrained conditions is schematically presented in Figure 5.2. The modified pressure cell consists of an acrylic plastic mould with a diameter of 101.6 mm (4 inches) and a height of 304.8 mm (12 inches). Two cover plates were placed at the top and bottom of the cylinder, with three stainless steel tie rods to hold the cylinder and the two plates together. The bottom plate is provided with a drainage valve to control the drainage conditions (i.e., water flow), and an axial loading piston is attached to the top plate to simulate the backfilling processes (curing under stress) of the mine stope by applying compressed air pressure into the CPB-PES specimen. The modified pressure cell is enclosed by a temperature-controlled chamber to simulate the non-isothermal curing conditions.

In addition, the modified pressure cell is equipped with a series of pressure gauges and pressure regulators to control the gradual application of the air pressures and various sensors to monitor the change in temperature, volumetric water content, and electrical conductivity (EC), as shown in Figure 5.2. The development of negative pore water pressure (suction) and positive pore water pressure (PWP) were continuously monitored during the specified curing time using MPS-6 dielectric water potential sensor and Omega PX309 pressure transducers, respectively. The testing and monitoring program, including the details of the used sensors, are further discussed in section 5.2.5 below.

5.2.4 Applied THMC curing conditions and monitoring program

The experimental program was planned to investigate the development of PWP of the CPB-PES samples with different initial compositions prepared according to the procedures explained above under various field curing conditions described below and summarized in Table 5.4.

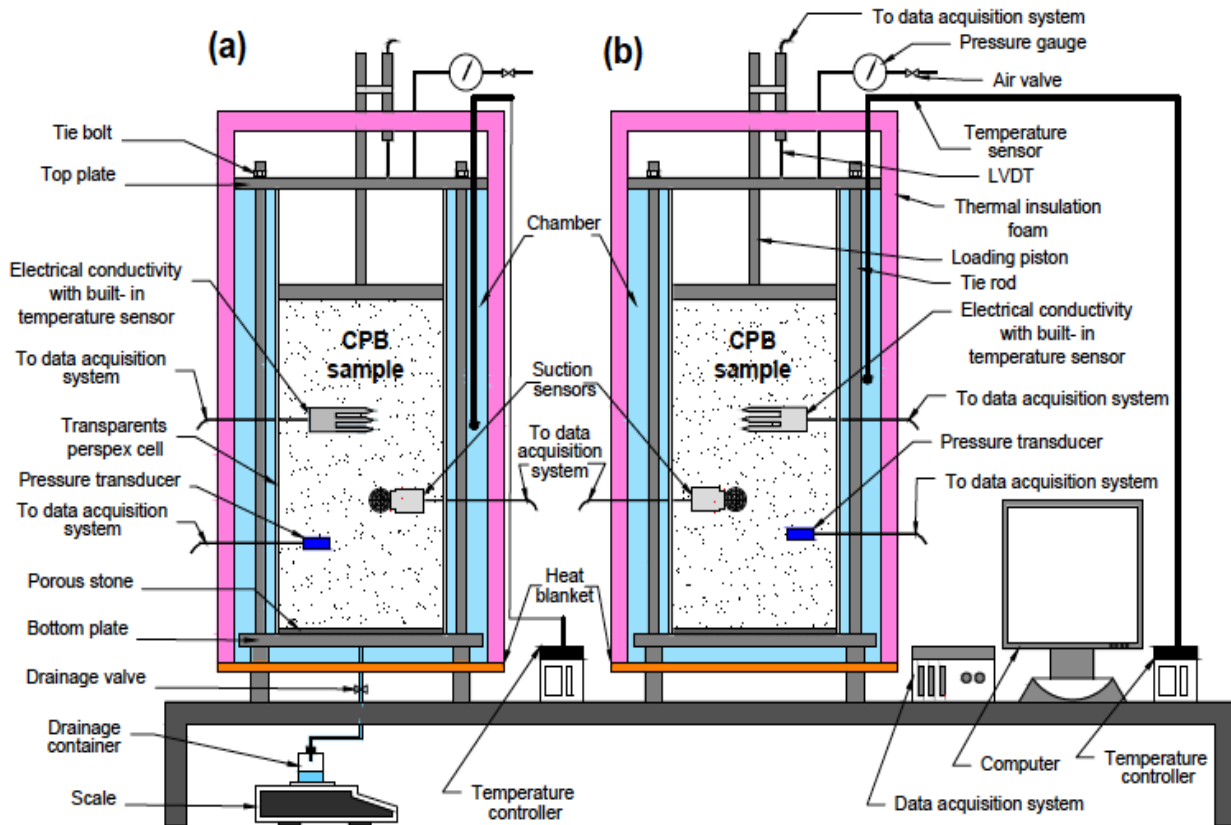


Figure 5.2 Schematic diagram of the pressure cells arrangement: (a) drained condition, and (b) undrained condition (modified from Ghirian and Fall 2015).

5.2.4.1 Mechanical curing conditions (curing under applied vertical field pressure)

The amount of the vertical field pressure applied to the CPB during placement into the stope and throughout its operational lifespan is intrinsically affected by the variation in the backfilling rate, stope depth, stope geometry, and cement content from mine to mine (Thompson et al. 2012; Al-Moselly and Fall 2022). Miscalculations of the specific stresses applied to the CPB materials and the related development of pore water pressure increase stope cycle times and can cause serious barricade failure. Accordingly, to address the critical importance of variation of the field pressures applied to the CPB materials, the curing system used in this study is designed to simulate and investigate the development of PWP of the CPB-PES materials cured under the application of field

vertical pressure or overburden pressure. The in-situ pressure data applied to the CPB-PES materials in this study were obtained from field measurements of a mining operation collected by Thompson et al. (2012) for a long hole stope of 32 m in height and a footprint of 28 x 19 m. Detailed vertical pressure and the equivalent backfill rate and height applied to the CPB-PES specimens with time are summarized in Table 5.5. Note that no pressure was applied to the CPB-PES sample at the first 2 hours; after that, a gradual air pressure increased to 600 kPa with an average filling rate of 0.26 m/h after 3 m height.

Table 5.4 Summary of specimens mixing composition and curing conditions.

Sample Name	Tailings type	Binder type (C)	PES content (%) (C)	Curing stress (M)	Drainage condition (H)	Curing temperature (T)	Curing time (day)
Control-UD-0.0% PES	ST	PCI	0	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
Control-UD-0.125% PES	ST	PCI	0.125	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
THMC-D-0.125% PES	ST	PCI	0.125	Field stress ^a	D	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-PD-0.125% PES	ST	PCI	0.125	Field stress ^a	PD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-UD-0.0% PES	ST	PCI	0	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-UD-0.125% PES	ST	PCI	0.125	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28

ST: silica tailings; PES: polycarboxylate ether-based superplasticizer; ^a simulated field curing stress (vertical pressure); ^b simulated field curing temperature; D: drained; PD: partially drained; UD: undrained conditions; PCI: Portland cement type I. C: chemical factor; M: mechanical factor; H: hydraulic factor; and T: thermal factor.

Table 5.5 Pressure application scheme and the corresponding equivalent CPB height.

Elapsed time	Applied vertical pressure (kPa)	Equivalent height (m)	Equivalent filling rate (m/hrs)
start	-	-	-
2 h	20	1.00	0.50
4 h	35	2.00	0.50
6 h	55	3.00	0.50
8 h	60	3.20	0.40
10 h	80	4.30	0.43
12 h	90	4.80	0.40
1 d	100	5.38	0.22
1.5 d	125	6.66	0.19
2 d	150	7.92	0.17
3 d	250	13.25	0.18
4 d	400	21.41	0.22
5 d	450	24.00	0.20
6 d	600	32.00	0.22

5.2.4.2 Hydraulic curing conditions

The experimental testing program was designed to assess the impact of drainage conditions on the evolution of pore water pressure in CPB-PES materials over time. In the field, the drainage capacity of the CPB mass is contingent upon various factors, including the permeability of the CPB materials, geological characteristics of the surrounding rock (such as fractures in the rock mass), and groundwater conditions in the mine. For instance, undrained drainage conditions may arise when the surrounding rock mass is solid and lacks fractures. Conversely, drained (D) conditions may manifest when the surrounding rock mass is extensively fractured. Furthermore, the permeability of CPB materials is not only affected by curing time and temperature, but also by factors such as mix components, binder content, and fineness of tailings particles (Fall et al., 2009).

To account for the diverse drainage conditions that a CPB mass may encounter in the field, this study adopts three drainage scenarios: undrained conditions (UD), partially drained conditions (PD), and drained (D) conditions. To replicate undrained conditions in the experimental setup of this study, the drainage valve at the bottom plate (see Figure 5.2) remained closed throughout the entire curing period. Conversely, to emulate drained conditions, the drainage valve was fully opened during this time. On the other hand, to model partially drained conditions, the drainage valve was partially opened for approximately 1.5 days during curing, facilitating the drainage of around 50% of the water from the CPB. It is important to emphasize that PD conditions are the most likely to occur in the field and occur when the drainage conditions of the CPB mass fall between UD and D conditions.

5.2.4.3 Thermal curing conditions

Isothermal (20°C) and non-isothermal curing temperatures (reflecting field conditions) were adopted to investigate the influence of temperature variations on the evolution of pore water pressure in CPB-PES over time. In the field, the backfill mass experiences non-isothermal curing, primarily attributed to heat generated during binder hydration within the backfill structure. Figure 5.3 illustrates temperature variations within a 30m-high stope backfilled with CPB material containing 4.5% binder content, as predicted by Nasir and Fall (2009) and Wu et al. (2013) using numerical modeling. Sets of CPB specimens were cured in accordance with the temperature profile depicted in Figure 5.3 to assess the influence of non-isothermal field curing conditions and THMC on the pore water pressure development in CPB-PES. Essentially, the application of the temperature profile illustrated in Figure 5.3 when curing CPB samples allows us to discern the role of in-situ backfill temperature in the progression of pore water pressure within the backfill. The experimental set-up described in Figure 5.2, comprising a heating blanket and a controller, was used to systematically, precisely raise and control the temperature over time. This configuration

facilitated the application and regulation of a gradual temperature increase. The incorporation of the heating blanket and controller allowed for the replication of temperature-time profiles observed or measured in the field CPB structure, ensuring consistent curing conditions for the CPB samples housed within the chamber. Curing the CPB-PES materials in these conditions allows for observation of the self-desiccation process within the CPB-PES structure and the development of pore water pressure.

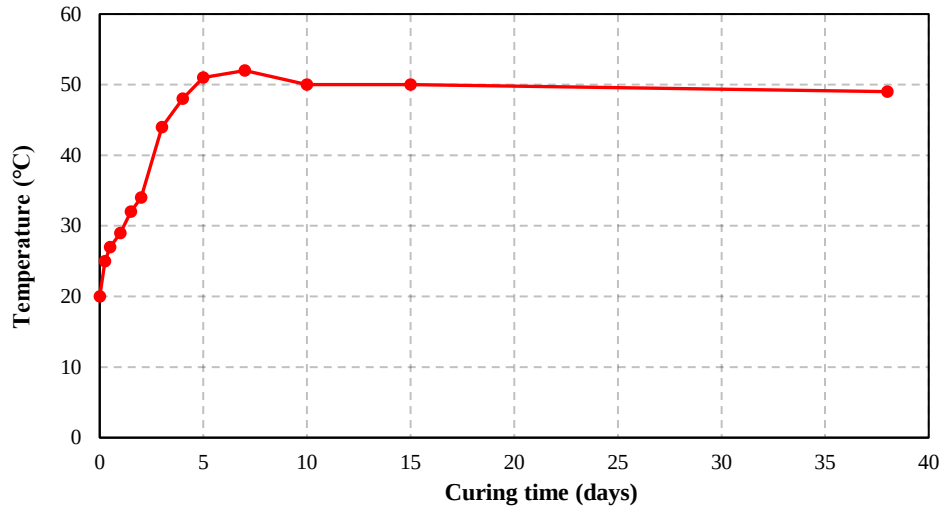


Figure 5.3 Predicted field temperature inside a 30 m stope height backfilled with CPB material of 4.5% binder content (from Nasir and Fall 2009 and Wu et al. 2013).

5.2.4.4 Chemical curing conditions

Various sensors were deployed in the modified curing system to examine the effect of the chemical factor on the development of PWP in the CPB-PES materials with time. The experimental program was designed to monitor, compare, and analyze the influence of the chemical composition of the CPB materials (i.e., tailings, cement, and water) on the development of pore water pressure in the CPB materials cured under various curing conditions with the aim to quantify the influence of the chemical additive (i.e., polycarboxylate ether-based superplasticizer) on the evolution of negative and positive pore water pressure of the mixtures with time. The chemical processes are mainly driven by the binder or cement hydration and the chemical interactions between the CPB-PES mix components, including tailings, binder, mixing water, and polycarboxylate ether-based superplasticizer. The various sets of curing conditions considered in this study program, as shown in Table 4, allow us to study the effect of chemical processes on the development of pore water pressure of the CPB-PES materials cured under various curing conditions (i.e., temperatures, free and field curing stress, and drainage conditions).

5.2.5 Testing and monitoring programs

5.2.5.1 Pore water pressure monitoring

The development of pore water pressure in the CPB-PES samples cured under various field conditions was monitored with time using various sensors. The development of negative pore water pressure (suction) in the CPB-PES samples cured under various field conditions with time was monitored using MPS-6 dielectric water potential sensors with a range of -9 to -100,000 kPa and an accuracy of $\pm$ (10% of reading +2 kPa) from -9 to 100 kPa. Following the proposed CPB-PES sample poured in the modified pressure cell curing cylinder, the recording of negative pore water pressure (suction) began at specific time intervals. The suction results were recorded using an applicable data logger.

The development of PWP in the CPB-PES samples cured under various field conditions was monitored with time by an Omega PX309 pressure transducer inserted inside the CPB-PES sample. The Omega PX309 pressure transducer can measure the pore water pressure between -15 to +15 PSI and $\pm$ 0.25% accuracy. The PWP monitoring data were recorded using a computer data acquisition system.

5.2.5.2 Electrical conductivity and temperature monitoring

The process of cement hydration and the chemical interactions between the CPB-PES mix components (tailings, binder, mixing water, and polycarboxylate ether-based superplasticizer) were monitored using a 5TE temperature sensor mounted in the pressure cell to record the electrical conductivity (EC) and temperatures of the CPB-PES sample with time. The 5TE temperature sensor can measure the electrical conductivity with an accuracy of $\pm$ 0.1 from 0 to 23 dS/m and monitor the evolution of temperature within the CPB-PES samples with an accuracy of $\pm$ 1°C and a range of -40°C to 60°C. The electrical conductivity data reveals the ion concentration and ion mobility changes in the CPB-PES specimen, which can help in assessing the progress of ions in the pore fluid of the CPB-PES mixture (Li and Fall 2016). The 5TE temperature sensor was connected to an applicable data logger to store the monitoring data with time.

5.2.5.3 Volumetric water content monitoring

The volumetric water content (VWC) of the backfill specimens was recorded with time using the 5TE temperature sensor, which is the same sensor used to monitor the EC. The 5TE is capable of measuring VWC in a range of percentages from 0 to 100% with an accuracy of $\pm$ 15% from 40-80. The VWC data reveals the percentage of water consumed by the ongoing cement hydration process of the CPB-PES sample.

5.2.5.4 Determination of physical properties and microstructure

The influence of the THMC processes on the development of PWP was further investigated by examining the pore structure (e.g., void ratio, porosity, density) of the CPB-PES with time. Gravimetric water content (ω %) and bulk density (γ) tests were performed on the CPB-PES samples at different curing times (0.5, 1, 3, 7, and 28 days) according to ASTM D2216-10 and ASTM D7263-09, respectively. The development of the samples' physical properties and pore structure, including void ratio (e) and porosity (n), were also measured and assessed with time.

In addition, to assess the types and the relative quantities of hydration products generated in the CPB-PES samples, thermogravimetric (TG and DTG) analyses were performed on selected cement paste samples ($w/c = 1$; to mimic the high-water content of CPB). The paste samples were prepared and cured in similar conditions as the CPB specimens. The tests were executed using a thermogravimetric analyzer, which implies continuous monitoring and recording of weight loss, heat flow, and temperature changes in the sample at a rate of 10°C per minute up to 1000°C.

5.3 Results and Discussion

5.3.1 Effect of THMC factors on the evolution of pore water pressure in the CPB-PES

Figure 5.4 presents the evolution of the PWP within the CPB materials cured under various simulated field curing factors or conditions with time, respectively. It shows the combined effects of the thermal (T), hydraulic (H), mechanical (M), and chemical (C) factors on the development of PWP in the CPB containing PES and cured under THMC factors (THMC-D-0.125% PES) compared to the CPB material without PES and cured under conventional laboratory (Control-UD-0.0% PES) conditions (i.e., stress-free, undrained, and cured under room temperature of 20°C). During the early hours of curing, the PWP value within the CPB material for the THMC-D-0.125% PES sample was initially recorded at 2.3 kPa, then progressively increased to reach the peak values of 34 kPa after around 4.5 hours of curing, whereas the PWP values within the CPB material for the control sample (Control-UD-0.0% PES) monotonically decreased with time from the initial recorded reading of 4.2 kPa. This initial increase in PWP observed in samples subjected to conditions reproducing real field scenarios has been observed in numerous field investigations of CPB structures (e.g., Thompson et al. 2012; Doherty et al. 2015).

The increase in the PWP values in the THMC-D-0.125% PES sample can be attributed to the following mechanisms: (i) the fluid behaviour of the fresh CPB-PES materials at the early hours of curing, resulting from large amounts of unbonded water (Simms and Grabinsky 2009); (ii) the weak microstructure of the CPB sample at the very early hours of curing, which is caused by the pressure applied to the CPB sample. The application of pressure induces microcracking and

displacement at the contact points between the cement hydration products (Ghirian and Fall 2016). Indeed, the microstructure of cemented paste, when subjected to excessive curing stress during its early stages, exhibits weakness. Consequently, the points of contact between the hydration products of cement are vulnerable to microcracking and displacement (Zhou and Beaudoin, 2003); (iii) the application of pressure in the early hours induces the sample to behave like a fluid and therefore increases the PWP (Ghirian and Fall 2015; Al-Moselly et al. 2022). Similarly, applying stress to the CPB-PES sample at the early hours of curing rearranges the solid particles (i.e., tailings and cement) and speeds up the release of additional free water, resulting in higher PWP measured (Ghirian and Fall 2016; Chen et al. 2021). The monitoring results of the volumetric water content tests for the THMC-D-0.125% PES and the control sample (Control-UD-0.0% PES) presented in Figure 5.5 demonstrate the higher amount of free water in the THMC-D-0.125% PES sample in the first few hours of curing compared to the control sample; (iv) the self-weight settlement and rearrangement of solid particles at the very early age of curing led to a decrease in the volume of voids (Yilmaz et al. 2012). The decrease in void volume can be observed by the results of the void ratio tests for the THMC-D-0.125% PES compared to the Control-UD-0.0% PES samples, as shown in Figure 5.6. In addition to the above mechanisms, the increase in the PWP values in the THMC-D-0.125% PES sample at the early ages of curing can also be accredited to the dispersion effect of polycarboxylate ether-based superplasticizer (PES). Superplasticizers derived from carboxylic compounds, such as PES, instigate two distinct repulsive forces between cement particles: i) electrostatic repulsion arising from the negative charges attributed to the carboxylic group, and ii) steric repulsion linked to the extensive polymer chains present in the compound (Huang et al. 2022; Haruna and Fall, 2022). The repulsive forces between the cement particles induced by the addition of PES to the CPB mixture release the water trapped by tailing particles and cause a delay in the setting time at early ages, which in turn is associated with the higher amount of free water, and thus the increase in the PWP values (Ercikdi et al. 2010; Mangane et al. 2018; Haruna and Fall 2022; Al-Moselly et al. 2022). The effect of adding polycarboxylate ether-based superplasticizer to the CPB mixture on the evolution of pore water pressure is further investigated and analyzed in the following subsections of this study.

Furthermore, Figure 5.4 shows that after reaching maximum PWP values, the PWP values for the THMC-D-0.125% PES sample begin to dissipate over time. This observed initial rise in pore water pressure, succeeded by a gradual decline (dissipation) in the pore water pressure of the CPB samples (THMC-D-0.125% PES) subjected to coupled THMC loading conditions, aligns well with findings from various field studies of CPB masses (e.g., Thompson et al. in 2012, Doherty et al. 2015, Wang et al. 2023). This consistency reinforces the efficacy of the experimental THMC testing techniques pioneered in this study. These techniques successfully replicate field-like loading conditions, substantiating their utility in subjecting laboratory CPB samples to realistic

field loading scenarios. This dissipation of the excess PWP is attributed to the chemical shrinkage (i.e., net volume reduction) caused by the reaction of cement with water in the ongoing cement hydration process and the related formation of hydration products (Hua et al. 1995; Helinski et al. 2006; Helinski et al. 2007), i.e. the self-desiccation process (Al-Moselley et al. 2022). Helinski et al. (2007) demonstrated that the cement hydration process produces a significant reduction in PWP values (self-desiccation) in CPB materials with time, and that the rate of PWP reduction (i.e., the amount of water consumed during cement hydration) depends on various factors such as cement composition, cement surfaces exposed to water for reactions, and the different amounts of water used in each reaction. This self-desiccation is also responsible for the time-dependent decrease in PWP observed in the control sample. Specifically, as the hydration reaction advances, capillary water (free water) undergoes a progressive transformation into chemically bound water within the solid phase. This transformation results in the formation of hydrates with a volume less than the combined volume of the original cement and water. Consequently, this process leads to a decrease in the water content within the CPB matrix, a phenomenon known as self-desiccation. The reduction in water content contributes to a corresponding decrease in PWP and could result in the development of suction within the CPB material or mass (Cui and Fall, 2017c). This explanation is also in line with the results of suction monitoring of the CPBs studied presented in Figure 5.7. This figure illustrates the influence of THMC factors on the development of suction within the CPB-PES materials with time. It should be stressed that the sensors used to monitor suction (MPS-6) and those used to monitor PWP (Omega PX309) were not placed at the same depth in the CPB cell. The Omega PX309 was located near the bottom of the cell, while the suction sensor was placed in the middle of the cell. Figure 5.7 shows that as CPB curing age increases, suction in CPB-PES materials increases, and the rate of increase in the sample cured under simulated field conditions (THMC-D-0.125% PES) is significantly higher than the control sample. In other words, self-desiccation is more intense in CPB cured under coupled THMC conditions. The higher suction observed in the sample cured under simulated field conditions can be attributed to the following mechanisms: (i) curing the CPB-PES sample under field elevated temperatures (thermal factor) expedite the cement hydration process, which leads to a higher consumption of water with time (Fall et al. 2010b). This faster cement hydration is experimentally demonstrated by the results of the monitoring of electrical conductivity (EC) at the early hours of curing presented in Figure 5.8. This figure shows an intensification of the chemical reactions of cement hydration for the THMC-D-0.125% PES sample in comparison to the control sample. As illustrated in Figure 5.8, the trends in electrical conductivity (EC) development among the analyzed samples exhibit distinct characteristics, beginning with an initial ascent to a peak value, followed by a subsequent decline, eventually stabilizing. The initial increase is attributed to a surge in ion concentration resulting from the chemical reaction of the binder (Thottarath, 2010). The subsequent decline can be

attributed to several factors, including the formation of hydration products of the binder, depletion of free water, and the transformation of capillary pores (Lea, 1970). At this later stage, the CPB is marked by intensified crystal formation and the establishment of a more robust crystalline network through crystal bonding. Consequently, the ions in free water encounter a more convoluted path as they traverse the capillary pores within the CPB (Morsy, 1999). It can be seen from Figure 5.8 that the THMC-D-0.125% PES sample reached its peaks at 2.6 mS/cm after about 3 hrs of curing, whereas the control sample (Control-UD-0.0% PES) peaks at 4.6 mS/cm after about 4 hrs of curing, which indicates a higher rate of cement hydration process in the CPB-PES sample cured under THMC factors (Al-Moselly et al. 2022); (ii) the dissipation of excess PWP caused by the drained conditions (hydraulic factor) and the related development self-desiccation results in less water in the pores (i.e., partially empty). The presence of menisci in these partially empty pores generates capillary tension within the pores and thus increases suction in the CPB sample (Bentz 2008). Also, allowing excess PWP to drain from the CPB-PES sample at an early age significantly contributes to binder hydration due to the rapid development of self-desiccation, and consequently, higher suction (Fall et al. 2010b). The influence of drainage conditions on the evolution of pore water pressure in the CPB mixture is further investigated and discussed in the following subsections of this research, (iii) curing the CPB-PES sample under field pressure (mechanical factor) significantly increases the water drainage, which results in more dissipation of excess PWP, and thus, higher suction (Yilmaz et al. 2009; Ghirian and Fall 2016), and (iv) the favouring of ionic diffusion produced by the addition of polycarboxylate ether-based superplasticizer (chemical factor) increases the cement hydration process, and therefore increases consumption of water, which in turn increases the suction in the CPB-PES sample (Haruna and Fall 2020).

Moreover, comparison of the results from PWP and suction monitoring, as depicted in Figures 5.4 and 5.7, reveals that self-desiccation triggered CPB desaturation or suction development at an earlier stage in the upper or middle section of the CPB cell than at its base. This discrepancy arises from the influence of gravity and/or applied pressure, causing a higher accumulation of interstitial water at the bottom of the cell as opposed to the top or middle regions. This observation is consistent with several field or numerical studies of PWP development or self-desiccation in CPB structures under undrained conditions (e.g., Cui and Fall 2018a).

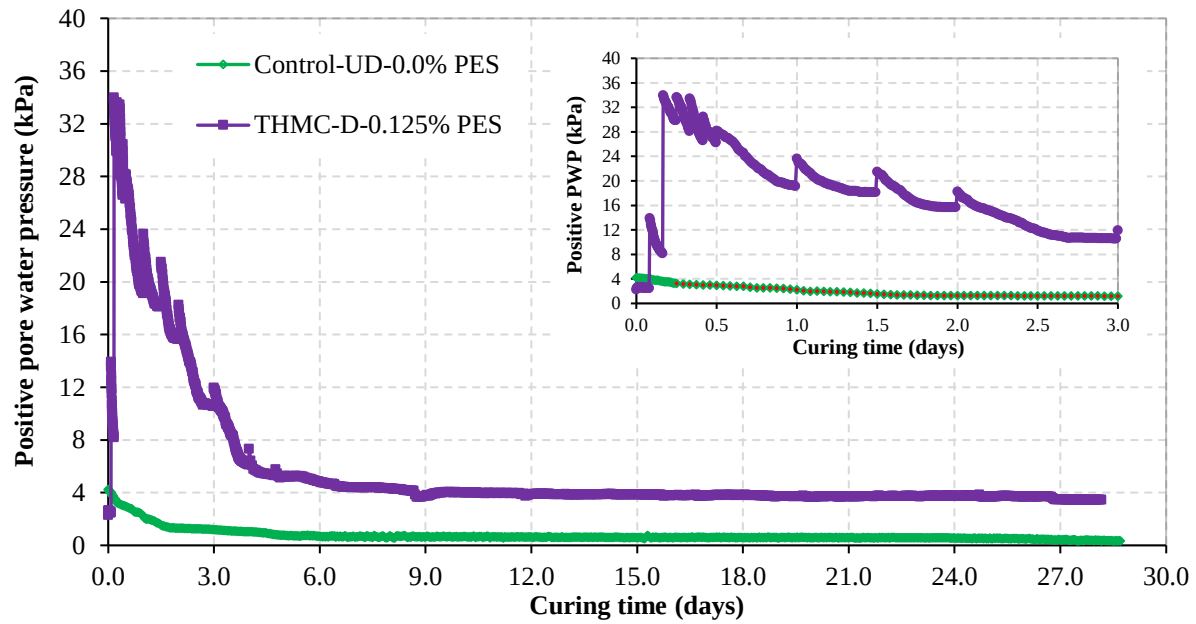


Figure 5.4 Positive pore water pressure evolution within the CPB-PES material cured under various THMC factors with time.

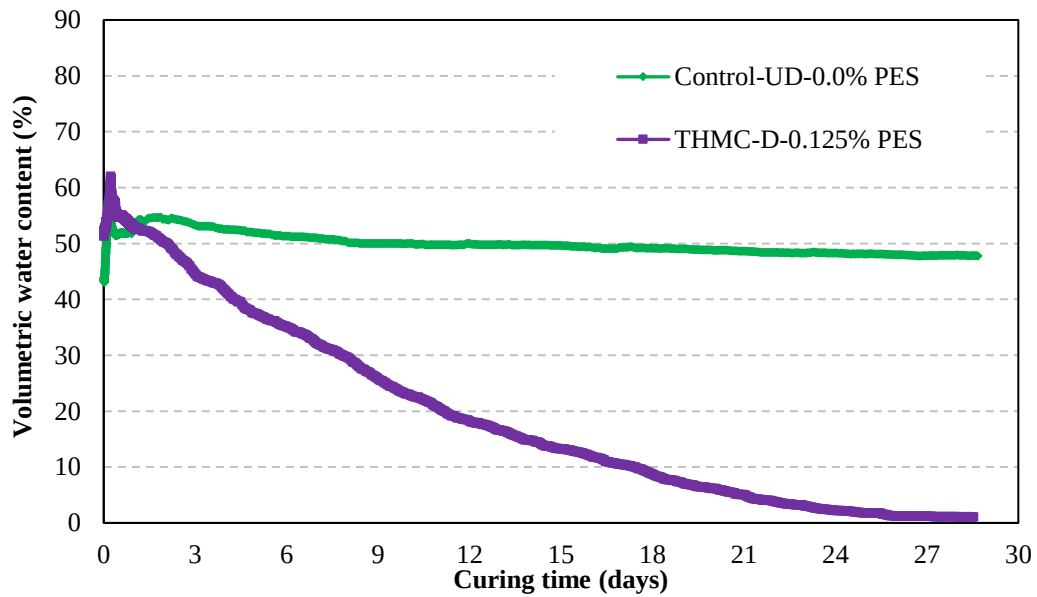


Figure 5.5 Volumetric water content monitoring results with time for different CPB-PES samples.

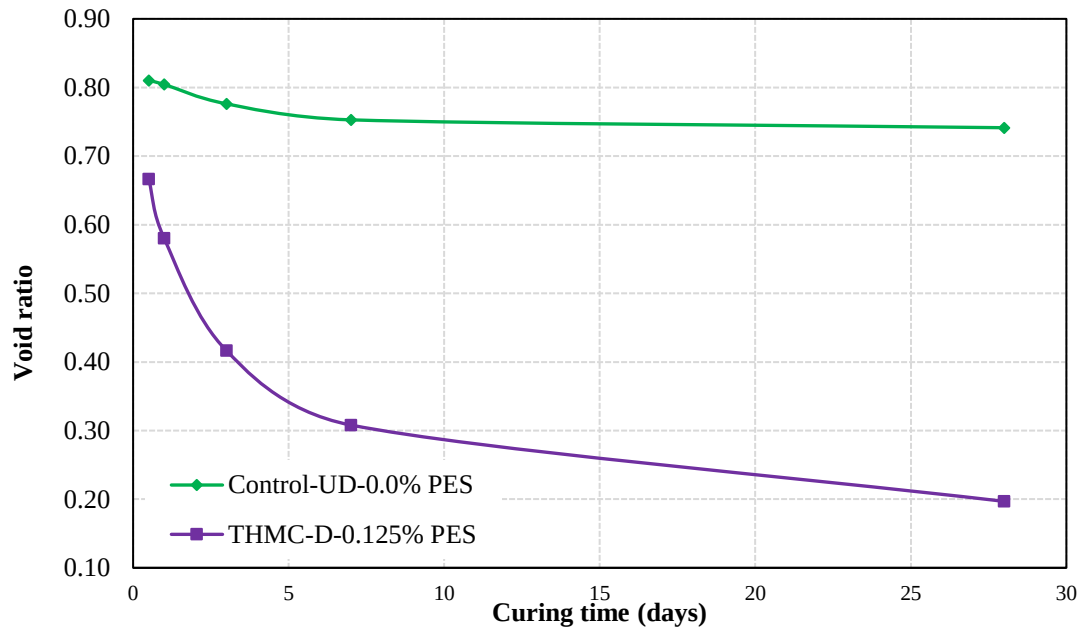


Figure 5.6 Changes in the void ratio of CPB-PES with time under various THMC curing conditions.

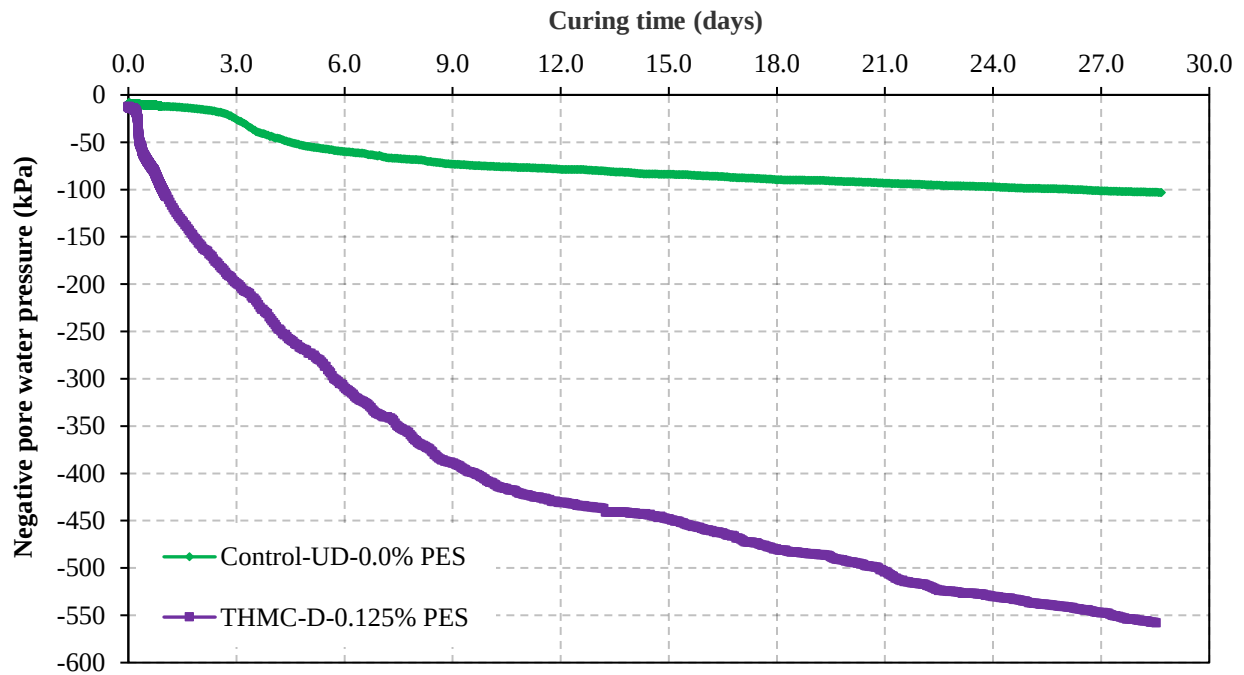


Figure 5.7 Negative pore water pressure (suction) evolution within the CPB-PES material cured under various THMC factors with time.

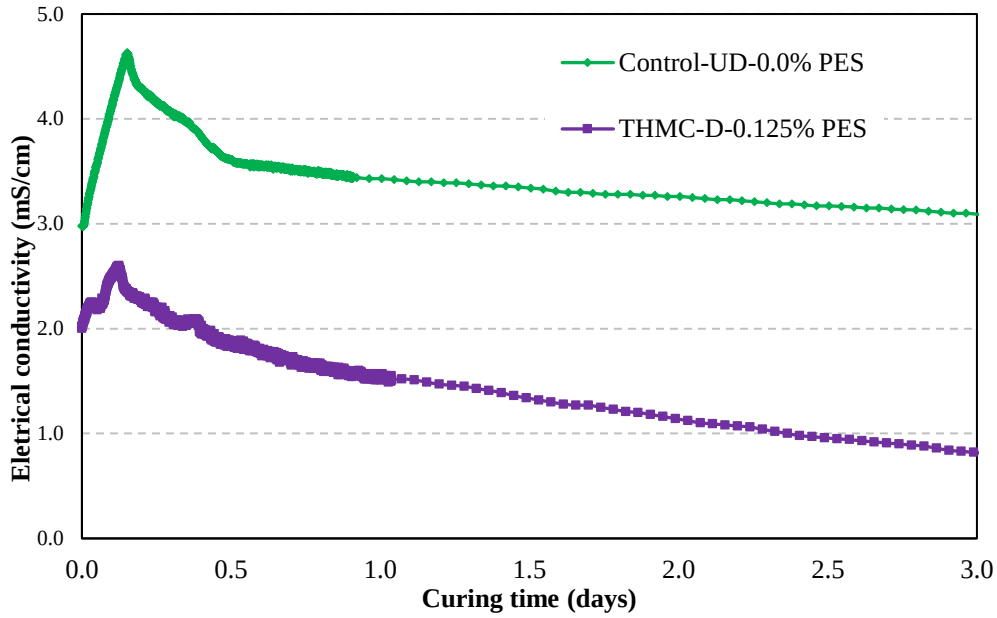


Figure 5.8 The EC evolution of CPB-PES with time under various THMC curing conditions.

5.3.2 Effect of drainage conditions on the evolution of pore water pressure within the CPB-PES

Figure 5.9 shows the influence of various drainage conditions (undrained, drained, and partially drained conditions) on the evolution of the PWP within the CPB-PES samples cured under various THMC factors. It is found that during the early ages (i.e., the first 24 hours), the PWP increased with time for all samples, regardless of the drainage conditions. The mechanisms responsible for this initial increase in PWP have already been explained above. Moreover, the measured PWP values within the undrained (THMC-UD-0.125% PES) sample is significantly higher than both the drained and partially drained CPB-PES samples (Figure 5.9). For instance, allowing the water to drain during the early ages of curing reduced the PWP by 58% when compared to the undrained sample (THMC-UD-0.125% PES). This significant reduction in the PWP values in the samples subjected to drainage is attributed to the following factors: (i) the dissipation of excess pore water pressure resulted from the drainage of water from the CPB-PES materials. The water contained in CPB-PES materials can be drained through the interconnected pore, and as the excess water drains away, the PWP decreases (Ghirian and Fall, 2015). The volumetric water content monitoring test results, as illustrated in Figure 5.10, provide a clear demonstration of the reduction in the volume of water with time for both samples. The drained sample (THMC-D-0.125% PES) exhibits a higher reduction compared to the undrained sample (THMC-UD-0.125% PES). (ii) Consolidation plays a vital role in pore water reduction in the CPB-PES with time (Helinski et al. 2007; Yilmaz et al. 2012). As the CPB-PES undergoes consolidation caused by the self-weight of the CPB-PES materials and the vertical pressure applied to the sample, the excess water in the CPB-PES sample void spaces is forced out of the material, and thus the PWP decreases with time. This expulsion of

water is confirmed experimentally by the results of water content determination presented in Figure 5.11. Indeed, Figure 5.11 exhibits the substantial reduction in the water content with time in the THMC-D-0.125% PES sample in comparison to the THMC-PD-0.125% PES and THMC-UD-0.125% PES samples. The decline in pore water pressure within CPB over time, resulting from a combination of processes such as consolidation and self-desiccation, has been consistently documented in various field investigations of CPB structures. An example is the study conducted by Hasan et al. (2013) in two operational stopes at the Raleigh mine in Western Australia, which took place underground. The research by Hasan et al. revealed that the drainage system implemented effectively reduced significantly both the total horizontal stress and the pore water pressure within the backfill mass. This reduction was directly associated with the processes of backfill consolidation and self-desiccation. Their findings underscored the positive impact of a well-designed drainage system for CPB.

From a practical standpoint, these findings on the influence of drainage conditions on pore water pressure within CPB underscore the pivotal role of CPB possessing effective water drainage capabilities or the implementation of a robust drainage system. This is instrumental in improving both the mechanical stability of the backfill structure and the integrity of barricades in underground mines. Indeed, a CPB system with optimal water drainage ability, and/or a well-designed drainage system, significantly contributes to enhancing mechanical stability. This is achieved by mitigating PWP, facilitating better consolidation, and minimizing horizontal stress. Consequently, these improvements positively impact the stability of barricades within underground mines, ensuring the safety and integrity of mine workers and the overall mining infrastructure. Furthermore, the rapid reduction of stress facilitated by effective drainage is pivotal for the timely opening of barricades. This, in turn, holds substantial implications for the mining cycle and, consequently, the productivity of the mine. The accelerated stress reduction due to drainage not only improves the stability of the barricades but also plays a crucial role in expediting their opening, thereby optimizing the efficiency of the mining operations.

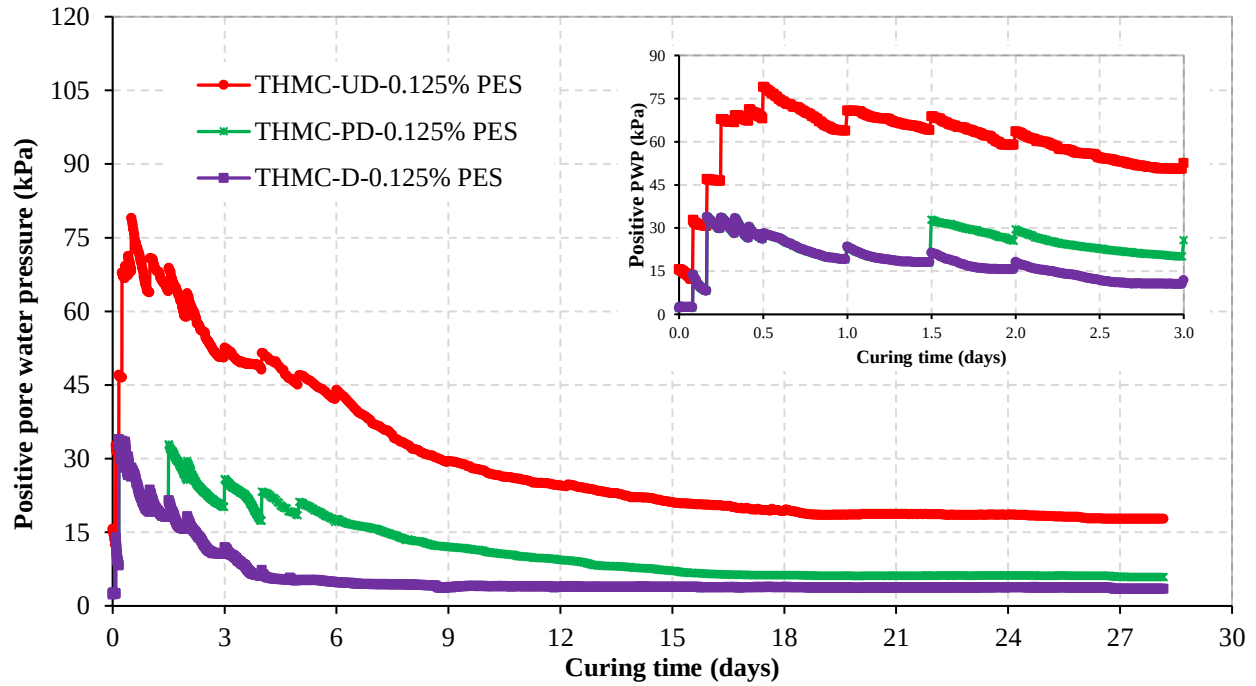


Figure 5.9 Influence of drainage conditions with time on the positive PWP within the CPB-PES samples cured under various THMC factors.

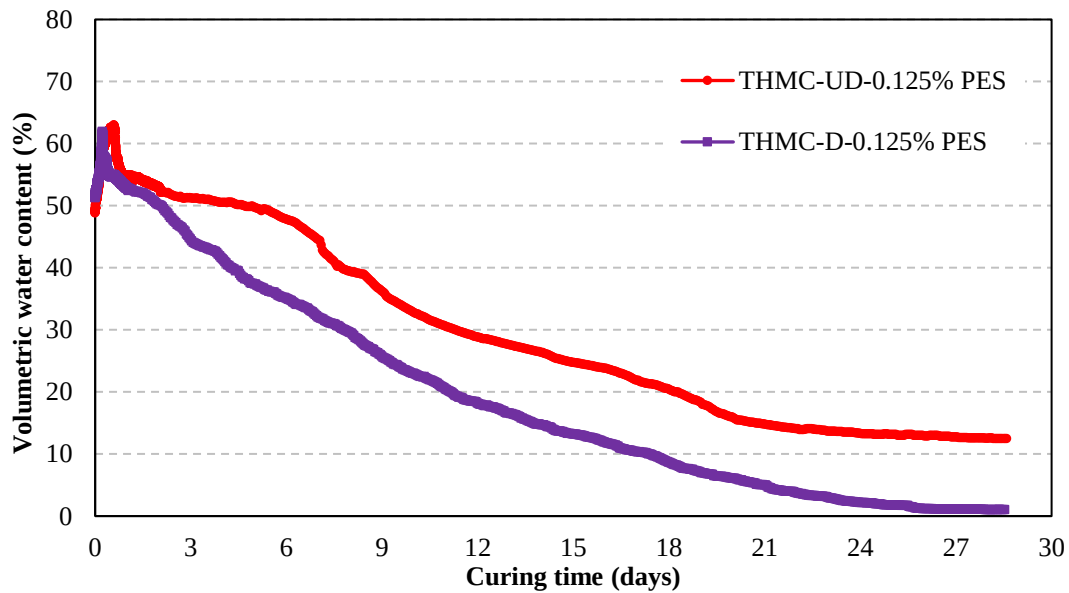


Figure 5.10 Effect of drainage conditions on the volumetric water content of CPB-PES samples cured under THMC factors.

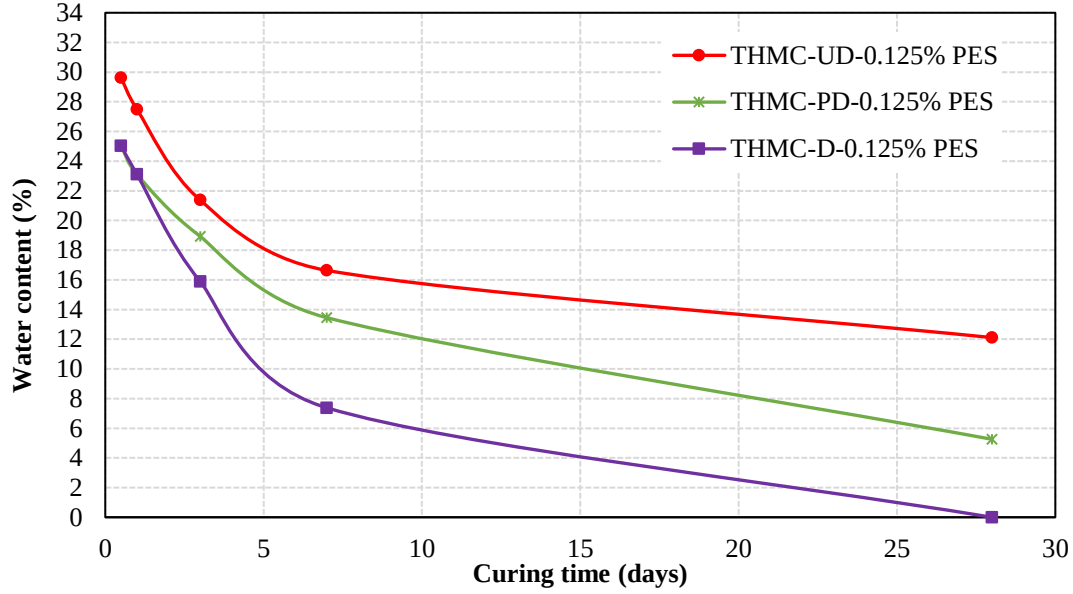


Figure 5.11 Water content variation with time of the CPB-PES cured under various drainage conditions and THMC factors.

5.3.3 Effect of superplasticizer on the evolution of pore water pressure within the CPB-PES

The evolution of PWP within the CPB-PES is closely associated with the addition of chemical additives, such as superplasticizers. Figure 5.12 illustrates the contribution of polycarboxylate ether-based superplasticizer (PES) addition to the reduction of the PW of the CPB-PES material cured under various in-situ conditions (i.e., THMC) with time, respectively. From Figure 5.12, it can be observed that at the early age of curing, the CPB sample containing 0.125% PES exhibited higher PWP compared to the CPB sample without PES. After that, the excess PWP buildup in the CPB sample containing 0.125% PES (THMC-UD-0.125% PES) is reduced and revealed lower values than the CPB sample without PES. The initial increase in the PWP values in the CPB sample containing 0.125% PES can be attributed to the primary function of the superplasticizer in dispersing the solid particles (tailings and cement), which leads to solid particles suspension and water release, which in turn results in higher PWP (Ercikdi et al. 2010, Haruna and Fall 2022). Previous studies demonstrate that when the superplasticizer is added to the CPB, it adheres to the cement particles' surface, creating a protective layer that inhibits or slows down the hydration process (Mangane et al. 2018; Haruna and Fall 2020; Al-Moselly et al. 2022; Cavusoglu and Fall 2022; Yan et al. 2023). Delayed initial hydration of cement by superplasticizer has also been demonstrated in other types of cementitious materials (e.g., Sakai et al. 2006). This early retardation effect of PES causes the initial increase in the PWP values in the CPB sample

containing 0.125% PES. Indeed, Figure 5.13 confirms the initial increase in the moisture content (%) in the CPB sample containing 0.125% PES compared to the CPB sample without PES. In practical terms, the findings indicate that CPBs incorporating PES experience initially higher PWP levels compared to those without PES. This implies that, in real mine backfill operations, CPBs with PES may achieve their early-age stability later than counterparts prepared without PES, which could lead to a delay in barricade opening. Furthermore, it is noteworthy that backfills containing PES will exert increased pressure on barricades compared to those without PES. In essence, this suggests the necessity of constructing more robust barricades to support CPBs with PES during their initial stages of development. While the initial rise in PWP may have adverse effects on the total stress or the decrease in effective stress for CPB materials during early stages, it is crucial to underscore the significance of the initial delay induced by PES in prolonging the setting time of CPB materials. This becomes particularly pertinent when considering the transportation of backfill over extended distances and/or exposure to high-temperature curing conditions, a circumstance often encountered in deep mining operations. Ensuring the seamless transportation of fresh CPB from the backfill plant to the stope (mine cavity) is imperative for the success of paste backfilling operations. The potential obstruction of pipelines, resulting from CPB with inadequate flow characteristics, carries substantial financial consequences for the mine.

Furthermore, Figure 5.12 also shows that as the curing progresses and the peak pore water pressure values are reached in both samples, the PWPs gradually decline over time. As mentioned above, the sample containing 0.125% PES exhibited lower PWP than those without PES. It can be seen that the addition of 0.125% PES can lead to a reduction in pore water pressure values by approximately 50% after 28 days of curing. This is due to the higher precipitation rate of the hydration products caused by the ionic diffusion of PES, which enhances cement particle dispersion (Haruna and Fall 2020). This higher rate of cement hydration in the sample with PES is confirmed by the EC monitoring results presented in Figure 5.14. This figure demonstrates that the EC in the CPB with 0.125% PES is lower than the EC in the CPB sample without PES after 28 days of curing (i.e., the ions in the sample with 0.125% PES have lower mobility than the sample without PES), which provide an indication of the intensifying rate in the hydration process and the associated cement hydration products (McCarter et al. 2003; Haruna and Fall 2020). This intensification of cement hydration and the resulting increase in hydration products are consistent with the TG/DTG analysis results of cement paste samples containing 0% and 0.125% PES dosages, which were cured for 7 days (Figure 5.15). In Figure 5.15, the first endothermic peak in the DTG curve, occurring between 100 °C and 200 °C, represents the rapid weight loss due to the evaporation of water and the disintegration of hydration products, such as ettringite, gypsum, carboaluminates, and C-S-H (Wang et al., 2016). The peak observed at 400 °C to 500 °C corresponds to the dehydroxylation of calcium hydroxide (CH), while the third peak at 650 °C to

750 °C is related to the breakdown of calcite (Fall et al., 2010). A comparison of the thermal analysis curves of the cement paste with 0% and 0.125% PES reveals that the specimen with 0.125% PES experiences a greater loss in the first and second peaks. This indicates that the presence of PES leads to the generation of more hydration products. This statement also in agreement with the experimental results concerning the variation in void ratio and dry density of CPB samples with 0.125% PES and without PES presented in Figure 5.16. The results show lower void ratio values for the CPB sample made with 0.125% PES compared with the CPB sample without PES after 12 hours curing. It can also be observed that after 12 hours of curing, the dry density values of the CPB sample made with 0.125% PES are higher than those of the sample without PES due to the intensification of the binder hydration rate, which in turn leads to greater free water consumption and higher packing density of CPB materials over time (Ghirian and Fall 2013b, 2014; Al-Moselly et al. 2022).

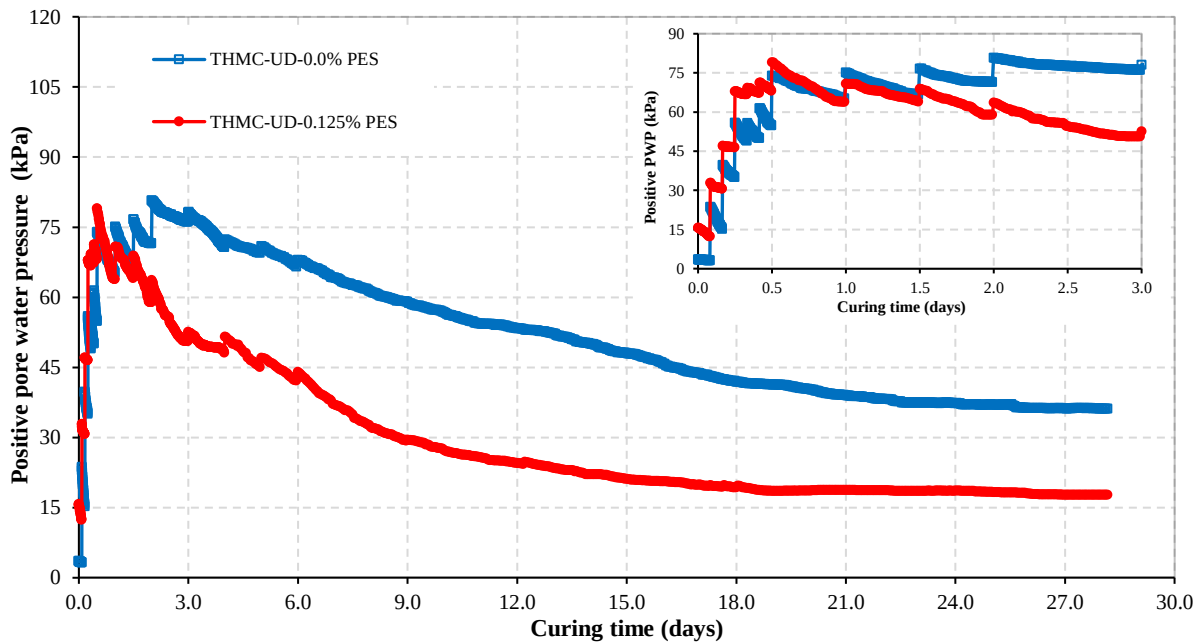


Figure 5.12 Effect of polycarboxylate ether-based superplasticizer on the positive pore water pressure development of CPB cured under various THMC factors.

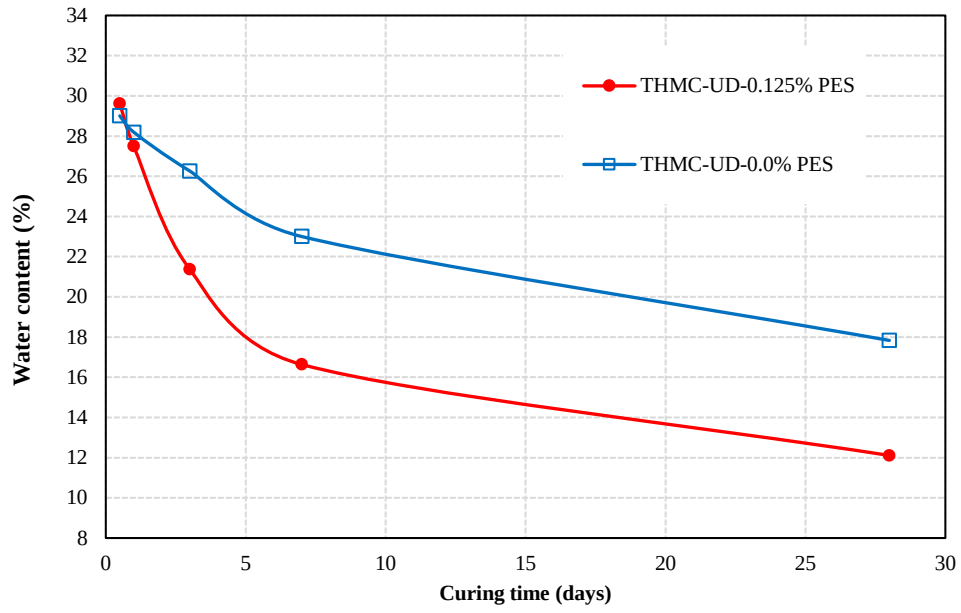


Figure 5.13 Effect of incorporating PES in the CPB mixture cured under various THMC factors on the water content (%) with time.

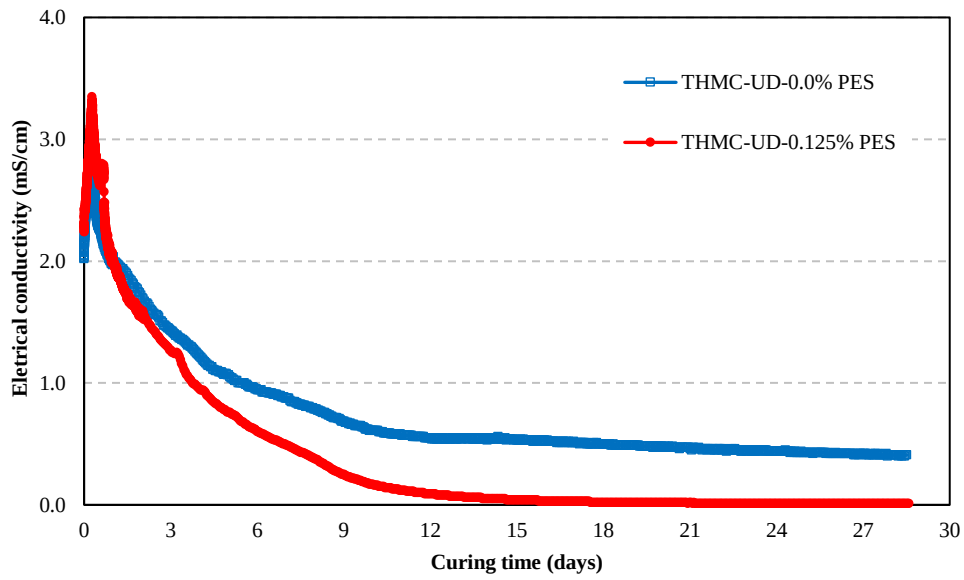


Figure 5.14 Time-dependent variation in electrical conductivity of CPB materials cured under various THMC factors with different PES content.

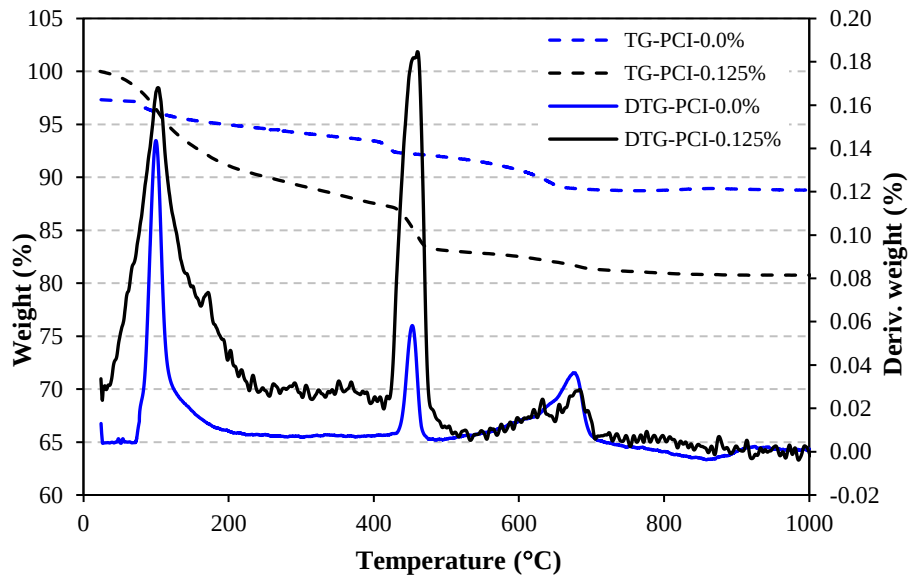


Figure 5.15 TG/DTG diagrams for 7-day old cement paste with 0.125% PES and without PES.

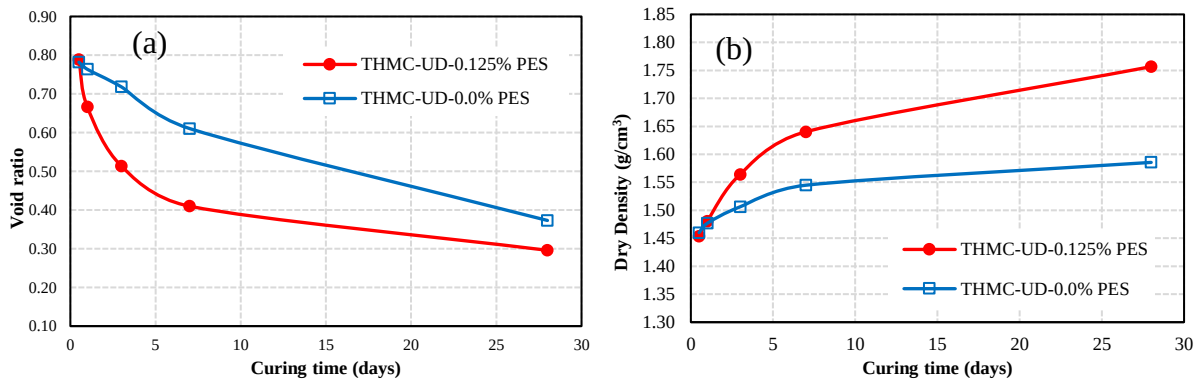
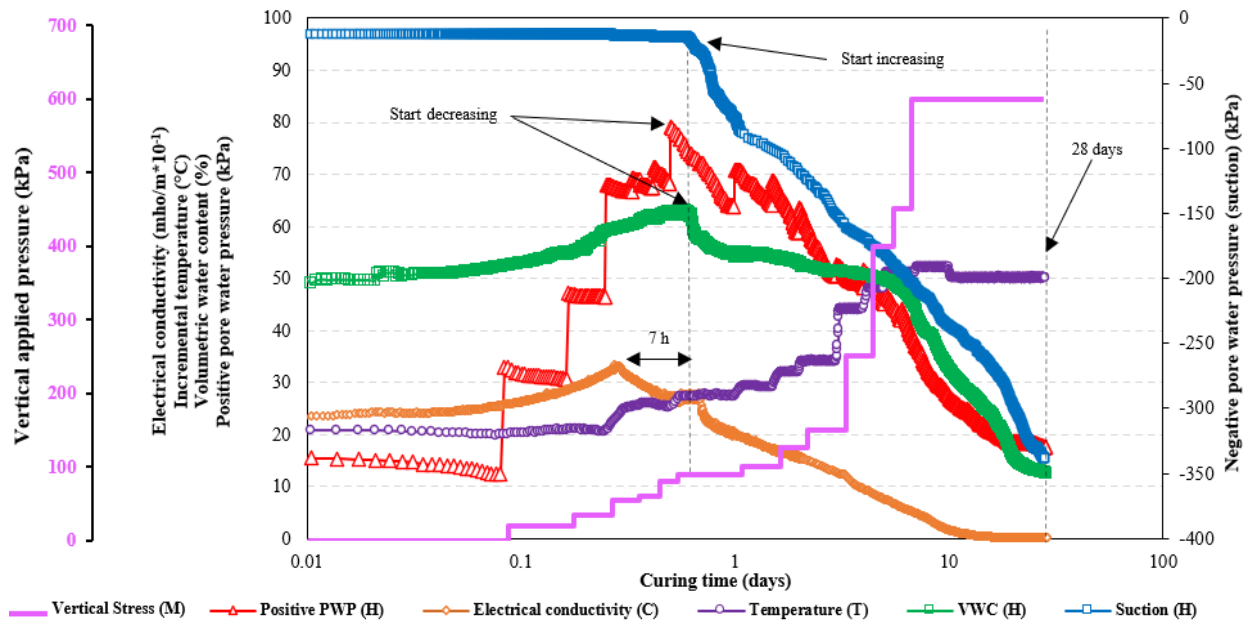


Figure 5.16 Variation in the physical properties of CPB materials cured under various THMC factors with different PES content (a) void ratio; and (b) dry density.

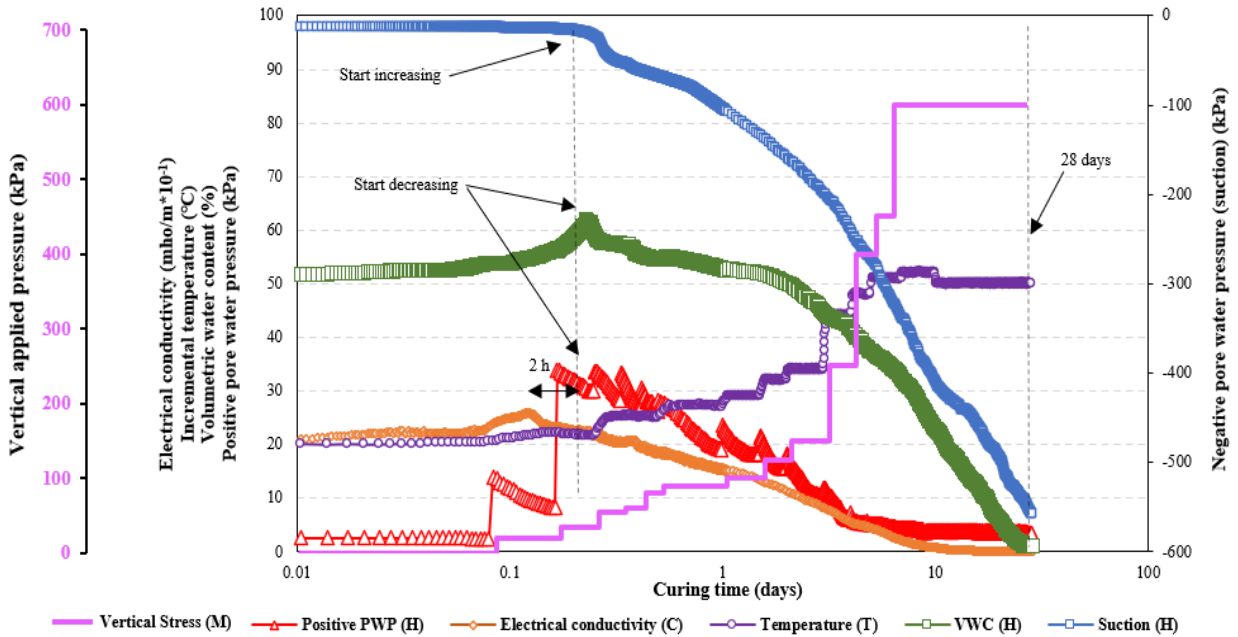
5.3.4 Coupled development of the THMC factors

The coupled effect of field conditions (i.e., the THMC factors) plays a crucial role in understanding the long-term performance and behaviour of CPB. The interplay between the in-situ conditions, such as temperatures, drainage conditions, stress, and chemical additives, significantly affects CPB materials' overall stability and durability. The complex interaction requires a thorough investigation to optimize CPB materials for cost-effective and sustainable applications. Figures 5.17a and 5.17b illustrate the interaction of the THMC factors and their effect on the PWP evolution within the CPB materials cured in drained and undrained drainage conditions,

respectively. The THMC factors are simulated as follows: (i) the thermal factor (T) effect is simulated by the elevated temperatures (i.e., the non-isothermal field curing temperatures); (ii) the hydraulic factor (H) is represented by the PWP pressure (PWP) and volumetric water content (VWC); (iii) the mechanical factor (M) is simulated by the vertical field stresses applied to the CPB-PES materials; and (iv) the chemical factor (C) is simulated by the electrical conductivity (EC), which provides valuable insight into the progress of cement hydration processes and imitates the changes in chemical composition and reactions within the CPB mixture. It can be observed from Figures 5.17a and 5.17b that as the curing temperatures and vertical stresses increase, a notable effect is observed in the EC curve, which demonstrates a rapid acceleration in its values. This acceleration in the EC values reflects the increase in the cement hydration process within the CPB-PES mixture triggered by the coupled influence of applied pressure and elevated curing temperatures, which resulted from the release of heat generated during the cement hydration reactions (Haruna and Fall, 2020), and curing the CPB-PES samples in non-isothermal curing temperatures. Concurrently, the PWP displays an upward trend, ultimately reaching its maximum value. This increase in the PWP values is directly linked to the VMC. It can be observed that the VMC exhibits a distinct behaviour, with its peak occurring approximately 7 hours after the maximum values of EC are reached for the undrained sample (THMC-UD-0.125% PES). In contrast, the drained sample (THMC-D-0.125% PES) experiences a VMC peak approximately 2 hours after reaching its maximum EC value. This time disparity suggests variations in water movement and consumption within the CPB-PES mixture, influenced by different drainage conditions, as explained earlier in subsection 5.3.2. After that, a noticeable decline in the VWC values in both samples occurs. This reduction in the VWC for both samples is reflected in the observed rapid decrease in the PWP values. This diminution in VWC and PWP is intricately linked to water consumption during cement hydration (self-desiccation). In the undrained samples, this process is the primary contributor, whereas in drained samples, the decrease in VWC and PWP results from a combination of self-desiccation and water removal through drainage. Consequently, the reduction in the pore water (i.e., the dissipation of excess PWP) began in an earlier curing time for the THMC-D-0.125% PES sample compared to the THMC-UD-0.125% PES sample due to the drainage conditions. For instance, the PWP values for the THMC-D-0.125% PES sample start to decrease at approximately 4 hours of curing, whereas the PWP values for the THMC-UD-0.125% PES sample begin to decrease after approximately 12 hours of curing time.



a) Undrained CPB-PES sample cured under various THMC factors (THMC-UD-0.125% PES).



b) Drained CPB-PES sample cured under various THMC factors (THMC-FD-0.125% PES).

Figure 5.17 Coupled evolution of electrical conductivity, volumetric water content, negative pore pressure (suction), and positive pore water pressure (PWP) of CPB material with 0.125% PES with time.

5.4 Conclusions

This paper significantly advances our understanding of the development and evolution of pore water pressure (PWP) in cemented paste backfill (CPB) containing a polycarboxylate ether superplasticizer (CPB-PES) under the influence of various field THMC factors (thermal, T, hydraulic, H, mechanical, M, and chemical, C) during the curing process. These factors include field non-isothermal curing temperature of the backfill mass (T factor), in situ drainage conditions (H-factor), in situ vertical stress applied to the CPB mass (M-factor) and the presence or absence of superplasticizer in the CPB mix (C-factor). By considering the impact of these multiple THMC factors, the study provides a comprehensive and holistic view of how these factors individually and collectively influence the PWP development and evolution over time, which is crucial for the safe and economical design of cemented tailings backfill and barricades structures, in other words for the safety and profitability of mining operations. The following conclusions are drawn:

- A THMC backfill curing system has been developed for curing and monitoring CPB samples under controlled THMC conditions mimicking field conditions. This systems successfully reproduces loading conditions close to those in the field, demonstrating its suitability for subjecting laboratory CPB samples to realistic loading scenarios in the field.
- The THMC factors play a crucial role in both the generation and evolution of PWP within CPB. The findings underscore the substantial impact of both individual THMC factors and their interactions on the development of PWP within CPB. Results reveal that both individual THMC factors and their interactions significantly influences the onset and progression of PWP within CPB structures.
- The results highlight the importance of taking field drainage conditions (i.e. drained, undrained or partially drained) into account when assessing the PWP in the backfill structure and its overall geotechnical behavior and mechanical stability. The results obtained show that the PWP values in the drained CPB-PES materials are significantly lower than those in the partially drained and undrained CPB-PES samples. Moreover, drainage allows a much faster dissipation of the excess of PWP.
- It is found that non-isothermal curing temperatures in the field have a significant impact on the magnitude of PWP generated in the backfill structure, as well as on the PWP dissipation rate. The results show a significant decrease in PWP values in CPB-PES exposed to higher field curing temperatures. In addition, higher curing temperatures accelerate the dissipation of excess PWP in the CPBs studied, which is beneficial for early barricade openings, i.e. for increasing mine productivity. The findings underscore the significance of taking into account elevated backfill field curing temperatures, when

assessing the progression of PWP in backfill structure, which is essential for cost-effective design of the CPB and barricade structures.

- The results indicate that the vertical stresses to which CPB-PES structures are subjected during curing can significantly impact the PWP values inside the CPB and their evolution with time.
- The magnitude and evolution of PWP in CPB systems are intricately connected to the introduction of chemical additives, such as superplasticizers. The findings suggest that CPBs incorporating PES initially (at very early ages) demonstrate higher PWP levels than their counterparts without PES due to the retardation of cement hydration by PES. Nevertheless, with the passage of curing time, CPBs with PES exhibit higher rates of PWP dissipation or lower PWP levels, attributable to the enhanced cement hydration facilitated by PES. Considering these two contrasting effects of PES on the magnitude and evolution of water pressure within the CPB is vital for designing backfills that are both safe and cost-effective.

In summary, this research holds vital significance for the mining industry and backfill designers, offering essential technical insights into THMC factors affecting pore water pressure in CPB-PES. Understanding these interactions is crucial for optimizing CPB and barricade design, ensuring structural integrity, enhancing mine productivity, and informing future research on numerical models for predicting PWP in all CPB structures.

5.5 References

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Chapter 6: Sulphate Influence on Strength Development of Cemented Paste Backfill with Superplasticizer under Field-Like Curing Conditions

(Submitted)

Zubaida Al-Moselly, Mamadou Fall

Abstract:

This study investigates the influence of sulphate on the strength development of cemented paste backfill (CPB) incorporating polycarboxylate ether-based superplasticizers (PES) under curing conditions designed to simulate real field environments. These conditions include thermal (T, CPB non-isothermal field temperature), hydraulic (H, drainage conditions), mechanical (M, CPB overburden stress, stress increase rate) and chemical (C, PES, sulphate ions) factors. CPB samples with different sulphate and PES contents were examined under these THMC conditions through a series of mechanical and microstructural tests and monitoring experiments. The results indicate that the traditional method of assessing the influence of sulphate on the development of CPB strength does not adequately capture the mechanical response of CPB structures to sulphate under real field conditions. This approach typically involves testing CPB specimens with different sulphate contents under standard laboratory conditions, neglecting crucial factors such as field curing temperature, drainage conditions and field curing stresses. Consequently, it does not accurately reflect the response of CPB to sulphate exposure in field scenarios. The results demonstrate that the combined effects of field curing conditions, including temperature, drainage, stress and the presence of PES, significantly influence CPB mechanical response to sulphate. CPB samples incorporating PES and sulphate show notable improvements in early-age strength, highlighting the positive influence of elevated temperatures and underscoring the complex relationship between drainage, sulphate and strength development. The study highlights the critical role of non-isothermal field (elevated) curing temperature as a counterbalance to the negative effect of sulphate, improving initial strength. In addition, drainage conditions were found to be an important factor influencing the development of CPB strength in the presence of sulphate. The application of stress at the start of curing promotes the rearrangement of solid particles, facilitating the release of free water and removal of sulphate ions through drainage water while facilitating the decrease of capillary water to further improve mechanical strength. Competitive adsorption

between sulphate ions and PES on the cementitious matrix critically influences the role of the superplasticizers in particle dispersion and subsequent strength development. These results provide valuable insights into adjusting sulphate and superplasticizer quantities to formulate durable CPB mixes suited to different on-site curing conditions. Overall, this research provides essential information for improving the performance of CPB, in particular by increasing initial strength under different curing conditions.

Keywords: Sulphate, cemented paste backfill, mines, tailings, in-situ conditions, THMC.

6.1 Introduction

When it comes to mine backfill techniques, cemented paste backfill (CPB) has emerged as an innovative technology, redefining industry norms and contributing significantly to operational efficiency and sustainability (Kesimal et al. 2005; Orejarena and Fall 2010; Cihangir et al. 2012; Walske et al. 2016; Haruna and Fall 2019; Sagade et al. 2023). This technology not only increases mine production rates, thereby optimizing ore recovery, but also serves as an invaluable method in mitigating the environmental challenges associated with conventional mine waste disposal practices and strengthening the underground mine geostructures (Fall et al. 2010; Ercikdi et al. 2014). CPB is a formulated mixture of a significant proportion of dewatered tailings (70% to 85% by weight) sourced from milling or processing operations of mines, hydraulic binder or cement (3% to 7% by weight), freshwater or water reclaimed from mining processes, and additives (Celestin and Fall 2009; Wu et al. 2012; Haruna and Fall 2020; Ali et al. 2021; Alainachi et al. 2022).

The CPB mixture is prepared at a specialized backfill plant on the ground surface and then transported to the underground mine stopes by either gravity and/or a pumping system using pipelines (Haruna and Fall 2020; Al-Moselly et al. 2022). The efficacy of implementing the CPB technique via the pipeline system to reach stopes without encountering blockages is closely tied to the flow characteristics of the CPB materials (Wu et al. 2013; Ercikdi et al. 2017). High range water-reducing admixtures, also known as superplasticizers, can be added to the CPB mixture to enhance the flowability of the high-density CPB materials (Ouattara et al. 2017; Ouattara et al. 2018; Haruna and Fall 2020). Adding superplasticizers to the CPB mixture facilitates mixing, reduces the possibility of backfilling segregation, improves its flowability, and increases its mechanical strength (Ercikdi et al. 2010; Ferrari et al. 2012).

The targeted mechanical strength of the CPB structure, typically assessed through uniaxial compressive strength (UCS), is significantly influenced by numerous field conditions or factors to

which the CPB is subjected in its operational environment (Ghirian and Fall 2013). These encompass a variety of environmental variables and situational factors in the field, including thermal (T) (e.g., heat generated from binder hydration, temperatures of the surrounding rocks in deep mines, geographical area of the mine (cold/warm region), mine temperature), hydraulic (H) (e.g., drained, partially drained, undrained conditions, negative and positive pore water pressure (PWP)), mechanical (M) (e.g., stress induced by the backfill self-weight, filling rate), and chemical (C) (e.g., binder reactions, mixing water chemistry, presences of sulphate, chemical interaction between CPB components and chemical additives) (Ghirian and Fall 2013, 2014, 2015, 2016; Cui and Fall 2017). These THMC factors and their interactions play a crucial role in the development of the short and long-term mechanical performance of CPB structures (Kesimal et al. 2003; Ghirian and Fall 2013, 2014).

In particular, the structural integrity and effective design of CPB materials for filling underground mine stopes are significantly influenced by the initial sulphate content within the CPB mixture. This factor can exert a considerable influence on the overall performance and long-term durability of the CPB structure (Li and Fall 2018). Sulphate ions present in CPB can come from different sources: (i) Sulphide minerals' oxidation in tailings. CPB created using tailings rich in sulphide minerals, such as pyrite, may experience oxidation upon exposure to oxygen. This process is known as weathering (Ghirian 2016). The extent of oxidation primarily depends on the pyrite content and degree of saturation. This weathering results in the release of metal ions and the generation of sulphate ions (Ghirian 2016). In addition, tailings oxidation and thus sulphate generation can occur before the tailings are used to prepare CPB mixtures; (ii) The sulphur dioxide/air method utilized in gold mining; (iii) the addition of gypsum ($\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$) or anhydrite (CaSO_4) to the cement; and (iv) the usage of mine processing water, typically rich in sulphate, during CPB preparation (Li and Fall 2016; Alainachi 2020).

Many studies (e.g., Fall and Benzaazoua 2005; Ercikdi et al. 2009a; Ercikdi et al. 2009b; Ercikdi et al. 2010; Fall and Pokharel 2010; Orejarena and Fall 2010; Li and Fall 2016, 2018; Rong et al. 2017; Wang et al. 2020; Yan et al. 2020; Aldhafeeri and Fall 2021) have examined the impact of sulphate on the mechanical strength (UCS) of CPB. These investigations have effectively shown that the influence of sulphate on CPB's strength is closely linked to factors such as initial sulphate concentration, curing time, isothermal temperature, and the type and dosage of the binder. Additionally, the findings indicate that sulphate can exert both positive and negative effects on CPB's mechanical strength, resulting in an increase or decrease in its overall strength (Fall and Pokharel 2010).

However, all these studies were conducted on the basis of CPB materials cured under standard laboratory curing conditions, i.e. where field non-isothermal curing temperatures (field T-factor), curing stress (M-factor) and drainage conditions (H-factor) were ignored. Moreover,

CPB samples without superplasticizer (a C-factor) were considered in these previous investigations. This means that the transferability of findings from these previous studies to real-world or actual field conditions is limited. These investigations failed to account for crucial field THMC (Thermal-Hydro-Mechanical-Chemical) factors and their interactions when assessing the impact of sulphate on CPB strength. Essentially, the effect of sulphate presence on the UCS of CPBs subjected to THMC factors or curing conditions similar to those experienced in the field remains unknown. Thus, it is crucial to address this knowledge gap. The main objective of this study is to conduct a comprehensive experimental investigation aimed at assessing the influence of sulphate on the strength of CPB with superplasticizer when exposed to THMC factors similar to those encountered in actual field conditions.

6.2 Experimental Programs

6.2.1 Materials

6.2.1.1 Tailings

In this study, synthetic silica tailings (ST) were employed. Characterized by a non-reactive silica powder composition, ST consists of 99.8% quartz (SiO_2) and exhibits a grain size distribution that closely mirrors the average of nine Canadian mine tailings (Figure 6.1). Quartz stands out as the predominant mineral in tailings derived from Canadian hard rock mines. The silica tailings fall into the category of medium-sized tailings (Figure 6.1), characterized by 35-60 weight percent of particles smaller than 20 micrometers (Landriault 2001). In addition, the utilization of silica tailings serves the specific purpose of precise control over the chemical and mineralogical compositions of the tailings. This deliberate choice aims to mitigate the impact of reactive chemical elements commonly present in natural tailings. Such elements, when interacting with cement, have the potential to influence the analysis and subsequent interpretation of results. The chemical composition of the silica tailings used in this study is presented in Table 6.1.

6.2.1.2 Binder

Portland cement type 1 (PCI) was selected as the binding agent for this study. Its global availability and cost-effectiveness make it a fundamental choice for CPB applications across various mining operations worldwide. Its versatile formulation enables compatibility with a wide range of mineral admixtures and chemical additives, offering flexibility in tailoring the paste backfill mixture to suit the specific demands of various mining environments. For detailed information on the chemical and physical properties of the binder utilized in this study, refer to Table 6.2.

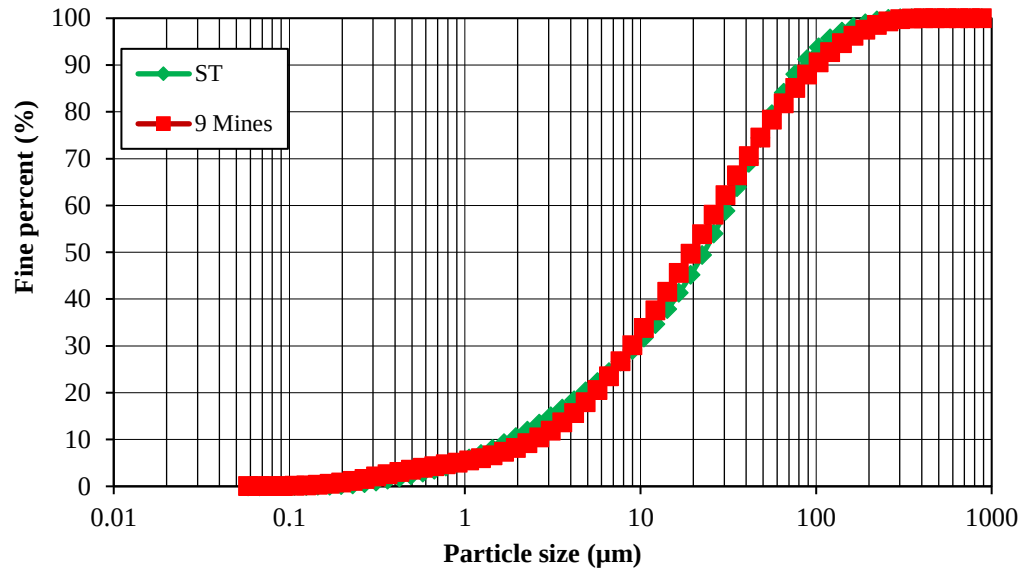


Figure 6.1 Grain size distribution of the silica tailings used and that of the average of nine natural mine tailings in Eastern Canada.

Table 6.1 Chemical composition of the silica tailings.

Concentration (wt.%)	Ingredient (symbol)								Loss on ignition
	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O	
	99.8	0.035	0.05	0.02	0.01	<0.01	<0.01	0.02	0.1

Table 6.2 Chemical and physical properties of the binder used.

Element (%)	SO ₃	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	CaO	MgO	Relative density	Specific surface (m ² /g)
PCI	3.82	2.70	4.53	18.03	62.82	2.65	3.20	1.30

6.2.1.3 Mixing water

In the mixing of the binder and tailings, a combination of distilled water and water containing specific amounts of sulphate was employed to prepare the CPB samples. Distilled water was specifically chosen to achieve precise control over the sulphate concentration. Ferrous sulphate (FeSO₄·7H₂O), the predominant sulphate in CPB, was added to the distilled water in specific measured quantities to attain mixing water with a targeted sulphate concentration of 15,000 ppm.

6.2.1.4 Chemical admixture

The preparation of CPB specimens involved the utilization of polycarboxylate ether-based superplasticizers. This superplasticizer type, denoted as PES, is synthesized from complex polymer of comp-like structures containing carboxylate functional groups (Aicha 2020). PES superplasticizers provide excellent particle dispersing properties through two mechanisms or dispersing forces, including electrostatic repulsive forces and steric hindrance forces (Ouattara et al. 2017). The PES used in this study is a commercial product supplied by Badische Anilin und Soda Fabrik BASF SE, Germany. It complies with the ASTM C 494/C 499M standards for both Type A water-reducing and Type F high-range water-reducing admixtures (BASF, 2015).

6.2.2 Specimen preparation

The CPB samples were prepared with a water-to-cement ratio (w/c) set at 7.35, a weight proportion of 4.5% PCI, two types of water (distilled water and water with a sulphate concentration of 15,000 ppm), two different percentages of PES (0% and 0.125%). To create the required CPB with polycarboxylate ether-based superplasticizer (CPB-PES) samples, the tailings, cement, specific water type, and the specified amounts of PES were blended and homogenized in a mechanical mixer for around 7 min. Subsequently, the freshly manufactured CPB mixes were introduced into pressure cells and subjected to various THMC conditions for specified curing durations, detailed in Table 6.3 and further discussed below.

6.2.3 Test apparatus and procedures

The modified experimental pressure cell apparatus for curing the CPB samples under various THMC factors or conditions, shown schematically in Figure 6.2, was used in this research. It is composed of a Perspex (acrylic plastic) mould with a diameter of 101.6 mm (4 inches) and a height of 304.8 mm (12 inches) to accommodate the CPB specimen. It also includes an axial loading piston for applying compressed air pressure to the CPB specimen, along with two cover plates to be placed at the top and bottom of the mould. In addition, three stainless steel tie rods are incorporated to secure the mould and cover plates together, ensuring stability during experimentation. Continuous compressed air pressure is applied to the CPB specimen using the axial loading piston to mimic the backfilling processes and filling rate of mine stopes. Pressure gauges and pressure regulators were employed to systematically apply air pressure in a controlled manner to the CPB samples.

In consideration of drainage requirements, a drainage hole with a connected drainage valve is integrated into the bottom cover plate, which in turn is linked to a water tube facilitating the collection of discharged water. This arrangement facilitates precise control over water flow,

allowing for the accurate measurement of the volume of excess pore water discharged from the base plate through the utilization of a digital scale. This system allows simulation of water drainage through the barricades and/or fractured rock mass adjacent to the backfill structure, thus understanding the effect of drainage on backfill response to sulphate attack.

Moreover, temperature-controlled chambers were used to cure the CPB samples cast in the pressure cell moulds under non-isothermal field curing conditions. The modified pressure cells were additionally outfitted with various sensors to monitor the development of negative pore water pressure (suction), temperature, volumetric water content, and electrical conductivity, as shown in Figure 6.2. The progression of the cement hydration process in CPB samples with time can be monitored by observing changes in ion concentration and ion mobility within the CPB specimen, which can be captured through the monitoring of electrical conductivity (Li and Fall 2016). The evolution of the electrical conductivity (EC), volumetric water content (VMC), and temperature of the CPB samples with time were recorded using 5TE temperature sensors. The 5TE temperature sensor can measure the electrical conductivity with an accuracy of ± 0.1 from 0 to 23 dS/m and record the temperature within the CPB samples with a precision of $\pm 1^\circ\text{C}$ and a range of -40°C to 60°C . The extent of self-desiccation in CPB samples, induced by water consumption during cement hydration, can be assessed by tracking the volumetric water content and suction within the backfill samples. The development of suction was recorded using the MPS-6 dielectric water potential sensor with a range of -9 to $-100,000$ kPa and an accuracy of $\pm 10\%$ reading $+2$ kPa from -9 to 100 kPa. The prepared CPB samples featuring distinct compositions were subjected to curing as per the detailed conditions outlined in the subsection below and summarized in Table 6.3.

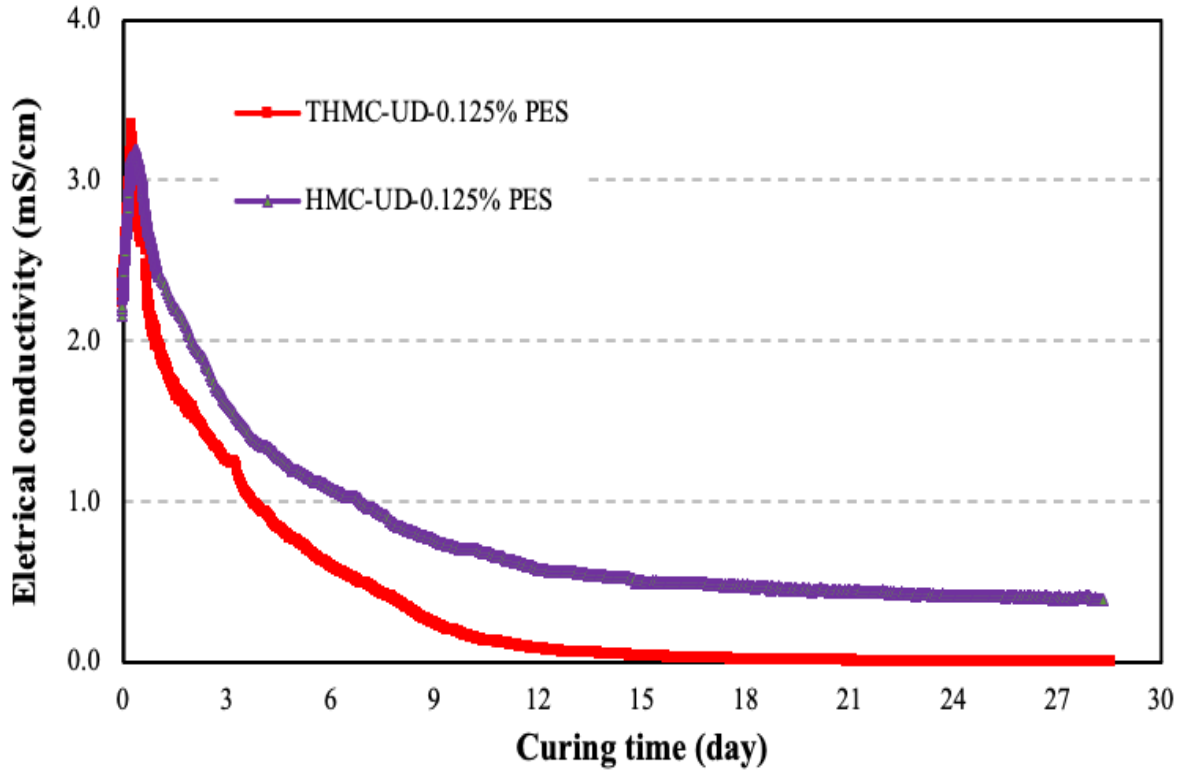


Figure 6.2 Setup of the pressure cells: (a) drained condition and (b) undrained condition (modified from Ghirian and Fall 2015).

Table 6.3 Summary of samples mixing composition and curing conditions.

Sample Name	Binder type (C)	PES content (%) (C)	Sulphate in mixing water (ppm) (C)	Curing stress (M)	Drainage condition (H)	Curing temperature (T)	Curing time (days)
Control-UD-0.0% PES	PCI	0	0	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
Control-UD-0.125% PES	PCI	0.125	0	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
Control-UD-0.0% PES-15000 ppm	PCI	0	15,000	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
Control-UD-0.125% PES-15000 ppm	PCI	0.125	15,000	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
THMC-UD-0.0% PES	PCI	0	0	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-UD-0.125% PES	PCI	0.125	0	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-UD-0.125% PES-15000 ppm	PCI	0.125	15,000	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-UD-0.0% PES-15000 ppm	PCI	0	15,000	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-PD-0.125% PES-15000 ppm	PCI	0.125	15,000	Field stress ^a	PD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-D-0.125% PES-15000 ppm	PCI	0.125	15,000	Field stress ^a	D	Field temp. ^b	0.5, 1, 3, 7, 28

PES: polycarboxylate ether-based superplasticizer; ^a simulated field curing stress (vertical pressure); ^b simulated field curing temperature; D: drained; PD: partially drained; UD: undrained conditions; PCI: Portland cement type I. C: chemical factor; M: mechanical factor; H: hydraulic factor; and T: thermal factor

6.2.3.1 Thermal curing conditions

Various thermal curing conditions, including isothermal (temperature of 20°C; standard laboratory curing temperature) and non-isothermal curing temperatures (field temperatures), were employed in the curing process for CPB samples. Isothermal temperature is applied to simulate controlled environments, ensuring uniform curing. This is beneficial for studying the effects of temperature on the CPB's hydration process. Non-isothermal curing temperatures are introduced to replicate real-world scenarios (backfill field temperature conditions) where temperature fluctuations occur. The non-isothermal temperature curing conditions aid in understanding how CPB material responds to temperature changes that can happen in underground mine environments. It is particularly relevant for assessing the sulphate-bearing CPB's resilience and performance under changing thermal conditions. The non-isothermal temperature curing conditions were adopted from studies conducted by Nasir and Fall (2009) and Wu et al. (2012). These studies employed a numerical tool to capture the real stope scenario, considering temperature variations within a stope height of 30 m. The stope was filled with CPB material with a binder content of 4.5%, enabling a thorough analysis of the thermal dynamics in this setting, as shown in Figure 6.3. The temperature-controlled chamber, shown in Figure 6.2, consisting of a heating blanket coupled with a regulating controller, was employed to adjust the temperature methodically and accurately throughout the experiment. This setup was crucial in achieving a controlled and incremental rise in temperature, which is essential for simulating the thermal profile typically encountered in in-situ CPB mass applications.

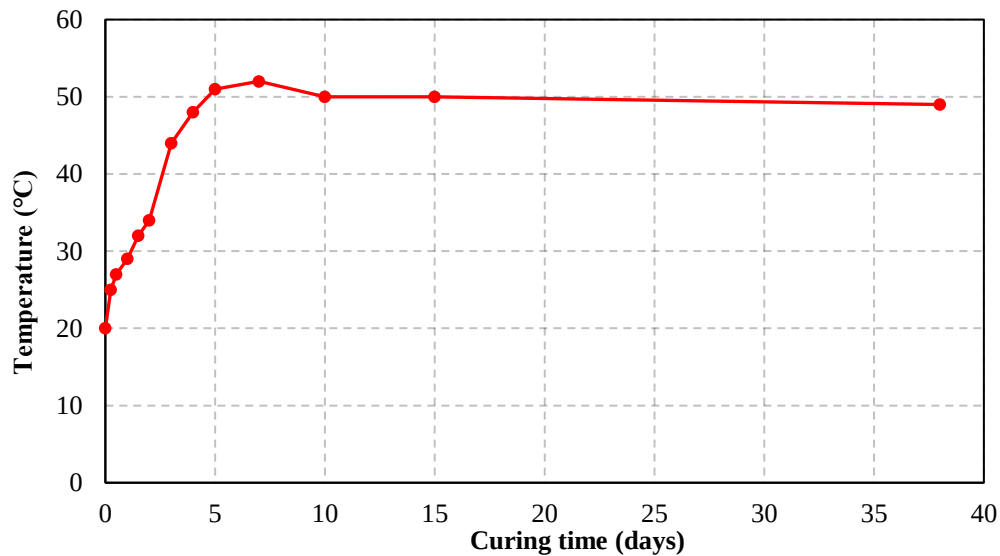


Figure 6.3 Field temperature-time history conditions of a 30 m high backfilled stope applied to the CPB samples during curing (after Nasir and Fall 2009 and Wu et al. 2012).

6.2.3.2 Hydraulic curing conditions

In this study, hydraulic curing conditions encompassing drained, undrained, and partially drained scenarios are implemented to replicate diverse drainage conditions encountered in the field and assess their impact on CPB's response to sulphate. The selection of these scenarios is informed by several factors, including the geological attributes of the mine (such as rock mass fractures), groundwater conditions, and the permeability of the CPB material. Under drained conditions, water is allowed to flow freely, mimicking scenarios where the CPB material is highly permeable (e.g., coarse tailings used). This condition also applies if the surrounding rock mass is highly fractured to let water flow away from the CPB mass. On the other hand, undrained conditions restrict water flow within the stope, representing scenarios where drainage is blocked or occurs very slowly. This is pertinent when CPB material exhibits low permeability, achieved through factors such as the use of fine tailings and high cement content, coupled with an absence of fractures in the surrounding rock mass, the CPB mass may block water drainage entirely. Nevertheless, in numerous field scenarios, the drainage conditions of the CPB typically fall between undrained (UD) and drained (D), i.e., the CPB material is partially drained (PD) conditions. Therefore, the three drainage conditions mentioned above (undrained (UD), drained (D), and partially drained (PD)) conditions were adopted in this study. The execution of partial drainage conditions involves the closure of the drainage valve after roughly 1.5 days of curing, allowing approximately 50% of the water that can be drained to exit the CPB sample. Non-drained conditions were achieved by keeping the drainage valves closed throughout the sample curing process, whereas drained conditions were ensured by keeping the valves open during curing.

6.2.3.3 Mechanical curing conditions (curing under applied pressure)

To replicate the in-situ backfilling processes within an underground stope and to evaluate the influence of pressure application resulting from the backfill self-weight on the strength development of sulphate-bearing CPB material incremental air pressures were systematically applied to the CPB samples over a specified duration. The backfilling rate and the associated vertical pressure or stress applied to CPB materials exhibit substantial variation from mine to mine and within individual stopes (Al-Moselly and Fall 2022). These variations are greatly influenced by factors such as stope geometry, stope depth, cement content and setting time, and the designated design pressure on the barricade (barrier or retaining wall structure constructed at the draw points of stope to confine and support backfill materials). The in-situ vertical pressures applied to the CPB samples were adopted from field measurement data for a long hole stope of 32 m height presented in Thompson et al. (2009). Table 6.4 presents the applied vertical pressure to the CPB samples, and the equivalent backfill rate and height. During the initial 2 hours, no pressure was

exerted on the samples, after which a systematic increase in air pressure commenced, reaching up to 600 kPa at an average filling rate of 0.26 m/h after attaining a height of 3 m.

Table 6.4 Pressure application scheme and the corresponding equivalent height of the CPB.

Elapsed time	Applied vertical pressure (kPa)	Equivalent height (m)	Equivalent filling rate (m/h)
start	-	-	-
2 h	20	1.00	0.50
4 h	35	2.00	0.50
6 h	55	3.00	0.50
8 h	60	3.20	0.40
10 h	80	4.30	0.43
12 h	90	4.80	0.40
1 d	100	5.38	0.22
1.5 d	125	6.66	0.19
2 d	150	7.92	0.17
3 d	250	13.25	0.18
4 d	400	21.41	0.22
5 d	450	24.00	0.20
6 d	600	32.00	0.22

6.2.3.4 Chemical curing conditions

The chemical processes or conditions of CPB adopted in this study are contingent on the chemical composition of its components, including the chemical composition and mineralogy of tailings, chemical composition and the reaction of binders used, chemistry of mixing water (i.e., the presence of sulphate), and chemistry of the admixtures used (i.e., the type and percentage amount superplasticizer used). In this study, the primary focus is investigating the effects of sulphate in the mixing water, the addition of polycarboxylate ether-based superplasticizers, and their interactions with other components, such as cement, on the mechanical strength of CPB under diverse curing conditions. Consequently, the preparation of specimens with varying sulphate and additive contents under different curing conditions is aimed at capturing the evolution of cement hydration and its complex interactions with sulphate and chemical additives. The different chemical conditions considered in this study are detailed in Table 6.3.

6.2.4 Testing programs

6.2.4.1 Mechanical test

The mechanical strength of the CPB materials was evaluated using uniaxial compressive strength (UCS) tests. The UCS tests were conducted according to the ASTM C39 procedure at various curing times (0.5, 1, 3, 7, and 28 days). After the designated curing period, the pressure cells were dismantled, and the CPB samples for the UCS test were precision-trimmed to adhere to the standard cylindrical specimens' length-to-diameter ratio (H/D) of two. The outcomes of the UCS tests were precisely recorded through a computer data acquisition system. The displacement rate of the press machine is 1 mm/min. To ensure the repeatability of the results, a minimum of two samples were tested at each curing time. The average value obtained from these tests was considered the representative strength of the analyzed samples.

6.2.4.2 Determination of physical properties and microstructure

This study employed multiple physical properties and microstructure testing techniques to assess the effect of the THMC curing conditions on the pore structure (e.g., void ratio, porosity, density) and the formation of cement hydration products in sulphate-bearing and sulphate-free backfill samples. The gravimetric water content (ω %) and bulk density (γ) tests were carried out on the CPB samples that had been prepared and cured, adhering to ASTM D2216-10 and ASTM D7263-09 standards, respectively. Furthermore, the progression of physical properties and pore structure of the CPB samples, encompassing void ratio (e) and porosity (n), was systematically measured and evaluated over time.

To determine the types and the related amount of cement hydration products produced in CPB samples, thermogravimetric analyses (TG and DTG) were performed using a thermogravimetric analyzer, which implies continuous monitoring and recording of weight loss, heat flow, and temperature changes in the sample at a rate of 10°C per minute up to 1000°C. The TG and DTG tests were conducted on some cement paste samples ($w/c = 1$; to mimic the high-water content of CPB), which were prepared in a similar way as the CPB specimens.

6.3 Results and Discussion

6.3.1 Effects of coupled THMC loading conditions on the strength development of CPB-PES with sulphate

The strength development of CPB samples, containing polycarboxylate ether-based superplasticizer (PES) and sulphate ions, under coupled THMC field curing conditions is illustrated in Figure 6.4. Additionally, the strength progression of CPB samples without PES and sulphate ions, cured under standard laboratory conditions (Control-UD-0.0% PES), is presented for comparison. These control samples undergo stress-free, undrained curing at room temperature (20°C). The analysis of Figure 6.4 reveals that, despite the well-documented decrease in strength associated with high initial sulphate content in CPB, as evidenced by numerous previous studies (e.g., Fall and Benzaazoua 2005; Fall and Pokharel 2010; Orejarena and Fall 2010; Li and Fall 2016; Rong et al. 2017; Li and Fall 2018; Wang et al. 2020; Yan et al. 2020; Aldhafeeri and Fall 2021), the strength of CPBs tested with sulphate and cured under THMC field conditions surpasses that of sulphate-free CPB samples cured under standard laboratory conditions at all ages. It is well-established that high initial sulphate contents (e.g., 15,000 ppm, 25,000 ppm) notably diminish the strength of CPB, particularly in the early stages (28 days curing time or less). This decrease in strength is attributed to the inhibition of cement hydration by sulphate ions. When CPB components are mixed with sulphate initially, the cement hydration process is delayed, resulting in slower chemical reactions responsible for binding cement particles together and consequently lower early-age strength for CPB samples containing sulphate (Li and Fall 2016). This inhibition of cement hydration is explained by chemical interactions between sulphate anions and the C3A (tricalcium aluminate) compounds present in the cement. These interactions lead to the formation of a protective coating around the C3A compounds, acting as a barrier that delays reaction with water and setting time. As a result of this protective coating, the normal hydration process of cement, which involves the chemical reaction between water and various cement compounds to form hydration products like calcium silicate hydrate (C-S-H) and calcium hydroxide (CH), is delayed. Consequently, this interference in chemical reactions affects the strength development of cementitious mixtures, including CPB materials (Li and Fall 2016). Remarkably, this sulphate-induced inhibition of cement hydration did not result in decreased strength for sulphate-bearing CPB samples with PES cured under field THMC conditions. These samples consistently exhibited higher strength than the sulphate-free control samples, with the difference in strength increasing as curing time progressed. For instance, there is a notable strength improvement of approximately 6%, 7%, 73%, 415%, and 450% at 12 hours, 1, 3, 7, and 28 days of curing, respectively, when compared to the control sample (Control-UD-0.0% PES). This resistance to sulphate damage and the superior mechanical performance observed in CPBs with PES and sulphate subjected to

simulated field curing conditions can be attributed to a synergistic effect of several factors. These include elevated field curing temperatures, hydraulic curing conditions, stress-curing conditions and the presence of PES, all of which are described in more detail below.

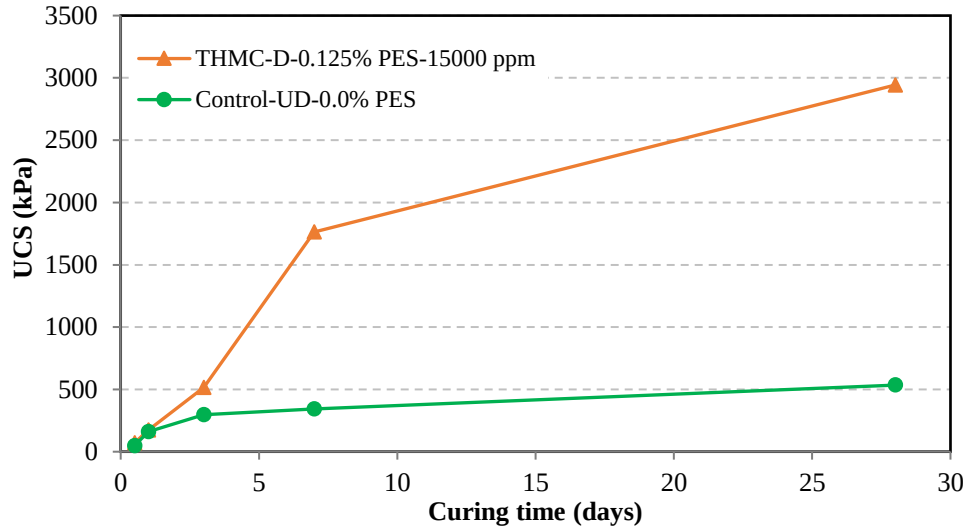


Figure 6.4 Coupled effect of THMC factors on the strength development of CPB with time.

Curing the CPB specimens under non-isothermal field conditions (i.e., elevated field temperatures) partially offsets the negative effect of sulphate on early-age strength. Higher temperatures accelerate the cement hydration process. In other words, the reactions that form the cement hydration products happen faster (Fall et al. 2010). Consequently, an accelerated formation of cement hydration products occurs within a shorter timeframe, leading to increased production of C-S-H and CH, as well as gypsum and ettringite through the reactions between sulphate ions with calcium hydroxide (CH) and tricalcium aluminate (C3A), respectively. C-S-H is the main binding phase in cementitious materials, enhancing their strength by improving cohesion and refining pore structure as its concentration increases (Taylor 1997). Moreover, the formation of gypsum and ettringite contributes to the hardening process, effectively reducing the porosity or void ratio of the CPB with time and ultimately enhancing its mechanical strength (Fall and Pokharel 2010). The decline in CPB porosity over time or refinement of the pore structure, commencing with the 12-hour sample, compared to the control sample, is clearly observable in the outcomes of the physical property analyses, as depicted in Figure 6.5. These findings affirm that sulphate-bearing CPB samples cured under non-isothermal conditions exhibit lower porosity (Figure 6.5a), reduced void ratio (Figure 6.5b), and higher dry density (Figure 6.5d) compared to control samples. This aligns with the earlier statement regarding the refinement of CPB pore structure due to increased hydration product formation. Detailed information regarding the

industrial effect of elevated temperature on the strength of CPB with various sulphate contents has been documented in previous publications (Fall and Pokharel 2010; Pokharel and Fall 2010).

Additionally, the drainage condition, whether drained or undrained, plays a significant role in determining the interaction of water, with or without sulphate ions, with the CPB material, thereby influencing the impact of sulphate on CPB strength. In drained samples, for example, superior water drainage facilitates the potential removal of sulphate ions from the backfill material, thus impacting strength development compared to undrained conditions. To illustrate, in drained settings, water movement aids in the leaching of sulphate ions from the CPB material (Aldhafeeri 2018). Consequently, this leaching reduces the presence of sulphate ions within the CPB material, thereby mitigating the adverse effects of sulphate on its early-age strength. Specifically, it diminishes the formation of a restrictive coating layer around the cement compounds, thereby promoting the reaction of compounds with water and, subsequently, improving the rate of cement hydration (Li and Fall 2016). Furthermore, studies have indicated that drained backfill exhibits greater mechanical strength compared to undrained backfill, primarily due to the improved effective stress and reduced water-to-cement ratio within the former (le Roux et al. 2005; Ghirian and Fall 2016). The influence of drainage and sulphate on the strength of CPB subjected to THMC factors will be further investigated and elaborated upon in subsequent sections, specifically in subsections 6.3.2.

Applying stress to CPB-PES specimens during curing, especially under drained conditions, induces a reorganization of solid particles, including tailings and cement particles (Cayouette 2003; Yilmaz et al. 2009a; Ghirian and Fall 2014, 2016). This process significantly improves the packing density of the CPB (refer to Figure 6.5d), directly correlating with its higher strength. Additionally, this phenomenon expedites the removal of excess free water, leading to a reduction in the water content of the CPB (see Figure 6.5c). Furthermore, it facilitates the extraction of sulphate ions from the CPB, thereby reducing the availability of sulphate ions within the backfill matrix that could hinder cement hydration. Consequently, both mechanisms contribute to the gradual enhancement of CPB strength over time when subjected to field curing conditions. Figures 6.5c and 6.5d show that CPB samples incorporating PES and sulphate (THMC-D-0.125% PES-15000 ppm) have lower water content and higher dry density and that their water content and dry density decrease and increase, respectively, more rapidly than those of control samples. The individual impact of curing stress on the strength development of CPB has been thoroughly examined in prior research (e.g., Ghirian and Fall, 2017; Ghirian and Fall 2016a,b) and, therefore, will not be covered again in this paper to maintain brevity.

Additionally, the incorporation of polycarboxylate ether-based superplasticizer (PES) into the CPB mixture leads to the creation of repulsive forces between solid particles, including tailings and cement. These forces arise from the formation of negatively charged particles, leading to an

increase in particle diffusion and consequently intensifying the cement hydration process (Ercikdi et al. 2010; Yang et al. 2018; Haruna and Fall 2019). Increased cement hydration leads to the formation of more cement hydration products, which offset the negative effect of sulphate on CPB strength. The intensification of cement hydration and the resultant increase in hydration products align with the findings from the TG/DTG analysis of cement paste samples containing PES dosages of 0% and 0.125%, subjected to a 7-day curing period (see Figure 6.6). In the graphical representation, the initial endothermic peak on the DTG curve, occurring within the temperature range of 100 °C to 200 °C, signifies rapid weight loss attributable to water evaporation and the breakdown of hydration products like ettringite, gypsum, carboaluminates, and C-S-H (Fall and Pokharel 2010). The peak observed between 400 °C and 500 °C corresponds to the dehydroxylation of calcium hydroxide (CH), while the third peak, ranging from 650 °C to 750 °C, is linked to the disintegration of calcite (Fall and Pokharel 2010; Wang et al. 2016). A comparative analysis of the thermal profiles of cement paste with 0% and 0.125% PES reveals that the specimen with 0.125% PES exhibits a more pronounced loss in the first and second peaks. This observation suggests that the presence of PES induces the generation of a greater quantity of hydration products. The impact of sulphate and PES on the strength of CPB cured under THMC factors is further discussed in subsection 6.3.3.

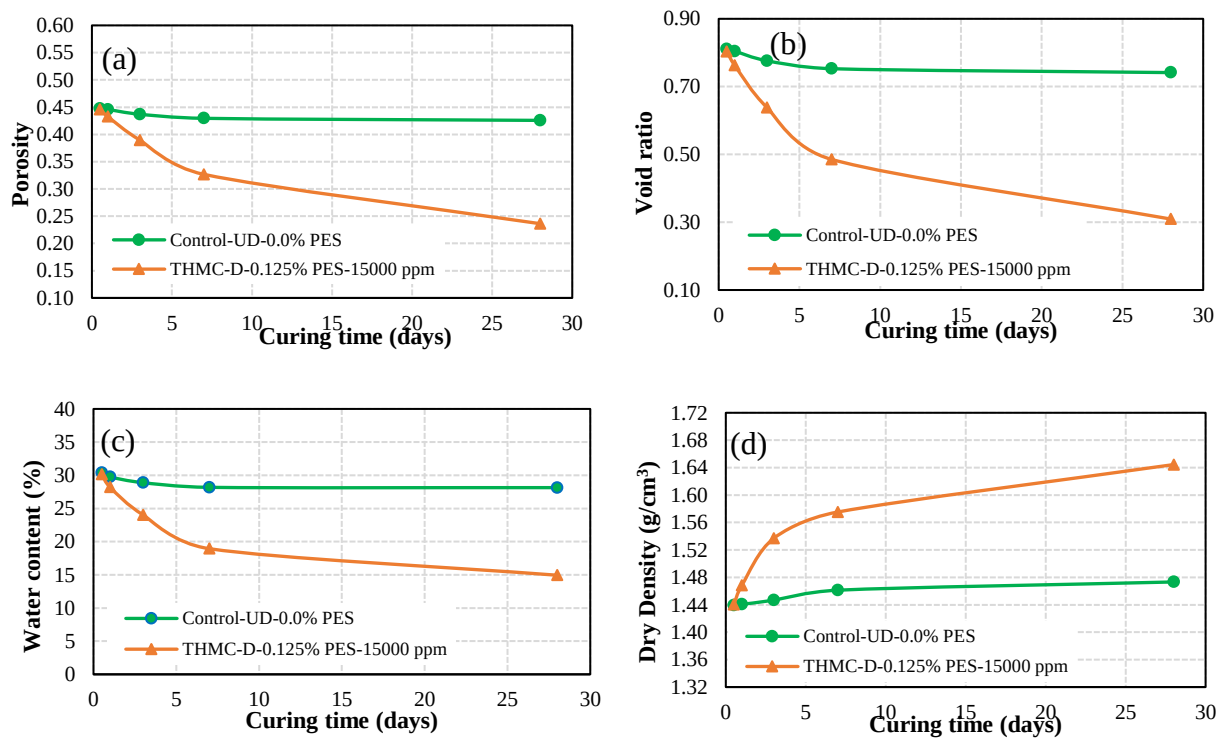


Figure 6.5 Changes in physical properties of CPB-PES with sulphate cured under THMC factors and common laboratory curing conditions (control): (a) porosity, (b) void ratio, (c) water content, and (d) dry density.

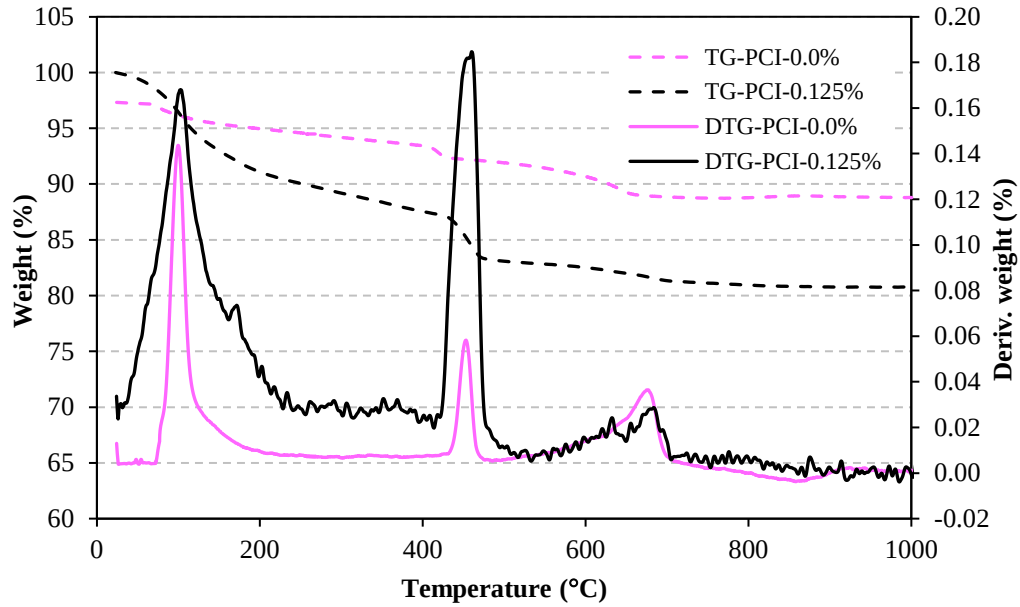


Figure 6.6 TG/DTG diagrams show the impact of adding 0.125% PES on the cement hydration process for a 7-day age cement paste sample.

The findings outlined above indicate that the common method of evaluating the impact of sulphate on CPB strength development may be unsatisfactory. This method typically involves testing CPB samples with different sulphate contents cured under standard laboratory conditions, disregarding crucial factors such as field curing temperature, drainage conditions, and curing stress. Consequently, this method fails to accurately reflect how CPB responds to sulphate exposure in real-world field conditions. It's evident that the combined influences of field curing conditions, including temperature, drainage, stress, and the presence of PES, significantly affect the mechanical properties in response to sulphate. However, while these results underscore the importance of these factors, they do not delineate the specific contributions of each to the observed enhanced mechanical performance of sulphate-bearing CPB under field conditions. This aspect will be further explored in the subsequent sections. Nevertheless, considering that previous studies have extensively examined and described the individual impact of elevated field temperature on enhancing CPB resistance to sulphate damage and strength development of CPB with various sulphate contents (e.g., Fall and Pokharel 2010; Pokharel and Fall 2010), the effect of curing stress on CPB strength (e.g., Ghirian and Fall 2017; Ghirian and Fall 2016a,b), the discussion here will focus on the hydraulic factors (drainage), PES and the interactions between PES and sulphate, which remain unknown. This approach is adopted for the sake of brevity and to concentrate on novel findings.

6.3.2 Effects of hydraulic factor (drainage conditions) on the strength of CPB-PES with sulphate and cured under field loading conditions

The effects of different drainage curing conditions (drained (D), partially drained (PD), and undrained (UD)) on the strength development of CPB subjected to various field loading conditions are illustrated in Figure 6.7. These conditions include curing under stress, non-isothermal curing temperatures, with a mixture containing 15,000 ppm of Ferrous sulphate in the water and incorporating 0.125% of polycarboxylate ether-based superplasticizer (PES). The results reveal that the drainage factor has a substantial influence on the UCS development of sulphate-bearing CPBs. Drained samples show higher UCS values than PD and UD samples, while the strength of PD samples is higher than that of UD samples. For instance, after seven days of curing, the UCS values were determined to be equal to 1098 kPa, 1346 kPa, and 1762 kPa for the undrained, partially drained, and drained specimens, respectively. Multiple reasons can explain such high UCS variation.

First, the high drainage of excess water from the CPB mixture at early ages reduces the porosity and void ratio with time (Yilmaz et al. 2009b; Ghirian and Fall 2014, 2016), as evidenced in Figure 6.8. Indeed, this figure shows a more significant reduction in the porosity and void ratio in the drained CPB sample over time compared to the undrained CPB sample.

Second, the decrease in water volume resulting from the drainage process, coupled with the utilization of free water in the ongoing cement hydration process, initiates the development of negative pore water pressure (suction). The evolution of suction further contributes to enhancing CPB strength (Ghirian and Fall 2016; Al-Moselly and Fall 2022). The pronounced increase in suction as time progresses in the drained CPB sample is clearly shown in Figure 6.9. For example, the suction measurement for the drained CPB sample with a sulphate content of 15,000 ppm (THMC-D-0.125% PES-15,000 ppm) is 291 kPa at 28 days compared to 214 kPa for the undrained CPB sample (THMC-UD-0.125% PES-15,000 ppm).

Third, the drainage of water from the CPB reduces the presence of sulphate ions within its interstitial water, thereby decreasing the number of sulphate ions available to delay cement hydration, as previously elucidated. This decrease in sulphate ions is associated with a diminished inhibition of cement hydration by sulphate ions (Bullard et al., 2011; Li and Fall 2018; Alainachi 2020). Notably, the outflow of water from the sulphate-bearing backfill material promotes the leaching or removal of sulphate ions from the CPB material, which is highly advantageous. This removal of sulphate ions effectively mitigates the formation of thin coating layers around the cement compounds within the CPB (Li and Fall 2018; Aldhafeeri 2018), thus favorably enhancing cement hydration and CPB strength. Consequently, the overall influence of sulphate on the early-age strength of CPB under drained conditions is significantly reduced, as it no longer impedes the essential cement hydration process to the same extent as in undrained conditions. This assertion is

supported by the findings from monitoring the electrical conductivity (EC) of drained and undrained CPBs with sulphate, as depicted in Figure 6.10, providing valuable insights. Specifically, in the drained CPB sample with a sulphate content of 15,000 ppm, the EC reaches its peak value of 1.86 mS/cm within approximately 5.5 hours. In contrast, the undrained CPB sample, also with a sulphate content of 15,000 ppm, achieves its peak EC value of 2.27 mS/cm after a longer duration, approximately 10 hours. This disparity in EC peak times between drained and undrained CPB samples, particularly the earlier peak observed in the drained sample, indicates a more rapid cement hydration process in the drained samples, aligning with the aforementioned proposition regarding reduced sulphate ion levels in drained CPB samples due to drainage. Furthermore, the reduction in the quantity of sulphate ions within the CPB material due to drainage is corroborated by the results of chemical analysis (Ion Chromatography) performed on the water obtained from the CPB through drainage. The analysis reveals that the drainage water possesses a sulphate concentration of 2129 ppm, indicating a substantial amount of sulphate ions could exit the CPB structure in the field via drainage. This has noteworthy practical implications concerning the early-age strength gain of the CPB structure, crucial for mine productivity, and the durability of backfill structures.

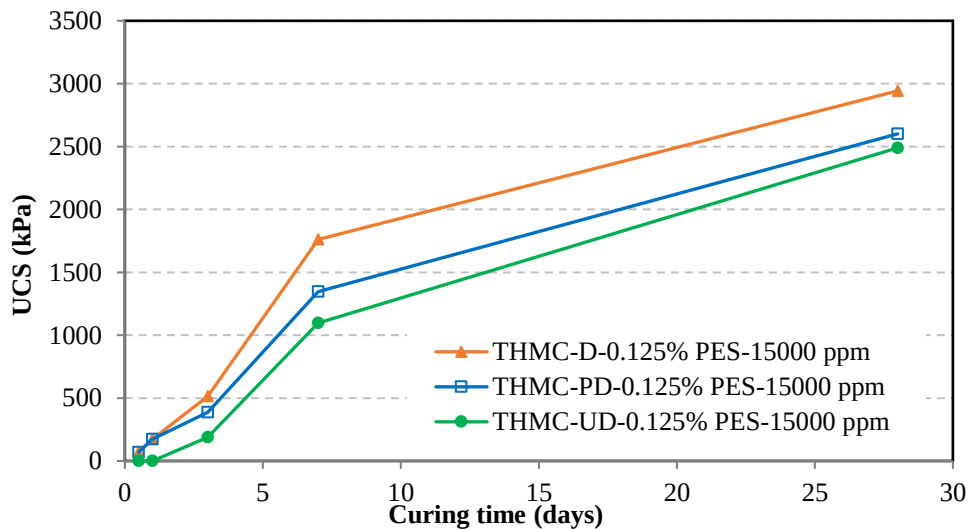


Figure 6.7 Influence of drainage conditions on the strength development of CPB with sulphate, 0.125% of PES, and cured under various field loading conditions.

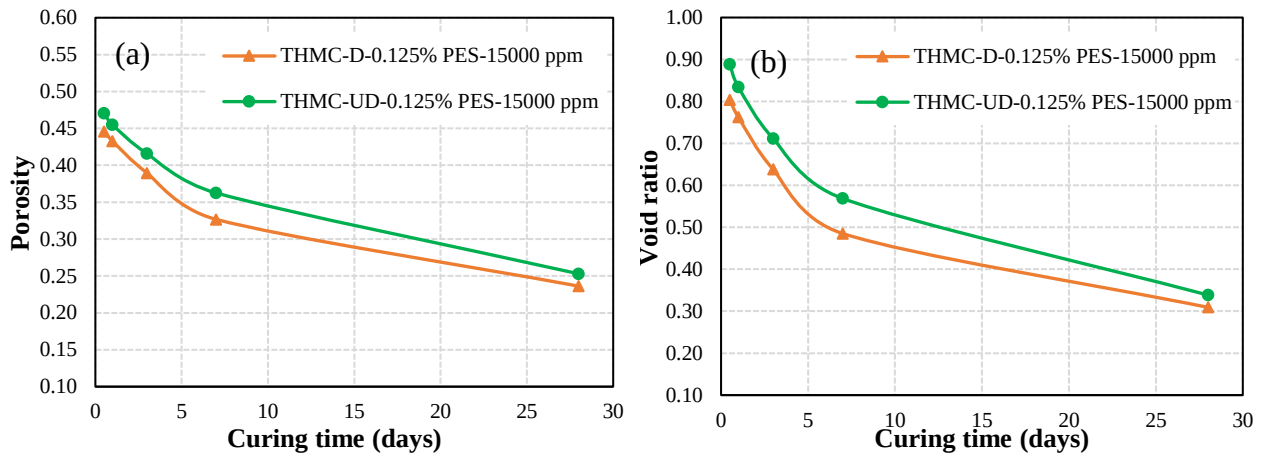


Figure 6.8 Effect of drainage conditions on physical properties of CPB-PES with sulphate cured under THMC factors: (a) porosity, and (b) void ratio.

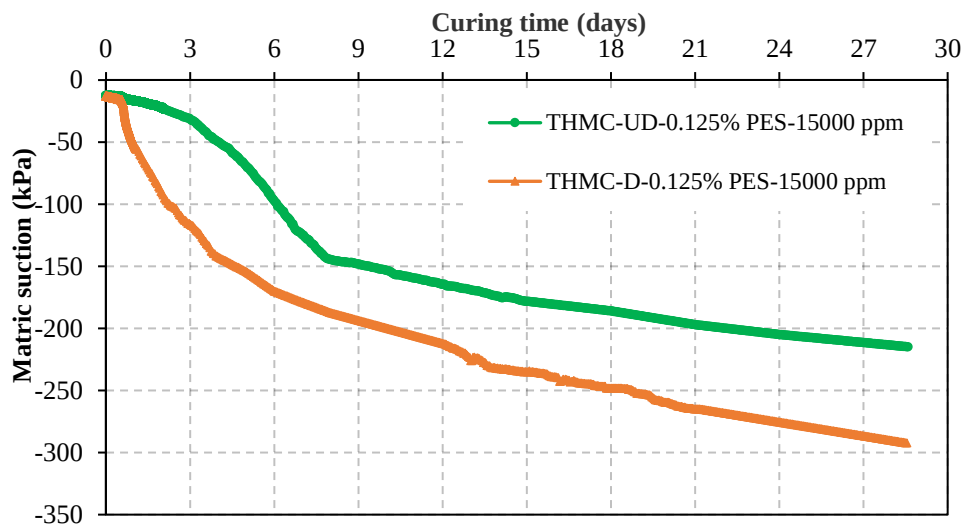


Figure 6.9 Effect of drainage conditions on negative pore water pressure (suction) of CPB-PES samples under THMC curing conditions.

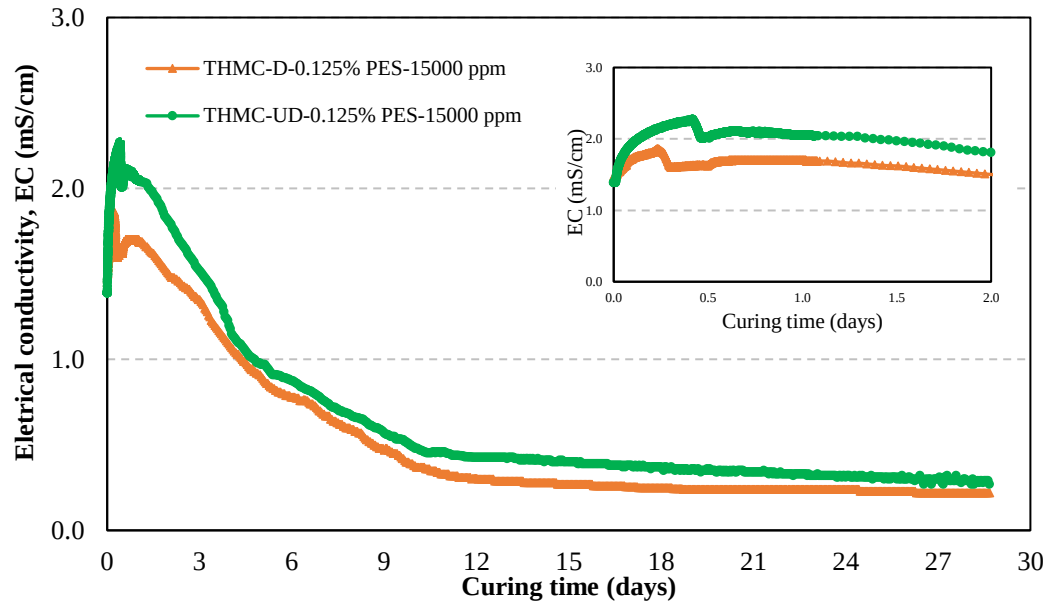


Figure 6.10 Effect of drainage conditions on the EC evolution of CPB-PES samples cured under THMC factors with time.

6.3.3 Effects of sulphate-superplasticizer interactions (chemical factors) on the strength of CPB cured under simulated field thermal and hydraulic conditions

This study further investigates the influence of Ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) and the inclusion of 0.125% polycarboxylate ether-based superplasticizers (PES) in CPB materials cured at early ages (0.5, 1, 3, 7, and 28 days). All the CPB samples were cured under various field loading conditions (i.e., curing under stress and non-isothermal temperatures), focusing on how they interacted and affected mechanical strength (UCS) over time. The findings are depicted in Figure 6.11. This figure noticeably illustrates the substantial impact of sulphate and polycarboxylate ether-based superplasticizers (PES) on the early-age mechanical strength of CPB samples. The CPB samples incorporating 15,000 ppm sulphate and 0.125% PES (denoted as THMC-UD-0.125% PES-15,000 ppm) exhibit much lower strength than those without sulphate, with or without superplasticizer and cured under similar conditions for 0.5, 1, and 3 days. However, in subsequent ages (7 and 28 days of curing), the CPB samples with 15,000 ppm sulphate and 0.125% PES demonstrate higher strength than those without sulphate and without superplasticizer (denoted as THMC-UD-0.0% PES). Yet, their strength remains lower than CPB samples without sulphate but with superplasticizer (expressed as THMC-UD-0.125% PES) under similar curing conditions. The impact and extent of effects on the mechanical strength of the studied CPB samples are primarily controlled by three main factors: curing time, sulphate content, and superplasticizer content. A comprehensive discussion of these factors is presented below.

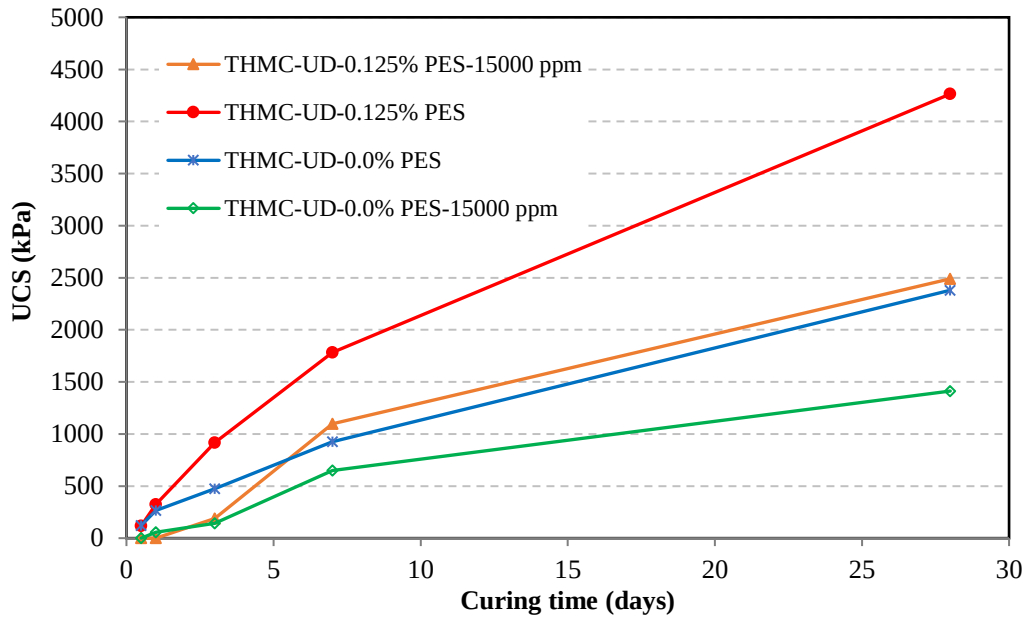


Figure 6.11 The effect of sulphate and polycarboxylate ether-based superplasticizer on the mechanical strength evolution of CPB material cured under THMC factors with time.

6.3.3.1 Curing age ≤ 3 days

From Figure 6.11, it can be noticed that the mechanical strength of the CPB samples containing 15,000 ppm sulphate and 0.125% of PES was recorded at approximately zero during curing times of 0.5 and 1 day. Additionally, during a 3-day curing period, the strength of these samples is significantly lower compared to the sulphate-free CPB samples. The reduction in the early-age mechanical strength of CPB samples can be attributed to a synergistic influence. The presence of sulphate ions plays a combined role: firstly, they act as retarding agents, impeding the reaction of cement compounds with water (Aldhafeeri 2018; Li and Fall 2018), as previously explained. Secondly, sulphate ions contribute to the dispersity of the superplasticizer; the presence of sulphate within the cement paste results in the shrinkage of PES molecules and thus weakens the dispersive role of the superplasticizer (He et al. 2017; He et al. 2019). He et al. (2017) indicated that sulphate reduces the adsorption rate of polycarboxylate ether-based superplasticizers on the cement particles. Also, their research revealed the presence of a competitive adsorption dynamic between sulphate ions and polycarboxylate ether-based superplasticizers on the cement particles, with the extent of this competition being significantly influenced by the concentration of sulphate ions. In addition, Yamada et al. (2001) verified that the polycarboxylate ether-based superplasticizer desorbed when the sulphate content increased in the solution, which in turn reduced the dispersing effect of superplasticizers. The inhibition of cement hydration processes at the early age is

demonstrated by the results of the electrical conductivity (EC) test shown in Figure 6.12. Assessing the progress of cement hydration is effectively achieved through the monitoring of electrical conductivity (EC), where EC serves as a measure of charge mobility within an electric field (Cui and Fall 2016). The EC monitoring tests were conducted on CPB samples cured under similar field curing conditions, both with and without the inclusion of sulphate and superplasticizers. The outcomes reveal that the presence of both sulphate and superplasticizer at the early ages in the CPB samples results in an extended duration to reach the peak EC, indicative of a delayed cement hydration process.

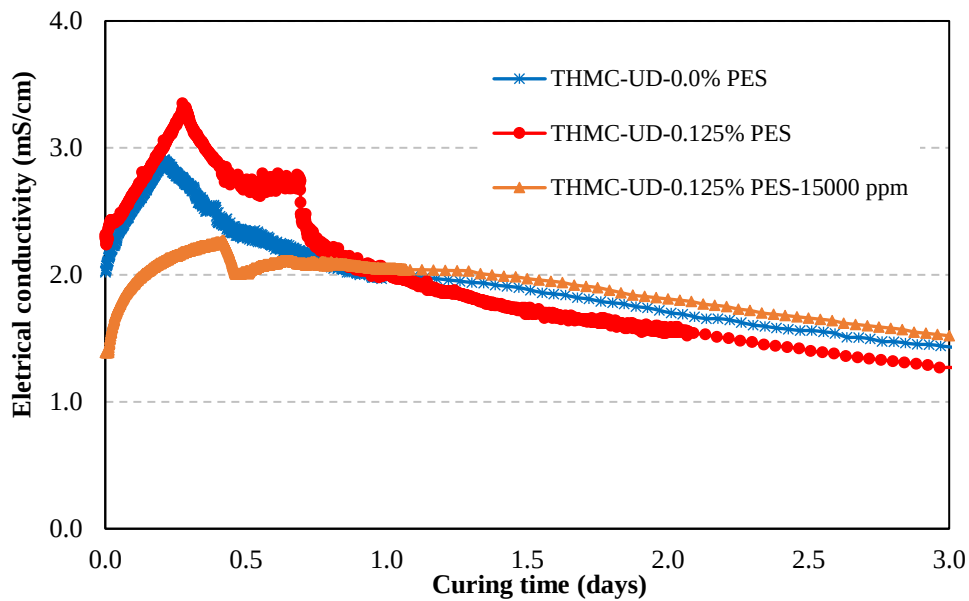


Figure 6.12 Evolution of electrical conductivity of the CPB cured under THMC factors and with various sulphate and polycarboxylate ether-based superplasticizer contents at the early ages.

6.3.3.2 Curing age > 3 days

From Figure 6.11, it can be noticed that after curing for 7 and 28 days, the mechanical strength of the CPB samples with 15,000 ppm sulphate and 0.125% PES is higher compared to the CPB samples without sulphate and without superplasticizer. Meanwhile, the CPB samples without sulphate and with 0.125% superplasticizer exhibit the highest strength among all samples. For instance, after a curing period of seven days, the CPB specimen with a high sulphate content of 15,000 ppm and 0.125% PES (THMC-UD-0.125% PES- 15,000 ppm) exhibited an 18% increase in compressive strength compared to its counterpart without sulphate and superplasticizer (THMC-UD-0.0% PES). Remarkably, the same CPB mixture showed a 62% enhancement in strength over the sample with 15,000 ppm sulphate but without superplasticizer (THMC-UD-0.0% PES- 15,000

ppm). This underscores the minimal impact of high sulphate concentrations (15,000 ppm) on CPB strength during this curing stage (i.e., after 7 days). Additionally, these findings emphasize the significant positive effect of incorporating 0.125% superplasticizer on the mechanical strength development of CPB after 7 days of curing. The increase in the mechanical strength of CPB with sulphate and PES at this stage of curing can be attributed to the influence of sulphate on pore structure of CPB, leading to a reduction in the porosity of CPB and, consequently, an enhancement in its strength. This is attributed to the precipitation of secondary hydrated minerals, including gypsum and ettringite, within the empty pores of CPB (Fall and Pokharel 2010). This precipitation occurs through the reaction of sulphate ions with calcium hydroxide (CH) and tricalcium aluminate (C3A). This is explicitly supported by the results of porosity of void ratio tests conducted on various CPB samples (i.e., with and without sulphate) and cured under similar curing conditions presented in Figure 6.13. It can be observed that the porosity and void ratio decreased after 7 days of curing within the CPB samples with a 15,000 ppm sulphate and 0.125% of PES compared to the CPB samples without sulphate and without superplasticizer.

The notable enhancement in strength in the CPB samples with 0.125% PES and no sulphate (THMC-UD-0.125% PES) can be attributed to the impact of PES on the cement hydration processes within the CPB mixture. The inclusion of polycarboxylate ether-based superplasticizer (PES) expedites a more homogeneous distribution of tailings and cement particles within the CPB matrix, generating repulsive forces that temporarily delay early-stage cement hydration (Ercikdi et al. 2010; Yang et al. 2018; Haruna and Fall 2019). This mechanism explains the initial lower strength values at early curing times, specifically at the 12-hour. Over time, however, the rate of cement hydration accelerates, driven by the PES-induced ionic diffusion, resulting in a greater amount of hardened cement hydration products (Haruna and Fall 2020). Additionally, the steric hindrance effect of this type of superplasticizer, coupled with its extensive polymeric chains, promotes increased interparticle connectivity, thereby reinforcing the mechanical strength of the CPB-PES structure with time (Ercikdi et al. 2010; Yang et al. 2018). The enhanced development of hydration products in cement paste with polycarboxylate ether-based superplasticizer (PES) is supported by the TG/DTG analyses of samples cured for a week, as depicted in Figure 6.6, and explained earlier in Sec. 6.3.1.

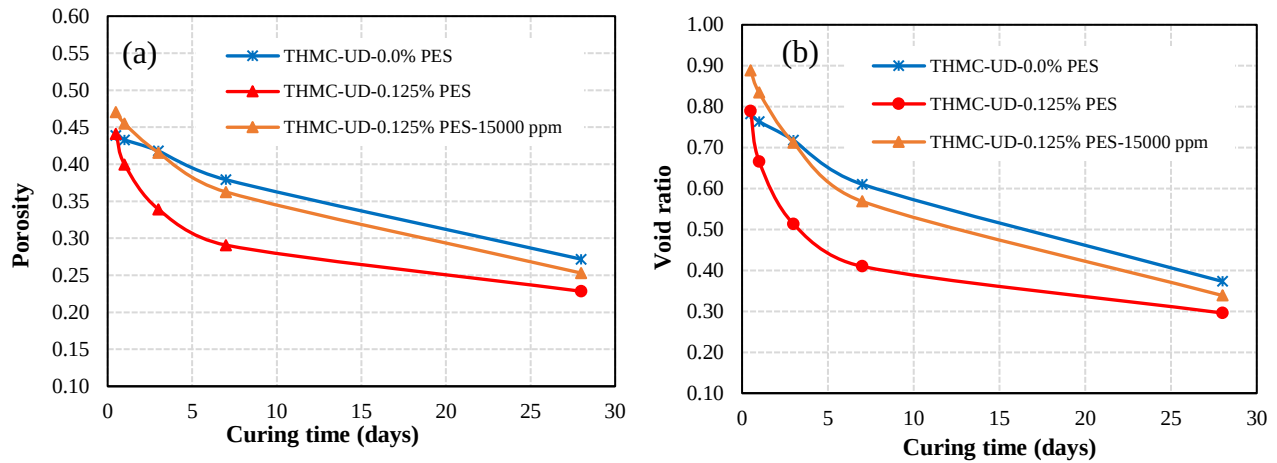


Figure 6.13 Changes in the physical properties of CPB cured under THMC factors with various percentages of PES, sulphate content, and time: (a) porosity and (b) void ratio.

6.4 Conclusions

This study highlights the impact of Ferrous sulphate ($\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$) and the inclusion of 0.125% polycarboxylate ether-based superplasticizer (PES) on the mechanical strength of Cemented Paste Backfill (CPB) materials cured under varied curing conditions. These conditions include thermal (T, CPB non-isothermal field temperature), hydraulic (H, drainage conditions), mechanical (M, CPB overburden stress, stress increase rate) and chemical (C, PES, sulphate ions) factors. The following conclusions are drawn:

The incorporation of polycarboxylate ether-based superplasticizer (PES) in sulphate-bearing CPB samples, subjected to THMC field curing conditions, results in notable strength improvements. A significant increase in strength, starting as early as 12 hours into the curing process, is observed compared to control samples (samples under standard laboratory conditions). Curing CPB specimens at elevated field temperatures mitigates the negative impact of sulphate on early-age strength. Higher temperatures accelerate the cement hydration process, leading to faster formation of hydration products like gypsum and ettringite. This accelerated hardening process reduces CPB porosity, enhancing its mechanical strength over time.

The drainage condition significantly affects CPB strength development in the presence of sulphate. Drained samples exhibit better water drainage, facilitating sulphate ions removal and chemical reactions. This mitigates the adverse impact of sulphate on early-age strength by reducing the formation of a restrictive coating layer around C3A compounds, demonstrating the intricate interplay of drainage, sulphate, and strength development.

Applying stress during the early stages of curing induces solid particle rearrangement, enhancing packing density and promoting the release of excess free water. This excess water is available for reactions with sulphate ions, contributing to sulphate dispersion and higher strength over time.

Stress and drainage conditions also allow capillary water to flow out of the CPB sample, further enhancing mechanical strength.

The addition of PES to the CPB mixture stimulates the production of more hydration products, enhancing mechanical strength. Notably, competitive adsorption between sulphate ions and PES on cement particles affects PES adsorption and its dispersing effect.

During the initial 0.5, 1, and 3 days of curing, CPB samples with 15,000 ppm sulphate and 0.125% PES exhibit lower mechanical strength, attributed to the dual effects of sulphate ions as retarding agents and their impact on superplasticizer dispersity. However, after 7 and 28 days, these samples demonstrate superior strength compared to those without sulphate, showcasing the minimal impact of high sulphate concentrations after 7 days.

The incorporation of 0.125% superplasticizer significantly enhances CPB mechanical strength, as evidenced by samples without sulphate and with 0.125% PES exhibiting the highest strength after 7 and 28 days of curing. This positive effect is associated with the reduction in CPB porosity and the precipitation of secondary hydrated minerals, emphasizing the complex interplay between curing time, sulphate content, and superplasticizer content.

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Chapter 7: Understanding Pore Water Pressure Responses to Sulphate in Cemented Paste Backfill with Superplasticizers under THMC Field Conditions

(Submitted)

Zubaida Al-Moselly, Mamadou Fall

Abstract:

This research investigates the impact of sulphate on the development of pore water pressure (PWP) in cement paste backfill (CPB) containing polycarboxylate ether (PES) superplasticizers under thermal-hydraulic-mechanical-chemical (THMC) conditions that simulate actual curing environments in the field. The PWP of CPB-PES with and without sulphate under non-isothermal field curing temperatures, varied drainage conditions and curing stresses was evaluated using a specially designed experimental set-up. The results obtained were compared with those obtained from sulphate-bearing and sulphate-free CPB-PES under standard laboratory conditions. The developed experimental set-up effectively reproduced the complex field conditions experienced by backfill structures. Key findings indicate that the behaviour of PWP in CPB with PES under field conditions differs significantly from that under standard laboratory conditions due to the profound influence of field curing temperatures, drainage conditions and backfill self-weight. The study reveals that high sulphate ion concentrations significantly increase initial PWP and slow its subsequent dissipation by interfering with the cement hydration process. This interference results in delayed hydration, reduced pore water consumption and lower capillary pressure. In addition, improved drainage under THMC conditions mitigates the negative effects of sulphates by facilitating the removal of sulphate ions, thus promoting more efficient cement hydration and CPB self-desiccation. The knowledge gained in this research is crucial for a thorough understanding of PWP behaviour in sulphate-bearing CPB-PES in the field, for the development of predictive THMC models for evaluating backfill performance, and for improving the safety and efficiency of mining backfills.

Keywords: Cemented paste backfill, tailings, mine, sulphate, pore water pressure, THMC, in-situ conditions.

7.1 Introduction

Cemented Paste Backfill (CPB) represents an essential innovation in underground mining techniques, offering a dual benefit of enhancing mine productivity while concurrently addressing environmental concerns related to mine waste disposal (Kesimal et al. 2005; Fall and Pokharel 2010; Gao et al. 2023). This innovative technology utilizes a mixture primarily composed of dewatered tailings, making up 70% to 85% by weight, combined with a hydraulic binder and supplemented with water and various additives (Haruna and Fall 2019; Sagade et al. 2023). CPB has been recognized not only for its role in improving ore recovery rates but also for its contribution to the stability of underground mine structures, mitigating risks such as surface subsidence and underground mine cavities or stopes collapse (Abdul-Hussain and Fall 2011; Chen et al. 2023; Saremi and Fall 2023).

The preparation and delivery of CPB are critical to its successful application. The mixture is formulated at specialized plants and then conveyed to the underground voids or stopes through pipeline system, relying on gravity and/or pumping to reach the stopes (Ercikdi et al. 2010; Haruna and Fall 2019). The flow properties of the CPB material are essential to ensure smooth transportation and to prevent blockages within the pipelines. In this context, the inclusion of superplasticizers into the CPB mix has advanced the handling of these high-density materials. These admixtures enhance the CPB's fluidity, facilitating its delivery and placement and reducing the potential for segregation (Al-Moselly et al. 2022). Moreover, superplasticizers have been found to adsorb onto the surfaces within the cementitious mixture, improving particle dispersion and consequently enhancing the mechanical strength of the backfilled material (Ercikdi et al. 2010; Haruna and Fall 2019; Huynh et al. 2006; Simon et al. 2011; Ouattara et al. 2017; Ouattara et al. 2018; Mangane et al. 2018).

To facilitate the transportation of fresh and hydrating CPB materials during the stope-filling process while simultaneously preventing the CPB from encroaching upon active mining areas, specialized retaining structures (barricades) are erected (Fall and Pokharel 2010). These barricades are strategically designed and constructed within the access points leading into the stope before the commencement of filling operations. These barricades are engineered to withstand the pressure of over ten vertical meters of continuous CPB pour, preventing the flow of freshly mixed CPB into adjacent stopes or active mining areas until the CPB achieves its target strength (Helinski et al. 2007; Helinski et al. 2011). The importance of preserving barricade stability throughout the backfilling process cannot be overstated, as the consequences of failure can be catastrophic, posing serious risks to the safety of mining personnel and imposing substantial economic setbacks due to production delays (Shahsavari and Grabinsky 2016; Cui and Fall 2017; Fang and Fall 2020). The primary risk to barricade integrity is the exertion of pressure by the CPB material that surpasses

the barricade's designed threshold (Cui and Fall 2017). This pressure is a function of various factors, including the CPB's self-weight, the dissipation of pore water pressure, and the subsequent buildup of effective stress within the CPB matrix (Ghirian and Fall 2015). Particularly at early stages, an excessive increase in positive pore water pressure within the CPB poses a profound threat to barricade stability. However, the gradual reduction of this excess positive pressure and the development of negative pore water pressure (suction) within the CPB contribute to strength gains, fostering the essential hardening phase of the CPB (Helinski et al. 2007).

Furthermore, in underground mining, the integrity and performance of CPB material are governed by complex interactions of Thermal-Hydraulic-Mechanical-Chemical (THMC) factors or conditions (Ghirian and Fall 2014, 2015). These conditions include variations in underground temperature influenced by the depth and geology of the mine, the exothermic nature of cement hydration, moisture levels from different drainage states, variations in the stresses impacting the CPB structure (largely dependent on the depth and geometry of the stope), self-weight and backfilling rate of CPB, designed pressure of the barricades, in situ stress conditions, and the intricate reactions of CPB components with sulphates, which is often introduced through binder reactions or oxidation of sulphide minerals in tailings (Fall et al. 2010; Helinski et al. 2011; Cui and Fall 2015; Al-Moselley and Fall 2022).

Understanding the evolution of pore water pressure within the CPB material is vital for the integrity of the structural components of the backfill, a process greatly affected by the THMC factors. Previous studies (e.g., Helinski et al. 2007; Shahsavari and Grabinsky 2015, 2016; Ghirian and Fall 2013, 2015; Al-Moselley and Fall 2022) have provided insights into how pore water pressure evolves due to cement hydration and the consequent self-desiccation, as well as the effects of filling rates and drainage conditions on pore water pressure development. These studies have mainly focused on specimens cured under controlled laboratory conditions, which do not adequately mimic the complex non-isothermal temperatures, stress variables, and drainage scenarios encountered in the field. In addition, these studies did not adequately capture the combined effects of sulphate concentrations and superplasticizer admixtures (chemical factors) on pore water pressure under the complex and coupled THMC conditions that CPBs encounter in the field. For instance, studies by Helinski et al. (2007) have modelled how pore water pressure can decrease in response to cement hydration, whereas Ghirian and Fall (2013, 2015) have investigated the development of pore water pressures under various drainage and stress conditions for CPB samples cured under isothermal curing temperatures (i.e., constant temperatures).

Despite the valuable findings of existing studies, the comprehensive effects of THMC factors, particularly the role of sulphate when combined with superplasticizers, have not been thoroughly examined in relation to pore water pressure under conditions that closely mimic the field. This knowledge gap is addressed in this manuscript. The aim of this research is to study the

effect of sulphate on the development of pore pressure in CPB exposed to THMC curing conditions that mimic in situ curing conditions. Sulphates, whether from the oxidation of sulphide minerals in tailings or from sulphate-rich mine water used in CPB preparation, can influence the pore water pressure in ways that are not yet fully understood, with the potential to either strengthen or weaken the structural integrity of CPB.

7.2 Experimental Program

7.2.1 Materials

7.2.1.1 Tailings

In this study, the chosen materials for experimental investigation were synthetic silica tailings (ST), which consist almost entirely of non-reactive quartz (SiO_2) at a concentration of 99.8%. The grain size distribution of these tailings closely looks like that of an average sample from nine Canadian hard rock mines, as shown in Figure 7.1. Quartz is the primary mineral present in tailings from Canadian hard rock mining operations. These silica tailings are classified as medium-sized, characterized by 35-60% of their particles being less than 20 micrometers in weight (Landriault 2001). Selecting silica tailings ensures precise control over the chemical and mineralogical makeup of the sample, thereby reducing the variability that reactive elements in natural tailings might introduce when interacting with cement. Such interactions have the potential to alter the analysis and interpretation of the cement behaviour. By using ST, the study aims to produce more reliable data on how the tailings will interact with cement. The chemical properties of the silica tailings used in this study are detailed in Table 7.1.

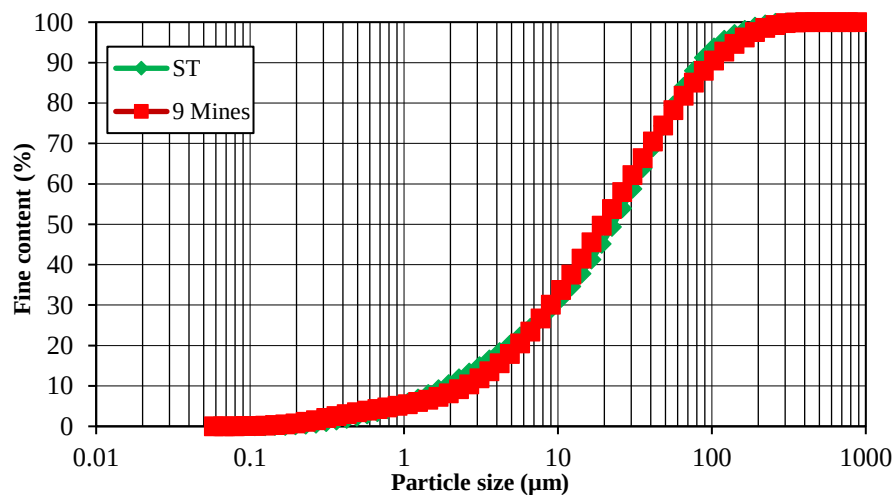


Figure 7.1 Particle size distribution of the synthetic silica tailings employed in this study compared with the average from nine natural mine tailings sourced from Eastern Canada.

Table 7.1 Chemical composition of the silica tailings.

Concentration (wt.%)	Ingredient (symbol)								Loss on ignition
	SiO ₂	Fe ₂ O ₃	Al ₂ O ₃	TiO ₂	CaO	MgO	Na ₂ O	K ₂ O	
	99.8	0.035	0.05	0.02	0.01	<0.01	<0.01	0.02	0.1

7.2.1.2 Binder

Portland Cement Type 1 (PCI) or General-Use cement (GU) was selected as the hydraulic binder due to its widespread availability and cost efficiency, which are key factors in its prevalent use in CPB applications in mining operations around the globe. Table 7.2 comprehensively lists detailed specifications concerning the chemical and physical characteristics of the PCI used.

Table 7.2 Chemical and physical properties of binder used.

Element (%)	SO ₃	Fe ₂ O ₃	Al ₂ O ₃	SiO ₂	CaO	MgO	Relative density	Specific surface (m ² /g)
PCI	3.8	2.7	4.5	18.0	62.8	2.6	3.2	1.3

7.2.1.3 Mixing water

A combination of distilled water and water with a specific amount of sulphate was utilized to mix the binder and tailings. The distilled water was used to control the sulphate content within the CPB mixture. To replicate the sulphate conditions often encountered in underground mines, ferrous sulphate (FeSO₄·7H₂O) was added to the distilled water to achieve a specific sulphate concentration set of 15000 ppm for the purpose of this study.

7.2.1.4 Chemical additives

A polycarboxylate ether-based superplasticizer (PES) was incorporated as a water-reducing additive for the preparation of CPB specimens in this investigation. The chosen PES is known for its superior efficiency in dispersing particles, a characteristic attributable to its complex polymeric structure with carboxylate functional groups. This structure imparts both electrostatic repulsive and steric hindrance forces due to its high molecular weight comb-like architecture, effectively preventing the agglomeration of cement particles (Yoshioka et al. 1997; Bjornstrom and Chandra

2003; Ouattara et al. 2017). The PES superplasticizer utilized here is a commercial formulation that satisfies the ASTM C 494/C 499M specifications for Type A water-reducing and Type F high-range water-reducing admixtures (BASF, 2015).

7.2.2 Sample preparation

To prepare the CPB mixtures with polycarboxylate ether-based superplasticizer (CPB-PES), tailings were blended with Portland Cement Type 1 (PCI) at a weight proportion of 4.5%. The mixing process began with a combination of these dry components for approximately 2 minutes. Then, while the mechanical mixer continued its operation, the designated percentages of PES, along with the required volume of water, were incorporated. The water-to-cement ratio (w/c) is set at 7.35. Two types of water were utilized, distilled water and water with a sulphate concentration of 15000 ppm, to explore the effect of sulphate on the CPB mix. This mixture was further mixed for an additional 7 minutes until a homogeneous CPB-PES material was achieved. Once the mixing phase was complete, the freshly made CPB-PES mixtures were immediately poured into designated pressure cell cylinders and subjected to a variety of field THMC curing conditions. These conditions were carefully chosen to replicate the complex environments typically encountered in underground mines and were maintained for predetermined curing periods. The specific details of the mixing composition, types of water used, and the curing conditions applied are comprehensively outlined in the following subsections.

7.2.3 Experimental methodology and procedures

In this study, a specialized curing system, initially developed at the University of Ottawa by Ghirian and Fall (2013, 2015) and further refined as reported by Al-Moselly et al. (2022), was employed to examine the effects of various THMC factors on the development and dissipation of pore pressure within CPB material with superplasticizers and sulphate (Figure 7.2). The system allows for an in-depth analysis of how THMC factors, including positive and negative pore water pressures, cement hydration, self-weight from backfilling processes, temperature changes, and drainage conditions, influence the CPB behaviour or properties. The setup includes a modified pressure cell constructed with an acrylic plastic mould with dimensions conducive to the specimen requirements. The cell is equipped with cover plates at both ends, stainless steel tie rods for assembly, a drainage valve at the base for managing water flow, and an axial loading piston at the top to simulate backfilling pressure.

This apparatus is encompassed within a temperature-controlled chamber to replicate non-isothermal field conditions. It features a series of pressure gauges, regulators, and sensors to monitor temperature, volumetric water content (VMC), electrical conductivity (EC), and pore

water pressure with time. 5TE temperature sensors were used to accurately record EC, VMC and temperature. Omega PX309 pressure transducers were used to record positive pore water pressure (PWP), as shown in Figure 7.2. This setup allows for continuous observation of the CPB samples, capturing the interaction between the chemical hydration process and physical conditions within the CPB materials. The CPB samples, with their specific composition, were subjected to a comprehensive curing regime in this experimental setup, with conditions detailed in the subsection below. The aim was to closely mimic the actual backfilling processes and filling rates of mine stopes, accounting for the various THMC factors that can impact the CPB's performance.

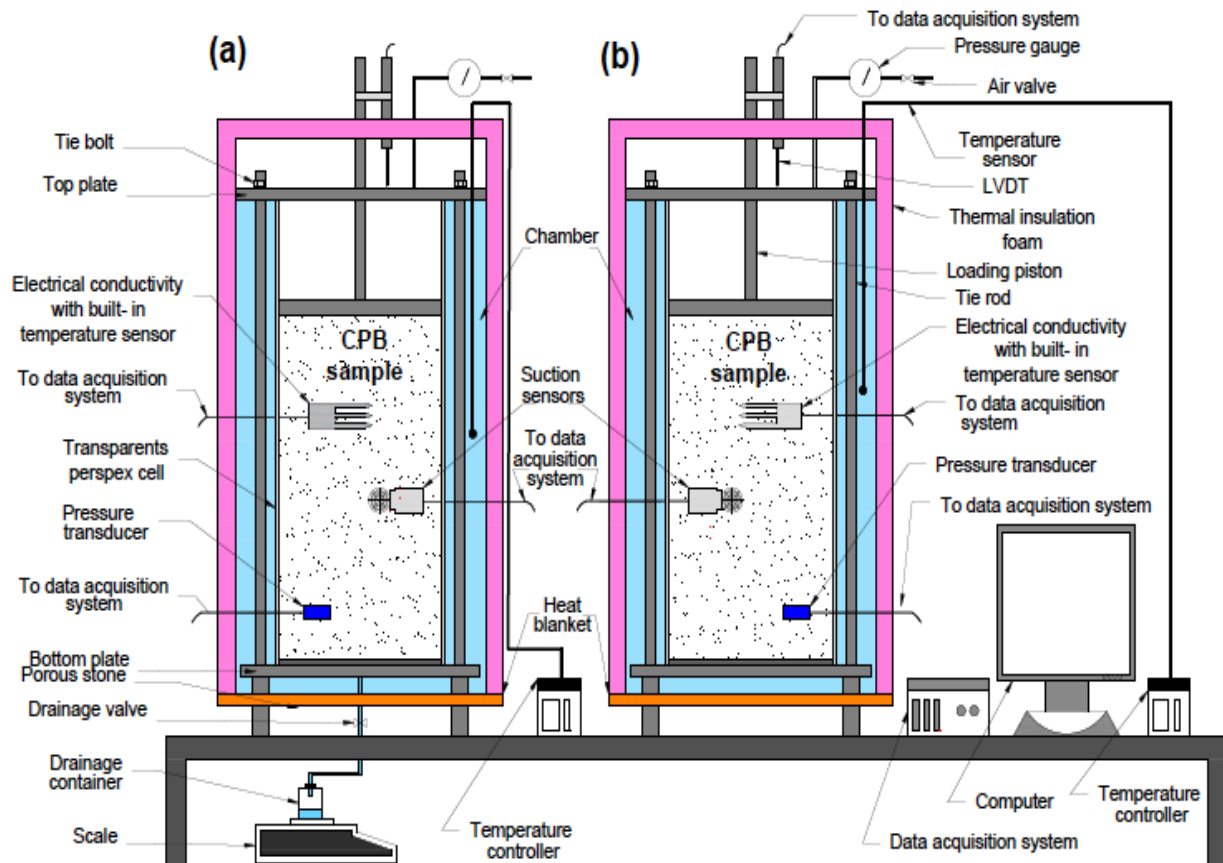


Figure 7.2 Diagrammatic representation of the pressure cell setup: (a) for the drained scenario and (b) for the undrained scenario (modified from Ghirian and Fall 2015).

7.2.4 Experimental program and curing conditions

The experimental program was structured to investigate the pore water pressure development in CPB samples, prepared as previously described, under a set of field-simulated curing conditions. For mechanical curing, variations in vertical field pressure to which the CPB mass is subjected during stope placement and across the operational life of CPB materials were replicated. This

vertical field pressure, influenced by backfilling rate, stope geometry, and cement content, is crucial, as its omission or incorrect consideration can extend cycle times and potentially affect barricade stability (Al-Moselley and Fall 2022). The system mimics the vertical pressures observed in field measurements from backfilling operations, applying incremental air pressures to simulate overburden pressure on the CPB materials. The pressures applied in the study follow data from in-situ field measurements carried out by Thompson et al. (2009), and a detailed account of the applied pressures, corresponding backfill rates, and heights are provided in Table 7.3. This table elucidates the applied vertical pressures over time, starting with no pressure for the initial two hours and gradually increasing to a maximum of 600 kPa.

Hydraulic considerations were also pivotal, with the setup allowing for undrained, drained, or partially drained scenarios. These replicate the range of drainage possibilities in the field, influenced by numerous factors, such as CPB material permeability, barricade water drainage abilities, geological features, degree of fracturing of the surrounding rock mass, and groundwater conditions. For instance, undrained conditions may prevail when fresh CPB material has low permeability due to fine particle size or high binder content, while drained states could occur in more permeable backfill materials. Partially drained conditions, which are the most common in field situations, were mimicked by closing the drainage valve after approximately 1.5 days of curing, permitting approximately 50% of the drainable water to discharge from the CPB sample. To maintain non-drained conditions, the drainage valves were kept sealed for the duration of the curing process. Conversely, to achieve drained conditions, the valves remained open throughout the curing period.

The curing program also adopted thermal curing conditions that included both isothermal and non-isothermal temperatures (field temperatures). Isothermal curing at a constant temperature of 20°C provided a controlled environment to observe the CPB's hydration process, whereas non-isothermal conditions replicated the temperature variations that occur within the field backfill mass. These thermal conditions are crucial for understanding the CPB's response to temperature changes and the resultant impact on the hydration process and, thus, the evolution of pore water pressure. The non-isothermal curing conditions were derived from the methodologies used by Nasir and Fall (2009) and Wu et al. (2012). These studies utilize a numerical model to reproduce the temperature gradients observed within a 30-meter-high field CPB structure. This model was conducted with CPB that has a 4.5% binder content, which facilitated a comprehensive examination of thermal behaviour in such an environment, as depicted in Figure 7.3. To replicate these conditions experimentally, a temperature-controlled chamber was used, as illustrated in Figure 7.2, comprising a heating blanket integrated with a control unit to adjust the temperature.

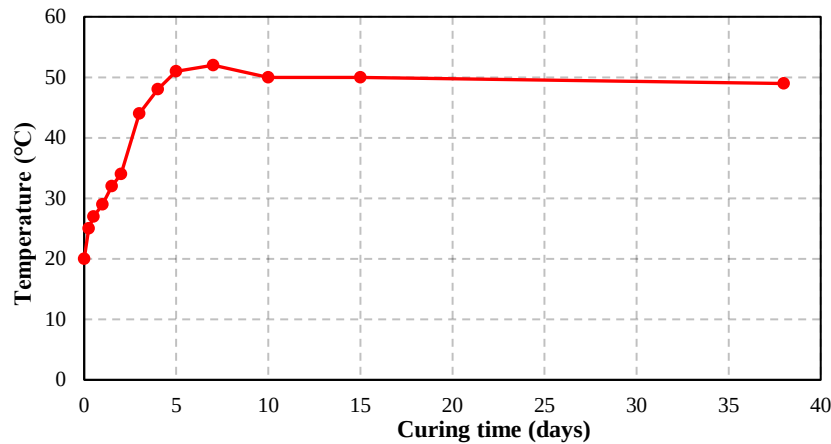


Figure 7.3 The non-isothermal curing conditions inside a 30 m slope height backfilled with CPB material of 4.5% binder content (from Nasir and Fall 2009 and Wu et al. 2012).

Chemically, the study focused on the effects of sulphate in the mixing water and the role of superplasticizers on the pore water pressure development within the CPB material cured under various curing scenarios. This involved preparing samples with different sulphate concentrations and superplasticizer content to understand the complex interactions between cement hydration, sulphate presence, and admixtures under various curing conditions.

Overall, the samples' exposure to mechanical stress, water drainage, thermal variation, and chemical interaction aimed to closely capture the complex conditions CPB materials face in actual stope operations. The prepared CPB samples were cured according to the methodology detailed above in Table 7.4.

Table 7.3 Scheme for applying pressure and corresponding equivalent heights in CPB.

Elapsed time	Applied vertical pressure (kPa)	Equivalent height (m)	Equivalent filling rate (m/hrs)
start	-	-	-
2 h	20	1.00	0.50
4 h	35	2.00	0.50
6 h	55	3.00	0.50
8 h	60	3.20	0.40
10 h	80	4.30	0.43
12 h	90	4.80	0.40
1 d	100	5.38	0.22
1.5 d	125	6.66	0.19
2 d	150	7.92	0.17
3 d	250	13.25	0.18
4 d	400	21.41	0.22
5 d	450	24.00	0.20
6 d	600	32.00	0.22

Table 7.4 Overview of sample mix formulations and applied curing conditions.

Sample Name	Binder type (C)	PES content (%) (C)	Sulphate in mixing water (ppm) (C)	Curing stress (M)	Drainage condition (H)	Curing temperature (T)	Curing time (days)
Control-UD-0.0% PES	PCI	0	0	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
Control-UD-0.125% PES	PCI	0.125	0	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
Control-UD-0.0% PES-15000 ppm	PCI	0	15000	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
Control-UD-0.125% PES-15000 ppm	PCI	0.125	15000	Stress-free	UD	20°C	0.5, 1, 3, 7, 28
THMC-UD-0.0% PES	PCI	0	0	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-UD-0.125% PES	PCI	0.125	0	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-D-0.125% PES	PCI	0.125	0	Field stress ^a	D	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-UD-0.125% PES-15000 ppm	PCI	0.125	15000	Field stress ^a	UD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-PD-0.125% PES-15000 ppm	PCI	0.125	15000	Field stress ^a	PD	Field temp. ^b	0.5, 1, 3, 7, 28
THMC-D-0.125% PES-15000 ppm	PCI	0.125	15000	Field stress ^a	D	Field temp. ^b	0.5, 1, 3, 7, 28

PES: polycarboxylate ether-based superplasticizer; ^a simulated field curing stress (vertical pressure); ^b simulated field curing temperature; D: drained; PD: partially drained; UD: undrained conditions; PCI: Portland cement type I. C: chemical factor; M: mechanical factor; H: hydraulic factor; and T: thermal factor

7.2.5 Testing and monitoring programs

7.2.5.1 Pore water pressure monitoring techniques

Monitoring the evolution of pore water pressure within CPB samples subjected to various field curing conditions involved data collection using specialized sensors. The evolution of the positive pore water pressure development was quantified using an Omega PX309 pressure transducer, which was placed within the CPB sample. This instrument is designed to measure a pressure range from -15 to +15 PSI with an accuracy of $\pm 0.25\%$. This monitoring commenced immediately following the placement of the CPB-PES sample in the pressure cell cylinder, with intervals set for specific time points, and the data were systematically logged. Data capturing the positive pore water pressure were collected and stored using a computerized data acquisition system, ensuring comprehensive documentation of the pressure changes over time.

7.2.5.2 Monitoring of electrical conductivity, temperature, and volumetric water content

Monitoring the hydration process of cement and the chemical reactions within the CPB mixture was conducted by employing a 5TE temperature sensor situated within the pressure cell. This sensor tracked changes in electrical conductivity (EC) and temperature over time. The 5TE sensor

is calibrated to measure EC with precision up to ± 0.1 dS/m for ranges between 0 and 23 dS/m and can accurately record temperature changes within the CPB samples from -40°C to 60°C with a margin of $\pm 1^{\circ}\text{C}$. These EC readings are vital for understanding the movement and concentration of ions in the CPB-PES, shedding light on the chemical activity within the pore solution (Li and Fall 2016). Additionally, the 5TE sensor also measured the volumetric water content (VWC) of the backfill samples, providing data on the water percentage utilized during the cement hydration process. The sensor's capacity to gauge VWC extends from 0 to 100%, with an accuracy of $\pm 15\%$ in the critical range of 40-80%. This VWC information is critical for evaluating the hydration progression within the CPB specimen. All collected data from the 5TE sensor were systematically logged, ensuring a comprehensive timeline of the hydration and chemical interaction processes.

7.2.5.3 Measurement of physical properties and microstructural analysis

The study extended to include an analysis of how THMC processes and sulphate affect pore water pressure by investigating changes in the physical properties of CPB samples, such as void ratio, porosity, and density over time. Gravimetric water content and bulk density tests, conforming to ASTM D2216-10 and ASTM D7263-09 standards, respectively, were conducted at various curing intervals of 0.5, 1, 3, 7, and 28 days. These tests provided an insight into the evolving physical properties of the samples, offering data on key parameters like void ratio and porosity.

To determine the composition of cement hydration products within CPB samples, thermogravimetric analysis (TG) and derivative thermogravimetry (DTG) tests were conducted using a thermogravimetric analyzer. Continuous monitoring and recording of the weight loss, heat flow, and temperature variations in the samples as they were uniformly heated at a rate of 10°C per minute up to a terminal temperature of 1000°C . These TG and DTG tests were performed on prepared cement paste specimens in a similar way as the CPB specimens with a water-to-cement ratio (w/c) of 1, mimicking the elevated water content characteristic of CPB.

7.3 Results and Discussion

7.3.1 Effect of Sulphate on the Development of Pore Water Pressure within Cemented Paste Backfill with Superplasticizers under THMC and Drained Conditions

The variations in pore water pressure (PWP) over time for the CPB materials containing polycarboxylate ether-based superplasticizer (PES), with sulphate (THMC-D-0.125% PES-15000 ppm) or without sulphate (THMC-D-0.125% PES), cured under THMC conditions, including drained (D) conditions, are illustrated in Figure 7.4. These conditions include thermal (T), hydraulic (H), and mechanical (M) factors such as non-isothermal field curing temperatures, drainage (drained conditions considered here), and vertical backfill curing stresses in the field, as

well as the chemical factor, which involves the progression of cement hydration interacting with PES alone or with both PES and sulphate. Furthermore, for comparative purposes, the variations in PWP over time for CPB materials (control samples) cured under common standard conditions are also presented in Figure 7.4. These standard conditions include stress-free environments, undrained conditions, and a constant room temperature of 20°C. Two categories of control samples are presented: one with PES but without sulphate (Control-UD-0.125% PES) and one without both PES and sulphate (Control-UD-0.0% PES).

This figure shows that the PWP of the drained CPB samples, whether containing sulphate (THMC-D-0.125% PES-15000 ppm) or not (THMC-D-0.125% PES), initially increased over time under THMC conditions until it reached a peak value. In contrast, the PWP of the control samples (Control-UD-0.125% PES, Control-UD-0.0% PES) did not show any increase during the same timeframe but did decrease slightly. For instance, during the initial stages of the curing process, the PWP in the THMC-D-0.125% PES-15000 ppm samples was initially recorded at 7.3 kPa and then gradually increased, reaching a peak of 84 kPa approximately 12 hours into curing. The observed initial increase in the positive PWP within CPB samples cured under THMC conditions that mimic actual field situations (i.e., curing under stress, drained and no-isothermal temperatures) is a phenomenon well-documented in various field studies of cemented paste backfill structures (e.g., Thompson et al. 2011; Doherty et al. 2015), confirming the ability of the experimental setup developed in this study (Figure 7.2) to reproduce curing conditions to which backfill structures are exposed in the field. This initial increase in PWP is mainly attributed to the increased curing stress applied at the top of the fresh CPB, simulating the progressive rise in CPB structure self-weight during stope filling, as described in Table 7.3. This increase in backfill self-weight is directly related to an increase in pore pressure within the backfill mass (Cui and Fall 2016, 2017). In fact, the early increase in pore water pressure is a direct response to the stress from backfilling, particularly when the CPB material is still in a fluid-like state or has a weak microstructure at an early age. Early exposure of CPB to high levels of stress can compromise its microstructure, potentially weakening the points where cement hydration products intersect (Zhou and Beaudoin 2003). This stress can cause a compression of the CPB pore structure and rearrangement of solid particles, including tailings and cement particles, thereby resulting in the refinement of the CPB pore structure and its densification (Figure 7.5d). Given water's incompressibility relative to the solid particles of CPB, this rearrangement and pore structure refinement increase the pore water pressure. The initial solid particle rearrangement and refinement of the pore structure of CPB cured under THMC conditions, driven by the backfill's own weight or curing stress (Yilmaz et al. 2012), is evidenced by a reduced void ratio or porosity, as shown in Figure 7.5a,b, which supports the densification (Figure 7.5d) of the material structure in the early stages of curing.

Furthermore, analysis of Figure 7.4 shows that both the magnitude and rate of initial increase in PWP are significantly higher in the THMC-CPB with PES and sulphate than in the THMC-CPB with PES but without sulphate. This implies that the presence of sulphate ions in the backfill mass with PES, when exposed to field curing conditions, significantly increases the pore water pressure within the CPB mass. This increase is closely associated with a significant reduction in the effective stress within the backfill mass and increased pressure on the barricades (Helinski et al. 2011, Thompson et al. 2011; Cui and Fall 2017). Such changes could have important implications for the stability of the backfill mass and the barricade, and the overall mining cycle. This sulphate-induced increase in PWP magnitude and increase rate is related to the fact that the high sulphate content imposes a retardation effect on the hydration process of cement, which lead to less consumption of pore water in the CPB samples and thus lower capillary pressure (Li and Fall 2016; Aldhafeeri 2018). The delay in cement setting or hydration is often due to the chemical bonds between sulphate anions and tricalcium aluminate (C_3A) within the cement (Aldhafeeri 2018). Sulphate anions tend to encase C_3A particles in a fine layer that acts as a barrier, impeding interaction with water (Li and Fall 2016). This protective layer thus retards the cement's ability to set promptly, impacting the timeline for generation of cement hydration products and reducing the amount of hydration products precipitated. Consequently, this delay manifests as a persistence of elevated PWP, as the usual consumption of free water by cement hydration is delayed and reduced. In addition, sulphate ions affect the performance of superplasticizers by causing PES molecules to shrink, weakening their ability to disperse particles in the cement paste, thereby affecting the cement hydration process. Studies by He et al. (2017, 2019) have shown that sulphate ions interfere with the bonding of polycarboxylate ether-based superplasticizers to cement particles and that the presence of sulphates leads to a competitive absorption process that weakens the superplasticizer's effectiveness. This effect becomes more pronounced at higher sulphate concentrations. Furthermore, Yamada et al. (2001) found that increasing sulphate levels causes the superplasticizer to detach from the cement particles, reducing its dispersing action. The assertion that sulphate inhibits cement hydration is experimentally supported by the electrical conductivity (EC) monitoring results shown in Figure 7.6. This figure illustrates the EC evolution in THMC samples with sulphate (THMC-D-0.125% PES-15000 ppm) and without sulphate (THMC-D-0.125% PES). EC serves as a reliable indicator of cement hydration, as it measures the mobility of ions in response to an electric field (Cui and Fall 2016; Haruna and Fall 2020). It is evident from Figure 7.6 evident that the EC peak is delayed in the sample with sulphate, indicating a retardation in cement hydration. The EC in the CPB without sulphate reaches a peak of 3.25 mS/cm in just 0.29 days (approximately 7 hours), whereas the CPB with 15000 ppm of sulphate reaches its peak after 0.44 days (approximately 11 hours) of curing.

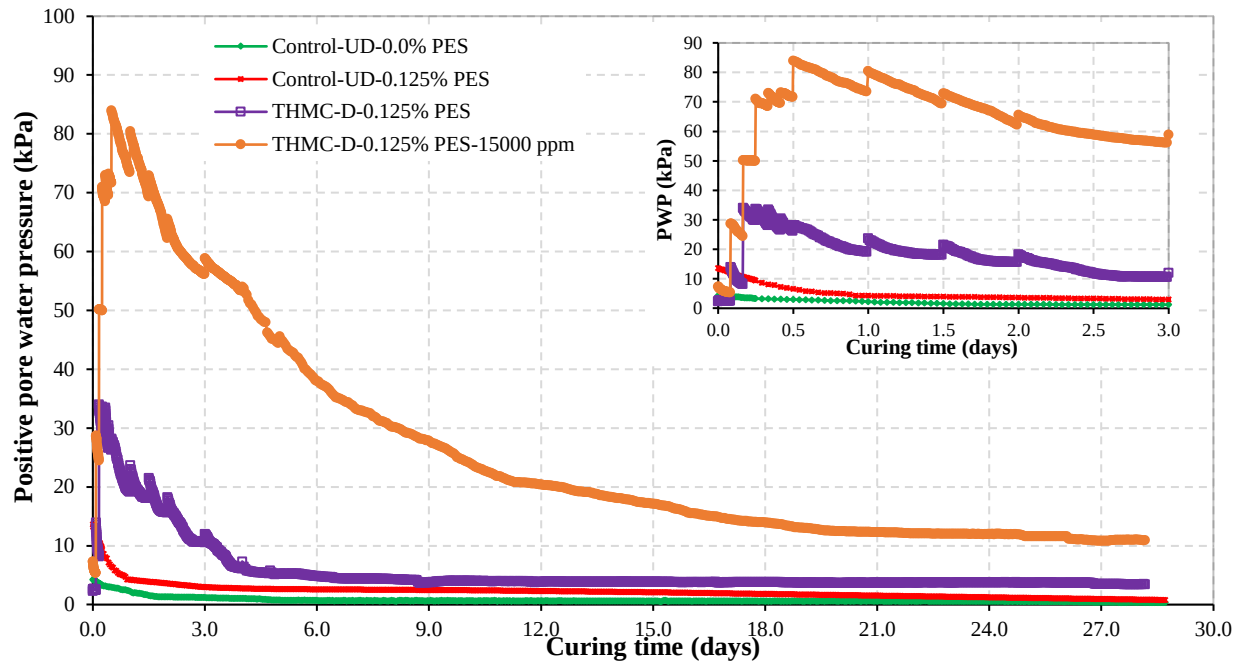


Figure 7.4 Pore water pressure evolution within the CPB materials with various sulphate and superplasticizer content and cured under various THMC factors with time.

Figure 7.4 also depicts that after reaching the peak pore water pressure (PWP), the CPBs with PES under THMC conditions experience a rapid dissipation of PWP over time, regardless of initial sulphate content. Furthermore, the rate of PWP decrease is significantly greater in the THMC- samples than in the control samples. This accelerated PWP reduction in THMC samples is due to several factors. Firstly, the elevated field (no-isothermal) curing temperatures (Figure 7.3) to which the THMC specimens are subjected, compared to the room temperature curing (20°C) of the control specimens, promote faster cement hydration in the THMC specimens (Fall et al. 2010). This increased curing temperature leads to the formation of more hydration products (e.g., C-S-H, CH, ettringite) in the samples exposed to elevated field temperatures than in the control samples. The rapid production of these hydration products is associated with higher water consumption, leading to more intense self-desiccation of the CPB (Helinski et al. 2006; Helinski et al. 2007; Al-Moselly et al. 2022), which in turn decreases the PWP more quickly in the THMC-samples. Indeed, as the hydration reaction progresses, the transformation of free capillary water into water that is chemically bound within the cement matrix leads to the creation of hydration products that occupy less volume than their constituent reactants (i.e., cement and free water). This net reduction of internal water volume initiates a decrease in PWP. To support this explanation, DT/DTG analyses were performed on 7-day old cement paste samples of CPB cured under non-isothermal field curing temperatures (Figure 7.3) and room temperature (20°C), and the results are

presented in Figure 7.7. The peaks and weight loss occurring between 30 and 105°C are attributed to the evaporation of free and bound water; between 110 and 200°C, they result from the dehydration of hydration products (C-S-H, ettringite, gypsum, etc.); and between 400 to 500°C, due to the decomposition of CH. Lastly, weight loss in the 600 to 700°C range is due to the decomposition of calcite (Al-Moselley and Fall 2022). The non-isothermal samples exhibit more weight loss and higher peaks than those cured under isothermal conditions. These TG/DTG findings indicate that non-isothermal CPB samples produce more hydration products than isothermal ones, confirming that non-isothermal curing conditions enhance cement hydration and accelerate the consumption of pore water (Figure 7.5c), thus speeding up the dissipation of PWP. Secondly, the consolidation process in the THMC samples, driven by the applied and sustained curing stress (from the backfill weight) and drained conditions, facilitates the drainage of water from the CPB pore over time. This process decreases the PWP more rapidly in the THMC samples compared to the control samples, which do not undergo consolidation due to their undrained and stress-free curing conditions. Indeed, subjecting or curing the CPB material under pressures (mechanical factor) similar to field conditions and drained conditions promotes water outflow, expediting the dissipation of excess PWP. This mechanism is supported experimentally by results from volumetric water content (VMC) monitoring conducted on CPB samples with PES and without sulphate under both THMC undrained (THMC-UD-0.125% PES) and drained (THMC-D-0.125% PES) conditions, as shown in Figure 7.8. The results clearly demonstrate a reduction in water volume over time for both samples. Notably, the drained sample (THMC-D-0.125% PES) shows a more significant and faster reduction in volumetric water content compared to the undrained sample (THMC-UD-0.125% PES), indicating a quicker dissipation of PWP. Several researchers (e.g., Cayouette 2003; Yilmaz et al. 2009; Ghirian and Fall 2014, 2016) have also concluded that applying stress to CPB-PES specimens triggers a reconfiguration of solid constituents such as tailings and cement. This activity increases the overall compactness and expedites the liberation of unbound water, promoting a more effective interaction with sulphate ions (Aldhafeeri and Fall 2021).

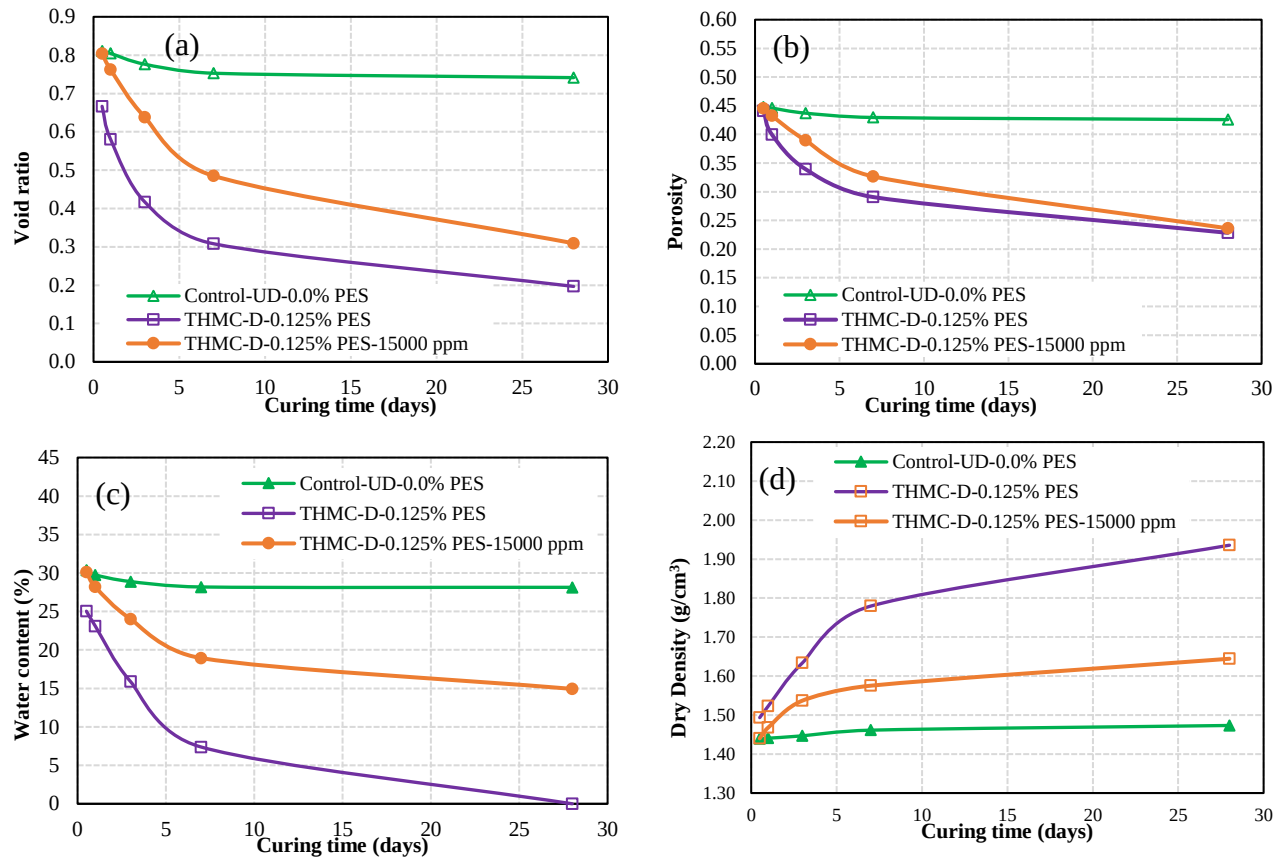


Figure 7.5 Changes in the physical properties of CPB materials with various sulphate and superplasticizer content and cured under various THMC factors (a) void ratio; (b) Porosity, (c) water content, and (d) dry density.

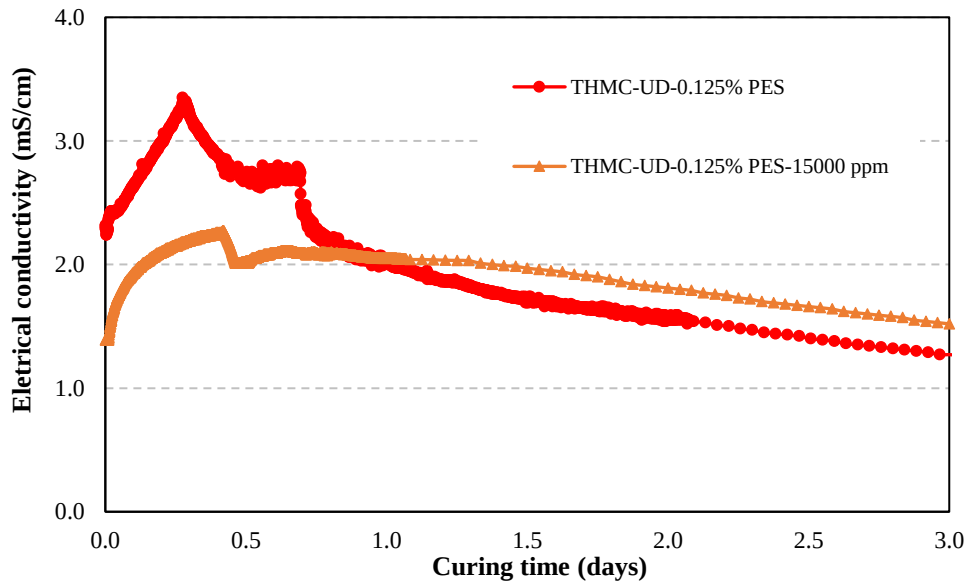


Figure 7.6 Development of electrical conductivity in the CPB cured under THMC factors and with various sulphate and polycarboxylate ether-based superplasticizer contents.

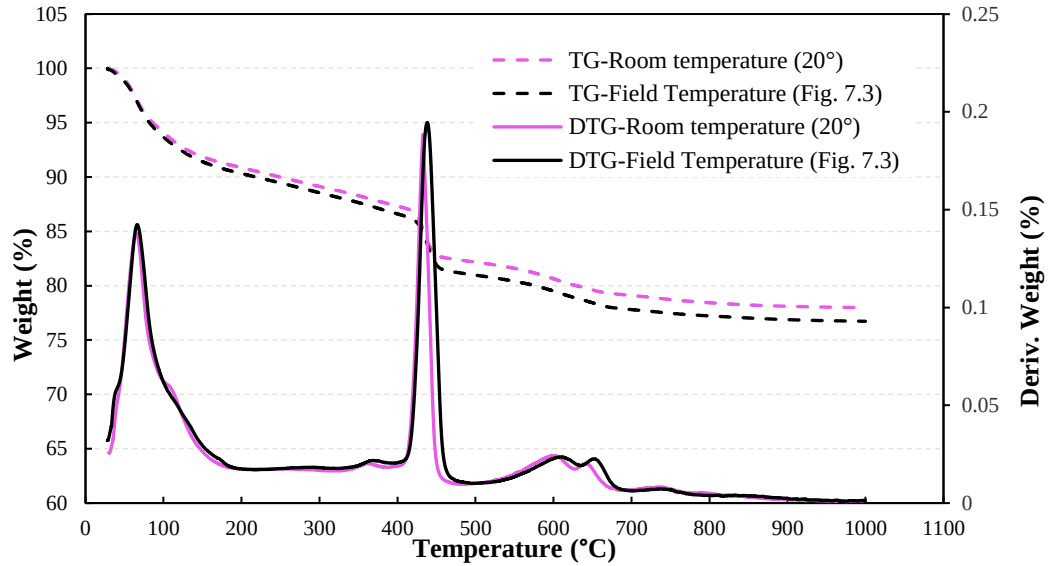


Figure 7.7 Results of TG/DTG analysis for cement pastes of CPB cured under constant room temperature (20°C) and non-isothermal field temperatures (Figure 7.3) CPB samples.

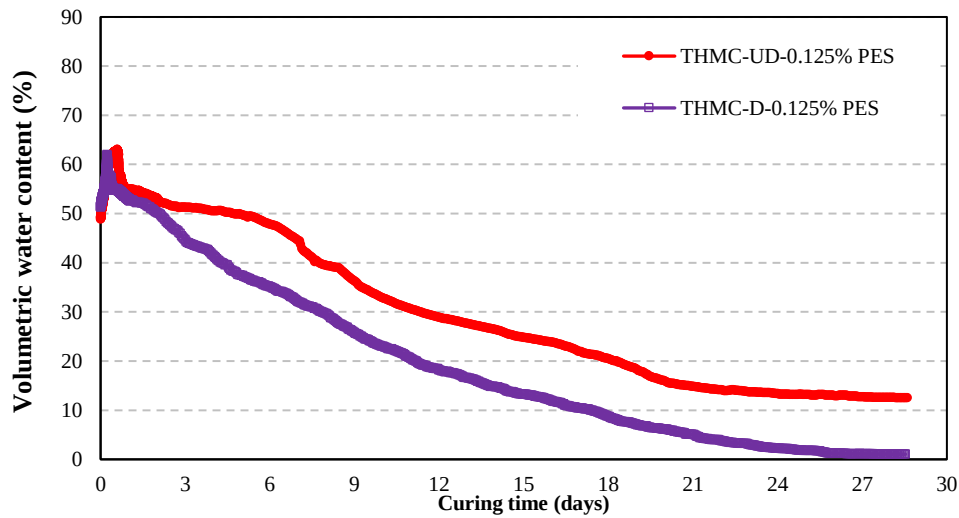


Figure 7.8 Effect of undrained (UD) and drained conditions on the evolution of volumetric water content in CPB with PES samples cured under THMC conditions

In addition, the analysis of Figure 7.4 indicates that samples subjected to field curing conditions (THMC-samples: THMC-D-0.125% PES-15000 ppm, THMC-D-0.125% PES) exhibit a more rapid post-peak PWP decline compared to control samples (Control-UD-0.125% PES, Control-UD-0.0% PES) maintained under standard laboratory conditions. However, it is noteworthy that THMC-samples containing sulphate (THMC-D-0.125% PES-15000 ppm) display a slower PWP decline and maintain higher PWP levels than those without sulphate (THMC-D-

0.125% PES). This observation suggests that the presence of high amounts of sulphate ions in the CPB delays the dissipation of PWP and the development of effective stresses, thereby slowing the enhancement of liquefaction resistance and mechanical stability in the backfill structure. Consequently, the stability of the barricade in field conditions would be adversely affected by high sulphate content. This sulphate-induced slowing of PWP dissipation is attributed to the inhibition of cement hydration by sulphate ions, which diminishes the self-desiccation intensity of the CPB material. This mechanism of sulphate-induced hydration inhibition has been previously discussed.

The findings presented and discussed in this section clarify how sulphate ions affect the development of pore water pressure (PWP) in CPB with PES under field conditions of non-isothermal curing temperatures, drained conditions, and stress induced by the backfill's weight. However, the drainage scenarios examined here, particularly the drained conditions, do not cover all potential field drainage situations that CPB structures might encounter. As a result, the impact of high sulphate content on PWP in CPBs under undrained or partially drained conditions remains uncertain. This knowledge gap will be addressed in the following section.

7.3.2 Coupled Effect of Sulphate and Drainage Conditions on the Development of Pore Water Pressure of Cemented Paste Backfill with Superplasticizers under THMC Conditions

Hydraulic factors, such as drained conditions, induce a decline in pore water (Bentz 2008), potentially leading to the formation of partially empty pores. Through capillary action, this can generate suction and/or elevate suction levels in the CPB matrix. Early drainage of excess pore water pressure (PWP) enhances the hydration of binders, promoting an environment conducive to accelerated self-desiccation and, consequently, decreased PWP and/or increased suction. The interrelation between drainage conditions and their effect on PWP development within CPB materials incorporating superplasticizers and sulphates is further investigated and depicted in Figure 7.9. This figure elucidates the time-based progression of PWP in CPB-PES samples with sulphate cured under varied drainage conditions (undrained, drained, and partially drained) within the context of field THMC influences. Observations during the early stages of curing indicate a progressive elevation in PWP within all samples, irrespective of the drainage condition applied.

The comparative analysis reveals that facilitating water drainage from the high-sulphate CPB mass in the initial stages of the curing process significantly influences the PWP. Specifically, permitting water egress from the high-sulphate CPB mass during the early ages of curing (i.e., for a duration of 72 hours) results in a substantial initial reduction of PWP by around 45% relative to conditions where drainage was not allowed, as represented in the undrained sample (THMC-UD-0.125% PES-15000 ppm). This significant initial reduction in PWP development, associated with drainage conditions, is attributed to several reasons: (a) excess pore water drainage is driven by

the interconnected pore structure of the high-sulphate CPB-PES mass, allowing water to migrate through its porous structure, thereby leading to a reduction in PWP (Ghirian and Fall 2015; Al-Moselly and Fall 2024); (b) the reduction in PWP within the CPB mass over time is also significantly influenced by consolidation and self-desiccation processes (Helinski et al. 2007; Yilmaz et al. 2012; Hasan et al. 2013). As CPB samples cure, the intrinsic self-weight of the CPB materials, along with the applied vertical stresses, induces the extrusion of excess water from the void spaces, accelerating the reduction of PWP. This consolidation effect is further enhanced in samples subjected to drained conditions, where the removal of excess water at the early ages expedites the decline in PWP. Such dynamics are not merely theoretical but have been substantiated through field observation across a range of CPB structures, revealing the pivotal role of effective drainage in enhancing the structural behaviour of backfill masses (Hasan et al. 2013); (c) under drained conditions, water drainage facilitates the removal or leaching of sulfate ions from CPB material, consequently reducing the number of sulfate ions present in the CPB materials to inhibit cement hydration (Bullard et al. 2011; Li and Fall 2018). Essentially, increased drainage from the CPB leads to more effective removal of sulfate ions from the CPB matrix, thereby diminishing the inhibition of cement hydration. This, in turn, promotes enhanced self-desiccation, characterized by greater consumption of pore water by cement hydration (Aldhafeeri and Fall, 2017). Put simply, increased self-desiccation accelerates the decline or dissipation of pore water pressure (PWP). Chemical analysis, specifically Ion Chromatography, conducted on drainage water collected from the CPB, supports the leaching of sulphate ions. The analysis reveals a substantial sulphate concentration of 2129 ppm in the drainage water, indicating significant removal of sulphate ions from the CPB through drainage. This reduction in sulphate ion content has critical practical implications, particularly concerning the early dissipation of PWP. Such changes are profoundly significant for mining operations, notably influencing the timeline for the safe opening of barricades.

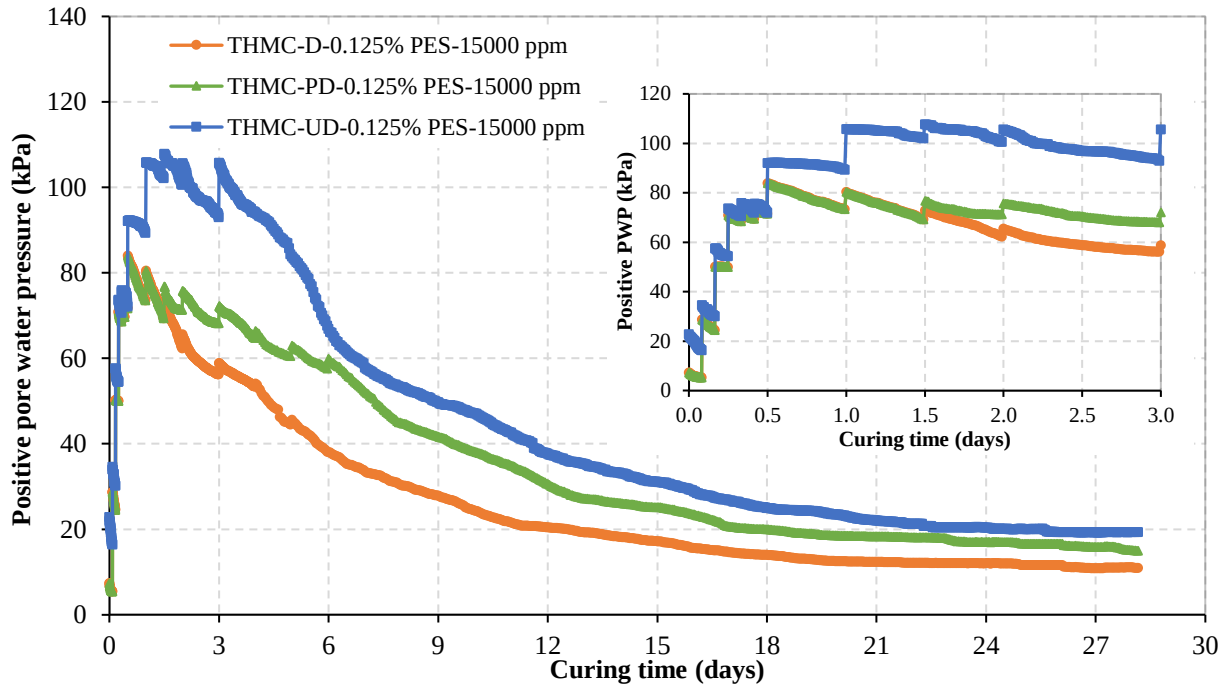


Figure 7.9 Influence of drainage conditions with time on the positive PWP within the high-sulphate CPB-PES samples cured under various THMC factors.

7.4 Conclusions

This study has provided substantial insights into the effects of sulphate on pore water pressure (PWP) development in cemented paste backfills (CPB) containing polycarboxylate ether-based superplasticizers (PES), under thermal-hydraulic-mechanical-chemical (THMC) conditions that imitate field curing conditions. The experimental setup developed here effectively reproduces the curing conditions that backfill structures face in the field. Key conclusions are summarized below:

- Independent of sulphate content, PWP development and dissipation in CPB with PES under field-like conditions differ markedly from those in CPB cured under standard laboratory conditions (stress-free, constant room temperature, no drainage). This difference is due to the significant effects of field curing temperatures, drainage conditions, and backfill self-weight on the rate and development of PWP.
- The presence of a large quantity of sulphate ions significantly affects the magnitude and rate of initial PWP development, leading to higher initial pressures. This impact is primarily due to sulphate interactions with the cement hydration process, which delay or inhibit hydration, leading to reduced pore water consumption and lower capillary pressure in CPB samples.

- After reaching peak PWP, both the magnitude and rate of dissipation in CPB are significantly influenced by field temperatures and drainage conditions, as well as by the presence of sulphate. High concentrations of sulphate ions slow the dissipation of PWP, which retards the development of effective stresses, thereby reducing the enhancement of liquefaction resistance and mechanical stability. This slowing is attributed to the inhibition of cement hydration by sulphate ions, which diminishes the self-desiccation intensity of the CPB material.
- The study underscores the crucial role of drainage conditions in mitigating the negative impacts of sulphate on PWP development and dissipation. Enhanced drainage in sulphate-bearing CPB under THMC conditions facilitates the significant removal of sulphate ions from the backfill, weakening the inhibition of cement hydration by sulphate ions. This promotes enhanced self-desiccation, characterized by greater consumption of pore water by cement hydration and thereby reducing the adverse effects of sulphate.

These findings offer valuable insights into the complex factors governing CPB PWP behaviour, with significant practical implications for mine backfill design and application. Understanding how various additives and field conditions affect the early-stage properties of CPB can guide the development of more predictive models for backfill performance, leading to safer and more effective mining practices.

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Chapter 8: Integration and Synthesis of Results

8.1 Introduction

This chapter integrates and synthesizes the findings from the five technical papers detailed in Chapters 3 through 7 of this dissertation to enhance the understanding of the geotechnical behaviour (compressive strength and pore water pressure development) of the cemented paste backfill (CPB) materials containing polycarboxylate ether-based superplasticizer (PES) subjected to various internal and external factors, including thermal (T), hydraulic (H), mechanical (M), and chemical (C) factors or conditions. The first paper, presented in Chapter 3, investigated the effect of polycarboxylate ether-based superplasticizer (PES) on the compressive strength development of CPB materials made with different mix components (tailing types, dosages of PES, cement and solids contents, tailings fineness, and water chemistry), and subjected to various individual THMC factors or curing conditions (stress-free, under stress, constant temperature, and non-isothermal temperatures). The initial investigation reveals that the inclusion of PES in the CPB mixture has a significant impact on the mechanical strength of CPB and greatly depends on the dosage of PES added and the curing period. The subsequent papers or chapters (Chapter 4 through Chapter 7) investigate the effect of the multiphysics THMC factors or curing conditions on the development of mechanical strength and pore water pressure with time. These chapters highlight the critical role of considering the THMC process or factors and their interplay or coupling, which significantly affect the mechanical strength of CPB structures in the actual field conditions. The improper laboratory procedures for curing and strength testing procedures for CPBs may yield misleading results. Such inaccuracies can result in an improper design of CPB structures, potentially leading to safety issues on-site and unwarranted financial repercussions. It is crucial to ensure that these laboratory practices accurately reflect field conditions to prevent such adverse outcomes. Across these chapters, the impact of various factors is investigated, including superplasticizer addition, presence of sulphate, isothermal and non-isothermal curing temperatures, stress-free and curing under stress, drained, partially drained, and undrained conditions. The summary of the experimental tests conducted is outlined in Table 8.1.

Table 8.1 Summary of studies factors and experimental program conducted in this dissertation

Technical Paper	Chapter	Thermal factor (T)		Hydraulic factor (H)			Mechanical factor (M)		Chemical factor (C)		Coupled THMC factors	UCS tests	Microstructural Tests	Monitoring Experiments
		Isothermal temperatures (20°C)	Field temperatures (non-isothermal temperatures)	Drained	Partially drained	Undrained	Stress-free	Field stress	Superplasticizer content	Sulphate content				
1	3	X	X			X	X	X	X	X		X	MIP, XRD, TG/DTG, SEM, Void ratio, Dry density, MC Porosity	EC, Suction, PWP
2	4	X	X	X	X	X	X	X	X	X	X	X	TG/DTG, Void ratio, Porosity, Dry density, MC	EC, VWC, Suction
3	5	X	X	X	X	X	X	X	X	X	X		TG/DTG, Void ratio, Porosity, Dry density, MC	EC, VWC, Suction, PWP
4	6	X	X	X	X	X	X	X	X	X		X	TG/DTG, Void ratio, Porosity, Dry density, MC	EC, VWC, Suction
5	7	X	X	X	X	X	X	X	X	X	X		TG/DTG, Void ratio, Porosity, Dry density, MC	EC, VWC, PWP

UCS: Unconfined compression strength test; THMC: Thermal, Hydraulic, Mechanical, and Chemical; MIP: Mercury intrusion porosimetry; SEM: Scanning electron microscopy; TG/DTG: Thermogravimetry, and derivative thermogravimetry; XRD: X-ray diffraction; EC: Electrical conductivity; VWC: Volumetric water content; MC: Moisture content; PWP: Pore water pressure; X: Conducted.

8.2 Effect of superplasticizer on the geotechnical performance of Cemented Paste Backfill

The experimental tests carried out in Chapter 3 offer insights into the effects of polycarboxylate ether-based superplasticizer (PES) on the compressive strength development of cemented paste backfill (CPB) materials cured under various individual factors, including the impact of various mix components (tailings, dosages of superplasticizer, solid content, tailings fineness, and water chemistry), different curing time, and various curing conditions (stress-free, under stress, isothermal and non-isothermal curing temperatures).

It has been suggested that the dosing of PES and the duration of curing are pivotal factors influencing the compressive strength of CPB specimens. The results indicate a noticeable enhancement in compressive strength when CPB samples incorporated with PES are allowed to cure for a period of 7 days. Conversely, samples subjected to a curing period of 3 days or less exhibit compressive strengths lower than those of CPBs without PES. This decrease in early-stage mechanical strength observed within the initial 3 days of curing can be attributed to the impact of PES on the cement hydration process over time. Polycarboxylate ether-based superplasticizer formulated from carboxylic compounds type introduces two primary types of repulsive forces between cement particles: (i) electrostatic repulsion due to the negative charges of the carboxylic groups and (ii) steric repulsion associated with the lengthy polymer chains found within the compound (Huang et al. 2022; Haruna and Fall 2022). The steric hindrance caused by PES increases the repulsive forces between particles and delays their interaction, thereby retarding the hydration process, thereby resulting in lower amount of hydration products (e.g. CH) in the CPB sample, and consequentially delaying the setting time during the early age of curing (Klein and Simon 2006). Such a reduction in interparticle contact leads to decreased mechanical strength of CPB specimens containing PES at these early curing stages. Moreover, the degree to which PES affects the setting time of CPB mixtures is directly proportional to its concentration. Excessive amounts or dosages of PES could result in an excessive prolongation of the setting time (Mangane et al. 2018), a correlation substantiated by the findings presented in Figure 8.1.

The observed enhancement in the compressive strength of the CPB with the addition of PES after 3 days of curing can be attributed to several mechanisms: Firstly, incorporating PES into the CPB mixture enhances the CPB microstructure and self-consolidation of the solid particles (Ercikdi et al. 2010; Mangane et al. 2018; Yang et al. 2018). The dispersion of the solid particles (i.e., cement and tailings) triggered by the addition of PES led to a higher precipitation rate of the cement hydration products and, thus, decreased the porosity and void ratio and increased the packing density. Secondly, the inclusion of PES reduces the layer of water surrounding the tailing particles, which leads to increased particle friction. This increase in friction intensifies the contact between particles, consequently increasing the strength of the CPB samples over time (Simon et

al. 2011; Zheng et al. 2016; Mangane et al. 2018). The steric repulsion mechanism inherent in the polycarboxylate ether-based superplasticizer, along with its long polymer chains, serves to link the contact points among the CPB particles (Ercikdi et al. 2010; Yang et al. 2018). This interaction enhances the compressive strength of CPB with time. Additionally, while the addition of PES initially retards the cement hydration process, this effect is offset by its role in promoting ionic diffusion at a later stage (Haruna and Fall 2020). This enhanced diffusion accelerates the cement hydration process, ultimately increasing the compressive strength.

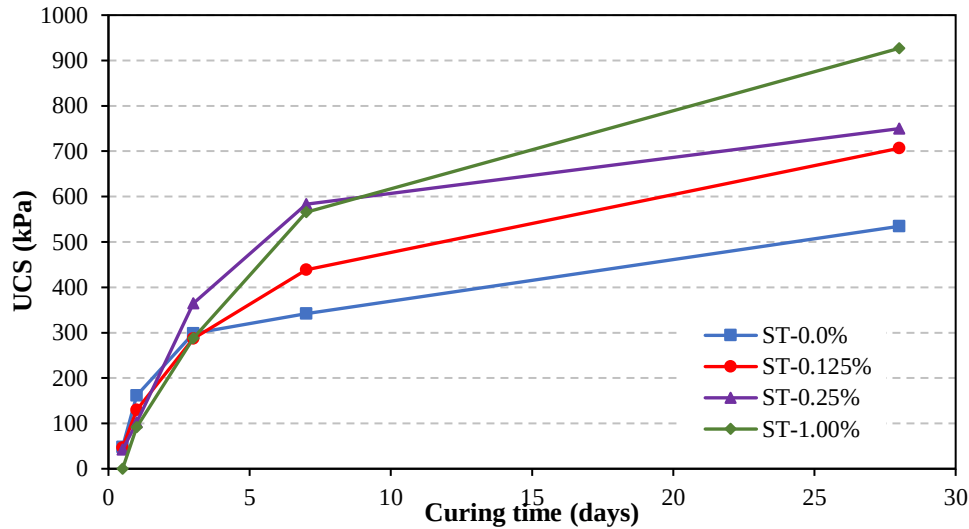


Figure 8.1 Effect of PES content on the strength development of CPB with time.

8.3 Effect of THMC factors on the geotechnical behaviour of Cemented Paste Backfill

This Ph.D. study investigates the importance of considering thermal, hydraulic, mechanical, and chemical (THMC) factors in the laboratory testing of CPB with polycarboxylate ether-based superplasticizer to accurately predict its real-world performance. It is crucial to understand the impact of these factors on the geotechnical behaviour of CPB, particularly how they influence strength and pore water pressure development, for designing stable and durable CPB structures. The research achieved this by comparing samples cured under field-simulated conditions with those in conventional lab settings, revealing the significant role of THMC factors and their interplay or coupling on strength and pore water pressure development. A modified pressure cell setup was employed to closely replicate various field scenarios, including curing the CPB samples under applied field pressure, with both isothermal and non-isothermal temperatures, in the presence of superplasticizers and sulphate, and under different drainage conditions (drained, undrained, and partially drained). The experimental results underscore the critical influence of each factor on CPB performance.

8.3.1 Thermal factor

Within the structure of CPB, the temperature can vary significantly due to several factors: the heat produced by the setting of the binder, the initial temperatures of the CPB mixture's components, the surrounding environment of the mine, and the CPB materials' own properties such as specific heat capacity and thermal conductivity (Fall et al. 2010; Fall and Pokharel 2010; Wang et al. 2016; Cui and Fall 2015, 2016). These temperature changes significantly affect the rate at which the binder sets, which in turn affects how the CPB's strength and pore water pressure develop over time. Warmer conditions (elevated temperatures), which are more representative of field conditions, accelerate the cement hydration process. This accelerated hydration results in a more substantial formation of cement hydration products. The generation of higher amounts of cement hydration products enhances the binding forces between the solid particles, increases the self-desiccation of the CPB material, and refines its pore structure, thereby significantly increasing the mechanical strength of the CPB (Haruna and Fall 2020). This refinement correlates directly with increased strength, showing the importance of thermal considerations in the curing process. The experimental findings confirm that the thermal factor on the CPB samples positively impacts several mechanical and hydraulic properties. These include the acceleration of compressive strength development, the efficient dissipation of pore water pressure, and the development of negative pore water pressure (suction). Moreover, it was found that the elevated field curing temperatures (non-isothermal) counterweight the early age retardation of the cement hydration process caused by the addition of PES. The results showed that starting from 12 hours of curing, the UCS value of the CPB samples cured under THMC factors is higher than that of the CPB samples cured under only HMC factors (i.e., cured under undrained drainage (H) conditions, under stress (M) and containing 0.125% PES (C) only or without the effect of field curing temperature), as demonstrated in Figure 8.2.

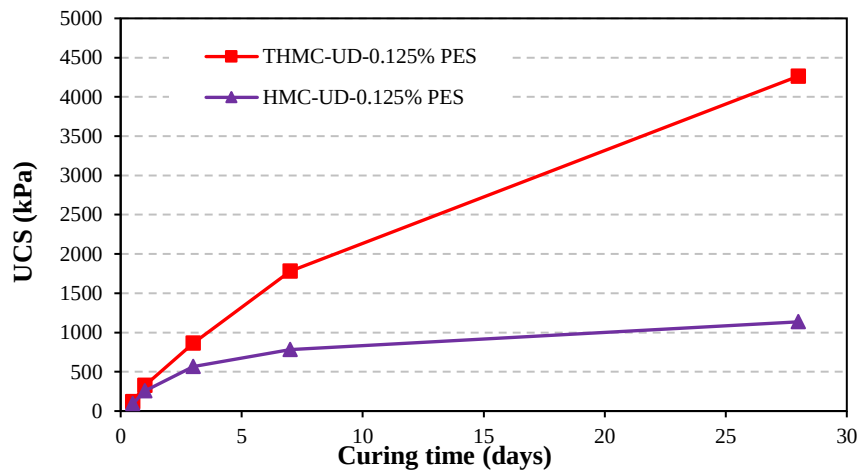


Figure 8.2 Effect of thermal factor on compressive strength development of CPB.

8.3.2 Hydraulic factor

The variations in the hydraulic condition of the CPB hold considerable importance in the design of backfill structures, mainly because of their influence on barricade stability and the enhancement of strength. The results indicate that CPB samples undergoing drained curing conditions show notably greater mechanical strength, lower positive pore water pressure (PWP), and higher negative pore water pressure (suction) over time than those in partially drained or undrained states. This enhancement is linked to several key mechanisms: (i) Allowing the water to drain during the early stages of curing reduces the water-to-cement ratio in CPB material, which leads to a denser pore structure. (ii) The dissipation of excess pore water pressure resulted from the drainage of water from the CPB materials. The water contained in CPB materials can be drained through the interconnected pore, and as the excess water drains away, the PWP decreases (Ghirian and Fall, 2015). (iii) The development of negative pore water pressure (suction) due to drainage significantly enhances the increase in strength. As free water gets consumed in the hydration process, suction development is a critical factor, substantially contributing to strength (Ghirian and Fall, 2016). (iv) The undergoing consolidation process in the CPB samples caused by the self-desiccation and the related vertical applied pressure to the CPB samples helps to lower PWP as time goes on. Figure 8.3 illustrates that the CPB samples that were allowed to drain and cured under simulated field conditions exhibited a significant increase in compressive strength and faster pore water pressure dissipation when compared to undrained or partially drained samples that cured under similar field conditions.

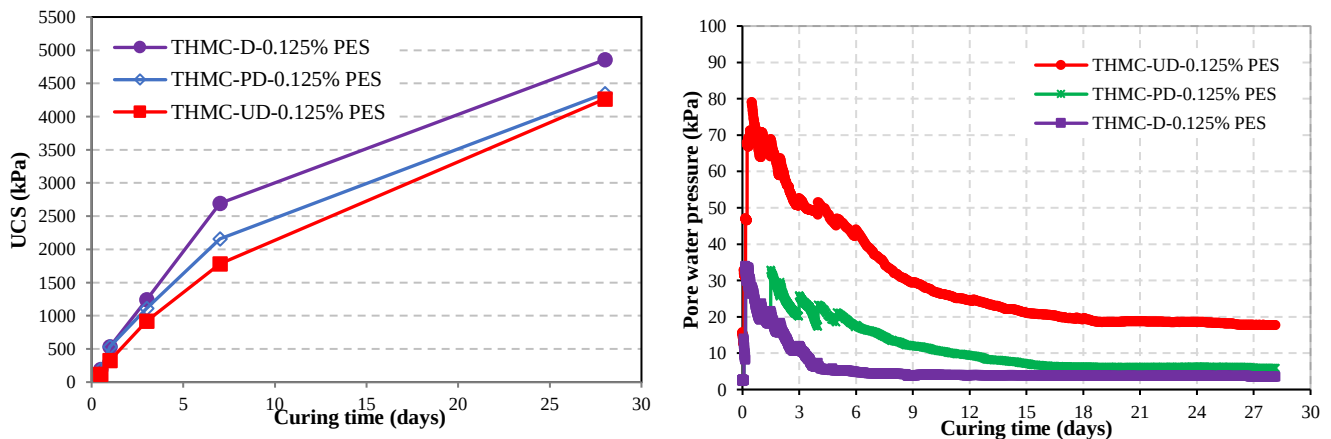


Figure 8.3 Influence of drainage conditions with time on the compressive strength and PWP within the CPB samples cured under various THMC factors.

8.3.3 Mechanical factor

The vertical pressures applied on cemented paste backfill (CPB) structures significantly vary not only from one mine to another but also from one stope to another, influenced by factors such as stope geometry, depth, backfilling rate, cement content, and the design pressure of the initial barricade plug. To assess the impact of the mechanical factors on the compressive strength and pore water pressure development of in-situ backfilling processes and their interaction with thermal, hydraulic, and chemical (THC) factors over time, this study applied stress-curing conditions (curing under stress) alongside other THC factors to CPB samples containing polycarboxylate ether-based superplasticizers. The finding results highlighted a noticeable enhancement in strength for samples subjected to all thermal, hydraulic, mechanical, and chemical (THMC) conditions over those cured under THC conditions alone (i.e., cured under non-isothermal curing temperature (T), undrained drainage (H) conditions, and containing 0.125% PES (C)), as presented in Figure 8.4. The increased mechanical strength, particularly notable after the early stages of curing, is a direct consequence of the applied stress, which rearranges particles, increases packing density, and promotes water interaction with the binder, thereby accelerating the cement hydration process. This acceleration leads to more hydration products filling particle voids, increasing the material's density, and enhancing mechanical strength over time. A subsequent decrease in porosity and void ratio further supports the increased strength. In addition, it has been observed that the lower influence of mechanical factors, when compared to chemical and thermal influences, suggests that while pressure application during early curing stages plays a role, it is the thermal conditions and chemical additives that more significantly drive the strength properties of CPB. These findings provide valuable insights into the engineering design and operational management of CPB structures in mining applications.

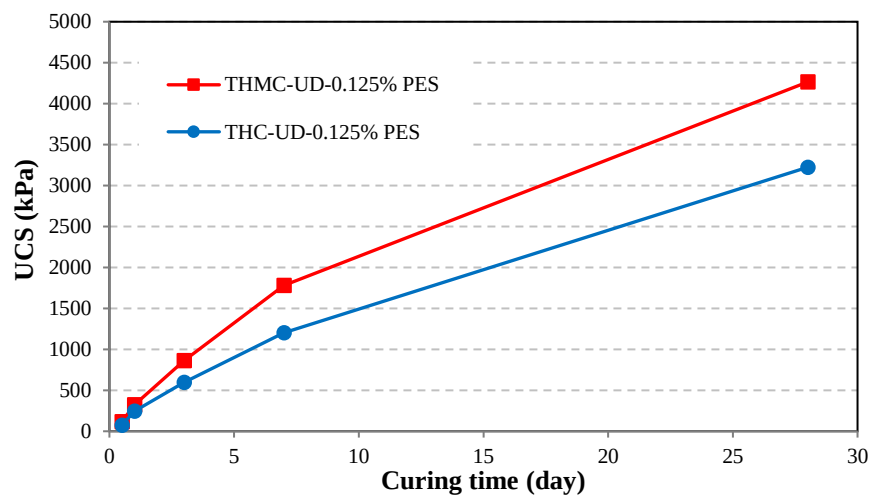


Figure 8.4 Effect of the mechanical factors (curing under stress) on the strength development of CPB with time.

8.3.4 Chemical factor

The chemistry of the mixing water (i.e., the presence of sulphate in the mixing water), dosages and types of chemical admixtures have considerable impact on the short- and long-term performance, transportation, and placement of CPB materials. For example, the inclusion of a polycarboxylate ether-based superplasticizer has a double effect on CPB strength and pore water pressure development. Initially, it may inhibit early cement hydration due to particle dispersion. However, over time, it promotes ionic diffusion, enhancing the cement hydration rate and leading to the formation of more hydration products. This chemical influence of the superplasticizer significantly improves the mechanical strength and pore water pressure development of CPB over time. In addition, the presence of sulphate in the CPB mixture significantly influences the development of pore water pressure and compressive strength, with these effects varying considerably over time. The presence of sulphate anions in the CPB inhibits cement hydration (Alainachi 2020). The reason for the inhibition of cement hydration is due to the chemical interactions of sulphate anions with the C3A compounds within the cement, which results in the forming of a thin coating around the C3A compounds, which will act as a barrier, preventing the C3A compounds from reacting with water and delaying the setting time, thus impacting strength development of cementitious mixtures (Li and Fall 2016). This dissertation investigates the effect of the presence of both polycarboxylate ether-based superplasticizer (PES) and sulphate on the strength and pore water pressure development of CPB materials with time. Figure 8.5 illustrates that CPB samples containing 0.125% of PES and cured under THMC conditions exhibit a noticeable improvement in unconfined compressive strength (UCS) from the first day of curing compared to the CPB sample without PES. This increase in UCS can be attributed to the individual impact of the superplasticizer on cement hydration within CPB compositions and its joint effect with elevated curing temperatures. Adding the superplasticizer causes dispersion among the solid particles in the CPB, creating forces that initially slow down the hydration process. This explains the reduced early strength in samples with added PES. Over time, the action of the superplasticizer promotes ionic diffusion, enhancing cement hydration and leading to an increase in hydration products. Additionally, the steric repulsion mechanism in the polycarboxylate ether-based superplasticizer and the associated long polymer chains help connect the particles and improve the inter-particle bonds, thereby strengthening the CPB as it cures. Moreover, it has been found that adding 0.125% of PES into the CPB samples cured under coupled THMC conditions causes a reduction in the positive pore water pressure values by approximately 50% after a curing duration of 28 days. This significant reduction can be attributed to the higher precipitation rate of the cement hydration products caused by the ionic diffusion of PES, which improves cement particle dispersion (Haruna and Fall 2020).

Additionally, this study reveals that CPB samples with sulphate exhibit a significantly higher initial PWP compared to those without sulphate, and this elevated pressure persists longer due to the retardation of cement hydration. This slow hydration directly affects the development of pore water pressure, as shown in Figure 8.6. Moreover, the presence of sulphate adversely affects the effectiveness of superplasticizers. It competes with these additives for bonding to cement particles, diminishing their dispersing action and thereby impacting the fluidity and mechanical properties of the CPB mix.

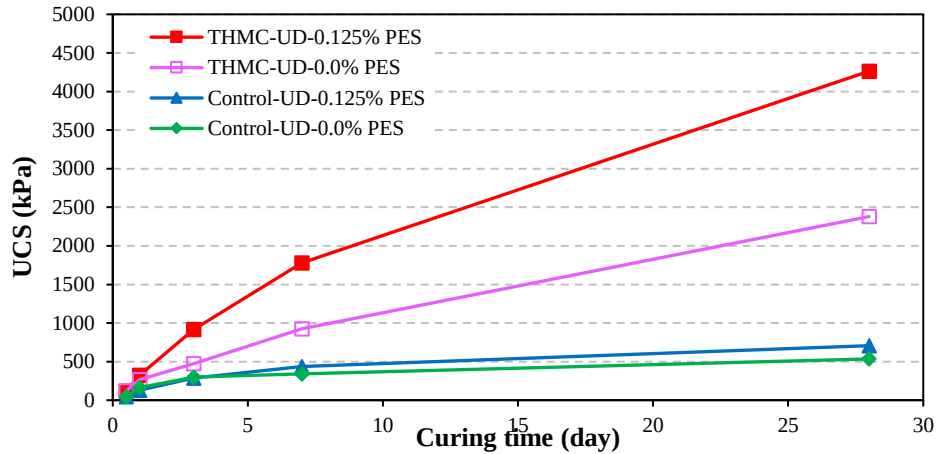


Figure 8.5 Effect of polycarboxylate ether-based superplasticizer (PES) on the strength development of CPB cured under THMC curing conditions.

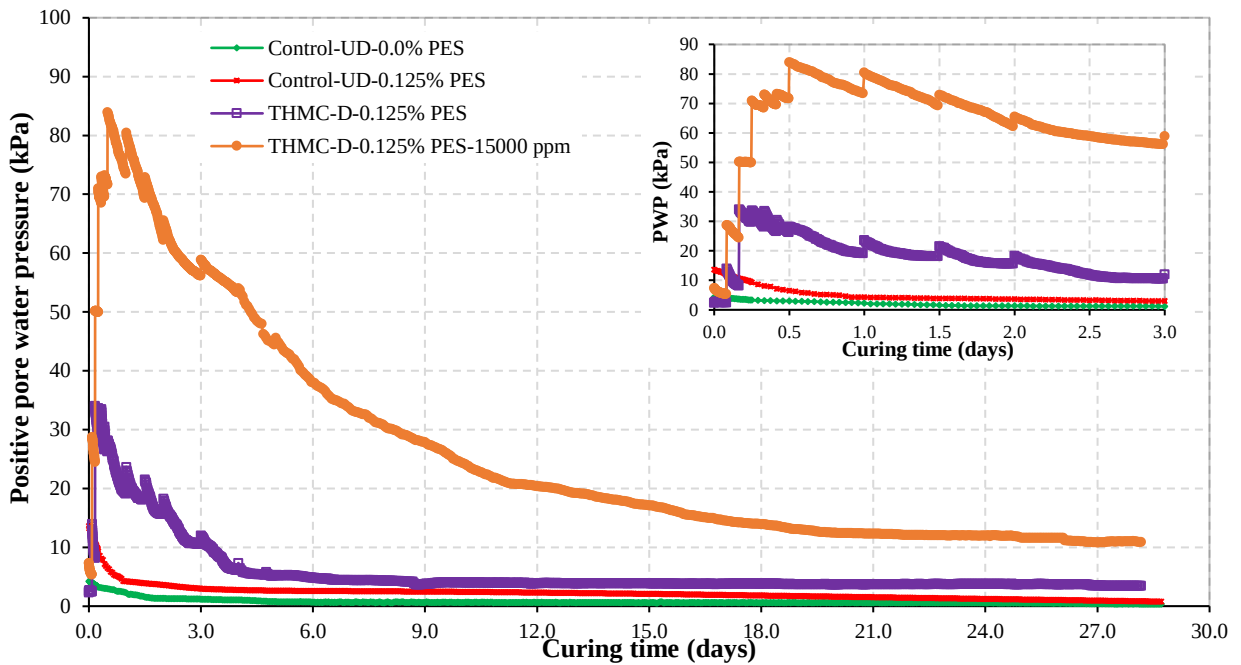


Figure 8.6 Pore water pressure development within the CPB materials with various sulphate and superplasticizer content and cured under various THMC factors with time.

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Chapter 9: Conclusions and Recommendations

9.1 General conclusions

This study highlighted the critical role of the coupled Thermal, Hydraulic, Mechanical, and Chemical (THMC) processes in understanding the behaviour of Cemented Paste Backfill (CPB). The finding results can be employed to optimize the design of the backfill systems, including CPB mixture and barricade designs for underground mining operations, ensuring safer and more efficient mining cycles. Furthermore, the design of the CPB structure should also encompass crucial parameters like filling rate, rheology, mix design, and the required mechanical strength. Accordingly, the analysis and discussion of the geotechnical behaviour of CPB derived from this study will help researchers and mine operators with insights into key design criteria. These include understanding the evolution of mechanical strength and pore water pressure within the CPB material with superplasticizers and cured under various THMC factors over time, applying this knowledge to design optimal CPB structures, constructing safe barricades, and free-standing backfills, monitoring how effective stress and pore pressure, and suction evolve within the backfill. The following conclusions are drawn from the obtained results in this study:

- The addition of polycarboxylate ether-based superplasticizer (PES) to the cemented paste backfill (CPB) mixture significantly influences its mechanical strength. This effect varies based on the PES dosage, the type of tailings employed, and the curing duration. For example, the uniaxial compressive strength (UCS) values of the CPB made with natural gold tailings (GT) and cured for 28 days increased from 388 kPa to 440 kPa with an increase in the dosage of PES from 0% to 0.125%. Notably, the UCS of the CPB exhibits an increase with higher PES dosages after a curing period of seven days.
- The short- and long-term strengths of CPB with PES are significantly influenced by the sulphate levels in the mixing water. Despite the dosage of PES used, CPB with sulphate exhibits lower strength compared to its sulphate-free counterparts after seven days of curing. Over time, however, the strength of CPB samples with PES progressively increases, irrespective of sulphate content. Specifically, CPB samples with sulphate and a 0.125% PES concentration show greater strength than those without sulphate and PES. After an extended curing period of 250 days, the strength of these samples either slightly decreases or increases.
- The in-situ thermal (T), hydraulic (H), mechanical (M), and chemical (C) conditions or factors significantly affect the strength development of the CPB with PES with time, and this effect mainly depends on each one of these factors and the interaction between these

factors. It was found that the UCS values for the fully drained CPB samples containing 0.125% superplasticizer cured under field vertical stress and field elevated temperatures were significantly higher than those for the control samples (0% superplasticizer undrained, cured under free stress and isothermal temperature of 20°C).

- The contributions of each one of the studied THMC factors on the strength development (i.e., the percentage of increase in the UCS values) are not equally similar and greatly depend on the interaction between these factors and curing time.
- The incorporation of 0.125 % polycarboxylate ether-based superplasticizer (PES) into the CPB mixture can remarkably enhance the UCS values of CPB materials, beginning from the first day of curing. This improvement was observed under THMC conditions, in contrast to similar CPB samples cured without PES.
- The study underscores the critical role of field drainage conditions (drained, undrained, or partially drained) in determining the pore water pressure (PWP) within the backfill structure, which significantly impacts its geotechnical behaviour and mechanical stability. The data reveal that PWP levels in drained CPB with superplasticizer are substantially lower compared to those in partially drained and undrained samples. Additionally, efficient drainage facilitates the rapid dissipation of excess PWP.
- The study reveals that non-isothermal curing temperatures significantly affect both the generation and dissipation rates of pore water pressure in CPB structures. The CPB samples with PES exposed to higher curing temperatures exhibit a noticeable decrease in PWP values. Furthermore, elevated temperatures accelerate the dissipation of excess PWP, which can expedite the opening of mine barricades, thus enhancing productivity. These findings highlight the importance of considering elevated backfill field curing temperatures in the design of cost-effective CPB and barricade structures to manage PWP progression effectively.
- Curing CPB specimens at elevated temperatures effectively mitigates the adverse effects of sulphate on early-age strength. Higher temperatures expedite the cement hydration process, resulting in quicker formation of hydration products such as gypsum and ettringite. This accelerated hardening significantly reduces the CPB's porosity, thereby enhancing its mechanical strength over time.
- The findings highlight that concentrations of superplasticizer and sulphate significantly influence the hydration process of cement in CPB, impacting the development of pore water pressure in the early stages. This research demonstrates the molecular interactions between sulphate ions and superplasticizers, which affect the dispersion of cement particles and, consequently, the variation in pore water pressure within CPB materials. The competitive adsorption of sulphate ions and superplasticizers on cement particles requires

a careful balance in CPB formulations, especially in environments with high sulphate levels. Furthermore, implementing effective drainage strategies is crucial for managing pore water pressure in CPB structures.

9.2 Recommendations

Based on the findings of this study, the following recommendations are made to direct future academic research and experimental investigations:

- Further studies investigating the performance properties of CPB using different types of superplasticizers beyond the polycarboxylate-based variants utilized in this study would be beneficial. Specifically, future investigations should examine how alternative superplasticizers, such as lignosulfonate-based, sulphonated melamine formaldehyde (SMF), and sulphonated naphthalene formaldehyde (SNF), influence the mechanical and pore water pressure of CPB. Such studies will enhance our understanding of the diverse interactions between these admixtures and cement particles, potentially leading to optimized formulations for specific geotechnical applications.
- Investigating the geotechnical behaviour of CPB materials using alternative mix designs not explored in this study. This includes CPB formulations prepared with different binder materials such as slag or fly ash, varying binder content levels, and different water-to-cement (w/c) ratios. Such research will expand the understanding of how these variables influence the mechanical strength of CPB materials containing superplasticizers that are cured under THMC conditions or processes.
- Investigating the effect of the presence of various sulphate and superplasticizer contents within the CPB materials, such as different dosages of sulphate and superplasticizer.
- Examine the impact of varying sulphate and superplasticizer concentrations within CPB materials cured under various THMC conditions or processes, focusing on different dosages and combinations of these additives.
- Conducting large-scale column experiments to study the coupled thermal, hydraulic, mechanical, and chemical conditions or processes in cemented paste backfill containing superplasticizers. This will provide essential insights into the near-field behaviour of CPB, helping optimize its performance and stability.
- To thoroughly evaluate the durability and mechanical stability of CPB, it is recommended that the long-term mechanical behaviour of CPB containing superplasticizers be monitored and analyzed in large-scale column samples, extending beyond the standard 28-day curing

period. This will enable a more comprehensive understanding of CPB performance over time, which is critical for assessing its suitability and effectiveness in mining operations.

- It would be beneficial to evaluate the effect of freezing temperatures (i.e., sub-zero temperatures) on the mechanical strength and pore water pressure development of CPB materials containing superplasticizers.
- It would be valuable to develop a THMC model and simulation tool to numerically assess and predict the geotechnical behaviour and performance of CPB structures with PES under various THMC field loading scenarios.