CONSOLIDATION AND STRENGTH CHARACTERISTICS OF DENSIFIED POLYMER-PASTE TAILINGS MIXTURE AS WASTE CONTAINMENT BARRIER MATERIALS

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ABSTRACT

During mining operations, substantial quantities of ore undergo processing to extract valuable metals. However, this extraction process inevitably generates a significant amount of waste, commonly known as tailings. These tailings, upon exposure, can pose considerable environmental risks due to their toxicity. Specifically, the high sulfur and heavy metal content of many tailings render them susceptible to acid generation, thus presenting a hazard to the surrounding environment. Consequently, tailings are often classified as hazardous materials. Recognizing the environmental challenges posed by conventional tailings disposal methods, particularly the risks associated with exposure and contamination, the mining and civil engineering sectors have endeavored to develop alternative strategies for managing and utilizing this waste material. One such strategy that has garnered attention is cemented paste backfilling (CPB).

Cemented Paste Backfilling (CPB) is an engineered material composed of approximately 2-7% binder, 15-30% water, and 70-85% tailings. CPB offers a compelling alternative to traditional tailings disposal methods, providing both environmental and operational advantages. By managing tailings in a manner that reduces their hazardous properties, CPB promotes more sustainable and safer mining practices. However, despite its broad adoption and numerous benefits, CPB technology has its limitations. Specifically, it can only utilize up to 60% of the tailings produced by mining activities for underground backfilling.

To further minimize tailings from the mining industry, their conversion into barrier material (liner, cover), known as SAP-paste tailings or SAP-pastefill, for waste containment facilities, is an effective strategy after CPB. This involves blending dewatered tailings with water and a superabsorbent polymer (SAP), creating a material with low hydraulic conductivity due to the nature of paste tailings and the high swelling capacity of SAP. Compacted SAP-paste tailings (PP) exhibit hydraulic conductivity below the required minimum for barrier design in waste containment facilities. Utilizing non-acidic, cement-free paste tailings for barrier materials (liners or covers) in these facilities, whether municipal, mining, or industrial, also necessitates a thorough evaluation of their mechanical properties, such as consolidation behavior and shear strength, by mining and civil engineers. While compacted PP shows promising hydraulic properties, its mechanical characteristics essential for barrier functionality are not well understood, as no studies have assessed these aspects. Effective waste containment facility design is crucial for managing and reducing the environmental risks associated with industrial waste disposal.

Therefore, this study investigates the consolidation behavior and shear strength properties of an innovative tailings barrier made of Superabsorbent Polymer (SAP) designed for waste containment facilities. Different percentages (0.0, 0.2, 0.5%) of a superabsorbent polymer (SAP) were incorporated into the tailings. The study also explores the impact of freeze and thaw cycles on consolidation and shear strength behavior (0, 1, 2, 3, 5, and 10 cycles) of the SAP-paste tailing.

To enhance the barrier properties, the SAP-paste mixture undergoes comprehensive laboratory testing. Oedometer tests are conducted to examine settlement over time under various stress conditions, revealing the consolidation behavior. Additionally, direct shear tests assess shear strength characteristics, providing insights into the material's resistance to sliding and deformation under different normal stresses.

Results indicate that increasing SAP content accelerates the consolidation process and affects the shear strength characteristics of the compacted SAP-paste tailings mixture. Initially, the material's shear strength rises with increasing SAP content up to 2% but declines when SAP content reaches 5%. This demonstrates that the shear strength of SAP-paste tailings fill is highly dependent on SAP concentration. Specifically, the cohesion angle increases with higher SAP content, whereas the friction angle decreases as SAP content rises. Therefore, careful testing and optimization of SAP content are essential to achieve the desired performance of SAP-paste tailing barriers in waste containment. Furthermore, when subjected to freeze/thaw cycles, the SAP paste tailing mixture exhibits increased strength and solid content initially, followed by a decrease in strength and solid content after a certain number of cycles. The lower solid content influences material compressibility, leading to higher initial void ratios with increasing cycles.

In conclusion, this study suggests that SAP paste tailing barrier materials have promising performance properties for barrier construction in waste containment facilities. The result of this study can help to further optimize mixtures and further reduce waste in mining. This study is also intended to open windows to new recycled materials and thus reduce harmful impacts on the environment. However, when using SAP paste tailings as a barrier, careful consideration of the climate is essential, particularly in cold regions, given their long-term application.

DEDICATION

This thesis is dedicated to my late parents, may their souls continue to rest in perfect peace.

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Lastly, I seize this opportunity to express profound gratitude from the depths of my heart to my cherished late parents. My current position would be unimaginable without the boundless love and unwavering support they gave to me in the past. I dedicate this thesis to them.

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LIST OF SYMBOLS AND ABBREVIATIONS

AMD: Acid mine drainage

CCL: Compacted clay liner

CPB: Cemented paste backfills

GCL: Geosynthetic clay liner

GML: Geomembrane liner

SBL: Sand – bentonite liner

TSF: Tailing storage facility

BPN: Bentonite polymer nanocomposite

CSB: Conventional sodium bentonite

MFT: Mature fine tailing

FA: Fly ash

SAP: Super absorbent polymer

hrs: Hours

min: Minutes

9MT: Nine mine tailings

PSD : Particle size distribution

Sec: Seconds

PP: Polymer-paste

ST: Silica tailings

Temp.: Temperature

UCS: Unconfined compression strength

UCSC: Critical unconfined compression strength

USCS: Unified soil classification system

CHAPTER 1

INTRODUCTION

1.1 General Statement

The mining sector has significantly influenced the economic and social development of various countries and regions worldwide. Despite these contributions, mining operations produce substantial volumes of waste, with tailings being a significant component that requires careful disposal. Tailings are residual materials, characterized as byproducts or (potentially toxic) engineered soils composed of ground rock and process effluents. These materials persist after the extraction and recovery phases of valuable minerals in mining operations (Fall & Samb, 2009a; Ghirian & Fall, 2014; Mohammad Pour, 2020; Bull and Fall 2020a,b). The volume of tailings generated by mines can be almost equal to the volume of raw material processed. For example, a mine that produces 200,000 tonnes of copper ore per day will very certainly also create that number of tailings each day, less the negligible mass of the copper mineral contained (*(MMSD)*, 2024).

Traditionally, tailings have been deposited on the Earth's surface within designated surface tailings facilities (STF) such as dams, ponds, and various surface impoundments. However, the utilization of surface tailings management methods carries inherent risks, including geotechnical challenges (e.g., potential tailings dam failure) and environmental hazards (such as acid mine drainage and the release of heavy metals into the biosphere). These risks can result in significant economic and social consequences (Fall et al., 2009; Mohammad Pour, 2020). However, the mining industry is trying to respond to the pressure for change by exploring the benefits of alternative tailings management practices and developing advanced methods to reduce risk and better respond to increasing environmental and social concerns (Carneiro & Fourie, 2018).

Therefore, to reduce the adverse effects of tailings, the mining industry has adopted cemented paste backfill or cemented paste tailings (CPB) technology in this case as a practicable way of disposing of tailings and use as construction materials in mining operations (Fall et al., 2009). However, CPB can only consume up to 60% of the tailings generated by a mine. In other words, at least 40% of tailings generated by a mine still require surface management, often through conventional STF methods. There is a pressing need to explore alternative applications for tailings, such as their use in construction materials. One promising option is the use of non-acidic, cement-free paste tailings to develop barrier materials, such as liners or covers, for waste containment facilities. These facilities include those designed for municipal, mining, and industrial waste. The design and construction of waste containment facilities, such as landfills for solid hazardous waste and repositories for mine waste, necessitate implementing effective barrier systems, including liners and covers. These barriers are crucial for proper waste management, especially in containment facilities like landfills and tailings storage areas, to prevent environmental contamination and ensure long-term stability.

Fall et al. (2010) have addressed the need for enhanced barrier materials in waste containment by developing densified polymer-paste tailings (PP) mixtures composed of paste tailings and small amounts of super absorbent polymer (SAP). These SAP-paste tailings demonstrate low hydraulic conductivity, offering a sustainable option for reusing tailings in waste containment facilities as liners or covers. However, critical engineering properties of compacted PP, such as consolidation and shear characteristics, are not fully understood. A comprehensive grasp of these properties is essential for designing robust, durable, and effective barrier systems (Islam et al., 2020; Qiu & Sego, 2001). Additionally, environmental stressors like freeze-thaw cycles can significantly impact the consolidation behavior and shear characteristics of compacted PP. Freeze-thaw cycles occur when water freezes and expands within the material, potentially altering its structure and properties. Understanding these effects is crucial for evaluating the performance of compacted PP in waste containment applications, particularly in regions with fluctuating temperatures.

Although SAP-paste tailings barriers offer promising benefits, there is still a significant lack of comprehensive understanding regarding their mechanical behavior, specifically concerning consolidation and shear strength characteristics, as well as their response to freeze-thaw cycles. This knowledge gap impedes the effective deployment of SAP-paste barriers in waste containment facilities.

1.2 Objective of the Research

The purpose of the present study is to comprehensively investigate the consolidation behavior and shear strength characteristics of SAP-paste tailings barriers in waste containment facilities. This research seeks to provide insights essential for the effective design, implementation, and long-term performance assessment of SAP-paste tailing barriers, contributing to the development of sustainable and environmentally friendly waste containment practices in mining and industrial applications.

The specific objectives are as follows:

i. Investigate the impact of incorporating SAP (superabsorbent polymer) on the consolidation behavior of tailings barriers as they settle and compress over time.
ii. Examine the shear characteristics (stress-strain behavior, shear strength, shear strength parameters) of SAP-paste tailings barriers under different loading conditions and SAP contents to offers insights into their stability and resistance to shear forces.
iii. Additionally, given the weather conditions in Canada, it is crucial to investigate the effects of freeze-thaw cycles on the consolidation and shear strength behavior of SAP-paste tailings barriers. Examine changes in settlement patterns, and overall consolidation and shear strength trends under varying freeze-thaw conditions.

1.3 Scope of Thesis

To achieve the objectives of this thesis, the geotechnical characteristics of the material in question are determined and monitored throughout the treatment. SAP material is managed by using three weight percentages of SAP, including 0%, 0.2%, and 0.5%. Also, two different mixing methods are applied to investigate the consolidation behaviour and shear strength characteristics of SAP-paste tailings barrier for waste containment facilities. Including freezing and thawing cycles, alternating sampling was carried out at cutoff temperatures of -20 °C and +20 °C at fixed time intervals sufficient to ensure that all ice lenses disappeared.

The analysis of the shear characteristics of SAP-paste tailing is conducted by using a direct shear test. Laboratory tests that determine the consolidation parameters are performed and variations in the void ratio with effective stress are studied. Tests are carried out in the geotechnical laboratory at the University of Ottawa by following the prescribed standard recommendations (2004 Revision of the ASTM).

1.4 Organization of the Thesis

The thesis is structured as a series of technical papers and is comprised of six chapters. **Chapter One** provides a brief introduction outlining its purpose and defines the problem statement, research objectives, and the scope of the study. **Chapter Two** includes an extensive overview of tailings and paste tailings technology, highlighting geotechnical barriers (such as liners and covers) for waste containment and their application in municipal waste disposal. It also covers essential background information on superabsorbent polymers, including their absorption capacity, types, properties, and characteristics. The chapter further examines the application of SAP-paste tailings barriers as liners and covers for waste containment, discussing the factors that influence their effectiveness. Additionally, a comprehensive review of past literature on the use of SAP-paste tailings as barriers is included. **Chapter Three** comprises technical paper I. This paper mainly presents a study of consolidation behaviour and shear strength characteristics of polymer-paste tailings barriers for waste containment facilities, i.e., the mechanical property of SAP-paste tailings barriers (liner/cover) for waste contamination facilities. **Chapter Four** contains the second technical paper, which examines the impact of freeze-thaw cycles on the consolidation behavior and shear strength characteristics of SAP-paste tailings barriers in waste containment facilities. Section 3.0 specifically discusses the effects of freeze-thaw cycles on both the consolidation and shear strength of SAP-paste tailings. **Chapter Five** summarizes the results obtained in this study, offering insights into the consolidation and shear behavior of SAP-paste tailings. This is followed by a discussion on how freeze-thaw cycles affect the consolidation and shear strength of SAP-paste tailing material. **Chapter Six** provides a summary of the conclusions and offers recommendations for future research.

It is important to note that due to the presentation of the primary outcomes of the thesis in the form of technical papers, certain information may be repeated. This repetition arises from the independent composition of each paper, without consideration of the content in other papers or the entirety of the document. The adherence to manuscript preparation guidelines for the respective publication medium also contributes to this repetition.

The following flow chart illustrates the structure of the thesis.

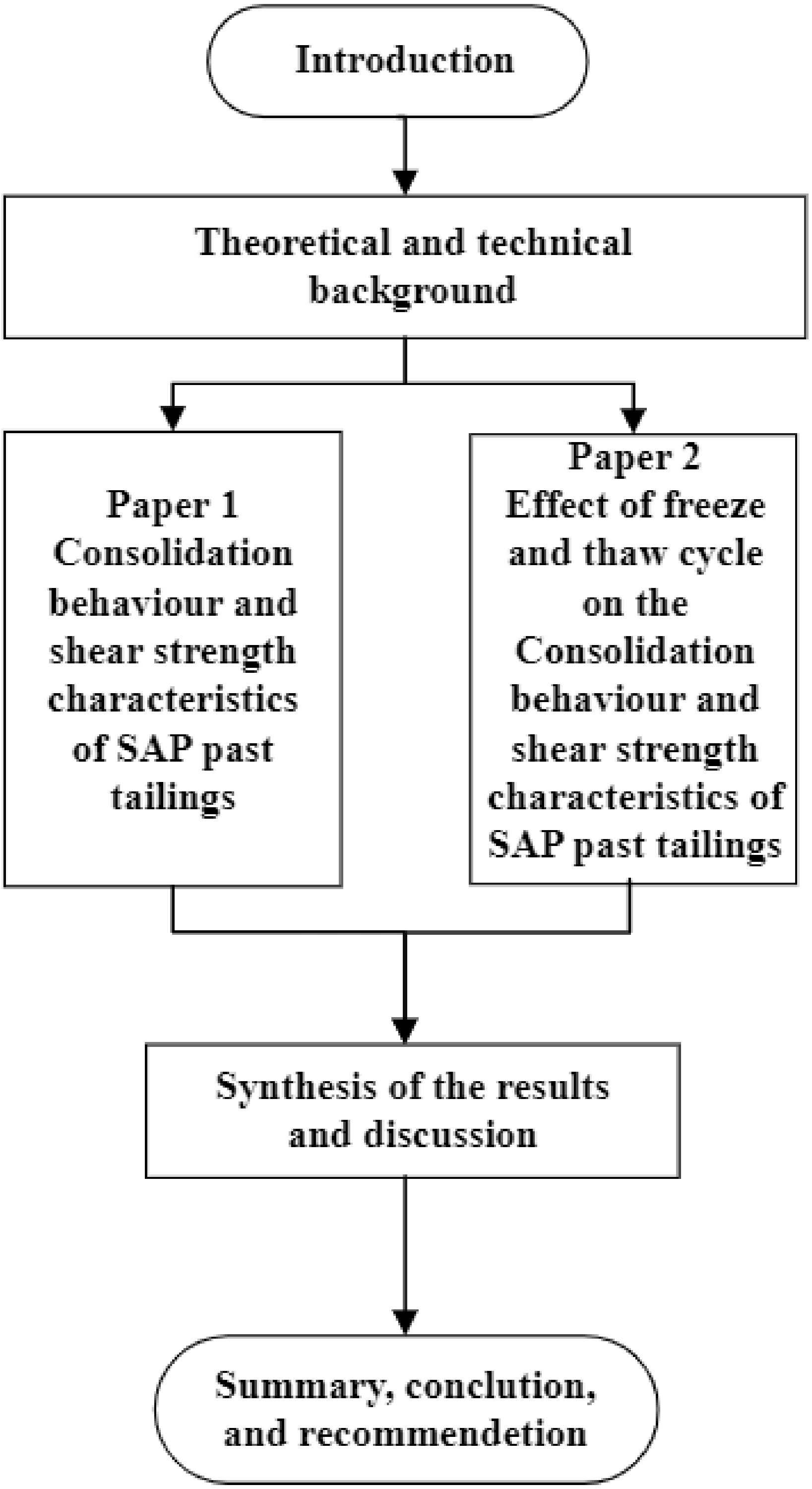

Figure 1.1 Schematic diagram that illustrates the organization of the thesis.

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CHAPTER 2

THEORETICAL AND TECHNICAL BACKGROUND

2.1 Introduction

The relevant background information was explored across several sections to provide a comprehensive understanding of the findings presented in this thesis. Section 2.2 covers tailings and paste tailings technology, while Section 2.3 discusses geotechnical barriers for waste containment. Section 2.4 provides an in-depth look into superabsorbent polymers (SAPs), including their absorption capacity, types, properties, and characteristics. Furthermore, Section 2.5 examines the application of SAP-paste tailings barriers as liners or covers, exploring the factors influencing their effectiveness. Section 2.6 reviews previous studies on implementing SAP-paste tailings as liners or covers.

2.2 Background on Tailings and Paste Tailings Technology

2.2.1 Background information on tailings

Tailings, a byproduct of mining activities, consist of fine-grained particles formed through processes like crushing, grinding, and milling to extract valuable ores (James et al., 2011). These materials include crushed rock and processing fluids left after mineral extraction, ranging in size from colloidal particles to sand-sized particles (Kossoff et al., 2014). Their plasticity is influenced by the fines content, which comprises particles smaller than 0.08 mm ((James et al., 2011); Mbonimpa et al., 2002). Tailings are commonly disposed of as a slurry into impoundments, where they consolidate over time due to low hydraulic conductivity, and such impoundments are intended to be permanent (James et al., 2011). Tailings dams, designed to contain high water content, often face environmental and geotechnical risks, including groundwater contamination, acid mine drainage, dam failures, and void collapses, arising from conventional disposal methods like surface impoundments and piling figure 2.1 (Wu, 2013; Yilmaz et al., 2014; Edraki et al., 2014).

Figure 2.1 Tailing storage conference (gtis, 2019).

2.2.2 Methods of tailing disposal

Tailings disposal methods are essential to modern mining operations, as they manage the substantial volumes of waste produced during mineral extraction. The importance of efficient tailings disposal arises from several key factors: environmental protection, operational efficiency, regulatory compliance, and long-term sustainability. Moreover, Figure 2.2 illustrates the stages of a typical mining operation, highlighting innovative approaches for tailings management and disposal (Yilmaz et al., 2023).

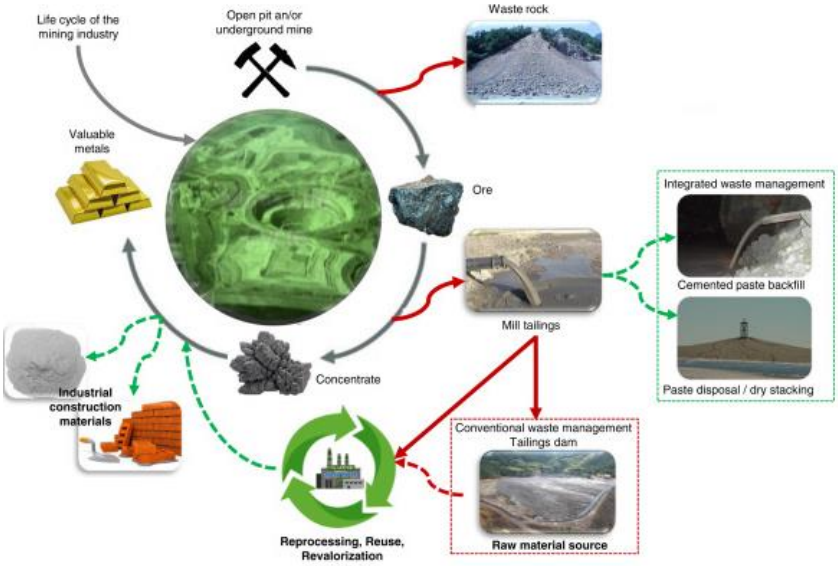


Figure 2.2 The formation of mining tailings and their contribution to the economy by reevaluating (Yilmaz et al., 2023).

Here is a detailed examination of various tailings disposal methods:

i. Conventional surface tailing disposal
ii. Submarine tailing disposal
iii. Backfilling
iv. Dry stacking (filtered tailings)
v. Paste tailings

2.2.2.1 Conventional surface tailing disposal (STD)

Surface disposal in engineered facilities remains the most common method for tailings storage and disposal in the mining industry (Oxenford & Lord, 2006). This method, often involving tailings storage facilities (TSFs), is cost-effective and scalable but comes with significant environmental and safety challenges requiring careful planning and management. Key environmental impacts, as shown in Figure 2.3, include dust generation, water pollution, land use conflicts, acid mine drainage, landslides, water contamination, and risks of dam failures.

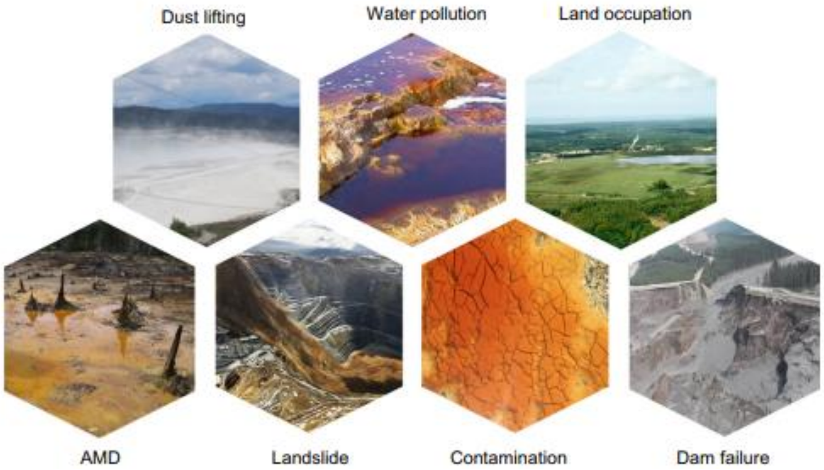


Figure 2.3 Environmental impacts relating to the disposal and/or treatment of mine tailings (Yilmaz et al., 2023).

2.2.2.2 Submarine Tailing Disposal

Submarine Tailings Disposal (STD) involves depositing mine tailings at deep-sea depths via pipelines, reducing land disturbance but posing risks to marine ecosystems, including toxic bioaccumulation, water loss, and seabed disruption (Ellis et al., 1995; Dold, 2014). The process uses a mix tank to create a slurry, transported through a pipeline to a deep-sea area below the photic zone to reduce immediate ecological impacts (Yilmaz et al., 2023) see figure 2.4.

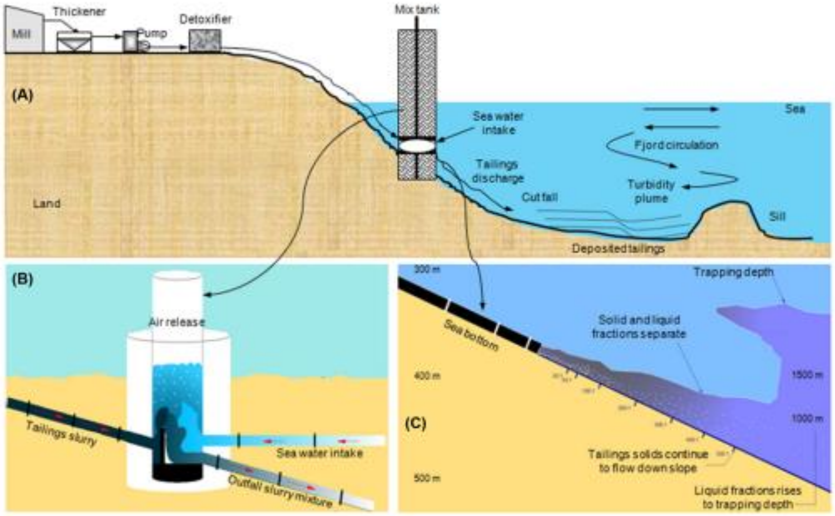


Figure 2.4 Some plots of (A) submarine tailings disposal, (B) mix tank, and (C) submarine pipeline (Yilmaz et al., 2023).

2.2.2.3 Backfilling

Backfilling underground mine openings with waste materials, such as waste rock, mill residue, and sand, offers a safe and sustainable alternative to surface tailings disposal (McPhail, 2015a; Benzaazoua et al., 2002; Al-Moselly et al, 2022). This method minimizes environmental impacts, stabilizes mining areas, and supports soil, enabling ore extraction from adjacent areas (Sivakugan et al., 2015). By burying tailings underground, backfilling eliminates the need for surface storage and reduces risks of chemical leaching into groundwater. It also reclaims degraded land and ensures safe site reuse for people and animals (Sheshpari, 2015). The addition of binders like lean cement enhances the strength and stability of backfills, making them a practical and environmentally friendly solution for mine tailings disposal (Fall & Benzaazoua, 2005). Several types of backfilling methods:

a. Cemented hydraulic backfills
b. Cemented rock backfills
c. Cemented paste backfills

Some types of backfill are more efficient at strengthening mines than others.

The typical grain size distribution of the three types of backfilling is illustrated in Figure 2.5

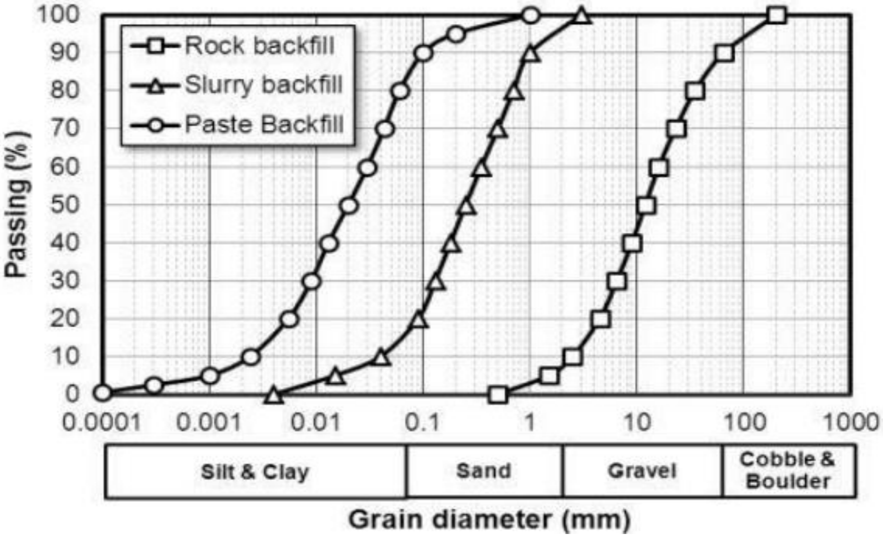


Figure 2.5 Grain size distribution of the three main types of mine backfills (Mohammad Pour, 2020).

A. Cemented hydraulic backfills

Cemented hydraulic fills (CHB) are a slurry mixture of tailings, sand, rock, water, and a binder, with 65% to 75% solids by weight (Sivakugan et al., 2015). Comprised mainly of coarse tailings and sands, with fines removed, CHB enhances flowability, solidification, and mechanical strength (Amaratunga & Yaschyshyn, 1997). The high water content allows gravity transport through pipelines, with drainage required as significant water is expelled during settling see figure 2.6 (Sivakugan et al., 2015).

Figure 2.6 Sample of hydraulic backfill (Mohammad Pour, 2020).

B. Cemented rock backfills

Rock fills, primarily composed of coarse aggregates from overburdened or surface-extracted rock, are combined with cement paste to create cemented rock backfill (CRB), a strong fill for heavily stressed soils (Amaratunga & Yaschyshyn, 1997; Karfakis et al., 1996). CRB offers high capacity and void utilization but involves high costs and complex structures (Wang et al., 2013). In Canada, CRB uses crushed waste rock with 5% Portland cement slurry, though low fines content reduces workability, requiring more cement for strength (Grice, 1998). Challenges include labor intensity, tire wear, and gas pollution in truck-operated mines.

C. Cemented paste backfilling

Cement paste backfilling (CPB) is critical for underground operations, comprising mining waste such as tailings, fly ash, cement, and water, as shown in Figure 2.7 (Doherty et al., 2015; Aldhafeeri and Fall, 2017). Produced at surface facilities, CPB is pumped through underground pipes to fill mine stopes (Wu et al. 2014; Haiqiang et al., 2016; Cui and Fall, 2018). It has a high solids content (75–85% by weight) and a typical slump of 20 cm (CSA A23.2-5C, ASTM C143) (Amaratunga & Yaschyshyn, 1997). Preparation involves thickening tailings to 55–60% solids, as milling introduces excess water. Hydro-cyclones remove fine particles to improve paste quality, while for coarser tailings, thickeners and vacuum filters produce a moist filter cake for transport. Flocculants assist filtration. Figure 2.8 depicts a typical CPB plant flow diagram.

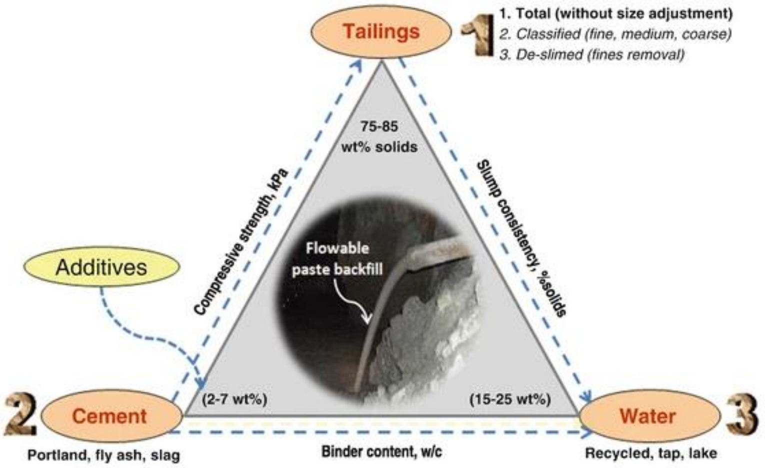


Figure 2.7 Component of CPB (Yilmaz & Fall, 2017).

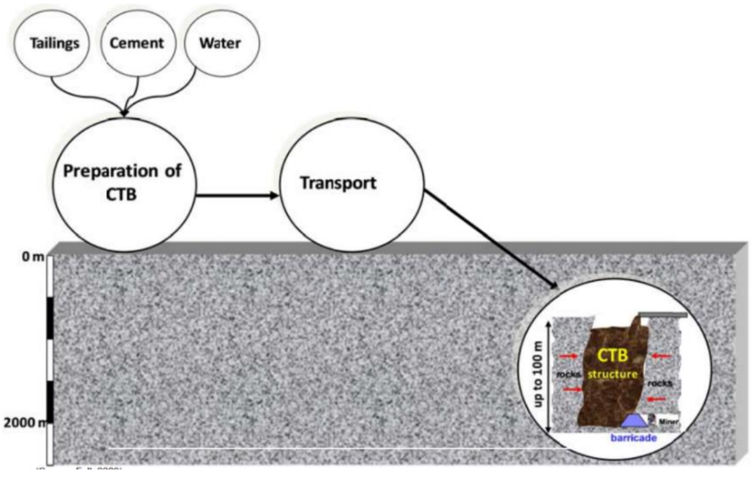


Figure 2.8 Schematic representation of CPB Technology (Fall et al., 2008)

Several publications delve into the specifics of cemented paste backfill (CPB) ((Tariq & Yanful, 2013), (Saedi et al., 2021), (Qi & Fourie, 2019), (X. Chen et al., 2018), (D. Wu & Cai, 2015), and

2.2.2.4 Densified Surface Tailing Disposal (DST)

Densified surface tailing disposal (DST) is a method of tailing disposal where tailings are dewatered and compacted (densified) before being placed on the surface of the ground. This process reduces the water content of the tailings, making them more stable and less prone to environmental risks like seepage, dam failure, or dust generation. The key benefits of DST include improved storage stability, reduced risk of catastrophic failures, and better environmental management.

Type of Densified surface tailing disposal (DST)

A Thickened Tailings Disposal (TTD)
B Surface Paste Tailings Disposal (SPTD)
C Dry Stacking (filtered tailings)
D Co-disposal of Tailings

A Thickened tailings disposal (TTD)

Thickened tailings disposal removes water from tailings to create a dense, paste-like material for safer, more efficient surface storage, reducing water volume, dam costs, and failure risks while enhancing water recovery (Bedell et al., 2002; Daliri et al., 2014). Dewatered using gravity thickeners, it separates slurry into clear liquid, sedimentation, and consolidation zones (Azam, 2009). First used at Canada's Kidd Creek mine, this method has gained global adoption for sustainable mining (Seddon & Williams, 2010).

B Surface Paste Tailings Disposal (SPTD)

Surface paste disposal (SPD) is an effective mine waste management method involving dewatering tailings into a paste-like form for surface deposition (Ichrak et al., 2016). SPD addresses geotechnical issues like dam failures and geochemical challenges such as acid mine drainage (Bascetin & Tuylu, 2018). It enables up to 80% water recovery but is typically applied on a small scale due to equipment limitations (Cacciuttolo et al., 2022). While SPD reduces the need for large dams and minimizes dust emissions through surface solidification, it requires costly positive displacement pumps for paste transport (Cacciuttolo & Atencio, 2022).

C Dry stacking (filtered tailings)

Filtered tailings (FT), or dry-stack tailings, involve dewatering tailings to a cake-like consistency, enabling storage in stacks without containment structures. This method maximizes water recovery, reduces land usage, and enhances stability through unsaturated storage, increasing strength from suction (Davies, 2011; Oldecop et al., 2017). Dewatering is typically achieved using vacuum or press filters, allowing tailings storage facilities to be built in lifts (Furnell et al., 2022).

D Co-disposal of Tailings

Co-disposal combines fine and coarse mine waste materials to create a single waste stream (Martin, Davies et al., 2002). Blending these materials reduces the void spaces typically associated with coarse waste, while the fines gain increased strength. This enhanced strength and quicker stabilization of the co-disposed material allows for earlier rehabilitation of the tailings area and mitigates the risks associated with both static and dynamic loading. Similar to dry stack methods, co-disposal generally eliminates the need for retention embankments, thereby removing the risk of embankment failure and preventing the spread of tailings beyond the storage zone (Smith & Leduc, 2003). However, the primary challenge with co-disposal lies in managing the deposition process to achieve optimal blending of the coarse and fine waste streams. This approach is most cost-effective when the two waste feeds can be pumped together or combined for in-pit storage.

2.2.3 **Background information on paste tailings technology**

Since 1995, paste technology (PT) has advanced to produce high-density, low-moisture-thickened tailings, offering significant economic and environmental benefits (Editors, 2022). PT improves mining efficiency by enhancing ground stability, accelerating production, and reducing environmental costs, while utilizing more industrial waste than other backfilling methods (A. Wu et al., 2016; Meggyes & Debreczeni, 2006). Despite its advantages, PT adoption is moderate due to equipment limitations and high costs of positive displacement pumping (Cacciuttolo &

Valenzuela, 2022). Paste tailings, with 10–25% water content and a consistency measured at about 20 cm slump, prevent particle settling in pipelines and reduce acid drainage by keeping sulfides saturated (Meggyes & Debreczeni, 2006). The process involves removing water via high-density thickeners, recycling water back into the plant, and producing a pumpable, non-segregating slurry. Additional filtration may be needed to achieve the desired consistency for disposal as self-supporting ridges or hills, reducing the need for confining dams.

2.2.3.1 The need for sustainable tailings disposal methods

Despite advancements in tailings disposal methods like Cemented Paste Backfill (CPB), dry stacking, and submarine disposal, more environmentally friendly solutions are needed. To address this, Fall et al. (2010) proposed SAP paste tailing disposal, which incorporates superabsorbent polymers into paste tailings. This method enhances mechanical and hydraulic properties, enabling reuse as construction materials like liners or covers, offering a sustainable approach to tailings management.

2.2.4. Components of SAP-paste tailings (SAP-PT)

Understanding the interactions and influences of these components on the physical, mechanical, and hydraulic properties of SAP pastefill is crucial for designing structures that meet performance and safety requirements. Factors such as particle size distribution, mineralogy, density, moisture content, and the SAP binder-to-tailings ratio can significantly affect the behavior and performance of the paste material. The primary components of SAP-paste tailings include the tailings themselves, the SAP binder, and water.

2.2.4.2 Preparation of SAP-paste Tailing (SAP-PT)

Figure 2.9 depicts the production process of SAP-paste tailings (SAP-PT). Tailings are first dewatered to achieve suitable moisture content, then mixed in a plant with water and SAP binder to ensure even distribution and desired paste consistency. The prepared paste is transported to the deposition area using pumps or pipelines and deposited in layers, forming a stack. Depending on site factors and regulations, deposition methods may include underwater or hydraulic techniques.

The paste then consolidates as excess water drains or evaporates, enhancing its stability and shear strength over time.

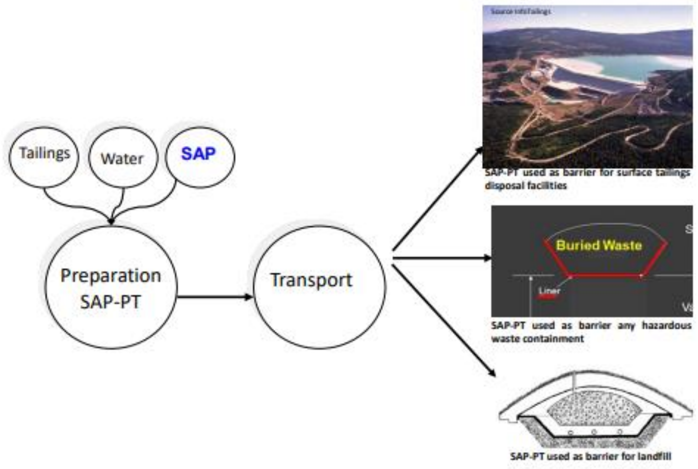


Figure 2.9 schematic representation of SAP-PT technology (Fall, et al., 2010).

Figure 2.9. Schematic representation of the different phases of SAP Paste Tailings (SAP-PT) technology: prepared and transported for use as a barrier for surface tailings disposal facilities, hazardous waste containment, and landfills.

2.3 Background on Geotechnical Barriers (Linear and Cover) for Waste Containments

Geotechnical barriers, including liners and covers, are crucial in waste containment systems. These barriers are designed to isolate waste materials from the surrounding environment and prevent contaminants from migrating into the soil and groundwater. The effect of a waste disposal facility on groundwater quality is influenced by several factors, such as the characteristics of the site, the prevailing climate, the type of waste being disposed of, the local hydrogeology, and the existence of a primary flow path. However, most critically, it relies on the type of barrier designed to restrict and manage contaminant migration. Modern barriers usually incorporate one or more of the following components: (Booker et al., 2014)

a. Natural clayey soils, such as lacustrine clay or clayey till
b. Re-compacted clay liners
c. Cut-off walls
d. Natural bedrock
e. Geosynthetics, used either alone or as part of a composite liner system (Booker et al., 2014).

2.3.1 Background on liner and cover for waste containments

Liners and covers are crucial components of waste containment systems, designed to isolate waste materials from the environment and prevent soil and groundwater contamination. These systems are commonly used in landfills, mining waste facilities, and industrial waste containment structures to ensure environmental safety and comply with regulatory standards (Booker et al., 2014).

Linear

A bottom or basal liner is primarily employed to stop contaminants, typically in the form of liquid leachate, from migrating into the surrounding environment, often the subsurface beneath a waste disposal site. This helps safeguard groundwater resources and prevents the buildup of contaminants in the subsurface. Since the contaminants of concern are carried by the liquid, the liner must be as impermeable as possible (Agency, 2023).

Types of liner system

Single liners

According to Agency (2023), single liners can be constructed from natural materials like clay or synthetic materials, such as various polymeric substances available today. The simplest lining systems consist of a low hydraulic conductivity layer, such as a compacted clay liner (CCL), a geosynthetic clay liner (GCL), a geomembrane liner (GML), or a compacted sand-bentonite liner (SBL), which is then covered by a collection layer, as illustrated in Figure 2:10. The primary function of the liner is to minimize the movement of liquid from the tailings into the soil beneath the tailings storage facility (TSF).

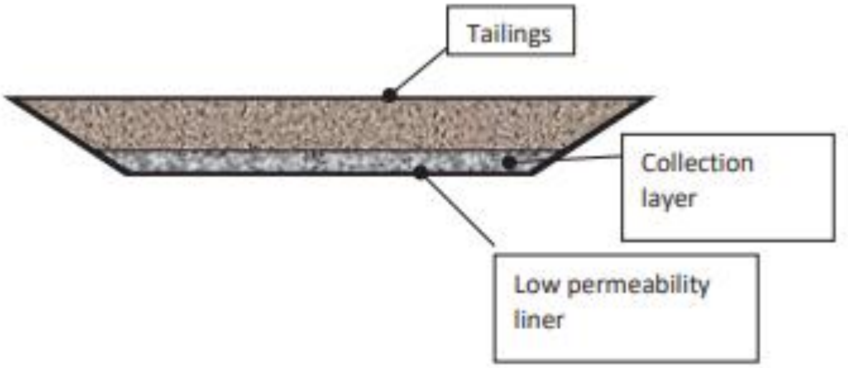


Figure 2.10 Illustration of a single liner system (Agency, 2023).

Composite liners

A composite liner consists of two different liners in close contact, typically featuring a geomembrane over a clay liner, geosynthetic clay liner (GCL), or sand-bentonite liner (SBL). For example, a geomembrane-clay liner (GML-CCL) composite, as depicted in Figure 2.11, is highly effective at preventing liquid migration compared to single liners. The synergistic effect of the composite liner exceeds the individual effects of its components, as a defect in the geomembrane is unlikely to align with a high conductivity zone in the underlying liner. Without the clay liner, leachate would flow directly into the subsurface, but the clay liner's low hydraulic conductivity impedes this infiltration (Agency, 2023).

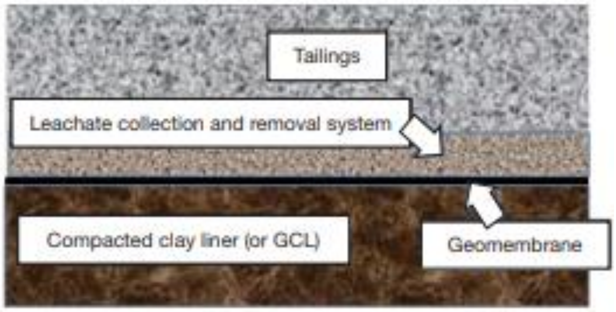


Figure 2.11 Schematic of the composite liner, illustrating a geomembrane liner placed over a compacted clay liner (or geosynthetic clay liner) (Agency, 2023).

Multiple liner systems

A well-constructed composite liner can still experience leakage (Fig. 2.12). Detecting seepage is challenging until contamination is found in downstream monitoring wells, by which time significant contamination may have occurred. Therefore, an effective method to intercept and collect seepage is necessary. A double-lining system addresses this by providing a mechanism to collect and remove seepage passing through the primary liner, though detecting seepage through the secondary liner remains difficult, similar to a single composite liner.

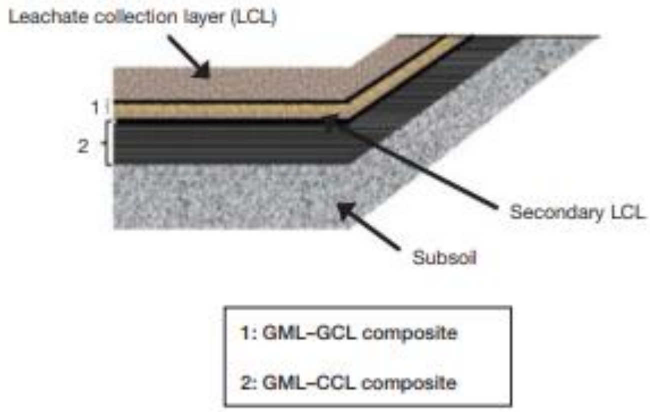


Figure 2.12 A multiple (double) liner system, comprising two composite liners separated by a leakage detection and collection system (Agency, 2023).

Freeze-thaw effects

Although freeze-thaw cycles generally do not significantly affect most liners because they are insulated by being buried beneath tailings, these cycles can still occur immediately after placement and before the liners are covered with drainage material and tailings. In extreme conditions, such as in very cold climates with a relatively thin layer of tailings, the liner may still be exposed to freezing and subsequent thawing.

Cover

Covers fulfill various roles based on the specific needs of each site. Generally, they are required to provide physical containment of the waste, control vector intrusion, minimize or eliminate the release of mobile contaminants to the surrounding environment through aqueous and gaseous pathways, persist for the design life of the containment facility or the hazardous life of the waste, and offer an acceptable end land use for the site of the containment facility (Agency, 2023).

Types of cover

Resistive barrier covers

Traditional cover designs employ low-conductivity materials to block water infiltration and gas escape. Known as "resistive barrier covers," these designs typically use geomembranes and compacted clays as the primary barriers against water movement. The effectiveness of these materials is assessed by their saturated hydraulic conductivity, which measures their ability to transmit water when fully saturated. The design and function of resistive barrier covers closely resemble those of conventional bottom liners, reflecting their shared evolution in engineering practices(Agency, 2023).

Evapotranspiration covers

Cover systems that depend on temporarily storing precipitation in surface soil and subsequently removing the stored water through evaporation and transpiration can offer exceptional performance, especially in arid climates. These covers are known by various names, such as evapotranspiration covers, store-and-release covers, and water balance covers (Agency, 2023).

2.3.2 Mining Application

Mining applications encompass a wide range of activities related to the extraction of valuable minerals and resources from the Earth's crust. Once mineral deposits are identified, extraction methods are employed to remove the ore from the ground. This may involve surface mining techniques such as open-pit, strip, quarrying, or underground mining methods such as shaft, drift, and slope mining (Celestin, 2009).

Mining operations generate large quantities of waste material, including overburden, tailings, and waste rock. Effective waste management practices are essential to minimize environmental impact and comply with regulatory requirements. This may involve containment, stabilization, reclamation, and closure of waste disposal facilities. Mining management units use protective material layers, such as soil or synthetic barriers, to act as buffers that prevent acid mine drainage or hazardous leachates from contaminating underground or surface water. These barriers shield waste materials from exposure to oxygen and water infiltration, adhering to Environmental Protection Agency recommendations. Additionally, the chemical reactions within the waste that consume oxygen pose environmental risks. To mitigate these issues, geotechnical barriers (liners and covers) are typically installed at waste containment or processing facilities.

In mine waste management, cover systems are engineered structures placed over mine waste containment facilities to reduce water infiltration, control erosion, and limit the release of airborne pollutants (Agency, 2023). These systems typically comprise multiple layers, including soil, geomembranes, geotextiles, and vegetation, designed to ensure long-term stability and environmental protection. One of their key functions is to offer low hydraulic conductivity, which limits water access, thereby reducing the production of leachates and acid mine drainage. Since oxygen is necessary for these reactions and its diffusion in water is very slow, maintaining a high saturation level in the cover layer effectively keeps oxygen away from the reactive waste.

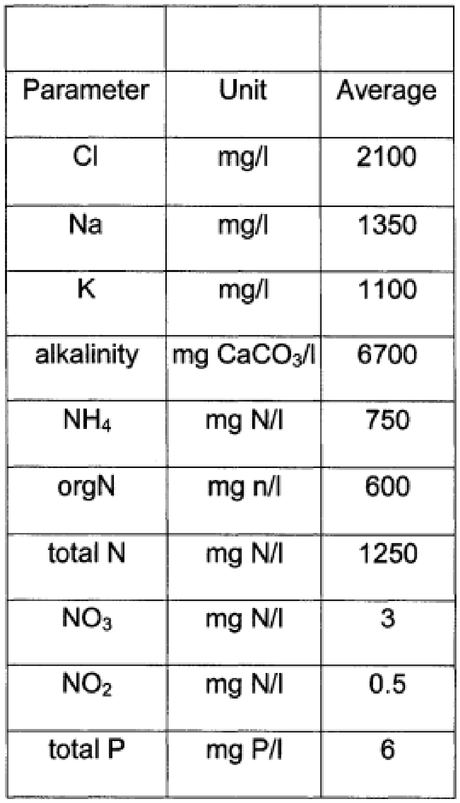
Several authors have studied the effectiveness of soil covers in environmental management. (Yanful, 1993) found that a multilayer cover system, consisting of fine-grained material sandwiched between two coarse-grained soil layers, acted as an effective moisture-retaining medium. In his study of acid tailings, he observed that this configuration reduced oxygen flux by 85% to 95% due to saturation. (Benson et al., 1994) noted that the coarse-grained materials served as protective layers in the capillary barrier, helping to maintain the saturation level. These covers, characterized by their use of coarse-grained sand, are identified as capillary break types. In contrast, another type of cover, known as the store and release cover, relies on maximizing moisture storage from rainfall in the cover material.

liners are impermeable or low-permeability barriers placed along the base and sides of mine waste containment facilities, such as tailings ponds and waste rock dumps. Their purpose is to prevent water infiltration and the leaching of contaminants into the underlying soil and groundwater. Therefore, covers and liners must meet a range of criteria, which may vary in strictness. These criteria necessitate considering the shape and geometry of the design, the nature of the waste to be contained, and the materials available for construction.

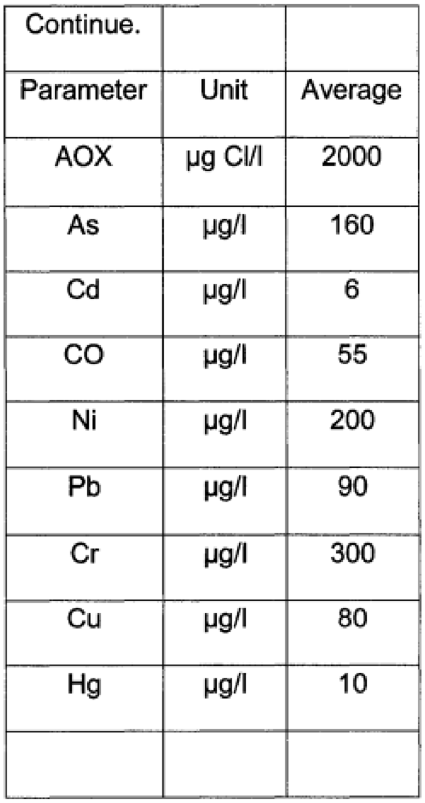
2.3.3 Municipal Waste Disposal Application

Municipal waste disposal involves the collection, treatment, and disposal of solid waste generated by households, businesses, and institutions within a municipality. Effective management of municipal waste is crucial to minimize environmental impact, protect public health, and ensure sustainability. For hazardous waste landfills, the Environmental Protection Agency (EPA) requires a compacted soil liner that is at least 0.9 meters thick and has a maximum hydraulic conductivity of 1x10-7 cm/s. Additionally, a leak detection system, usually made of geotextile, must be in place with a response time of 24 hours. A double-liner system, which includes a leachate collection layer between the two liners, is also mandatory. Conversely, non-hazardous waste landfills have less rigorous standards, typically needing at minimum a single composite liner with a leachate collection system. Table 2.1 details common contaminants found in hazardous landfill waste (Celestin, 2009).

Table 2.1. AOX adsorbable organic halogen (Celestin, 2009)



Parameter	Unit	Average
Cl	mg/l	2100
Na	mg/l	1350
K	mg/l	1100
alkalinity	mg $CaCO_3$/l	6700
NH_4	mg N/l	750
orgN	mg n/l	600
total N	mg N/l	1250
NO_3	mg N/l	3
NO_2	mg N/l	0.5
total P	mg P/l	6



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Parameter	Unit	Average
AOX	µg Cl/l	2000
As	µg/l	160
Cd	µg/l	6
CO	µg/l	55
Ni	µg/l	200
Pb	µg/l	90
Cr	µg/l	300
Cu	µg/l	80
Hg	µg/l	10

2.4 Superabsorbent Polymer

Superabsorbent polymers (SAPs) are functional polymer materials with highly hydrophilic gels that have a network of polymer chains in which water is a dispersion medium and a three-dimensional network structure (Zhang et al., 2021). SAPs can absorb and retain extraordinarily large amounts of water or aqueous solutions with their mass (Farkish & Fall, 2013). They are generally composed of ionic monomers and are characterized by a low cross-linking density, which results in a large fluid uptake capacity (up to 1000 times their weight) (Mignon et al., 2019). A typical granular SAP is shown in Figure 2.13. Over the last 15 years, SAPs have been adopted and deployed across multiple industries and products, and today numerous applications depend on SAPs.

p (Super Absorbent Polymer), n.d.)

Figure 2.13 Super absorbent polymer (SAP)

2.4.1 Absorption capacity

SAPs are hygroscopic materials that physically trap water in their macroporous structure through capillary forces and the hydration of functional groups as an absorption mechanism (Farkish, 2013).

To evaluate the water absorption capacity of SAPs, three key parameters are crucial to be characterized, namely (J. Chen et al., 2022):

- The absorption capacity under free pressure
- The absorption capacity under pressure and
- The absorption speeds.

2.4.1.1The absorption capacity under free pressure

abbreviated as absorptive capacity is the most used parameter in studies of SAPs. When the term absorptive capacity is mentioned without a specific condition, it means the ability to absorb distilled water or saline (0.9 wt% NaCl solution) under free pressure (Farkish, 2013; Masuda et al., 2021). The absorption capacity can be measured and calculated as follows (Farkish, 2013; Schröfl et al., 2017):

$\text{Absorption capacity(g/g)} = [(W_3 - W_2) - (W_5 - W_4)]/W_1$ (1)

Where:

W1: Weight of the dry absorbent material (in grams).

W2: Weight of the container before the test (in grams).

W3: Weight of the container with the sample after absorption (in grams).

W4: Weight of the container with the sample after centrifugation or removal of excess liquid (in grams).

W5: Weight of the container alone after centrifugation or liquid removal (in grams).

2.4.1.2 The absorption capacity under pressure

Absorption capacity under pressure is defined as the ability of SAP materials to absorb liquid under free pressure. This property is important for evaluating the performance of SAPs used under pressure, for example in baby diapers or adult care products. The method for measuring absorption under pressure is like that under free pressure. The absorption capacity under pressure is calculated as follows (Farkish, 2013; Zohuriaan & Kabiri, 2008) :

$$\text{Absorption capacity under pressure(g/g)} = (W_3 - W_2)/W_1 \qquad (2)$$

Where:

W1: Weight of the dry absorbent material (in grams).

W2: Weight of the container before the test (in grams).

W3: Weight of the container with the sample after the absorption test under pressure (in grams).

2.4.1.3 The absorption speed

The absorption rate, also known as the swelling rate, is a key technical characteristic of SAPs (superabsorbent polymers). It refers to the parameter that represents an SAP sample's free pressure absorption capacity over time. The method described above describes the measurement process for the absorption capacity under free pressure. In this method, the absorption capacities of the SAP under free pressure are evaluated at successive time intervals. These capacities are then fitted into a Voigt model, as shown in equation (3) (Farkish, 2013; Zohuriaan & Kabiri, 2008) .

$$S_t = S_e\,(1 - e^{-t/r}) \qquad (3)$$

Where:

St: The value of the parameter (e.g., absorption or saturation) at time.

Se: The equilibrium or maximum value of the parameter.

t: Time (e.g., in seconds, minutes, or another time unit).

r: Time constant or characteristic time.

e: The base of the natural logarithm.

The swelling behavior of polymers depends on two factors; one that is in the SAP and one that is in the solvent. The number of crosslinks (bonds that link one polymer chain to another) in a polymer chain will affect the expansion of the polymer so that more crosslinks result in less swelling. In other words, a network with higher crosslink density means lower equilibrium swelling capacity. The other factor is the number of ions and organic components present in the solvent, which affect the electrical stability of the polymer chain, thus reducing the swelling capacity (Farkish, 2013; Zohuriaan & Kabiri, 2008).

Table 2.2 shows the effects of solvent properties on the processability of SAPs. Based on these characteristics, the behavior of SAPs under different conditions can be predicted; Consequently, conditions can be adjusted to remove the absorbed water from the swollen polymer chains. Significant temperature increases can lead to dewatering of SAPs. The temperature at which desorption occurs depends on the type of SAP and the material in the chemical structure of the polymer. In addition, lowering the pH value by using strong acids as solvents leads to the release of the absorbed water.

Table 2.2. Important factors that influence the functionality of SAP (Zohuriaan & Kabiri, 2008)

Factor	**Absorption capacity**	**Absorption rate**	**Swell gell strength (AUL)**	**Soluble fraction**
Increase in particle size	Non-effective	Decreasing	Increasing	Non-effective
Increase in porosity	Non-effective	increasing	Decreasing	Non-effective
Increase in ionic strength	decreasing	Decreasing	De/Increasing	Non-effective
Increase in temperature	Non-effective	increasing	Non-effective	Non-effective
Photo/ biodegradation	increasing	Decreasing	Decreasing	Increasing
pH>7	increasing	increasing	De/Increasing	Non-effective
pH<7	decreasing	Decreasing	De/Increasing	Non-effective

2.4.2 Water absorbing mechanism of SAPs

There are normally four main mechanisms for absorbing materials to absorb liquid (J. Chen et al., 2022; Damiri et al., 2023).

1. Through reversible changes in their crystal structure (e.g. silica gel and anhydrous inorganic salts)
2. Through the physical inclusion of water and capillary forces in its macroporous structure (e.g. soft polyurethane sponge)
3. Through a combination of mechanism and hydration of functional groups (e.g. tissue paper)
4. Through a combination of mechanisms and natural dissolution of hydrophilic polymer segments and thermodynamically favored expansion of macromolecular chains constrained by crosslinks, which is also the main mechanism of SAP materials.

Visual and schematic representations of a representative example of SAPs (acrylic-based anionic SAPs) in dry and water-swollen states are shown in Fig. 2.14.

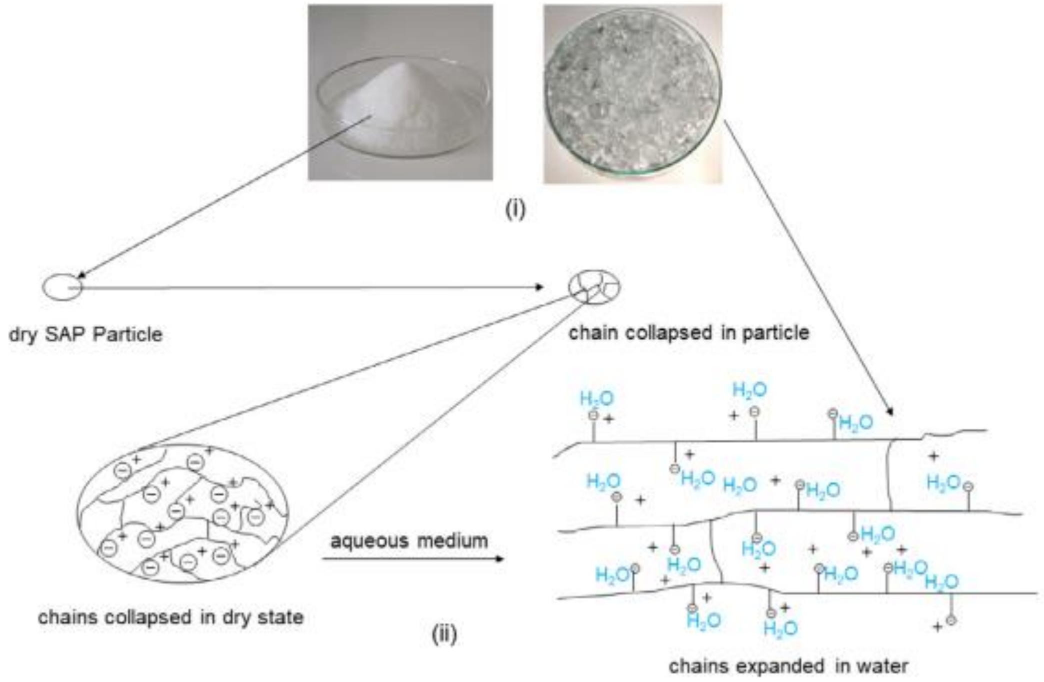

Figure 2.14 Illustration of a schematic drawing of a swelling SAP (Aida, 2013; J. Chen et al., 2022; Mignon et al., 2019) .

2.4.3 Types of SAPs

SAPs are categorized based on different features but mainly based on three aspects. (Zohuriaan-Mehr and Kabiri, 2008):

- Original source
- Presence or absence of electrical charge in the cross-linked chains
- Type of monomeric unit used in their chemical structures.

2.4.3.1 Original source

Based on their original sources, SAPS is often divided into two groups: synthetic and natural. The majority of SAPs are created from fully synthetic materials or have petrochemical origins. They are produced from acrylic monomers, most frequently acrylic acid (AA), its salts, and acrylamide (AM). Natural-based SAPs are prepared by adding different synthetic groups into a natural substrate and categorized into two groups:

1. Hydrogels based on polysaccharides
2. Hydrogels based on polypeptides.

2.4.3.2 Electrical charge in the cross-linked chains

Given the consideration solely of electrically charged molecules in the cross-linked chains, SAPs can be categorized into four groups:

1. Non-ionic.
2. Ionic (including anionic and cationic).
3. Amphoteric electrolyte (ampholytic) which contains both acidic and basic groups.
4. Zwitterionic (polybetaines) which contain both anionic and cationic groups in each structural repeating unit.

2.4.3.3 Type of monomeric unit

monomer types that have been used in the preparation of SAPs have a significant effect on the behavior of SAPs. Therefore, SAPs are categorized based on the type of monomeric units as follows:

1. Cross-linked polyacrylates and polyacrylamides.
2. Hydrolyzed cellulose-polyacrylonitrile (PAN) or starch-PAN graft copolymers.
3. Cross linked copolymers of maleic anhydride

2.4.4 Properties of SAPs

SAPs are used in various industries and their rare and unique properties ensure optimal results. Below are some of the key and defining features of SAPs (Zohuriaan & Kabiri, 2008):

1. **High absorption capacity**: The most outstanding feature of SAPs is their high absorption capacity. These materials can absorb and retain extremely large amounts of liquid relative to their mass. including water and other fluids. This property allows them to swell and store significant amounts of liquid within their structure.

2 **High absorption under load (AUL)**: because of crosslinking which provides a networked structure, these materials will not dissolve under moderate pressure. This feature has led to the widespread commercial acceptance of SAPs.

3 **Maximum equilibrium swelling**: At the equilibrium swelling point, the chemical potential of water inside and outside of a gel must be equal. Therefore, the elastic and mixing contribution to the chemical potential will balance each other. The swelling characteristics of polymers are highly important, especially in biomedical and remedial applications, since they influence (Ratne et al., 2004):

   a. The solute diffusion coefficient of gels
   b. The surface properties and surface mobility
   c. The optical properties
   d. The mechanical properties.

4 **Environmentally harmless**: nowadays, environmental issues are attached to high public attention and defined as one of the most significant and outstanding features of every project, and being environmentally feasible should be proven for all projects. SAPs are highly feasible for use as they do not release any toxins and harmful chemicals into the environment during degradation. In addition, SAPs are colorless and odorless.

5 **Reusability**: the high cost of SAPs can be considered a disadvantage but is negligible by focusing on the reusability of SAPs. SAPs can be released and be rewetted again several times with approximately equal swelling ratios. 36

6 **Photostability:** another important feature of SAPs is their resistance to changes under the influence of radiant energy and especially light. This advantage adds to the durability of their application and stability under different situations.

One type of SAP would not present all these characteristics and achieving the maximum level of some of these features will lead to inefficiency of the rest. Therefore, the SAP types are chosen precisely based on the need to achieve optimal results.

2.4.5 Characteristics of SAP

The first commercially available super absorbent polymer (SAP) was created using a process known as alkaline hydrolysis of starch-graft-polyacrylonitrile (SPAN). This innovative product was developed during the 1970s at the Northern Regional Research Laboratory, part of the US

Department of Agriculture. Despite its pioneering nature, this early SAP failed commercially due to its high production costs and structural weaknesses, particularly its inadequate gel strength.

The commercial production of SAP saw a significant milestone in 1978 when Japan began manufacturing it for use in feminine hygiene products. This marked the beginning of SAP's commercial viability. Building on this initial success, further advancements in the SAP materials were made, leading to their adoption of baby diapers. By 1980, these enhanced SAP products were being used in Germany and France, revolutionizing the diaper industry with their superior absorbency capabilities (Zohuriaan & Kabiri, 2008). Super absorbent polymers (SAP) have a wide range of applications, particularly in the fields of hygiene and agriculture (Levy et al., 1995; Roshani, 2017). Super absorbent polymers (SAP) have a wide array of applications beyond hygiene and agriculture, extending into several other fields such as entertainment, interior design, cryogenics, food packaging, construction, and the electrical industry (Pó, 1994).

Superabsorbent polymers have been proposed for the use of recycling mining waste as a liner/cover for waste contamination facilities (Fall, Célestin, et al., 2010). When mixed with the mining waste (Tailings) to produce a paste-like mixture called paste-tailing. This is achievable because of some of the characteristics of SAP:

- SAPs can absorb substantial liquid quantities compared to their mass. When integrated into liners or covers, they can efficiently confine and immobilize contaminants existing in mining waste, thereby halting their leakage into the nearby environment.
- Reduced Leachate Formation: Mining waste often contains substances that can produce harmful leachate when exposed to water. By using SAPs as a barrier, they can absorb any water that encounters waste, reducing the formation of leachate and thus minimizing the risk of groundwater contamination.
- Enhanced Stability and Durability: SAPs have the potential to bolster the stability and resilience of liners and covers by offering supplementary strength and resilience against both physical and chemical deterioration. This fortification contributes to the sustained efficacy of containment systems for mining waste over the long haul.
- Improved Moisture Control: SAPs aid in regulating moisture levels in waste containment facilities by absorbing surplus water and gradually releasing it over time. This assists in sustaining ideal conditions for waste stabilization, consequently lowering the likelihood of environmental repercussions.

- Compatibility with Waste Materials: SAPs can be tailored to match types of mining waste, guaranteeing efficient containment, and reducing the risk of interactions that may undermine containment integrity.
- Cost-Effectiveness: In certain instances, the utilization of SAPs in waste containment systems may offer greater cost efficiency when juxtaposed with conventional methods, especially if they minimize the necessity for extra liners or covers, or if they prolong the lifespan of current infrastructure. This assertion was corroborated by (Fall, Célestin, et al., 2010)

2.5 SAP-Paste Tailings Barrier (Liners, Covers) for waste Containing factors affecting it

When considering SAP (Sustainable Alternatives for Mine Tailings Disposal) paste tailings as linear or cover applications, additional factors come into play, specifically relating to their use as liners for containment or covers for rehabilitation. Here are the factors affecting SAP paste tailings:

1. Hydraulic Conductivity
2. Environmental factor
    a. Temperature
    b. PH levels
    c. Salinity
3. Mechanical factors
    a. Consolidation
    b. Shear strength
4. Aging and degradation
5. Moisture content
6. Interaction with surrounding materials

2.5.1 Hydraulic Conductivity

Hydraulic conductivity is critical for SAP paste tailings used as liners and covers, as it restricts water flow, prevents contaminant movement, controls leachate, and minimizes groundwater pollution. Key factors include composition, particle size, SAP content, mixing, compaction, and environmental conditions. Farkish & Fall (2014) found SAP-treated mature fine tailings (MFTs) had very low hydraulic conductivity, particularly after freeze-thaw cycles, enhancing consolidation and suitability for waste containment barriers. Achieving low hydraulic conductivity depends on both paste properties and environmental factors.

2.5.2 Environmental factor

Environmental factors like temperature, pH, and salinity are critical for the performance of SAP paste tailings as liners and covers. Temperature affects absorption and swelling, pH extremes degrade efficiency, and high salinity reduces swelling and structural integrity, impacting hydraulic conductivity and contaminant control. Farkish & Fall (2013) found SAP enhances dewatering and densification of mature fine tailings (MFT), reducing void ratios and improving consolidation, particularly with freeze-thaw cycles. However, freeze-thaw cycles can degrade SAP, causing microcracks, reduced strength, and increased permeability, compromising stability. Studies (Y. Liu & Liu, 2020; Li et al., 2022) show repeated cycles weaken mechanical properties, increase pore deformation, and reduce shear strength, emphasizing the need for stability evaluation in cold, seismic regions to ensure long-term effectiveness in mining applications.

2.5.3 Mechanical factors

Mechanical factors like compaction, shear strength, and particle size distribution are key to the effectiveness of SAP paste tailings as liners and covers. Proper compaction reduces void spaces, lowering hydraulic conductivity and increasing stability. Adequate shear strength ensures resistance to mechanical stresses, while optimal particle size distribution enhances permeability and cohesion. Studies highlight these impacts: Bohnhoff & Shackelford (2014) found that bentonite polymer nanocomposites (BPN) exhibit distinct stress-strain behaviors, and Roshani et al. (2017) observed that atmospheric drying improves shear strength in mature fine tailings (MFT) by developing suction.

2.5.4 Aging and degradation

Aging and degradation can significantly impact the effectiveness and durability of SAP paste tailings in mining. UV radiation, temperature fluctuations, and chemical interactions can deteriorate the SAP, diminishing its water absorption and structural integrity. This degradation decreases the SAP's swelling capacity, increases hydraulic conductivity, and weakens its barrier against water and contaminants. Acidic or alkaline chemical reactions can speed up this process. Therefore, understanding and mitigating these factors is essential for ensuring the long-term performance of SAP paste tailings in mining operations.

2.5.5 Moisture content

Moisture content is crucial for the effectiveness of SAP paste tailings as liners and covers in mining. It determines the SAP's swelling and water absorption abilities, impacting hydraulic conductivity and structural stability. Optimal moisture levels create a low-permeability barrier that prevents water and contaminant migration. Too little moisture results in inadequate swelling and higher conductivity, while too much makes the paste too fluid, compromising stability and handling. Therefore, maintaining the right moisture content is essential for reliable environmental protection and stability in mining operations.

2.5.6 Interaction with surrounding materials

Interactions with surrounding materials greatly affect the performance of SAP paste tailings in mining. The chemical and physical properties of these materials can alter the SAP's swelling and absorption capabilities, reducing its effectiveness. Contact with acidic or alkaline substances, fine particles, or contaminants can clog the SAP structure and trigger degrading chemical reactions. These interactions compromise permeability and structural integrity, diminishing the barrier's effectiveness. Thus, managing these interactions is crucial for the long-term performance and reliability of SAP paste tailings in mining applications.

2.6 Review of Previous Studies on SAP-Paste Tailing as Liners/Cover

Limited research exists on the application of superabsorbent polymers (SAPs) mixed with tailing SAP-Paste tailing to serve as a linear/cover for waste contamination facilities, with the only prior study conducted by (Fall, et al., 2010). In their study, Fall et al. examined the appropriateness of mixtures comprising non-acid generating paste tailings (pastefill) and polyacrylates (SAP) as barriers in waste containment facilities. Their study focused mainly on assessing the compaction and permeability of the proposed SAP-pastefill barrier with different SAP contents and exposed to various conditions. Their findings suggested that SAP-paste tailing materials exhibit promising performance attributes for barrier construction, leveraging the inherent low hydraulic conductivity of paste tailings. Additionally, they observed that the hydraulic conductivity of the proposed barrier material (PP) diminishes with increasing SAP content (refer to figure 2.15). Employing varying proportions (0.05, 0.1, 0.2, 0.5%) of a superabsorbent polymer (SAP) following the moisturization of tailings, Fall et al. prepared densified polymer-paste fill (PP) materials, which were subsequently compacted and subjected to permeability assessments at ambient temperature. Moreover, performance evaluations under cyclic freeze-thaw and wet-dry conditions were conducted to ascertain their efficacy as barriers for waste containment facilities. The principal findings from Fall et al.'s (2010) prior investigations concerning SAP paste tailings as liners/covers for waste contamination facilities are delineated below.

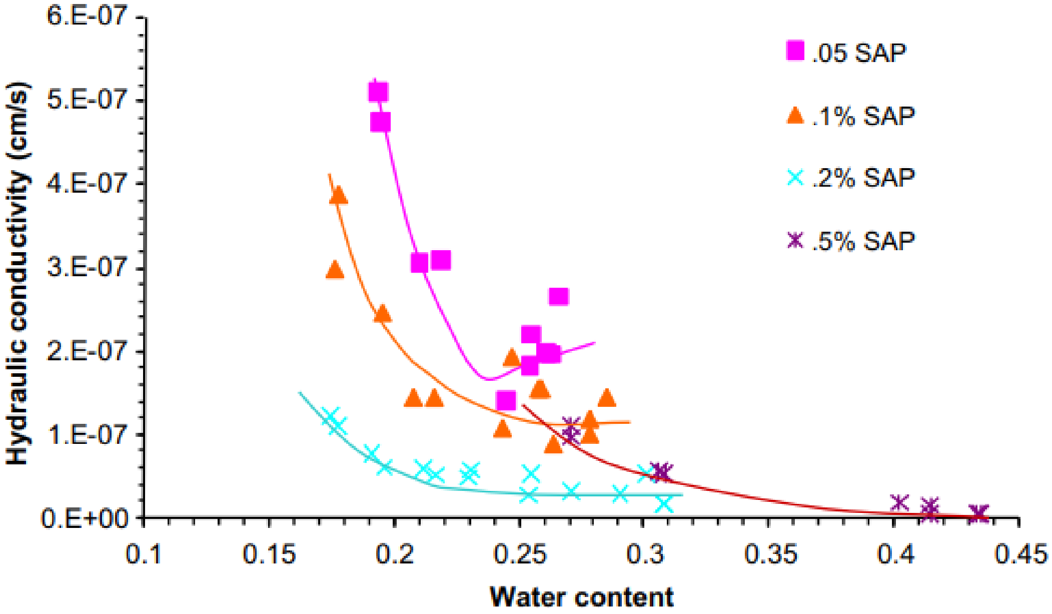

Figure 2.15 Effect of different SAP proportions and water content on the hydraulic conductivity of PP (Fall, Célestin, et al., 2010).

Compaction test results

Figure 2.16 shows the result of the effect of the SAP proportion on polymer-paste tailings proctor compaction characteristics. Compaction procedures were employed to augment the dry density of the material and consequently diminish voids within it. A series of paste fill specimens, composed of synthetic silica tailings, were fabricated and subjected to testing across a spectrum of water content ranging from 4% to 24%, incrementally increasing by 2%, to ascertain the optimum moisture content (OMC). The compaction results indicate that the moisture content corresponding to the wet of optimum lies approximately at 20%, yielding a maximum density of 1580 kg/m³.

This particular moisture content corresponds to the point of minimal voids, thus facilitating the attainment of optimal hydraulic conductivity for the pastefill material. Furthermore, it serves as a guideline for determining the approximate optimal water content for subsequent blends of pastefill with SAP additives. Each compaction cycle was repeated twice, and the mean value was considered as the water and dry density for the samples analyzed at each SAP percentage (0.05, 0.1, 0.2, 0.5%).

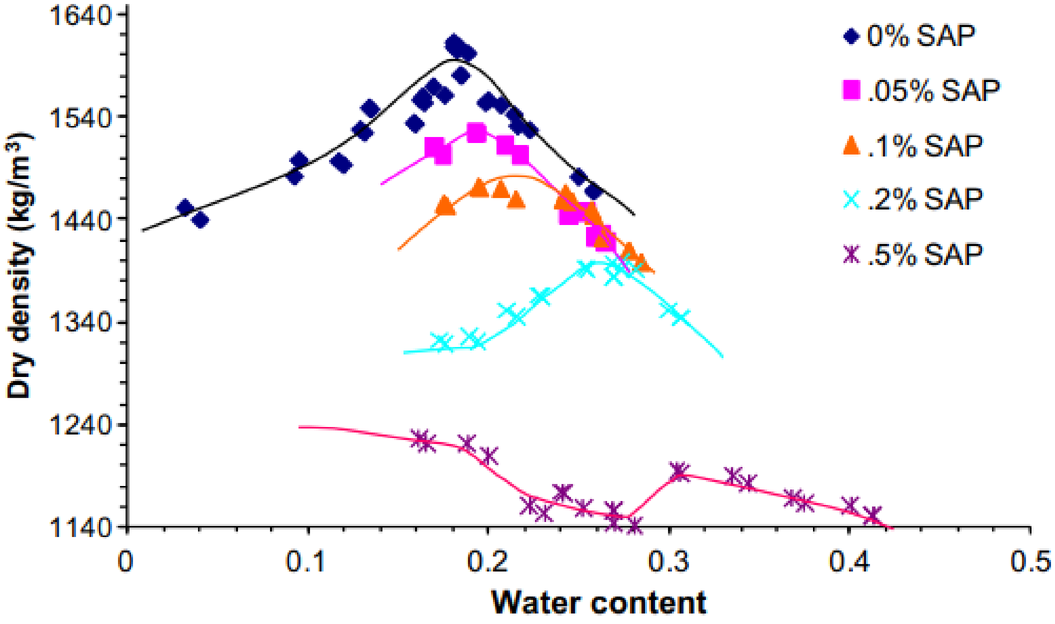

Figure 2.16 Effect of the SAP proportion on the characteristics of the proctor compaction of PP (Fall, Célestin, et al., 2010).

Hydraulic conductivity test results

The consistent decrease in hydraulic conductivity with increasing water content during compaction suggests a significant influence of both polymer content and water content on the relationship between hydraulic conductivity and compaction water content. One of the notable observations is the correlation between higher SAP content and lower conductivity at elevated water content levels, attributed to the increased water absorption capacity of the polymer. This phenomenon underscores the necessity for additional water to adequately saturate the tailings grains in samples with higher SAP content. Moreover, the study reveals interesting trends in the rate of decrease in hydraulic conductivity, with a steeper decline observed at the dry optimum, followed by a gradual slowdown as it approaches the wet optimum. This deceleration is attributed to maximum pore clogging and reduced swelling pressure in SAP at specific water absorption levels. Additionally, the study highlights the effectiveness of swelling SAP particles in fitting into pores at the wet optimum, further reducing conductivity. Comparative analysis of different mix proportions underscores the inverse relationship between SAP percentages and hydraulic conductivity, indicating a positive effect of polymer content on conductivity. This effect is attributed to the high absorption capacity of the polymer, which enables it to fill pores and inhibit water flow, even in the absence of an additional water supply. Including visual evidence depicting the transformation of tailings and water mixture following polymer addition enhances the findings' clarity and underscores the study's practical implications.

Effect of freeze-thaw cycles on the hydraulic conductivity of PP test results

Fall et al. 2010 also investigated the influence of freeze-thaw cycles on the hydraulic conductivity of (PP) samples, with a specific focus on the role of superabsorbent polymer (SAP) proportions. The findings emphasis that wet-compacted PP samples change hydraulic conductivity due to freeze-thaw cycles, although these changes are within a relatively modest range, falling short of one order of magnitude. Particularly noteworthy is the revelation that higher SAP proportions result in more pronounced alterations in conductivity, despite initially displaying lower conductivity levels. Illustrative figures depicting the impact of freeze-thaw cycles on PP samples with varying SAP percentages reveal diverse trends. Samples containing 0.5% SAP exhibit a substantial increase in hydraulic conductivity with cycles, contrasting with those containing 0.1% SAP, which displays a positive trend albeit with a lesser magnitude of change. In contrast, PP mixes with 0.05% SAP showcase a minor decrease in hydraulic conductivity with freeze-thaw cycles. The observed rise in permeability in PP mixes featuring 0.5-0.1% SAP is ascribed to the formation of cracks within frozen specimens, facilitated by ice lens expansion and SAP swelling. Visual inspections corroborate the presence of cracks, particularly pronounced in samples with higher SAP content, owing to increased water absorption and gel expansion.

Effect of wet–dry cycles on the hydraulic conductivity of PP test results

The study by Fall et al. 2010 provides compelling evidence regarding the positive impact of superabsorbent polymer (SAP) on the resistance of the proposed barrier materials to wet-dry cycle, as evidenced by hydraulic conductivity data and normalized trends observed in (PP) samples containing 0.5% SAP compacted wet optimum. Notably, the results illustrate minimal fluctuations in both hydraulic conductivity and normalized conductivity despite subjecting the PP samples to multiple wet-dry cycles. Visual inspections corroborate these findings, revealing the absence of desiccation cracks in the PP samples. This remarkable resistance is attributed to two primary mechanisms: firstly, the inherent self-healing processes inherent in diverse soil types, and secondly, SAP's capacity to enhance moisture retention within the barrier, thereby mitigating PP shrinkage potential. The addition of SAP is proposed to reduce PP's susceptibility to cracking by preserving moisture, likely driven by the absorption properties of the polymers themselves.

2.6.1 Conclusion

The hydraulic conductivity of SAP-paste tailings has been studied by Fall et al. (2010). However, other engineering properties of compacted polymer paste tailings, crucial to the design of a liner or cover, are not well understood. These properties include factors such as consolidation and shear characteristics. A comprehensive understanding of these characteristics is essential for designing a stable, effective, and long-lasting barrier system. No studies have been conducted on the consolidation and shear characteristics of PP, and there is a lack of research on the specific impact of freeze-thaw cycles on these properties in compacted PP. Therefore, this study aims to fill this research gap by experimentally investigating how freeze-thaw cycles affect the consolidation behavior and shear characteristics of compacted PP barrier materials.

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CHAPTER 3

TECHNICAL PAPER 1

Consolidation Behaviour and Shear Strength Characteristics of Polymer-Paste Tailings Barrier for Waste Containment Facilities

Chinaza C. Paul, Mamadou Fall

3.1 Abstract

The substantial amount of solid waste and tailings produced through mining operations can lead to severe environmental and geotechnical problems if not properly managed. To meet these challenges, the mining sector faces significant public pressure and strict government regulations on waste disposal, requiring adopting environmentally sustainable and economically feasible strategies. In response to this pressing need, the reconversion of waste into construction materials for mining and civil engineering applications has emerged as a vital undertaking. One innovative solution recently proposed is the development of a new barrier (liner, cover) material for waste containment facilities known as densified polymer paste tailings or polymer-paste fill mixtures (PP), made from a compacted mixture of paste tailings and superabsorbent polymer (SAP). Utilizing the low hydraulic conductivity inherent in paste tailings and the high swelling capacity of SAP, compacted PP has a hydraulic conductivity below the minimum threshold required for barrier design in waste containment facilities. However, although compacted PP shows promising hydraulic properties, its mechanical characteristics relevant to barrier functionality, such as consolidation behavior and shear characteristics, are not yet understood. No studies have assessed these mechanical characteristics. The present study therefore aims to investigate these aspects of PP. Compacted PP samples with different concentrations of SAP (0.0%, 0.2%, 0.5%) were prepared, and the samples were subjected to consolidation and shear tests. Consolidation behavior was investigated using oedometer tests, monitoring settlement over time under different stress conditions. In addition, shear characteristics were assessed by direct shear tests to evaluate the material's resistance to shearing and deformation under different normal stresses. The results indicated that increasing SAP content accelerates the consolidation process. In contrast, the shear strength of the material increases with SAP content up to 0.2%, after which it decreases when the SAP content reaches 0.5%. This means that the shear strength of the compacted PP is strongly dependent on the amount of SAP concentration. Specifically, the cohesion angle increases with

higher SAP content, whereas the friction angle decreases with increasing SAP content. The findings position this PP material as an attractive option for barrier design, offering the benefits of minimizing waste management and lowering the expenses associated with tailings management at the earth's surface.

Keywords: tailings; mine; barrier; paste backfill; super absorbent polymer; mechanical properties.

3.2 Introduction

In the modern time of environmental awareness and sustainable resource management, containment, and safe disposal of waste materials, particularly in mining and industrial operations, have become paramount concerns. Waste disposal facilities play a critical role in protecting the environment from potential pollution and contamination, a critical responsibility, especially within the mining industry. Mining operations produce valuable metals through the processing of vast quantities of ore. However, this process generates a considerable volume of waste, technically termed tailings (Celestin, 2009). The quantity of tailings produced by mining operations can closely match the volume of raw materials processed. For instance, a mine processing 200,000 tonnes of copper ore daily will likely generate a similar amount of tailings each day, except for the minor mass contributed by the copper mineral itself (*MMSD*, 2024).

Traditionally regarded as just waste rather than a valuable resource, these tailings have generally been deposited in tailings storage facilities (TSFs) placed on the surface of mine sites, using a variety of deposition techniques (Fall et al., 2010; Tian et al., 2022a). Yet these TSFs have caused significant environmental damage, including water and soil pollution, as well as the development of acid mine drainage. For instance, these tailings can contain high concentrations of ferrous sulphide minerals like pyrite and pyrrhotite and they are discharged during concentration (Elberling, et al., 1994; Fall, Célestin, et al., 2010). These sulphide minerals can oxidize in the presence of water, and oxygen from the atmosphere, resulting in low-pH effluent with elevated levels of sulfate ions (SO_4^{2-}), iron (Fe), and other metallic elements (e.g., heavy metals). If pyrite and pyrrhotite are not managed appropriately, they can continue generating acid mine drainage (AMD) hundreds of years after deposition (Yilmaz et al., 2014). In addition, TSFs have been associated with catastrophic geotechnical failures such as dam failures with numerous casualties, leading to profound social and economic repercussions for the mining sector and society, observed in various parts of the world (Reid et al., 2009; Carneiro & Fourie, 2018).). In addition to the considerable economic losses and significant casualties entailed by TSF's failure, the implications are more far-reaching regarding public perception, increased regulatory burden, and government oversight.

To address the challenges inherent in traditional tailings management through TSFs and to meet the growing demand for change, the mining industry has been actively exploring alternative practices. One of the main strategies adopted by the mining sector to promote the sustainable management of mining waste is the conversion of tailings into construction materials for mining and/or civil engineering applications. Cement paste backfill (CPB) technology stands out as a pioneering approach to reconverting tailings for mining applications (Fall et al., 2009). CPB is an engineered material composed of approximately 2-7% binder (often), 15-30% water, and 70-85% tailings, with a minimum of 20% of the percentage of particles having a dimension less than 20 µm. (Fall et al., 2009; Fall & Benzaazoua, 2005; Fall et al., 2010; Celestin, 2009). Typically produced in a specialized backfill plant situated on the surface of the mine, CPB is then transported via a pipeline network to fill underground voids. The use of CPB offers many advantages, including a marked reduction in the cyclical nature of mining operations, improved ground stability, enhanced integrity of underground excavations, increased mining productivity, and a substantial reduction in environmental impact (Hassani and Bois, 1992). Moreover, CPB applications facilitate the disposal of considerable quantities of fine tailings that conventionally necessitate permanent surface storage and management. This not only addresses environmental concerns but also yields considerable cost savings for mining operations (Archibald et al., 1998). Owing to its myriad and substantial benefits, CPB has garnered widespread adoption across mining operations globally.

Despite its widespread adoption and the array of advantages it presents, CPB technology has its limitations. Notably, it can only accommodate the utilization of up to 60% of the tailings produced by mining activities for underground backfilling (Fall et al., 2007). Consequently, at least 40% of produced tailings still require surface management, often through conventional STF methods. In other words, there remains a necessity to discover alternative applications for tailings, such as their utilization as construction materials. One such alternative being considered is the use of non-acidic producing cement-free paste tailings to develop barrier materials (liners or covers) for waste containment facilities, including those for municipal, mining, and industrial waste.

The design and construction of facilities designed for waste containment, such as landfills for solid hazardous waste and repositories for mine waste, typically involve the implementation of a barrier, which can be either a liner or a cover. These components play a critical role in waste management, particularly in containment facilities like landfills and tailings storage areas. In a waste containment system, a liner serves as a crucial barrier between the waste material and the surrounding environment. Its primary role is to prevent the infiltration of pollutants from the waste into the surrounding soil, groundwater, or surface water bodies. Meanwhile, the cover helps minimize water infiltration into the waste containment area, thereby reducing the generation and migration of contaminated water.

Utilizing the naturally low hydraulic conductivity of paste tailings (pastefill) (i.e., cement-free CPB), Fall et al. (2010) have developed a new type of barrier material known as densified polymer-paste tailings or pastefill (PP) mixtures. PP consists of mixtures of paste tailings and small amounts of super absorbent polymer (SAP). SAPs are polymers that are chemically linked and can absorb, expand, and hold substantial amounts of liquid from their environment without dissolution. The growth speed of small SAP particles can range from under a minute to several hours, contingent upon the diffusion coefficient and the distance the polymer must travel during diffusion (Lee et al., 2010). Fall et al. (2010) demonstrated that compacted PP can have hydraulic conductivity values below the minimum required for liner design in compliance with EPA regulations (10^{-7} cm/s), indicating that compacted PP mixtures can serve as liners or covering materials for waste containment facilities. The potential applications of utilizing compacted PP blends as barrier substances show great potential due to their good hydraulic properties and cost-effectiveness, stemming from the minimal admixture required to enhance performance further.

However, other engineering properties of compacted PP, crucial to the design of a liner or cover, are not well understood. These properties include factors such as consolidation and shear characteristics. A comprehensive understanding of the consolidation and shear characteristics of liners or covers is essential for designing a stable, effective, long-lasting, and operational barrier system (Islam et al., 2020; Qiu & Sego, 2001; Zreik et al., 1997). However, no studies have been conducted on the consolidation and shear characteristics of PP. Thus, the main objective of this research is to experimentally investigate the consolidation and shear characteristics of compacted PP barrier materials.

3.3 Materials and Experimental Procedures

3.3.1 Materials

3.3.1.1. Tailings

In this study, industrially produced synthetic silica tailings (ST), which are made from ground silica (ground quartz, ST), are used. They closely simulate the physical properties of natural tailings that arise during the milling process. The grain size distribution of ST tailings, which was established through the utilization of sieve and hydrometer examinations according to ASTM D698-00, is shown in (Fig 3.1) below. The grain size distribution curve of the silica tailings is largely consistent with the average distribution observed in the tailings from nine mines in eastern Canada.

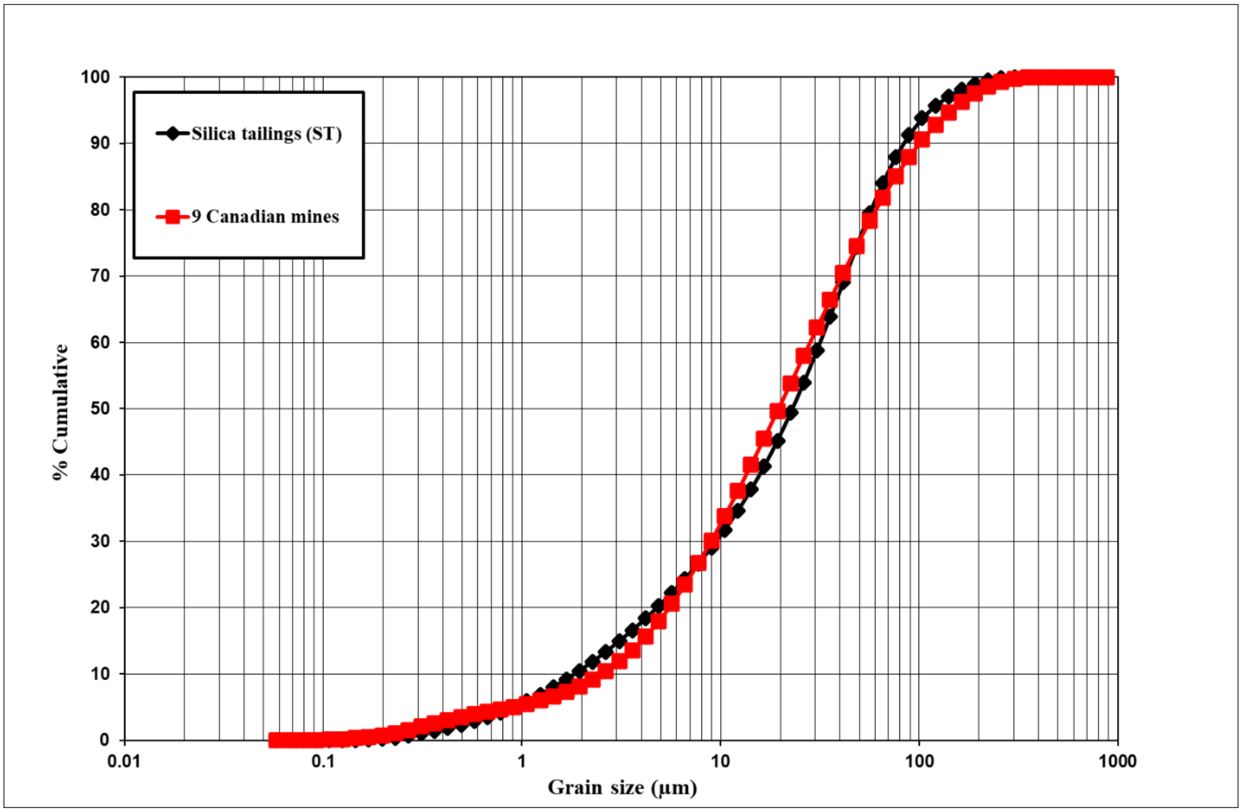


Figure 3.1 Grain size distribution of synthetic (silica) tailings used compared to the tailings from 9 Canadian mines from east Ontario.

The predominant mineral in this material is quartz, which makes up 99% of its composition. Approximately 40% of the particles are less than 20 microns in diameter, exceeding the minimum requirements for the development of paste tailings. The experimentation reveals that the utilized tailings belong to the category of sandy silts with minimal plasticity, falling under the ML designation within the Unified Soil Classification System (USCS). Such categorization is commonly observed in tailings originating from hard rock metal mining operations. Typically, for the paste tailings blend, the tailings material must comprise a minimum of 15% by weight of fine particles (sized <20 µm) to adequately retain water and facilitate paste formation (Kesimal et al., 2005b). Tables 3.1 and 3.2 list the most important physical and chemical properties of the silica tailings used.

Table 3.1 Physical properties of tailings used

Element	G_s	D_{10}	D_{30}	D_{50}	D_{60}
unit	–	µm	µm	µm	µm
ST	2.7	1.9	9	22.5	31.5
Average of 9 natural Canadian mine tailings	–	1.8	9.1	20	30.8

Table 3.2 Mineralogical composition of the tailings used

Element unit	Al_2O_3	CaO	S_iO_2	Fe_2O_3	Na_2O	Pb	S_IO_2	K_2O
unit	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%
SI	0.1	<0.01	99.8	<0.01	<0.01	0	0	0

3.3.1.2 Polymer material

This study used commercially accessible cross-linked sodium polyacrylates (SAP) that are insoluble, showcasing a swelling capability of 250 grams (equivalent to around 8.82 ounces) per gram in deionized water. SAPs are gel-like substances that are hydrophilic and possess the capacity to absorb and retain substantial quantities of water relative to their weight. It's worth noting that about 95% of worldwide SAP production serves as absorbent materials for urine in disposable products (Fall, et al., 2010; John et al., 2003). The ion exchange capability inherent in SAP imparts hydrophobic characteristics and effective retention properties. Moreover, their strong ion exchange ability allows SAPs to bind heavy metals. However, SAPs exhibit reduced absorption capacity in ionic liquids, reaching their maximum absorption potential with distilled water. The size of SAP particles varies from diameters of 6,350 mm (0.250 in) to 45 mm (0.00177165354 in) (ARK 2003). Moreover, upon solvation, SAP chains unfurl, and ionic repulsion forces cause the molecules to expand, resulting in significant absorption capacities.

3.3.1.3 Mixing water

Deionized water was utilized for blending the PP material, ensuring the absence of any chemical variables throughout the testing procedures.

3.3.2 Preparation of the specimens

The tailings were oven-dried at 60 °C for 3 days to remove any moisture. The tailings and the required amount of deionized water were mixed for about 3 minutes to obtain a homogeneous water distribution in a mechanical blending device. While mixing continued, the necessary percentage of superabsorbent polymer (SAP) (0%, 0.2%, and 0.5%) was added and mixed thoroughly for 8 minutes to produce a homogenized polymer-PP mixture material. The prepared PP mixtures were packed in airtight polyethylene bags and then hydrated for 48 hours to reach moisture equilibrium. The prepared PP mixtures were then compacted in a Proctor mold according to ASTM D 698-00a. After the compaction, a cutting cylinder ring with a height of 15 mm and a sample diameter of 60 mm or a ring with a height of 16 mm and a plan dimension of 60 x 60 mm was used to cut undisturbed cores for consolidation and direct shear strength testing, respectively. The cut samples underwent trimming before being installed in a consolidation and direct shear testing machine for testing. The compaction characteristics and the coefficients of permeability (determined according to ASTM D 5084-00) of the prepared PP samples are shown in Table 3.3.

Table 3.3: Compaction characteristics of the prepared PP samples

Sample name	SAP content (%)	Optimum Water content, W_{opt} (%)	Maximum Dry Density (kg/m^3)	Coefficient of Permeability, k (m/s)
0% SAP (control)	0	18.2	1602	12.0×10^{-8}
0.2% SAP	0.2	25.6	1391	2.7×10^{-8}
0.5% SAP	0.5	30.7	1191	5.5×10^{-8}

3.3.3 Testing methods and procedures

Consolidation experiment

Consolidation tests were carried out according to ASTM D 2435 standard. Fixed ring gauges with a brass ring, an inner diameter of 60 mm, and a height of 15 mm were used. Undisturbed samples were extracted from each sample using a ring. Porous stones were placed at both ends of each sample to ensure vertical drainage in both directions. Filter papers were placed between the sample and the porous stones to prevent fine particles from being pushed into the pores of the stones. The intensity of saturation was calculated based on the moisture content of the sample at the end of the test. Samples were subjected to nine different effective stresses: 5, 10, 20, 40, 80, 160, 320, 640 and 1280 kPa. The duration of each stage was 24 hours. A dial gauge was used to monitor and record the consolidation process over time. At the end of the charging process, the sample was unloaded to 5 kPa in the order of 1280, 640, 320, 160, 80, 40, 20, and 10, and the duration of each discharging phase was 24 hours. The resulting data were recorded both automatically and manually.

Direct shear test

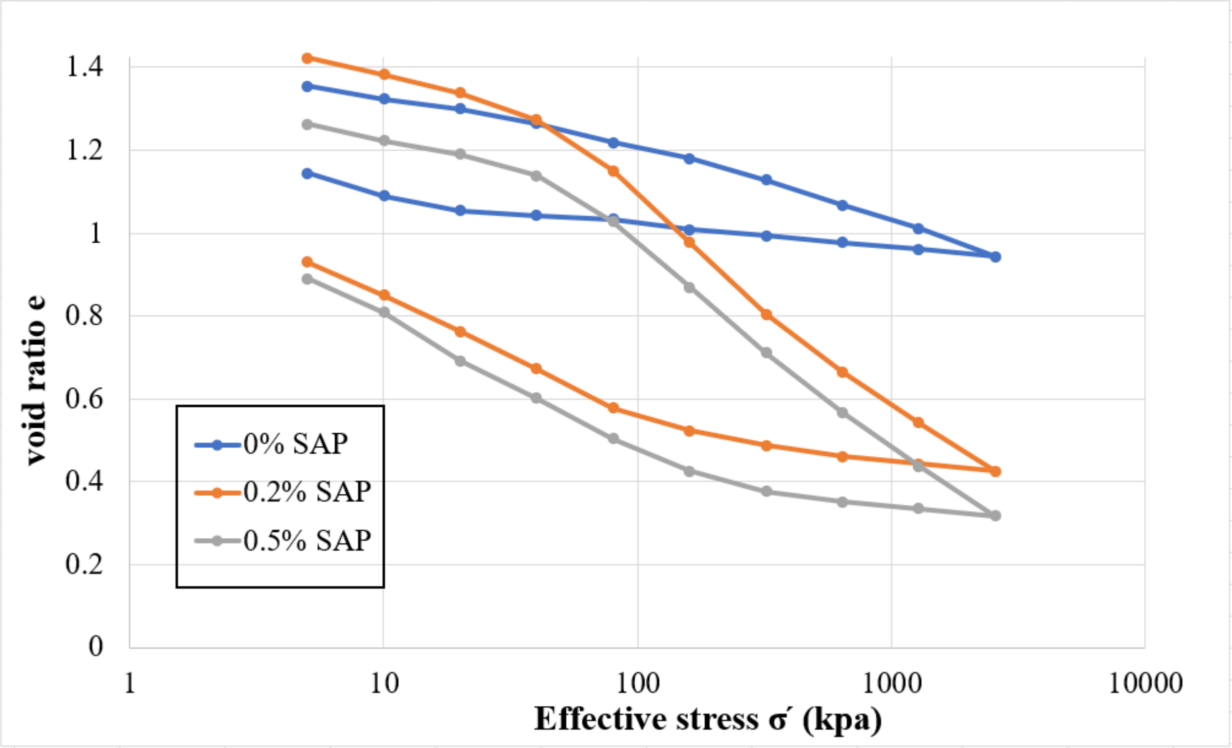
The direct shear experiments on PP mixtures were conducted utilizing a direct shear box device following ASTM D6528-17 standards. The lower section of the shear box was supported by rollers and connected to a motor via a gear unit, enabling consistent extension at a fixed rate. The upper section of the shear box was linked to a test ring for measuring horizontal (shear) force. The specimens underwent the application of normal stress via a loading frame with a lever arm ratio of 10:1. Normal stresses of 100, 200, and 400 kPa were applied in this study. Shearing was performed at a strain rate of 0.5 mm/min to determine the shear strength parameters. The tests utilized statically compacted samples measuring 60 mm in diameter and 60 mm in height. These tests were conducted under compacted circumstances (compacted samples), with varying concentrations of SAP (0% SAP, 0.2% SAP, and 0.5% SAP). Vertical deformations recorded during the test, including normal stress application and shearing, were monitored to assess changes in sample volume (void fraction).

3.4 Results and Discussion

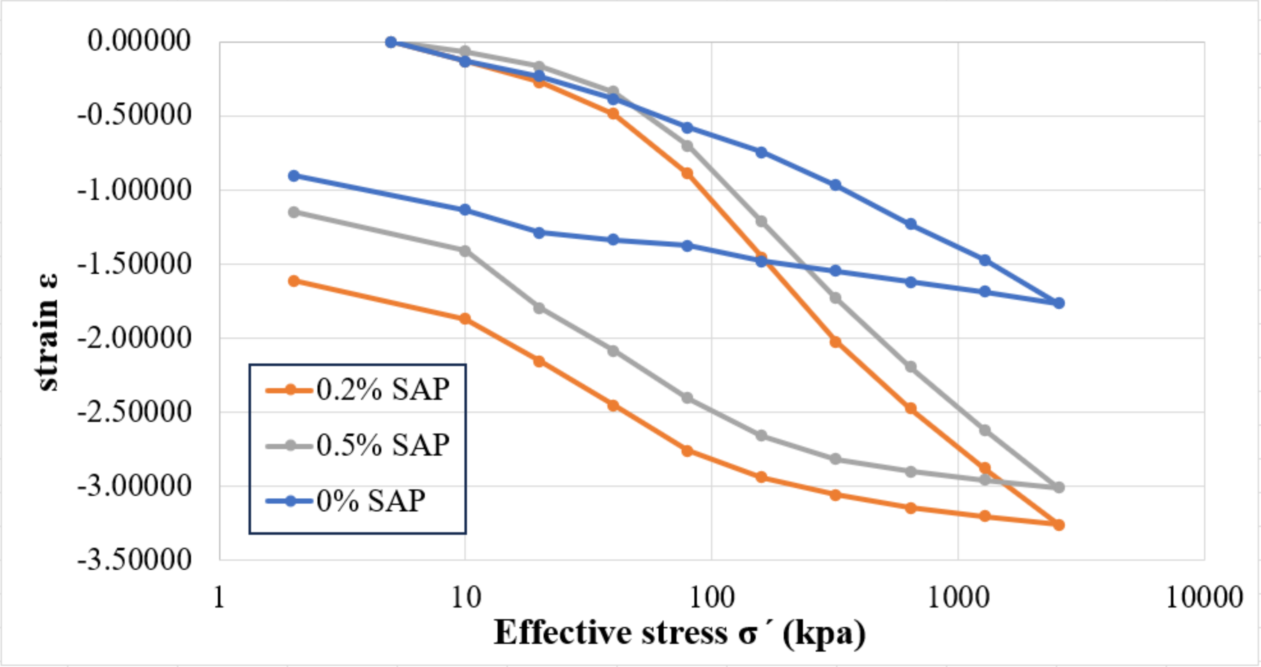
3.4.1 Consolidation behavior of polymer-pastefill

3.4.2 Stress-strain behavior

The results of consolidation experiments carried out on compacted polymer-pastefill (PP) samples with varying SAP contents (0% SAP, 0.2% SAP, and 0.5% SAP) are depicted in Fig. 3.2. The consolidation results are illustrated through curves of void ratio, e, versus the logarithm of effective consolidation stress, log σ', (Fig. 3.2a), and strain, ε, versus log σ' (Fig. 3.2b). The compression index, Cc, and the swell index, Cs, which denote the inclines of the loading and unloading segments of the stress-strain curves σ' respectively, are summarized in Table 4. Cc and Cs were derived from relevant sections of the e-log curves shown in Fig. 2 for each PP sample. Both loading and unloading sections of the stress-strain curves exhibited a bisemilog linear behavior when PPs with SAP were tested, with slopes at lower effective stress σ' being higher than those at higher effective stress σ'. Moreover, these slopes are influenced by the presence of SAP and its content. Specimens with SAP have lower values of Cc, but higher values of Cs (Table 3.4). For instance, the Cc value for 0.0% SAP was 0.0601, and for 0.5% SAP, it was 0.0551, while the swelling index for 0.0% SAP was 0.1944, and for 0.5% SAP, it was 0.2673. Moreover, the values of Cc and Cs decrease and increase slightly, respectively, as the SAP content increases. This pattern is likely due to the increased polymer content in the 0.5% SAP sample. Super Absorbent Polymers (SAP) are hydrophilic with high water absorption capacity, and they are recognized for their susceptibility to variations in stress conditions (Buchholz and Graham 1998). Consequently, the higher SAP content in the 0.5% SAP sample exhibited greater swelling potential compared to the 0% SAP and 0.2% SAP samples, resulting in increased resistance to compression. Furthermore, the decrease in the compression index (Cc) from 0% to 0.5% SAP, as shown in Table 3.4, indicates that the addition of SAP to the PP mixture and increasing its content up to 0.5% result in a decreased susceptibility of the proposed PP barrier to significant deformation under compressive mechanical load. For example, the void ratios for 0%, 0.2%, and 0.5% SAP decreased during compression from 1.1443 to 0.0601, 0.9300 to 0.0574, and 0.8900 to 0.0551, respectively. This behavior is due to the sufficient amount of polymer present in the 0.5% SAP. Table 3.4 also indicates that the values of the compression coefficient of C_c for 0.2%SAP samples (0.0574) and 0.5% SAP samples (0.0551) are relatively close, indicating that these PP materials exhibit relatively similar compressive behavior (Figure 3.2). The findings presented and discussed above highlight the critical role of superabsorbent polymer in modulating the compression and swelling behavior of PP barrier under varying mechanical loading conditions.



a) Effective consolidation stress versus void ratio



b) Effective consolidation stress versus strain

Figure 3.2 Effective consolidation stress versus (a) Void ratio; (b) Strain for PP with 0%, 0.2% and 0.5% SAP.

Table 3.4: Compression index (Cc), Swell index (Cs) and Void ratio

SAP (%)	Compression index, Cc	Swell index Cs	Final void Ratio, ef	
0	0.0601	0.1944	1.1443	
0.2	0.0574	0.2497	0.93	
0.5	0.0551	0.2673	0.89	

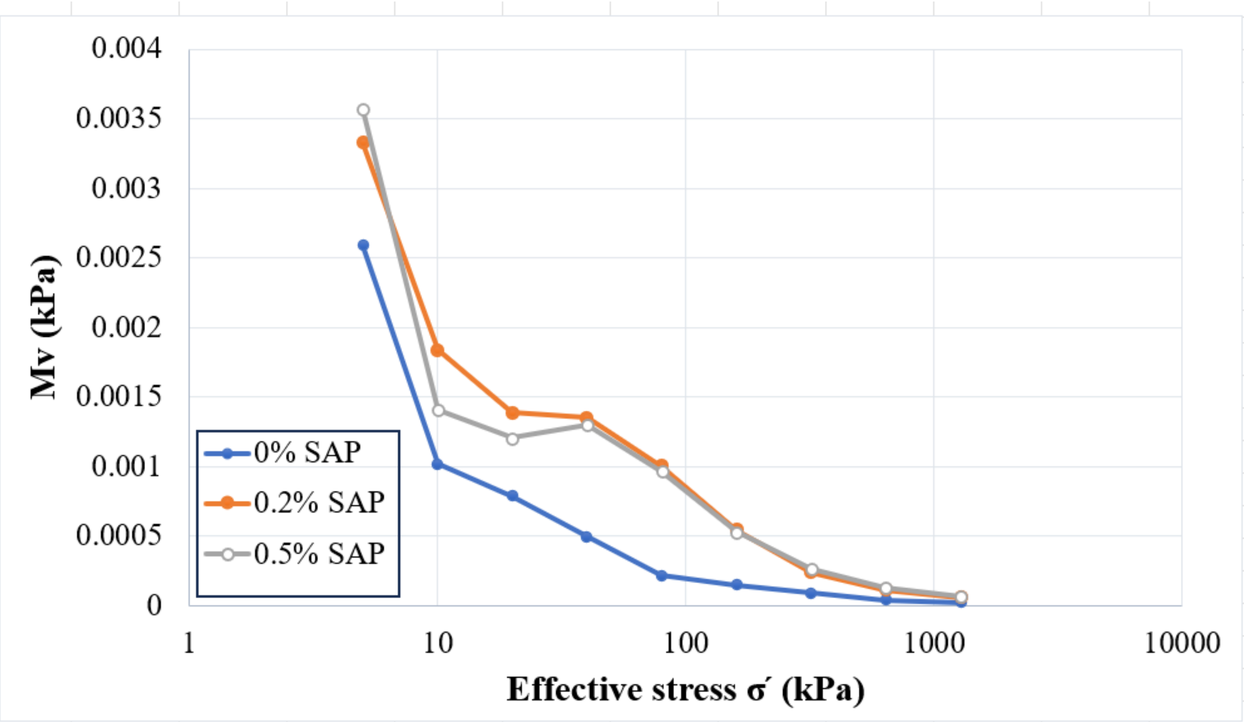
3.4.1.2 Coefficients of volume change, compressibility, and consolidation

The volume change coefficients, m_v, and compressibility coefficients, a_v, were derived from the slopes of the curves depicting void ratio versus effective stress σ′ and strain versus effective stress σ′, respectively, throughout the consolidation test loading phases. These calculated m_v and a_v values are compiled in Table 3.5 and illustrated against effective stress σ′ in Fig. 3.3, where effective stress σ′ represents the ultimate stress for each load increment. Generally, as σ′ increases, mv and av values decrease, typically following the sequence of 0%, 0.2%, and 0.5% SAP, as indicated in Table 3.5. This sequence correlates directly with the quantities of superabsorbent polymer present in each PP sample. Consequently, the variations in compressibility among the three PP samples can be primarily ascribed to differences in the SAP content. However, the presence and amount of SAP in the PP samples significantly impact their compressibility during consolidation. Higher SAP content leads to higher initial compressibility due to increased void spaces, but this effect diminishes as effective stress increases, and the SAP particles are compressed.

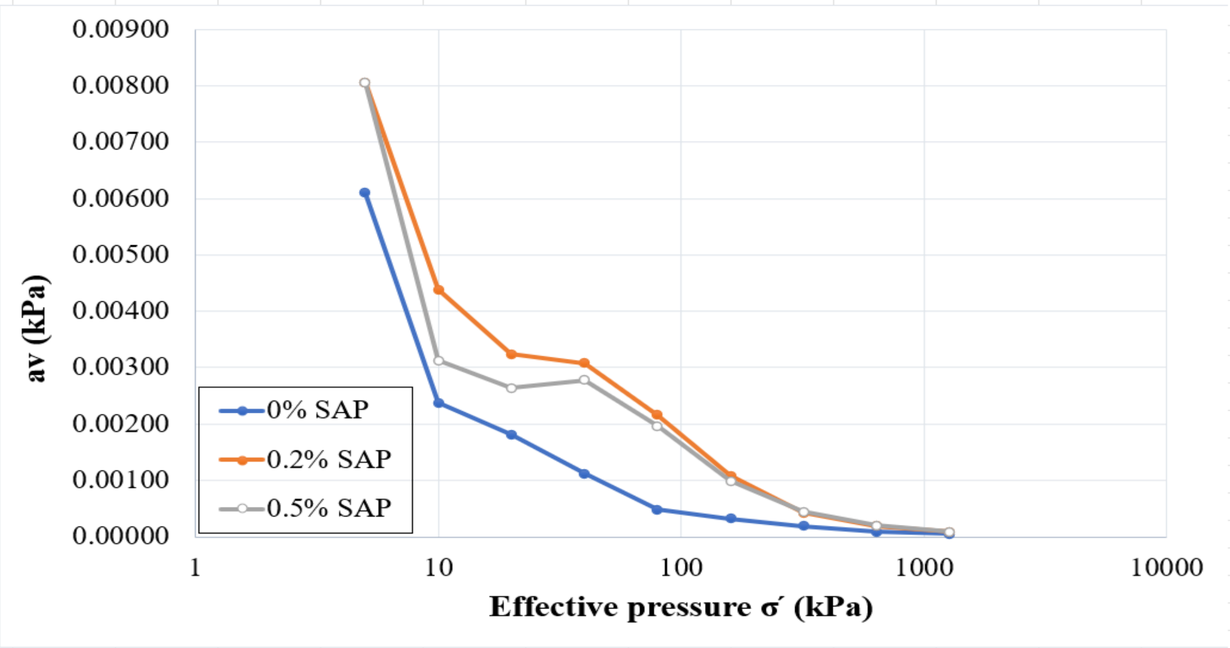
Table 3.5: Coefficient of volume change (M_v) and coefficient of compressibility (a_v)

SAP (%)	Coefficient of volume change M_v ($x10^{-3}$ kPa^{-1})	coefficient of compressibility a_v ($x10^{-3}$ kPa^{-1})
0	2.592	6.103
0.2	3.329	8.065
0.5	3.564	8.065

The consolidation coefficients c_v were determined for the consolidation tests' loading levels using the logarithm of time method (Casagrande) and the square root of time method (Taylor). The C_V values are summarized in Table 3.6. All c_v values shown in Figure. 3.4 (a, and b) are plotted against the mean consolidation stress for the load increment. Typically, the coefficient of consolidation increases as the average effective consolidation stress increases for all PP specimens and both methods. This is also evident in the SAP in the pastefill mixture. Conversely, c_v also exhibits an inverse relationship with the volume change coefficient m_v (Figure 3.3a), which diminishes as the effective stress increases (Duncan 1993). Therefore, if m_v decreases with increasing load, an overall increase in c_v can be expected with increasing load. The ratios of c_v values obtained using the Taylor method to those obtained using the Casagrande method, denoted as CvTaylor / CvCasagrande, are graphed against the mean in Fig. 3.4(c). Typically, the values derived from the Taylor method exceed those obtained from the Casagrande method, as indicated by a ratio greater than one. This discrepancy can be attributed to several factors, including the strain rate at various effective stress levels (σ') and the subsequent compression occurring during initial consolidation (Duncan 1993; Yeo et al., 2005; Shukla et al., 2009). The coefficient of consolidation (Cv) for samples with 0% SAP, 0.2% SAP, and 0.5% SAP increases as the average effective consolidation stress increases in Figure 3.4 (a, b, and c) and Table 3.6. This increase can be attributed to factors such as enhanced pore water pressure dissipation, reduced void ratios, improved soil structure stability, and the dynamic water-absorbing properties of SAP. These factors collectively facilitate a more efficient and rapid consolidation process. The presence of SAP further influences this process by modifying the water retention and expulsion characteristics of the pastefill mixture. However, excessive SAP can lead to reduced Cv due to over-swelling and potential structural disruption, as observed in the Taylor method results (Fig. 3.4(b)).

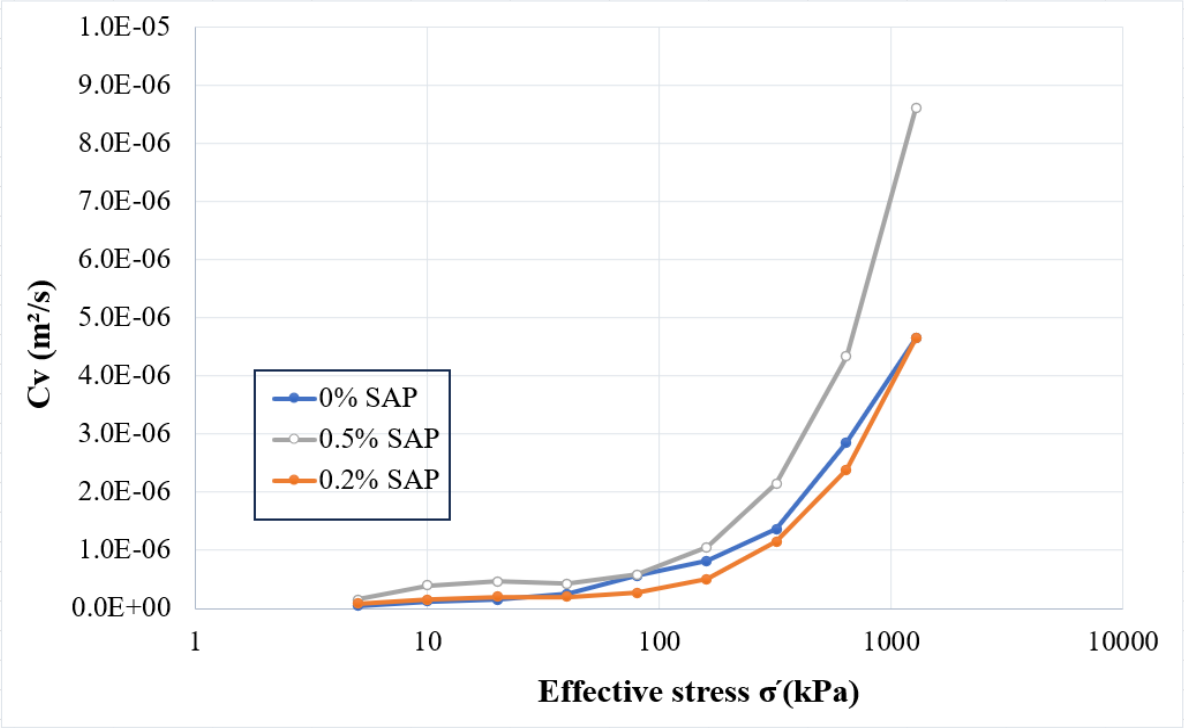


a) Effective consolidation stress versus coefficient of volume change

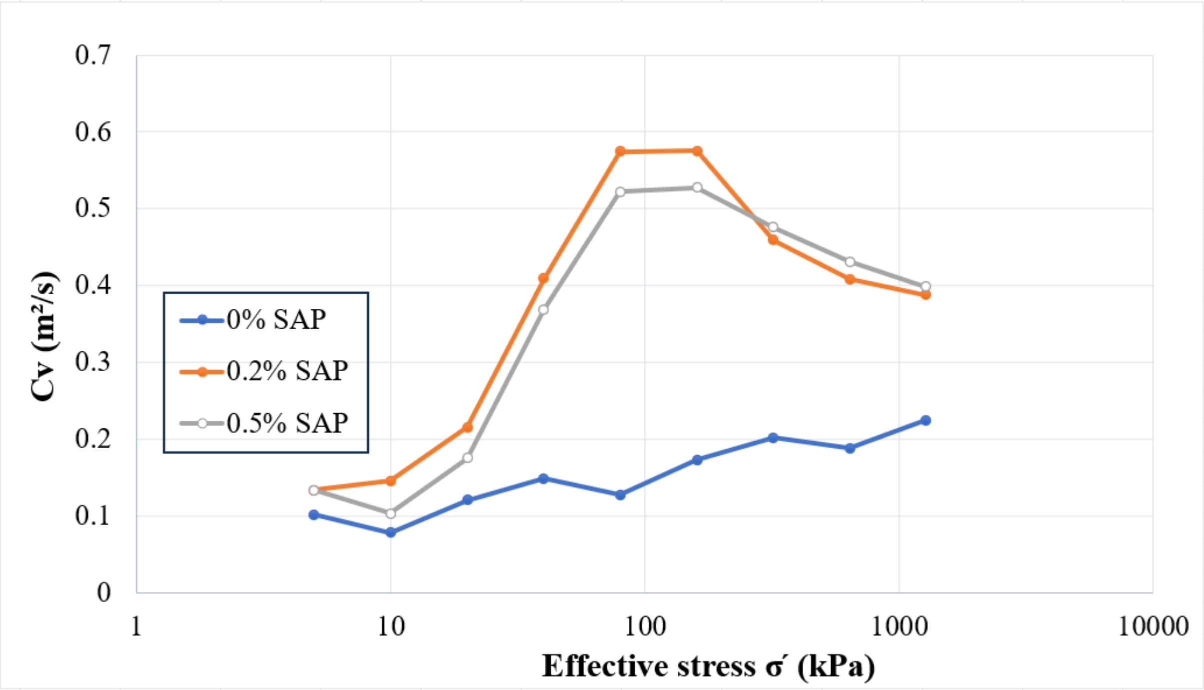


a) Effective consolidation stress versus coefficient of compressibility

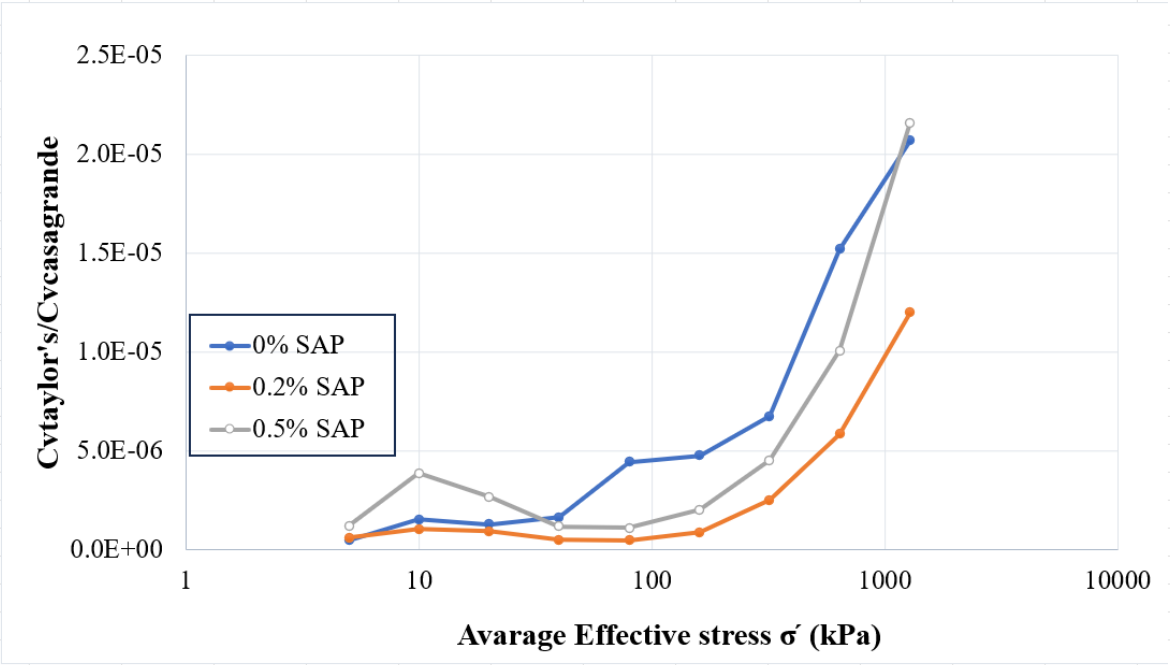
Figure 3.3 Effective consolidation stress versus (a) Coefficient of volume change (b) Coefficient of compressibility for PP with 0%, 0.2%, and 0.5% SAP.



a) Effective consolidation stress versus Casagrande's method



b) Effective consolidation stress versus Taylor's method



c) Effective consolidation stress versus a ratio of Taylor's method to Casagrande's method

Figure 3.4 Coefficient of consolidation based on (a) Casagrande's method; (b) Taylor's method; (c) a Ratio of Taylor's method to Casagrande's method for PP with 0%, 0.2%, and 0.5% SAP.

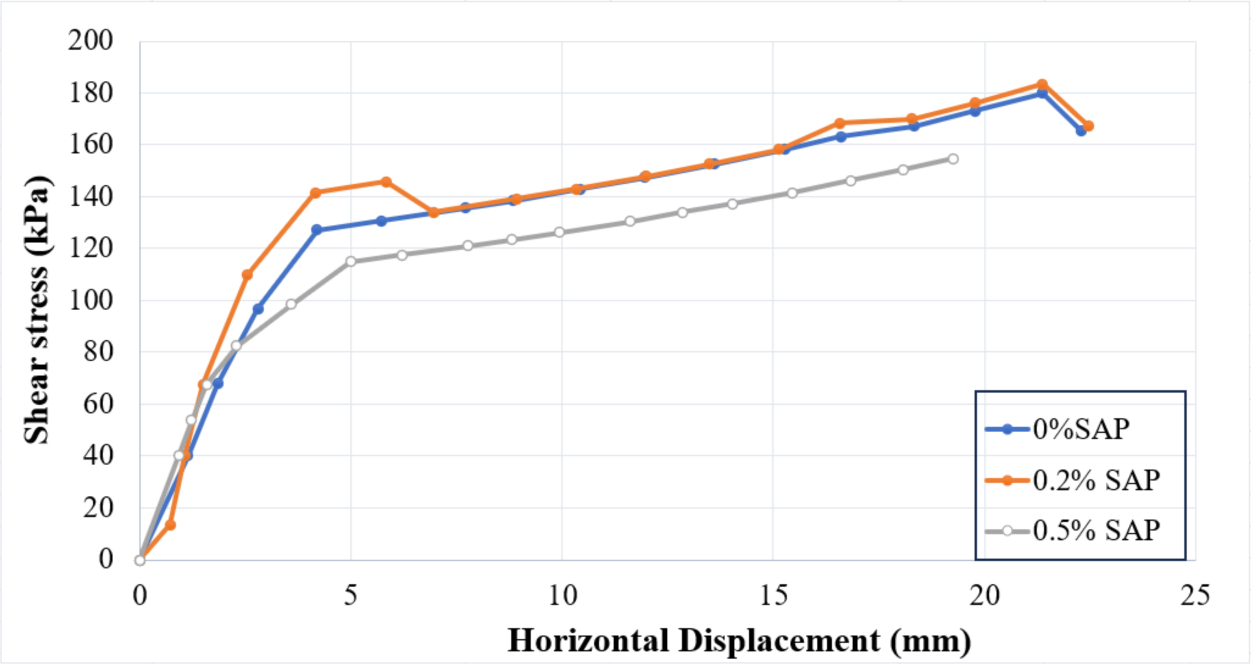
Table 3.6: Casagrande's method, Taylor's method, and Casagrande / Taylor method

	Casagrande's method	**Taylor's method**	**Casagrande / Taylor**
SAP (%)	C_v (x10^{-7} m^2/s)	C_v (x10^{-6} m^2/s)	C_v (x10^{-6} m^2/s)
0	0.047	0.225	2.068
0.2	0.082	0.388	1.198
0.5	0.157	0.399	2.158

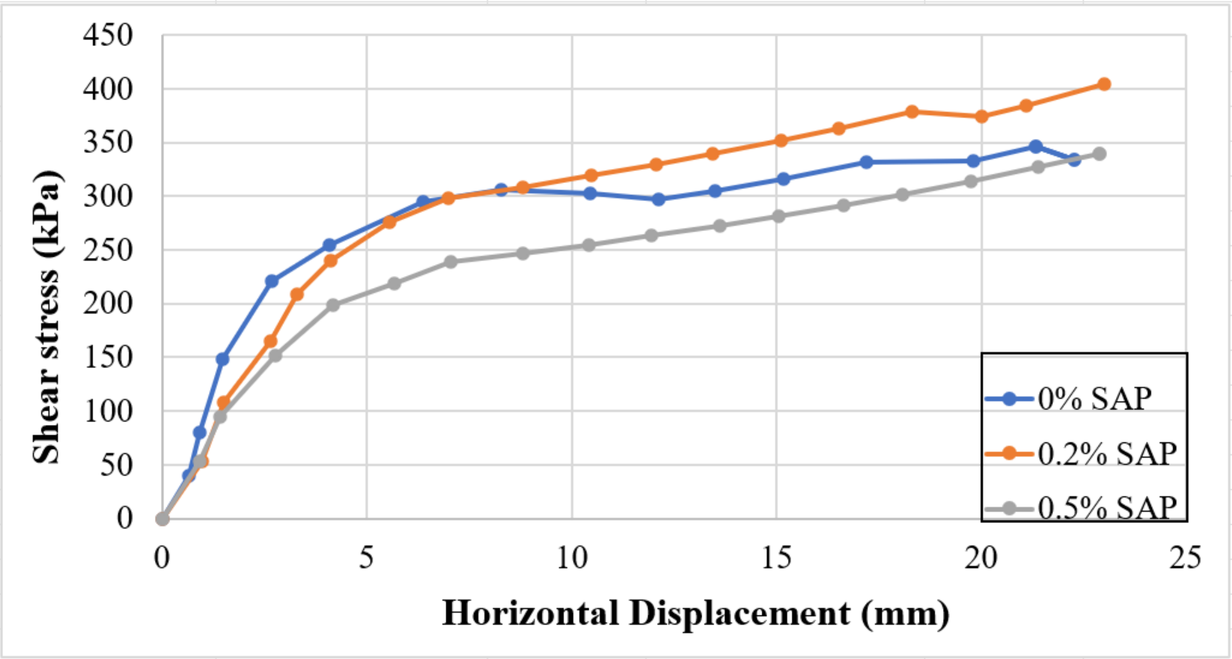
3.4.2 Shear characteristics of PP

Figure 3.5 (a, b, and c) presents plots of horizontal displacement against shear stress for PP samples (0% SAP, 0.2% SAP, and 0.5% SAP) with the normal pressure of 100 kPa, 200 kPa, and 400 kPa respectively. The graphs show that the horizontal displacement-shear stress curves follow similar patterns and shapes, regardless of the presence or amount of SAP. This suggests that SAP content does not significantly influence the form of the displacement-stress curves for the PP barrier material. Additionally, Figure 3.5 illustrates that the stress-displacement curves for the PP samples generally show no distinct peak shear stresses. In the absence of a clear peak, the shear stress at 15% shear strain is considered the peak shear stress or shear strength, as per ASTM guidelines.

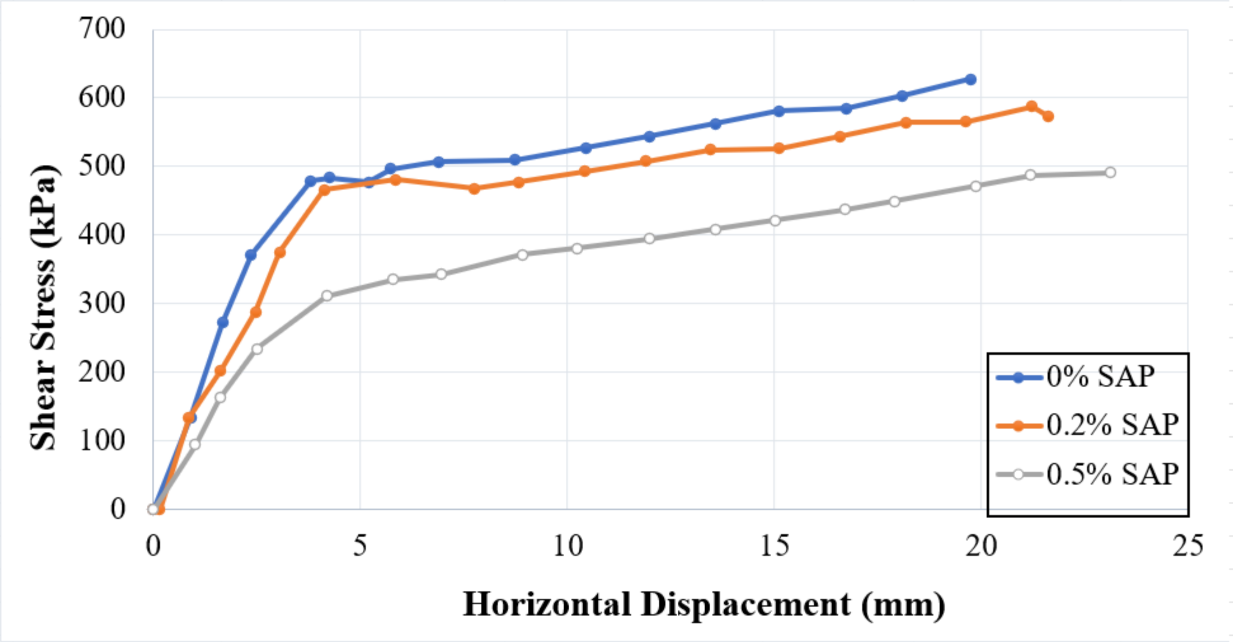
Observations reveal that shear strength increases with 0.2% SAP but decreases when the SAP content is raised to 0.5%, particularly under high normal stress (200 kPa). This SAP-induced increase in shear strength behaviour can be attributed to the swelling properties of SAP, which may enhance the interparticle bonding in the pastefill and create a more interconnected and stable structure, particularly at 2% SAP. While a certain amount of SAP can improve shear strength, excessive SAP can lead to over-swelling, which disrupts the pastefill mixture. Excessive swelling can break particle bonds and increase the void space between particles. Additionally, the over-swollen SAP may act as lubricants or fillers within the pastefill mixture, reducing overall cohesion and friction between particles, as observed with the 0.5% SAP sample.



a) Horizontal displacement versus shear stress for 100 kPa stress



b) Horizontal displacement versus shear stress for 200 kPa stress



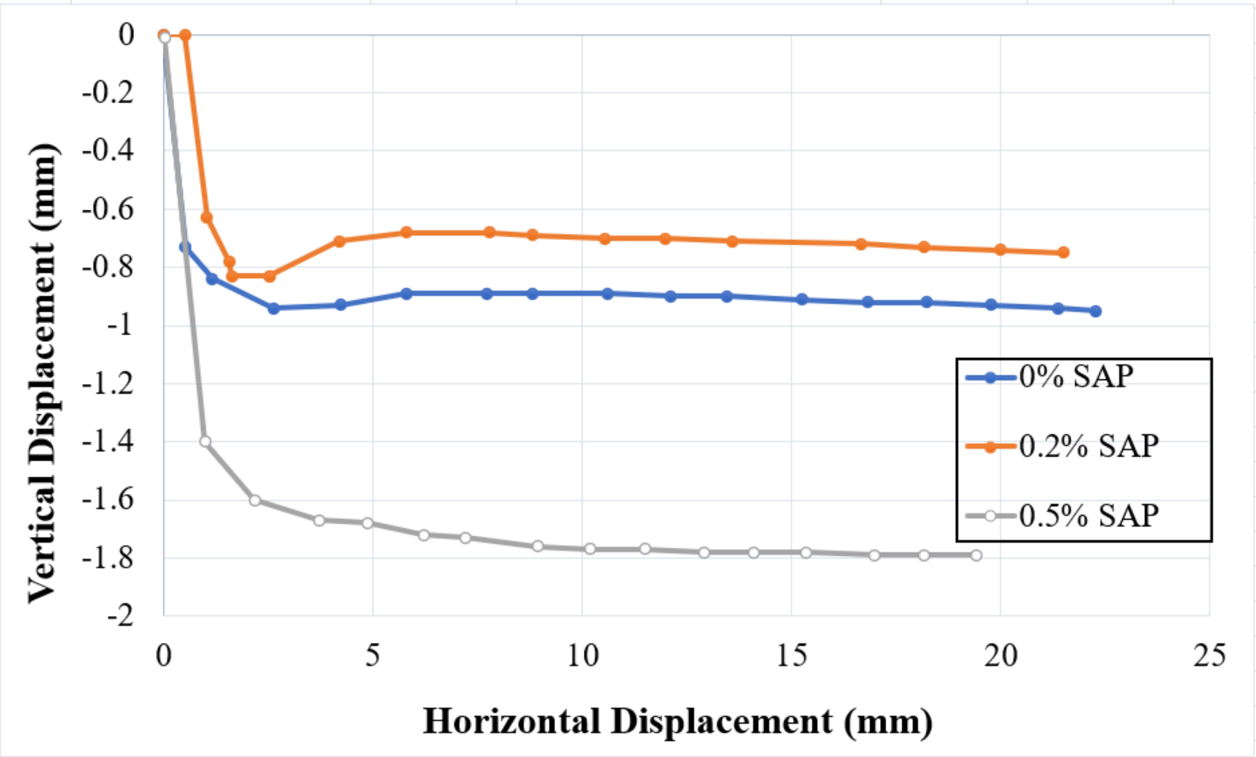
c) Horizontal displacement versus shear stress for 400 kPa stress

Figure 3.5 Shear stress-horizontal displacement for SAP-Pastfill mixture for 0%, 0.2% and 0.5% SAP. (a) 100kPa (b) 200kPa and (c) 400 kPa.

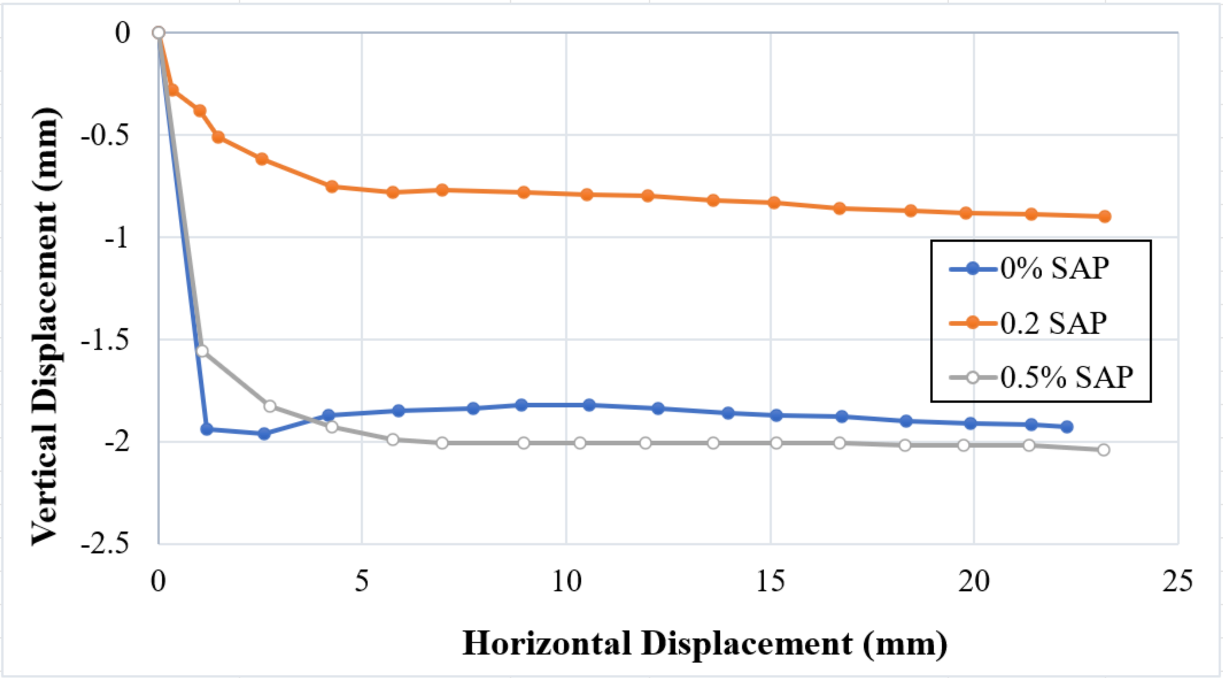
Figure 3.6 (a, b, and c) presents typical results of the volume change curves, depicted as variations in vertical displacement relative to horizontal displacement. The results clearly demonstrate that the volume deformation of the PP samples, both with and without SAP, can be broadly grouped into two stages during horizontal displacement under a given normal stress. Irrespective of the presence or absence of SAP and its content, the first stage is characterized by vertical contraction of the barrier material, which corresponds to an increase in shear stress. This contraction occurs because, at the onset of shear loading, additional contacts are formed between tailings particles, reducing local void spaces and decreasing the void ratio (Fang and Fall, 2022). Larger vertical deformations were observed in specimens subjected to higher normal stresses (200, 400 kPa) due to a more significant reduction in local voids under these conditions.

Furthermore, Figure 3.6 indicates that the magnitude of contraction is influenced by the SAP content in the barrier material. Specifically, the contraction follows this decreasing order with respect to SAP content, regardless of the applied normal stress: 0.2% SAP < 0.0% SAP < 0.5% SAP. These observations suggest the existence of a threshold SAP content at which the SAP-bearing PP samples become less contractive than the control PP samples, i.e., those without SAP. The presence of this SAP threshold can be explained as follows. Below the threshold, SAP swelling is accommodated within the voids between tailings particles, meaning that the structure of the PP mixture remains unchanged as the SAP swells in contact with water. Consequently, once consolidated and sheared, the presence of this optimal (threshold) SAP content results in less space between the solid particles (tailings and SAP) in the tested barrier material, leading to reduced contraction. However, beyond the threshold SAP content, the SAP swells excessively, filling the voids and pushing the tailings particles apart, causing the paste tailings–SAP mixture to swell. An excessively high SAP content would lead to over-swelling, disrupting the mixture and creating additional void spaces. This over-swelling increases the space between solid particles in the tested barrier material, resulting in greater contraction when the sample is subjected to consolidated undrained shear tests. Similar behaviors have been observed in compacted clay-sand mixtures with different clays under shear stress (Elkady et al., 2015). In conclusion, the variation in contraction behaviors observed for different SAP concentrations can be fundamentally attributed to the swelling properties of SAP and its impact on the structural integrity of the pastefill mixture. At lower concentrations (0.2%), SAP enhances stability by improving interparticle bonding, whereas higher concentrations (0.5%) lead to over-swelling, creating void spaces and disrupting the mixture, which results in increased volume changes and reduced stability.

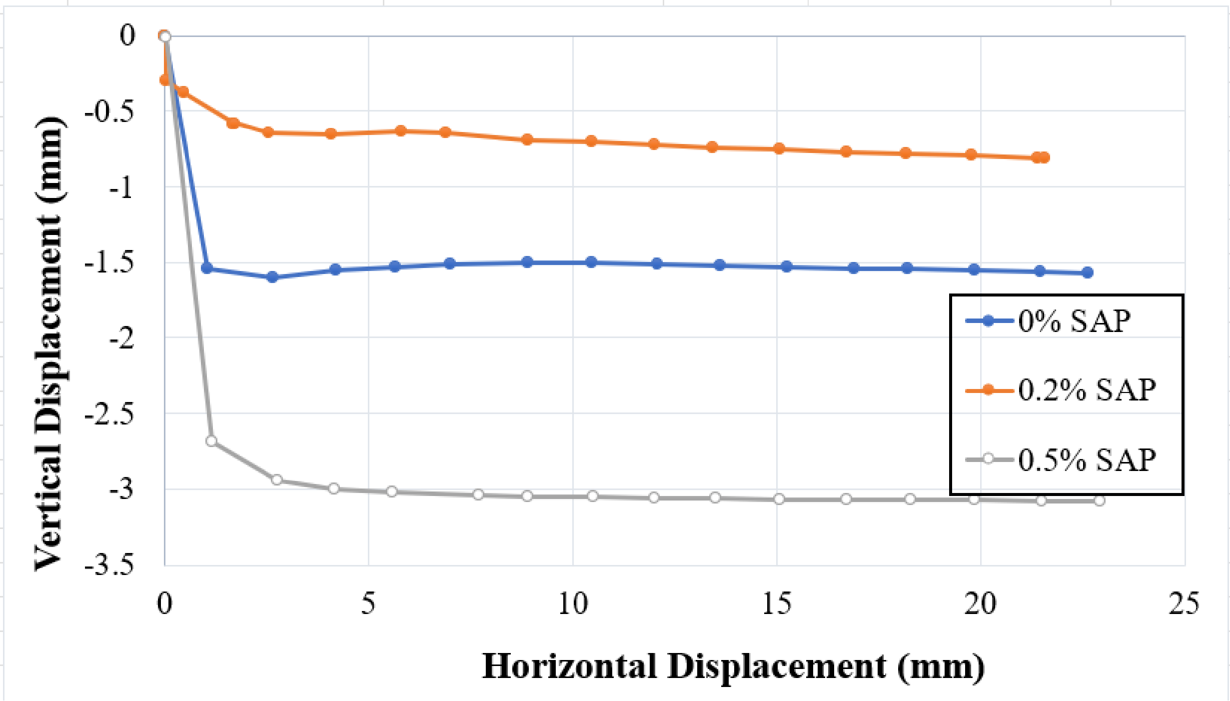
Moreover, Figure 3.6 reveals that during the second stage, under low applied normal stress (100 kPa), the barrier materials without SAP and with low SAP content (0.2%) exhibited slight expansion due to dilatancy as shear loading progressed, while the volume deformation of the specimen with high SAP content remained relatively constant. This dilatancy in the 0.0% SAP and 0.2% SAP samples is attributed to the higher density of these samples compared to the lower density of the 0.5% SAP sample (Table 3.3). The higher density results in more tightly packed tailings particles in the 0.0% SAP and 0.2% SAP samples compared to the 0.5% SAP sample. Consequently, under shear stress, the tailings particles in the denser samples attempt to rearrange into a more stable configuration to reduce internal resistance caused by particle interlocking. This rearrangement leads to an increase in void ratio and, therefore, an overall increase in the material's volume (Yin and Zhu, 2020). For higher normal stresses of 200 and 400 kPa, no dilatation was observed after the contraction phase, regardless of SAP content. This absence of dilatation is due to the high applied normal stresses compressing the void spaces between solid particles, which counteracts any attempt by the particles to move apart during shearing (Yin and Zhu, 2020). This suppression of void space expansion prevents the barrier material from dilating, as there is no room for the volume to increase.



a) Horizontal displacement versus vertical displacement for 100 kPa stress



b) Horizontal displacement versus vertical displacement for 200 kPa Stress



c) Horizontal displacement versus vertical displacement for 400 kPa stress

Figure 3.6 Volume change behavior-horizontal displacement for SAP-Pastfill mixture for 0%, 0.2% and 0.5% SAP. (a) 100kPa (b) 200kPa and (c) 400 kPa.

The shear strength, defined as the maximum shear stress that the barrier material can withstand, is a critical parameter for assessing the mechanical performance of barriers used in waste containment. Figure 3.7 illustrates the relationship between peak shear stress (shear strength) and normal stress for PP mixtures with varying superabsorbent polymer (SAP) content. The peak shear stress versus normal stress curves were well-fitted using linear regression in accordance with the Mohr–Coulomb failure criterion, with all fitted lines demonstrating a high correlation ($R^2 > 0.95$).

$$\tau = c + \sigma_n \tan(\phi) \qquad (1)$$

where τ is the shear strength, c is the cohesion, σ_n is the normal stress, and φ is the friction angle. The values of c and φ are presented in Figure 3.8 and Table 3.7.

As shown in Figure 3.7, shear strength generally increases with rising SAP content, reaching a peak at 0.2% SAP. However, further increasing the SAP content to 0.5% leads to a decline in shear strength. This trend in shear strength variation with SAP content can be attributed to changes in the structural arrangement of the paste tailings–SAP mixture, which depends on the interaction between tailings grains and SAP particles. Up to the SAP threshold content, the SAP contributes positively to the shear strength of the SAP–paste tailings mixture, as grain-to-grain contact is maintained. However, when the SAP content exceeds this threshold, the over-swollen SAP particles begin to push apart the tailings grains, resulting in a reduction in shear strength.

Figure 3.8 and Table 3.6 also demonstrate that SAP content significantly influences the cohesion and internal friction angles of the barrier specimens. The cohesion values (c) for samples with 0%, 0.2%, and 0.5% SAP content are 30.0, 54.7, and 62.0 kPa, respectively, while the corresponding internal friction angles (φ) are 50.7º, 47.5º, and 38.6º respectively These elevated friction angle values are attributed to the pronounced angularity of the tailings particles. Greater particle angularity is typically linked to higher friction angles, as noted by Holubec and D'Appolonia (1973). These results also indicate that higher SAP content substantially enhances cohesion while reducing the internal friction angle. The increase of cohesion with rising SAP content can be attributed to the interaction between SAP and water. Superabsorbent polymers absorb and retain water, causing them to swell. The swollen SAP particles act as a binding agent within the tailing's matrix. Thus, this expansion of SAP improves the overall interparticle bonding. This enhanced bonding increases leads to an increase in the measured cohesion during shear tests. Additionally, the water retention capacity of SAP contributes to maintaining a stable soil moisture content, further enhancing the cohesive properties of the SAP-PP mixture. These combined effects contribute to greater cohesion in the barrier material. The observed decrease in friction angle values with higher SAP content can be attributed to the swollen SAP particles acting as a lubricant between the tailing's particles, reducing the frictional resistance as the particles slide past each other during shearing.

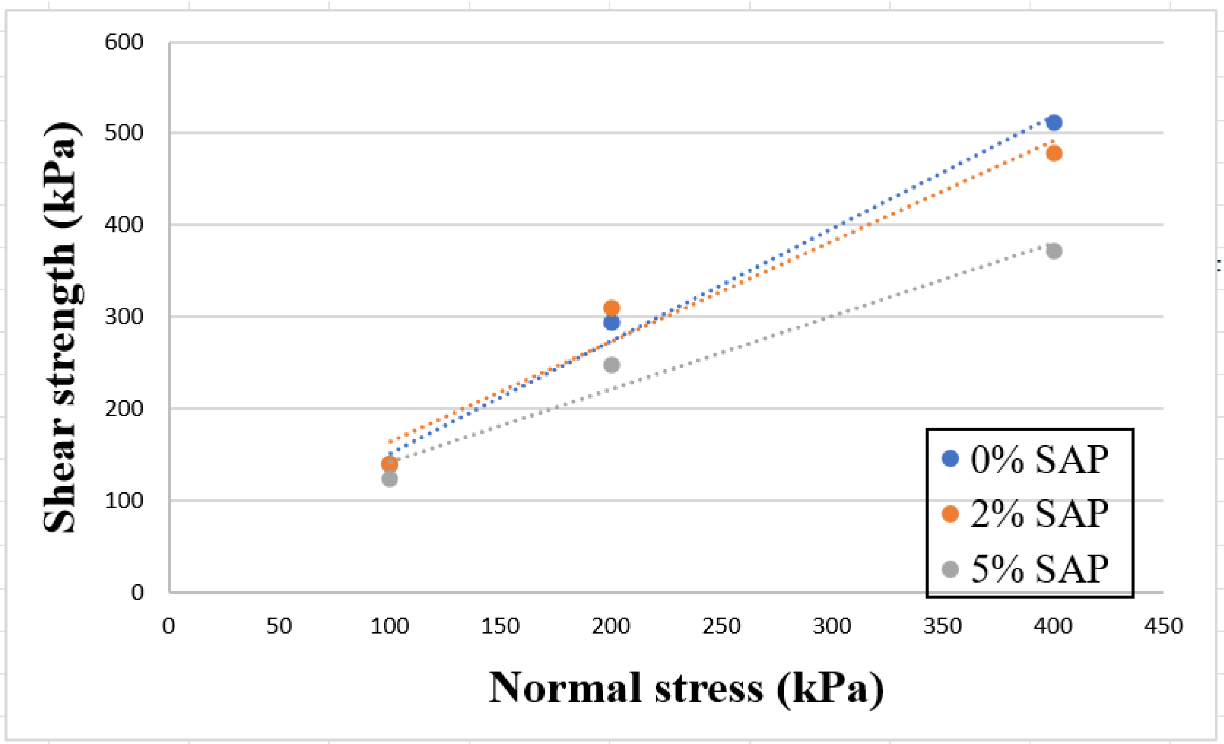


Figure 3.7 Normal stress vs the shear strength of the SAP-Pastfill mixture. for 0%, 0.2% and 0.5% SAP.

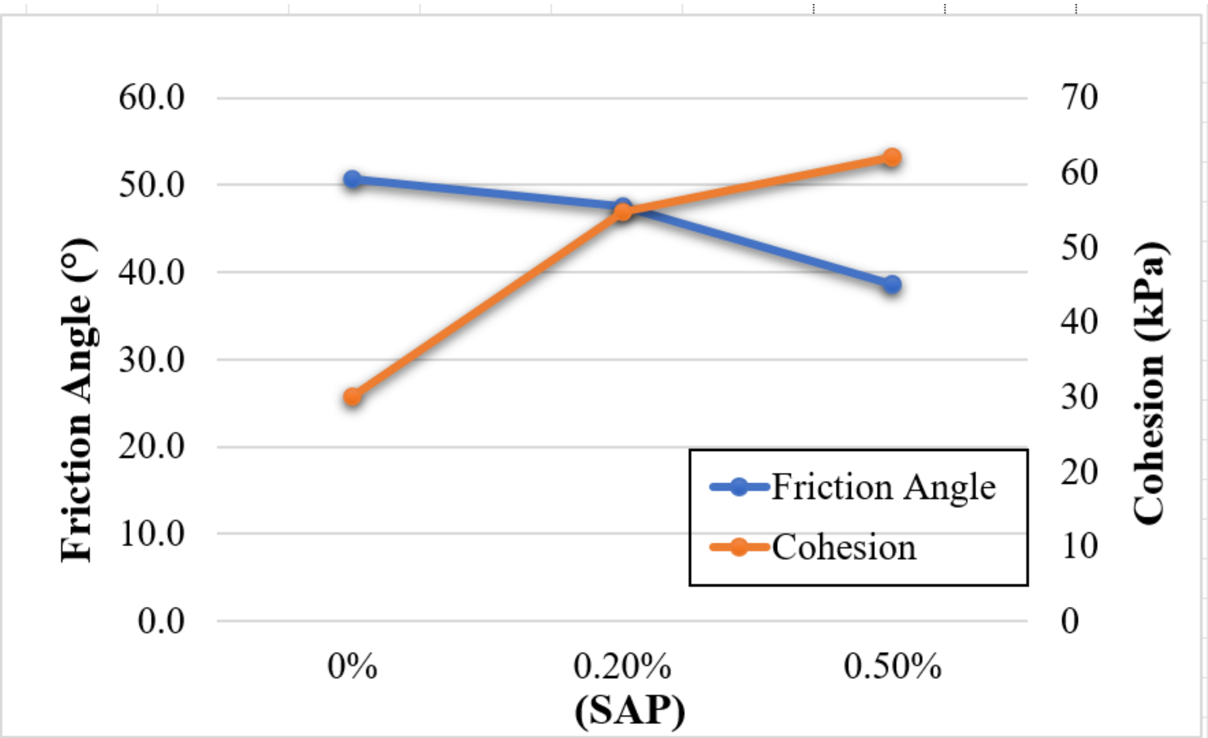


Figure 3.8 Friction angles vs the cohesion angles of SAP-Pastfill mixture. for 0%, 0.2% and 0.5% SAP. (a) 100kPa (b) 200kPa and (c) 400 kPa.

Table 3.7: Cohesion C and Angle of Friction (º)

% SAP	**Cohesion, C**	**Angle of Friction**
0%	30.0	50.7
0.20%	54.7	47.5
0.50%	62.0	38.6

3.5 Summary and Conclusions

This study provides a comprehensive analysis of the consolidation behavior and shear strength characteristics of polymer-paste fill (PP) barriers enhanced with superabsorbent polymer (SAP) for waste containment applications. The experimental findings demonstrate that the inclusion of SAP significantly influences the mechanical performance of PP barriers, with notable impacts on both consolidation and shear properties.

The consolidation tests revealed that the rate and magnitude of consolidation increases with higher SAP content, particularly at 0.5% SAP. This behavior is attributed to the superior water absorption capacity of SAP. The results underscore the importance of selecting an optimal SAP concentration to achieve the desired balance between consolidation rate and structural integrity.

Shear strength analyses indicated a peak in shear strength at 0.2% SAP content, beyond which an increase in SAP to 0.5% resulted in a reduction in shear strength. The decline at higher SAP concentrations is likely due to the over-swelling of SAP particles, which disrupts the interparticle bonding within the pastefill, reducing friction and increasing void spaces. This finding suggests that there should be a threshold SAP content above which the mechanical stability of the barrier material may be diminished.

Overall, the study confirms that SAP-pastefill mixtures hold significant promise as a barrier material for waste containment facilities, offering the dual benefits of enhanced consolidation behavior and sufficient shear strength at optimal SAP concentrations. However, while the results are encouraging, further research is recommended to explore the long-term durability of these materials, particularly under varying environmental conditions such as freeze-thaw cycles.

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CHAPTER 4

TECHNICAL PAPER 2

Effect of Freeze-Thaw Cycles on The Consolidation Behaviour and Shear Strength Characteristics of SAP-Paste Tailings Barrier for Waste Containment Facilities

Chinaza C. Paul, Mamadou Fall

4.1 Abstract

The mining industry produces large amounts of solid waste and tailings, which can lead to significant environmental and geotechnical problems if not managed properly. With increasing public concern and strict government regulations, the industry is under pressure to implement waste disposal methods that are both environmentally sustainable and cost-effective. To meet these demands, innovative approaches are needed that effectively combine ecological responsibility with operational efficiency. One promising approach is the conversion of waste into construction materials for mining and civil engineering applications. A novel solution to this challenge is the development of densified polymer paste tailings or polymer-paste fill mixtures (PP) for waste containment facilities. These materials, created by compacting paste tailings with superabsorbent polymers (SAP), achieve very low hydraulic conductivity, well below the threshold required for effective barrier design in waste containment systems. While the hydraulic properties of compacted PP are promising, the mechanical characteristics such as consolidation behavior and shear strength remain largely unexplored, particularly under freeze-thaw conditions. This research aims to bridge this knowledge gap by investigating the effects of freeze-thaw cycles on the consolidation behavior and shear properties of PP materials. This study is especially crucial for improving waste containment strategies in cold climate regions where freeze-thaw cycles are prevalent. The experimental procedure involved subjecting 0.2% SAP paste tailings to multiple freeze-thaw cycles, ranging from 0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles, at temperatures between 20°C and −20°C. Following these cycles, the material underwent consolidation and direct shear testing per ASTM standards. Consolidation behavior was assessed through oedometer tests, where settlement was monitored under various stress conditions, while shear properties were evaluated using direct shear tests to measure the material's resistance to shearing and deformation under different normal stresses. The results revealed that freeze-thaw cycles significantly impact the consolidation behavior of SAP paste tailings, leading to an increased void ratio as the number of cycles increases. Repeated freeze-thaw cycles can cause material degradation, forming finer particles and further increasing the void ratio. The shear strength of SAP paste tailings exhibited complex behavior under freeze-thaw conditions: initial resilience was observed, but subsequent cycles showed fluctuations in strength, likely due to partial recovery, stabilization, or damage accumulation. Overall, this study emphasizes the need to carefully consider environmental factors, such as freeze-thaw cycles, in the design of waste containment strategies to ensure the long-term stability and effectiveness of these facilities.

Keywords: tailings; mine; barrier; paste backfill; super absorbent polymer; mechanical properties.

4.2 Introduction

Effective waste management, including containment and safe disposal, has become a top priority due to the significant waste generated in the mining and industrial sectors. Without proper management, there is the risk of pollution and contamination, with severe consequences for ecosystems and human health. Waste disposal facilities play a critical role in preventing such harm by responsibly handling waste materials and preventing pollutants from seeping into the environment. The waste generated by mining operations includes tailings, which have a significant environmental impact (Reid et al., 2009). Traditionally, these tailings are often regarded as waste rather than a valuable resource, and therefore, they are commonly placed in tailings storage facilities, known as tailings impoundments, situated on the surface of the mine (Fall, et al., 2010; Ma et al., 2002). Due to the high water content in tailings, the construction of tailings dams is typically required to contain them within storage facilities (M. P. Davies & Martin, 2000). Nonetheless, there are over 3500 notable tailings dams globally, according to some studies (Rico et al., 2008). Numerous major geotechnical failures such as dam breaks and liquefaction have taken place globally in the last three decades. These events have created major challenges, especially because there is a growing need to manage mining waste (tailings) in an environmentally sustainable way.

The consequences of TSF failure extend beyond economic losses and human causalities, impacting public perception, regulatory requirements, and government supervision. However, tailings can contain iron sulfide minerals such as pyrite and pyrrhotite, which are expelled during the concentration process (Elberling, et al., 1994; Fall, et al., 2010). If not properly managed, sulfide minerals have the potential to undergo oxidation when exposed to water, atmospheric oxygen, and trace metals in tailing impoundments. This process leads to the formation of wastewater that is characterized by low pH levels and high concentrations of (SO_4^{2-}), Fe, and various other metals. The presence of pyrite and pyrrhotite in these impoundments can result in the generation of acidic mine drainage (AMD) for several centuries following their deposition (McPhail, 2015b; Yilmaz et al., 2014). These substances can thus be categorized as dangerous materials. AMD is acknowledged as the primary environmental risk confronting the mining sector. Consequently, to address these issues, the mining industry is actively exploring alternative tailings management practices and developing advanced methods to mitigate risks and address environmental and social concerns (Carneiro & Fourie, 2018). As a result, the mining industry has embraced Cemented Paste Tailings (CPB) technology as an effective solution to mitigate adverse effects caused by tailings by recycling them as a construction material (Fall et al., 2009).

Cemented paste backfill (CPB) is a crucial element in underground mining operations. It is composed of mining by-products such as tailings, binder material (typically cement), and water (Doherty et al., 2015). The mixture typically has a solids content by weight of 70% to 85% (Fall et al., 2005). with the hydraulic binder constituting 3% to 7% of the total dry paste weight and water making up 15% to 30% (Kesimal et al., 2005a). CPB is produced at a backfill facility often located on the surface of a mine, and subsequently transported via underground pipelines to designated mine stopes (Haiqiang et al., 2016). CPB is extensively employed in Canadian underground mines and various global locations, with a rising trend attributed to its multiple technical and economic benefits (Fall et al., 2008). In addition to its economic and environmental advantages, CPB also plays a crucial role in preserving ground stability within mining sites, ultimately leading to a higher ore recovery rate (Fang & Fall, 2022). Although the CPB has successfully been used to recycle the tailings piles for construction purposes in recent years, there is still a need to explore further potential applications for tailings in mining construction, considering the large amount of tailings produced by the mining sector. During CPB operation only up to 60% of tailings produced by the mining industry are utilized (Fall, Celestin, et al., 2010). At least 40% of the tailings produced will still be disposed of through surface management. Which remains a challenge to the mining industry. In recent years, new surface tailings disposal techniques have emerged to mitigate geotechnical and environmental risks linked to traditional impoundments.

However, one potential option under consideration involves utilizing non-acidic cement-free paste tailings to create barrier materials (liners) for various waste containment facilities, ranging from municipal to mining and industrial waste sites. The construction and design of waste containment facilities, such as landfills for hazardous waste and repositories for mine waste, typically involve the incorporation of a barrier, which can take the form of a liner. A liner serves as a vital barrier between the waste material and the surrounding environment. Its primary function is to prevent the infiltration of pollutants from the waste into the nearby soil, groundwater, or surface water bodies. However, the liner alone is not sufficient to effectively manage the influence of AMD on groundwater resources. This is because, over time, the infiltrating water infiltration into the tailing's impoundment can lead to acidic. If the infiltrating water is unable to escape through seepage, it will gradually build up until it overflows the liner. Therefore, constructing a cover is a viable solution to regulate water infiltration and control oxygen supply to the tailing's impoundment (Fall et al., 2009). Thereby reducing the production and movement of contaminated water.

Fall et al. (2010) introduced a new barrier material called pastefill (PP) mixtures, which consist of paste tailings and a small amount of super absorbent polymer (SAP). SAPs are polymers that can absorb and retain liquid without dissolving. The growth rate of SAP particles can vary depending on factors like diffusion coefficient and distance traveled, ranging from seconds to hours (Lee et al., 2010). And the study focused on the hydraulic conductivity values of compacted polymer-pastefill mixtures (PP) and their potential use in waste containment facilities. The results showed that these mixtures had hydraulic conductivity values below the minimum required for liner design in compliance with EPA regulations (10^{-7} cm/s), indicating that compacted PP mixtures can serve as liners or covering materials for waste containment facilities. While the hydraulic characteristics of the PP material were examined in detail, the study did not investigate the consolidation behavior and shear characteristics of these materials. Understanding these mechanical properties is crucial for evaluating the performance and stability of barrier materials in waste containment applications. Furthermore, environmental stress conditions such as freeze-thaw cycles can have a significant impact on the consolidation behavior and shear characteristics of compacted PP. Freeze-thaw cycles occur when water within the material freezes and expands, leading to potential changes in the material's structure and properties. These cycles can occur in cold regions with, and it is important to understand how they affect the performance of compacted PP in waste containment facilities.

Nonetheless, there is currently a lack of research on the specific impact of freeze-thaw cycles on the consolidation behavior and shear characteristics of compacted PP. Therefore, this study aims to fill this research gap by investigating experimentally how freeze-thaw cycles affect the consolidation behavior and shear characteristics of PP material.

4.3 Materials and Experimental Procedures

4.3.1 Material

4.3.1.1. Tailings

The study utilizes industrially produced synthetic silica tailings (ST) sourced from ground silica (ground quartz, ST). These ST tailings accurately replicate the physical properties of natural tailings from Canadian hard rock mines generated during the milling process. The grain size distribution of the ST tailings was assessed through sieve and hydrometer tests by ASTM D 698-00 standards. The resulting grain size distribution curve is illustrated in Figure 1. Interestingly, the curve closely matches the average distribution observed in tailings extracted from nine hard rock mines situated in eastern Canada. Quartz is the predominant component of this material, making up 99% of its total composition. More than 40% of the particles have a diameter of less than 20 microns, exceeding the required criteria for paste tailings development. Typically, for the production of paste tailings, the material must contain a minimum of 15% fine particles by weight (sized <20 μm) to effectively retain moisture and facilitate paste formation. (Kesimal et al., 2005b). Analysis indicates that the utilized tailings fall within the sandy silt category with minimal plasticity, falling under the ML classification in the Unified Soil Classification System (USCS). This classification is commonly linked to tailings originating from hard rock metal mining operations.

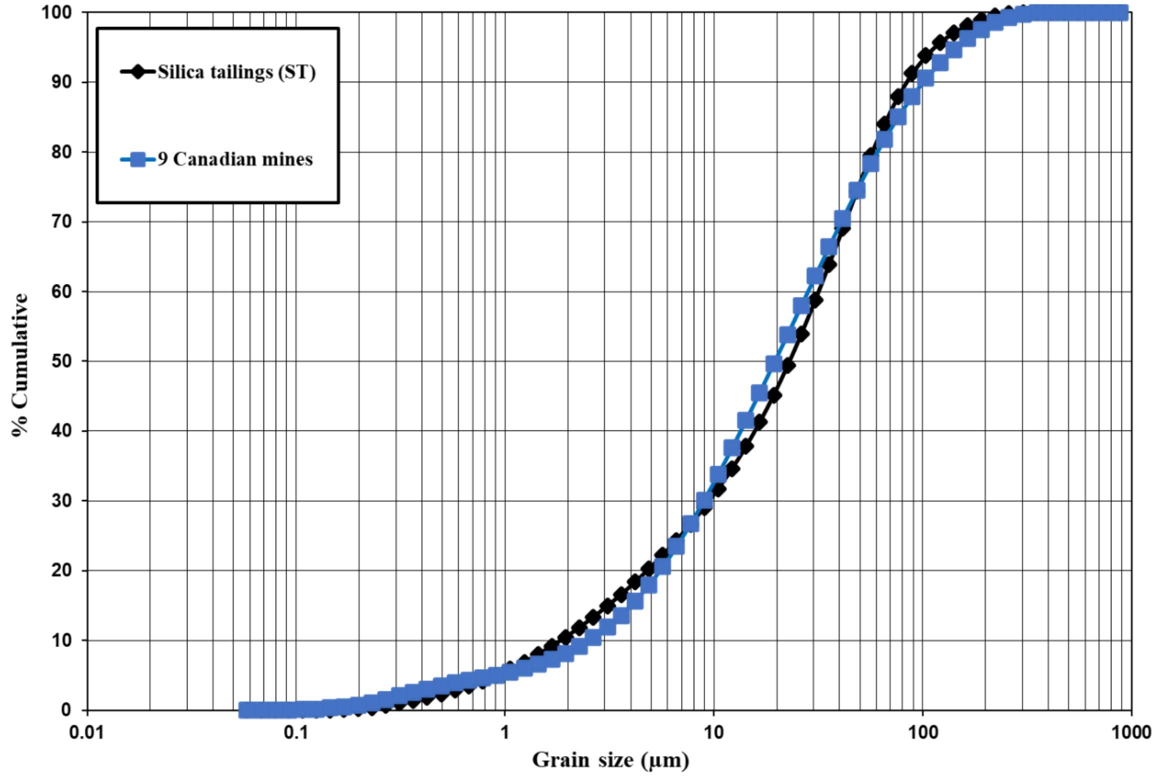


Figure 4.1 The grain size distribution of synthetic (silica) tailings is being compared to the tailings obtained from nine Canadian mines located in eastern Canada.

Tables 4.1 and 4.2 list the most important physical and chemical properties of the synthetic silica tailings used.

Table 4.1: Physical properties of tailings used

Element	G_s	D_{10}	D_{30}	D_{50}	D_{60}
unit	–	µm	µm	µm	µm
ST	2.7	1.9	9	22.5	31.5
Average of 9 natural Canadian mine tailings	–	1.8	9.1	20	30.8

Table 4.2 Mineralogical composition of the tailings used

Element unit	Al_2O_3	CaO	S_iO_2	Fe_2O_3	Na_2O	Pb	S_IO_2	K_2O
unit	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%	wt.%
SI	0.1	<0.01	99.8	<0.01	<0.01	0	0	0

4.3.1.2 Polymer material

The research focuses on commercially available cross-linked sodium polyacrylates (SAP), which are insoluble substances with a remarkable swelling capacity of 250 grams per gram in deionized water, roughly equivalent to 8.82 ounces per gram. SAPs, derived from acrylic acid and its salts, possess a gel-like structure and are highly hydrophilic, allowing them to absorb and retain substantial quantities of water relative to their weight. Notably, around 95% of SAP production worldwide is dedicated to manufacturing absorbent materials for disposable products (Fall, et al., 2010) underlining their widespread industrial significance. SAPs exhibit hydrophobic properties due to their ion exchange capability, enabling effective retention and binding of heavy metals. However, their absorption capacity diminishes in ionic liquids, reaching its peak with distilled water. The size of SAP particles varies, ranging from 6,350 mm to 45 mm in diameter (0.00177165354 in) (ARK 2003). Upon solvation, SAP chains unfurl, expanding due to repulsion forces between ions, resulting in significant absorption capacities. SAPs find diverse applications, particularly in coatings, adhesives, and films for packaging, where their water absorption and retention properties create durable moisture-resistant barriers, safeguarding products from damage.

4.3.1.3 Mixing water

Deionized water was employed to blend the PP material, guaranteeing the exclusion of any chemical variables throughout the testing procedures.

4.3.2 Preparation of the specimens

The moisture content of the silica tailings was eliminated through an oven-drying process at a temperature of 60°C for a duration of 3 days. To ensure a uniform distribution of water, the tailings were mixed with the recommended amount of deionized water for approximately 3 minutes using a mechanical blending device. During the mixing process, a designated percentage of superabsorbent polymer (SAP) (0.2%) was added and thoroughly mixed for 8 minutes to create a consistent polymer-PP mixture. This SAP content was selected because it allows the compacted PP to attain the hydraulic conductivity values necessary for liner or cover design in waste containment facilities, as demonstrated by Fall et al. (2010). Subsequently, the resulting PP mixtures were sealed in airtight polyethylene bags and allowed to hydrate for 48 hours, ensuring moisture equilibrium. Subsequently, the PP mixtures were compacted using a Proctor mold in accordance with ASTM D 698-00a standards. After the compaction, the compacted sample was subjected to a number of freeze-thaw cycles (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, and 10 cycles). After which undisturbed cores were cut using a cutting cylinder ring with a height of 15 mm and a sample diameter of 60 mm for consolidation testing. For the direct shear strength testing, a ring with a height of 16 mm and a plan dimension of 60 x 60 mm was utilized to cut the cores. The cut samples were trimmed before being installed in a consolidation and direct shear testing machine for testing. The compaction characteristics and permeability coefficients (as determined by ASTM D 5084-00) for the prepared PP samples are presented in Table 4.3.

Table 4.3 Compaction characteristics of the prepared PP samples

Sample name	SAP content (%)	Optimum Water content, Wopt (%)	Maximum dry density, $\rho_{d(max)}$ (kg/m^3)	Coefficient of permeability, k(m/s)
0.2%SAP	0.2	25.6	1391	2.7 x 10^{-8}

4.3.3 Testing methods and procedures

4.3.3 Consolidation experiment

The consolidation experiments were conducted following the standardized procedure outlined in ASTM D 2435 to ensure the accuracy and reliability of the results. The fixed ring gauges used were crafted, comprising a brass ring with precise dimensions, featuring an inner diameter of 60 mm and a height of 15 mm. These gauges were essential for maintaining consistent sample dimensions throughout the experiment. To facilitate vertical drainage in both upward and downward directions, porous stones were strategically positioned at the ends of each sample. These porous stones acted as conduits for the drainage of excess water, ensuring that the consolidation process occurred uniformly throughout the sample. The saturation level of the samples was determined based on the moisture content after the test. This parameter provided valuable insights into the water content of the sample under different stress conditions, thereby enhancing the understanding of the consolidation behavior. During the testing procedure, the samples were subjected to nine different effective stresses, ranging from 5 to 1280 kPa. Each stress level was applied for 24 hours to allow sufficient time for the consolidation process to occur. Throughout the test duration, a dial gauge was employed to monitor and record the consolidation process continuously. This real-time monitoring was crucial for tracking the deformation of the sample under varying stress conditions and capturing any transient behavior that might occur during the test. Upon completion of the loading phase, the samples were gradually unloaded to 5 kPa following a specific sequence of stress levels, including 1280, 640, 320, 160, 80, 40, 20, and 10 kPa. Each unloading step was executed, with a duration of 24 hours allocated for each step. This stepwise unloading process allowed for the observation of any residual deformation or recovery that might occur within the sample following the removal of applied stresses. Data collection during the experiment was conducted, utilizing a combination of automatic recording systems and manual measurements at various stages of the testing process.

4.3.4 Direct shear tests

The direct shear tests conducted on PP mixtures adhered to the standardized procedures outlined in ASTM D6528-17, ensuring consistency and reliability of the experimental results. The tests were carried out using a direct shear box apparatus, a fundamental instrument designed to evaluate the shear strength properties of soil and other granular materials. The apparatus consisted of two main parts: the lower part, supported by rollers and connected to a motor via a gear unit, and the upper part, linked to a test ring for measuring horizontal (shear) force. This setup ensured uniform extension at a constant pace during the shearing process, crucial for obtaining accurate and reproducible data. A loading frame with a lever arm ratio of 10:1 was utilized to apply normal stress on the specimens. Normal stresses of 100, 200, and 400 kPa were precisely imposed on the specimens, providing a range of stress conditions for comprehensive analysis. Shearing was performed at a controlled strain rate of 0.5 mm/min, allowing for the determination of in-situ shear strength parameters under varying stress levels. This controlled shearing rate ensured consistent and controlled deformation of the samples throughout the testing procedure, enabling accurate characterization of their mechanical properties. The experiments were conducted on statically compacted samples with specific dimensions of 60 mm in diameter and 60 mm in height. These samples were prepared under compacted conditions to simulate real-world scenarios and ensure representative testing conditions. Throughout the experiment, vertical deformations of the samples were monitored, including during the application of normal stress and shearing. This continuous monitoring allowed for the assessment of variations in sample volume, commonly referred to as void fraction, which is crucial for understanding the mechanical behavior and response of the specimens under different stress conditions. Any changes in sample structure or integrity during the testing process could be identified and analyzed by monitoring vertical deformations, providing valuable insights into the overall performance of the PP mixtures in response to applied loads and shearing forces.

4.3.4 Freeze-thaw cycle application

Freeze-thaw tests are crucial for evaluating the behavior of fine-grained soils when subjected to freezing and thawing conditions, particularly in permafrost-affected areas or cold regions. Surface tailings disposal facilities and other waste containment facilities face the challenge of undergoing multiple freeze-thaw cycles, which can impact the consolidation and shear strength properties of the lining and cover materials as a waste-contaminated barrier. This may compromise their effectiveness as barriers against seepage and containment. Therefore, it is crucial to assess the influence of freeze-thaw cycles on the mechanical properties (consolidation and shear strength) of the proposed barrier material. To evaluate the performance of the proposed barrier materials under freeze-thaw conditions, compacted SAP samples were subjected to cyclic freeze-thaw testing. The freeze-thaw testing involved subjecting the samples to the following freeze-thaw cycles: 0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles, with ASTM D 6035-96 standards followed to ensure proper stress application. All samples were submitted to the freeze-thaw influence at their molded water content. The samples froze from 20 to −20 °C at 140 min and thawed by returning to room temperature within 180 min. Each sample was allowed to rest for 12h for each of the alternations for uniformity. This process was repeated according to the number of cycles. Thermal loading was administered in a three-dimensional fashion. This effectively hindered any modifications to the original water content when subjected to fluctuations in temperature. This comprehensive testing approach provides insights into the behavior of the barrier materials under freeze-thaw conditions, aiding in the design and implementation of effective surface tailings disposal facilities in cold climates. The graphs of the temperature evolution with time are presented below in Fig 4.2.

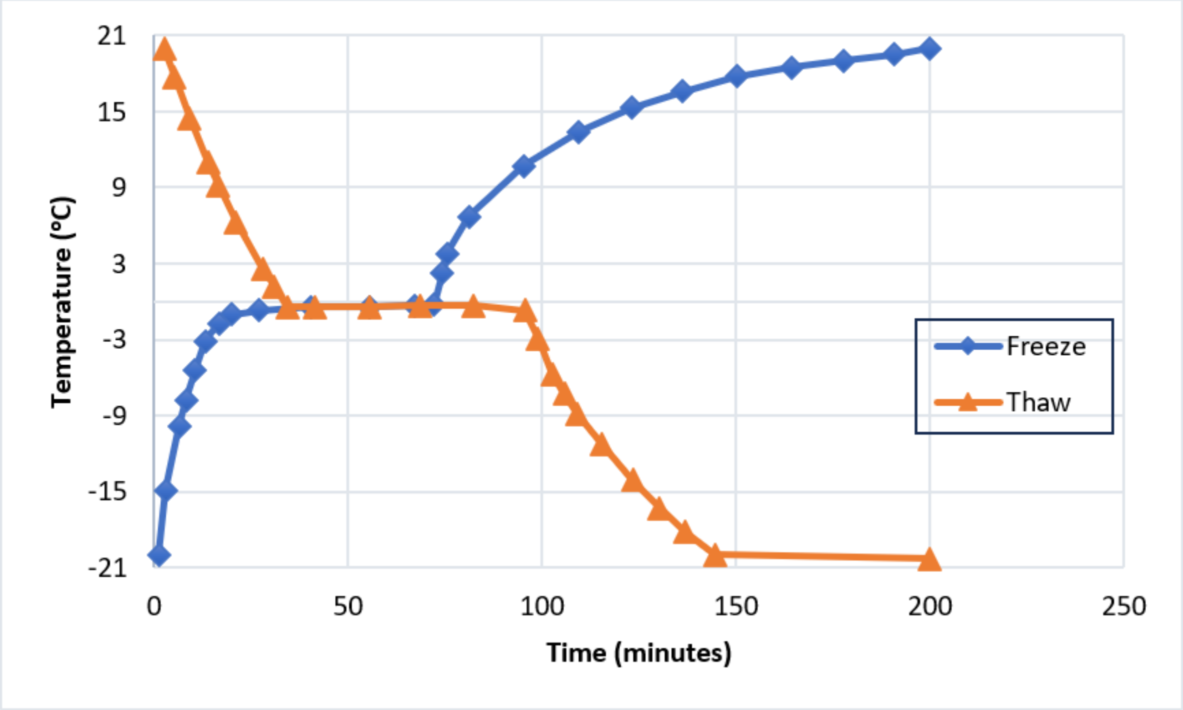


Figure 4.2 Phase change curve.

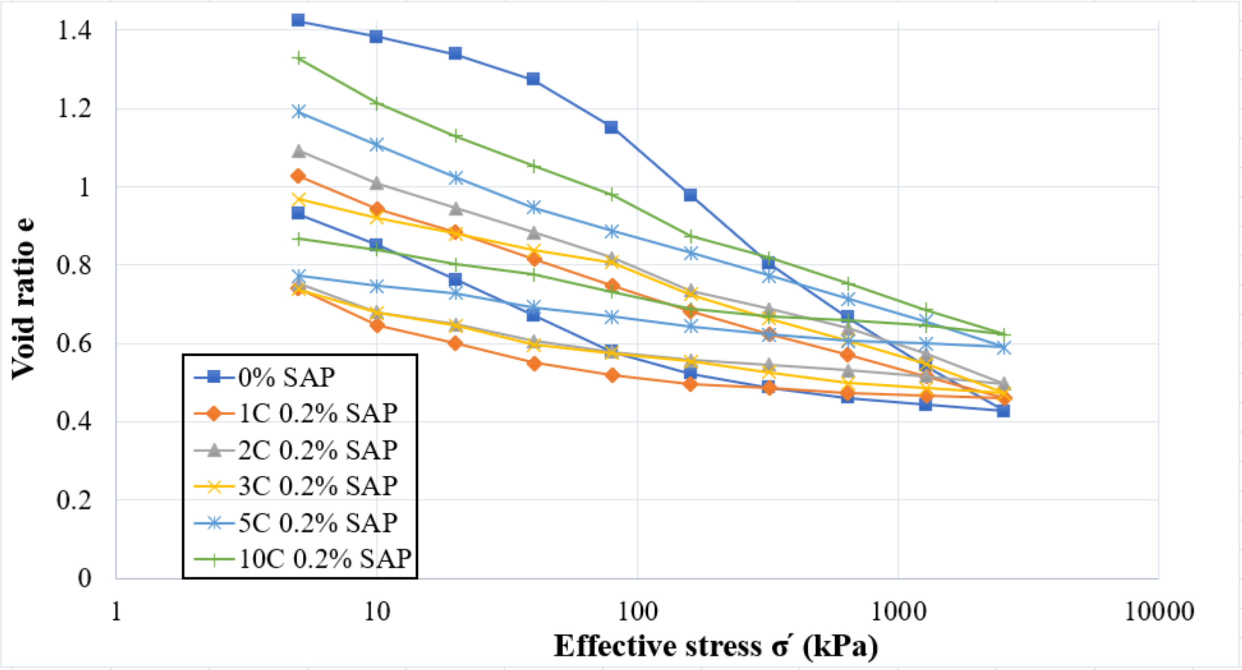
4.4 Results and Discussion

4.4.1 Consolidation Behavior of polymer-pastefill

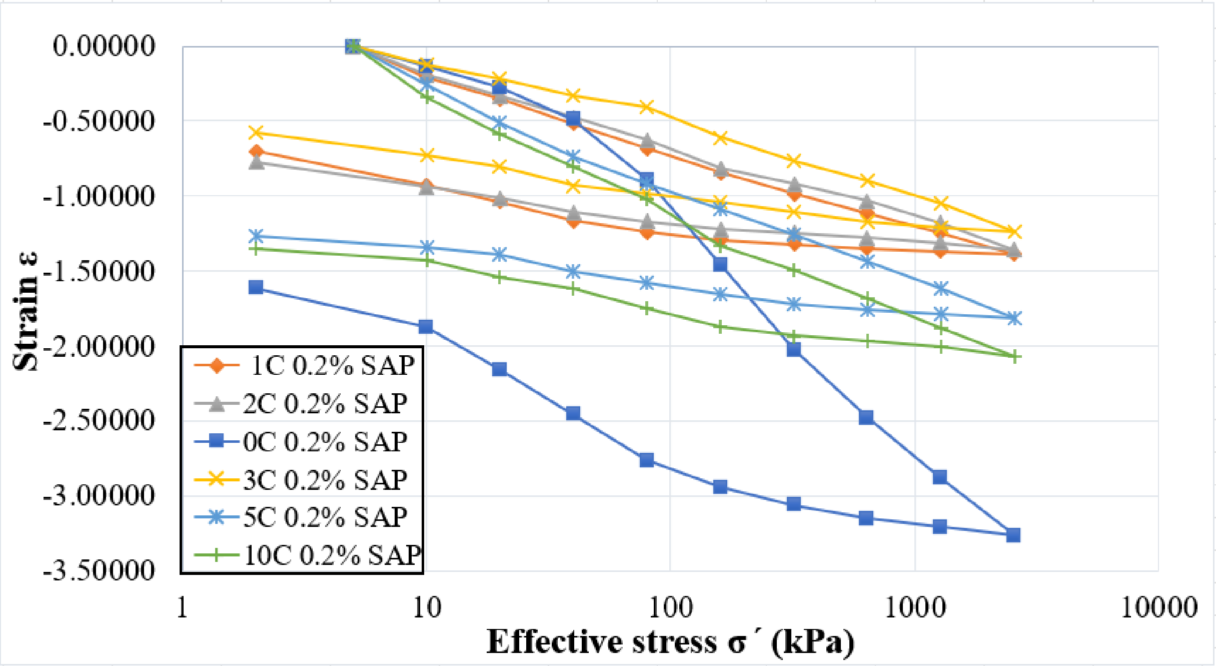
4.4.1.1 Stress-strain behaviour

Figure 4.3 shows the consolidation behaviour of SAP paste tailing materials after being exposed to various freeze-thaw cycles and subjected to nine different effective stresses: 5, 10, 20, 40, 80, 160, 320, 640, and 1280 kPa. The void ratio, represented by **e**, denotes the proportion of pore volume to solid particle volume within the paste tailing. It is utilized as a metric to clarify the structural characteristics of the paste tailing. The smaller the value of the void **e**, the more compact the past tailing, whereas the larger the value of e, the more porous or loose the past tailings (Xu et al., 2021). The results of consolidation experiments conducted on SAP paste tailing samples with varying SAP contents of 0.2% and subjected to different freeze-thaw cycles (0 cycles, 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles) are presented in Fig. 4.3. The consolidation results are illustrated through curves of void ratio, e, versus the logarithm of effective consolidation stress, log σ', (Fig. 4.3a), and strain, ε, versus log σ' (Fig. 4.3b). The initial void ratio of 0 Cycle is 0.93, and 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles are 0.74, 0.75, 0.73, 0.77 and 0.87 respectively.

It was noted that the void ratio decreases after the first freeze-thaw circle and starts increasing during the subsequent circles of the freeze-thaw circle. This behaviour is due to the growth of ice crystals which can destroy the particle agglomeration (Shi et al., 2024). For instance, repeated freezing and thawing could lead to the formation of ice lenses or cracks, creating more void spaces within the material (Shi et al., 2024). Additionally, the repeated expansion and contraction of ice could lead to mechanical disruption of the material, altering its structure and potentially increasing void spaces. The compression index, Cc, and the swell index, Cs, denote the inclines of the loading and unloading segments of the stress-strain curves σ′ respectively, are summarized in Table 4.4. Cc and Cs values were determined by extracting pertinent data from the electronic log curves depicted in Fig 4.3 for every (PP) sample. When subjected to testing, both the loading and unloading phases of the stress-strain curves displayed a characteristic bi-semilog linear trend. For instance, in Table 4.4 the Cc value for 0 Cycle SAP was 0.0574, while the values for 1 cycle, 2 cycles, 3 cycles, 5 cycles, and 10 cycles were 0.0261, 0.0637, 0.413, 0.0297, and 0.0758, respectively. The pattern of varying Cc values with different freeze-thaw cycles indicates that the freeze-thaw process significantly affects the material's consolidation behavior. The changes in compressibility (Cc values) suggest that the material's internal structure is being altered by the freeze-thaw cycles, leading to fluctuations in how easily it can be compressed under stress. This could be due to factors like ice formation, particle rearrangement, or the breakdown of bonds within the material, all of which are influenced by repeated freezing and thawing. For example, the behaviors of the void ratio of cycles decrease as the circle increases, and the compression increases as the circle increases. This is as a result of the effect of the freeze and thaw cycle recorded. The larger the compressibility index, the higher the compressibility (*Compressibility* n.d.). Generally, the higher the value of C_C is, the higher the compressibility is. The 10th cycle exhibited greater swelling potential and compressibility index compared to the 0-cycle sample, resulting in increased compression. Furthermore, the increase in Cc from the 0 cycle to the 10th cycle in Table 4.4 indicates a relatively incompressible consolidation process.



a) Effective consolidation stress versus void ratio



b) Effective consolidation stress versus strain.

Figure 4.3 Effective consolidation stress versus (a) void ratio; (b) strain for PP with (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles).

Table 4.4: Compression index (Cc), Swell index (Cs) and Void ratio

Cycle	**Compression index, Cc**	**Swell index**	**Final void Ratio ef**
0 Cycle	0.0574	0.2497	0.9300
1 Cycle	0.0261	0.6209	0.7402
2 Cycles	0.0637	0.5933	0.7535
3 Cycles	0.0413	0.3645	0.7378
5 Cycles	0.0297	0.5876	0.7717
10 Cycles	0.0758	0.7386	0.8664

4.4.1.2 Coefficients of Volume Change, Compressibility, and Consolidation

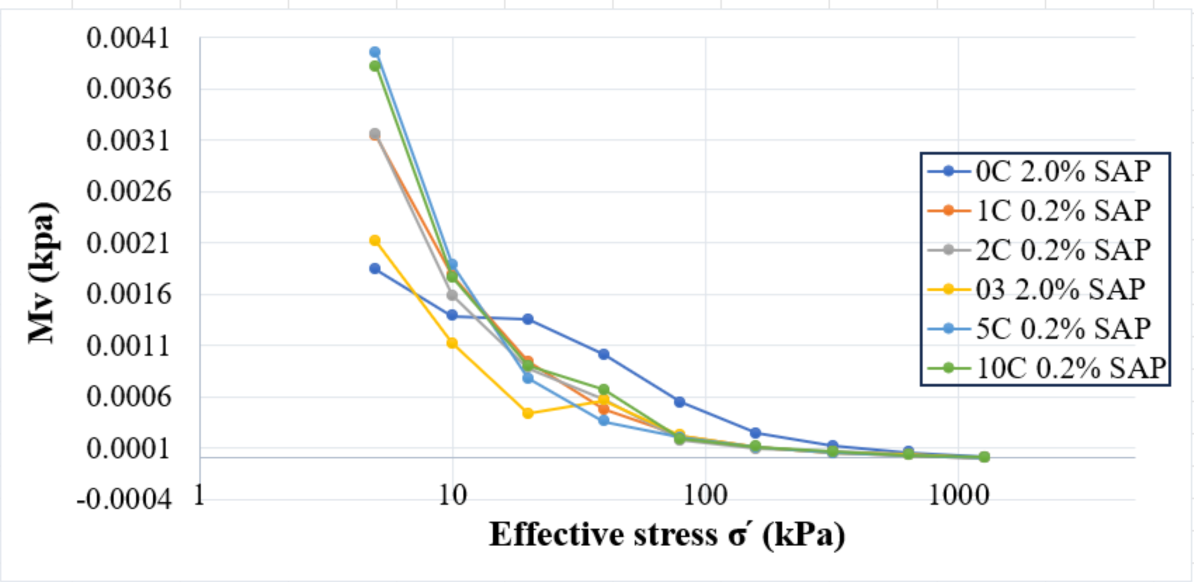
The volume change coefficients, represented by *mv*, and compressibility coefficients, denoted as *av*, were obtained by analyzing the slopes of the curves that depict the relationship between void ratio and effective stress (σ'), and strain and effective stress (σ'), respectively, over the loading phases of the consolidation test. These derived values for *mv* and *av* are organized in Table 4.5 and graphically presented against effective stress (σ') in Figure 4.5. Effective stress (σ') signifies the ultimate stress corresponding to each incremental load. Generally, as σ′ increases, mv and av values decrease, typically following the sequence of (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles) (as indicated in Table 4.5). This succession directly corresponds to the quantity of freeze and thaw cycles present in each paste filling. Therefore, the differences in compressibility among the 6 cycles can mostly be attributed to variations in the number of cycles undergone by the paste tailing. However, differences in their behavior could also have contributed to the observed differences in compressibility. The relatively low compressibility of the 0 cycle of the paste filling further supports the idea that the effect of freeze-thaw cycles did not predominantly influence the consolidation behavior of this paste tailing.

Table 4.5: Coefficient of volume change (M_v) and Coefficient of compressibility (a_v)

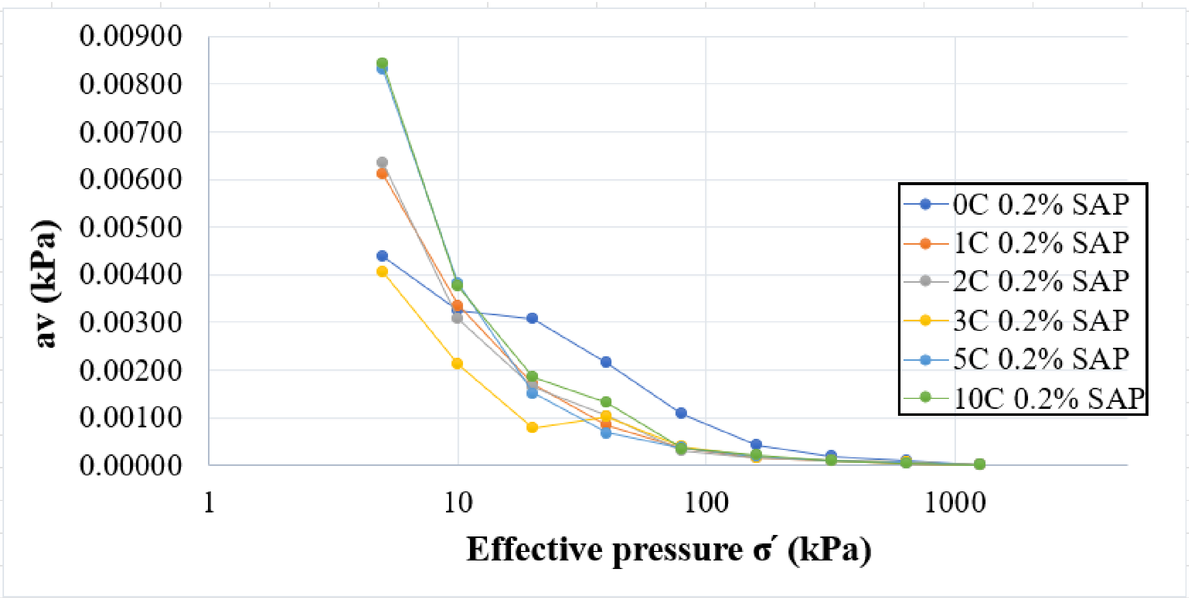
Cycle	**Coefficient of volume change M_v (x10^{-3} kPa^{-1})**	**Coefficient of compressibility a_v (x10^{-3} kPa^{-1})**
0 Cycle	0.183	0.438
1 Cycles	0.313	0.609

2 Cycles	0.315	0.630
3 Cycles	0.211	0.0450
5 Cycles	0.395	0.832
10 Cycles	0.381	0.840

The consolidation coefficients (C_V) for the loading stages of the consolidation tests were calculated utilizing two distinct methods: the logarithm of time approach (Casagrande method) and the square root of time approach (Taylor method). The data presented in Table 4.6 provides a summary of the coefficient of volume C_V values, while Figure 4.5 (a and b) illustrates the relationship between all C_V values and the mean consolidation stress for each load increment. It is observed that as the average effective consolidation stress rises for the entire paste tailing mix under both methods, there is a corresponding increase in the coefficient of consolidation. This pattern is consistent with the impact of freeze-thaw cycles. On the other hand, C_V demonstrates a negative correlation with the volume change coefficient m_v (Figure 4.4a), which diminishes as the effective stress increases, as highlighted by Duncan in 1993. Consequently, an increase in C_V can be expected with a rise in load if mv decreases with increasing load. The ratios of C_V values obtained through the Taylor method compared to those obtained through the Casagrande method represented as CvTaylor/CvCasagrande, are graphed against the mean in Figure 4.5(c). Usually, the result obtained from the Taylor method surpasses that acquired through the Casagrande method, as indicated by a ratio exceeding one. This discrepancy stems from several factors, including differences in strain rate at various σ' levels and the subsequent compression that takes place during the initial consolidation process (Yeo et al., 2005). The coefficient of consolidation (Cv) for 0 cycle, 1 cycle, 2 cycles, 3 cycles, 5 cycles, and 10 cycles samples increases as the average effective consolidation stress increases in Figure 4.5 (a, b, and c) and Table 4.6. However, the increase in the coefficient of consolidation (Cv) with increasing effective consolidation stress and number of loading cycles can be attributed to the combined effects of barrier material’s densification, improved particle contacts, increased stiffness, and changes in permeability. These factors collectively enhance the barrier material's ability to consolidate more rapidly under subsequent loads, reflecting a higher Cv in the observed data.

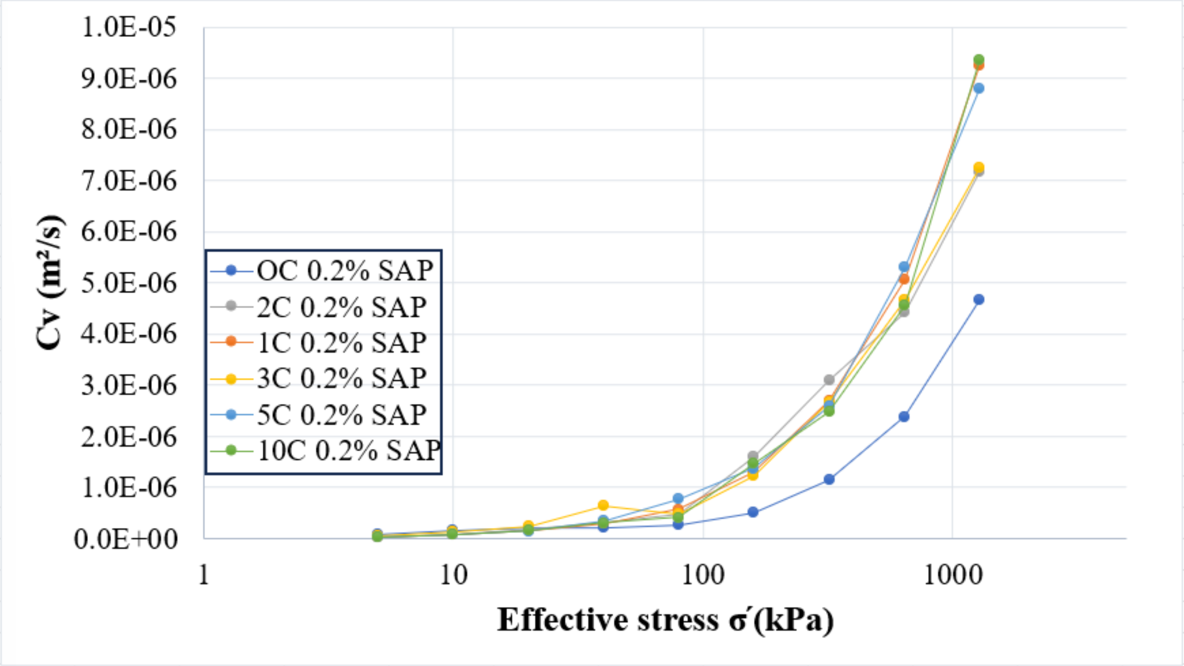


a) Effective consolidation stress versus coefficient of volume change

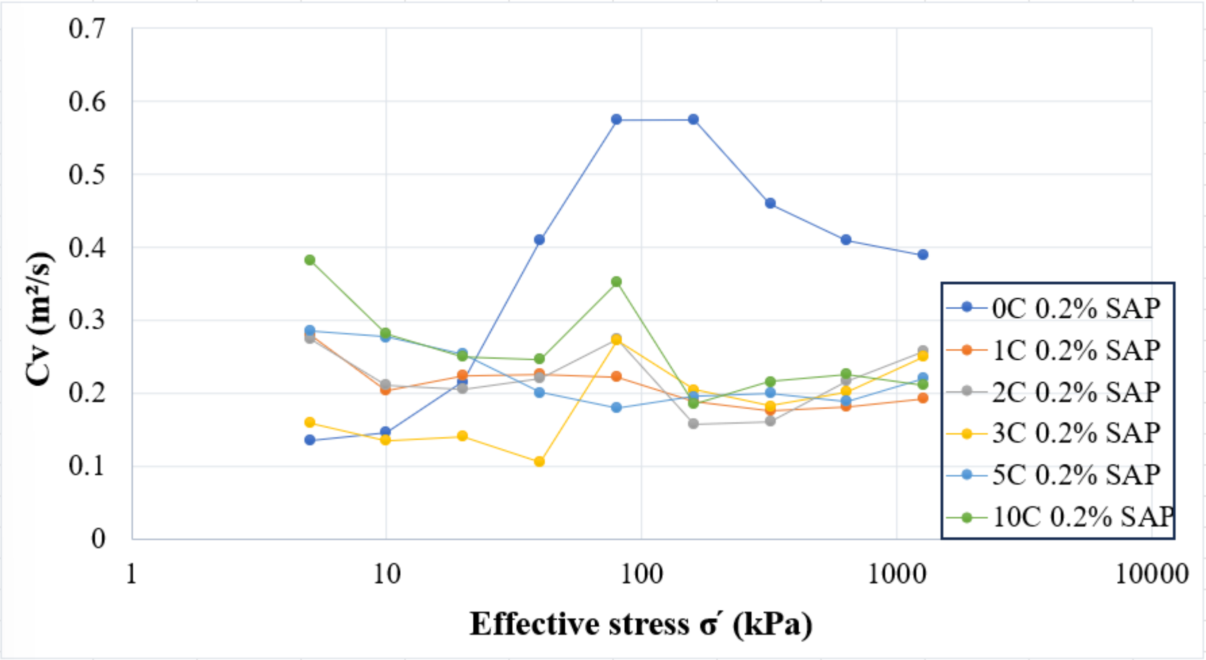


a) Effective consolidation stress versus coefficient of compressibility

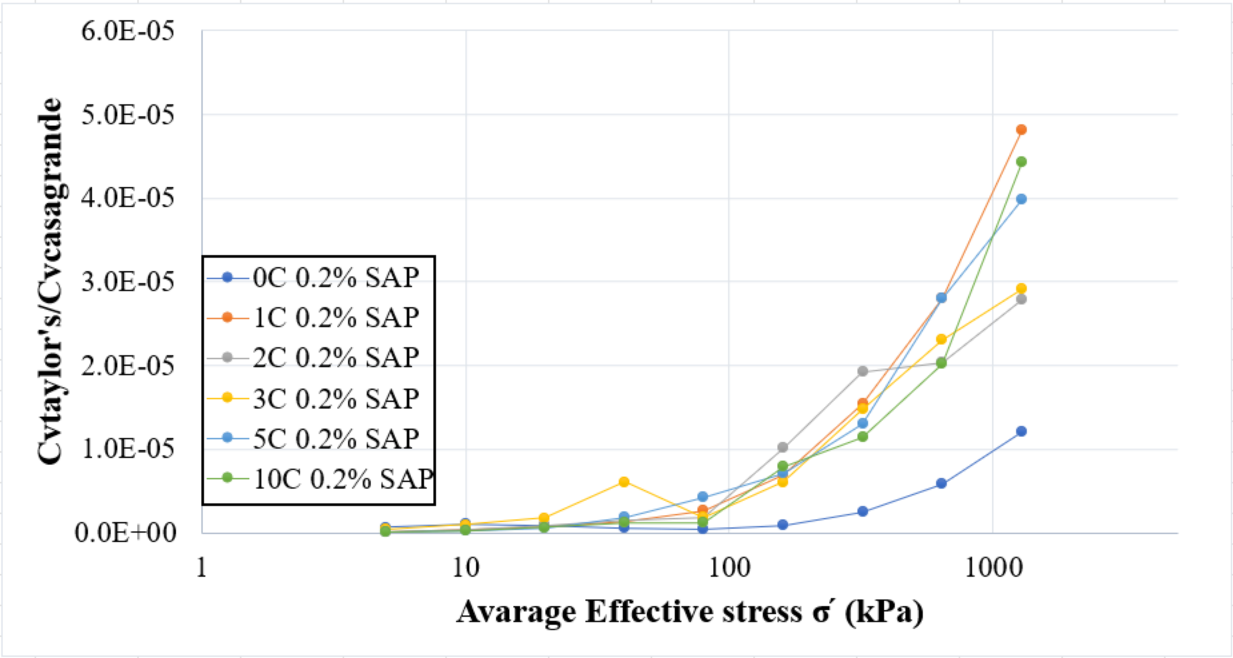
Figure 4.4 Effective consolidation stress versus (a) Coefficient of volume change (b) Coefficient of compressibility for PP with (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles).



a) Coefficient of consolidation based Casagrande's method



b) Coefficient of consolidation based on Taylor's method



c) Ratio of Taylor's method to Casagrande's method

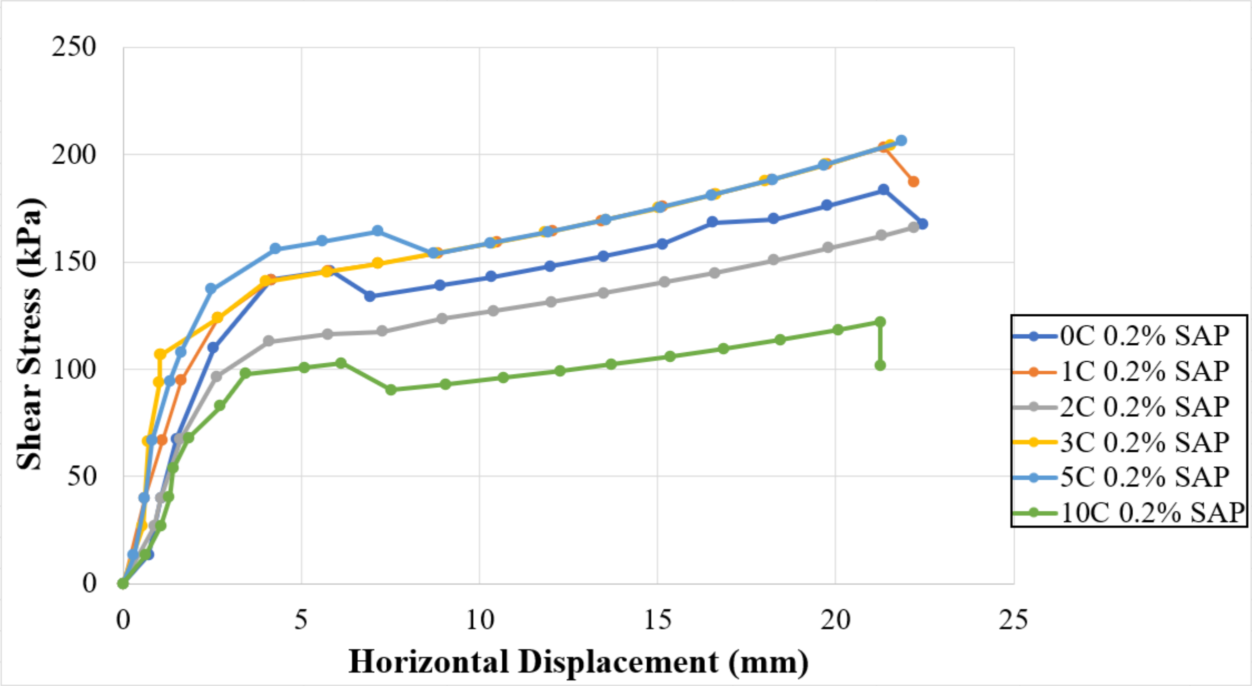
Fig. 4.5. Coefficient of consolidation based on (a) Casagrande's method; (b) Taylor's method; (c) a Ratio of Taylor's method to Casagrande's method for PP with (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles).

Table 4.6: Coefficient of consolidations based on Casagrande's and Taylor's methods, and Casagrande / Taylor ratio

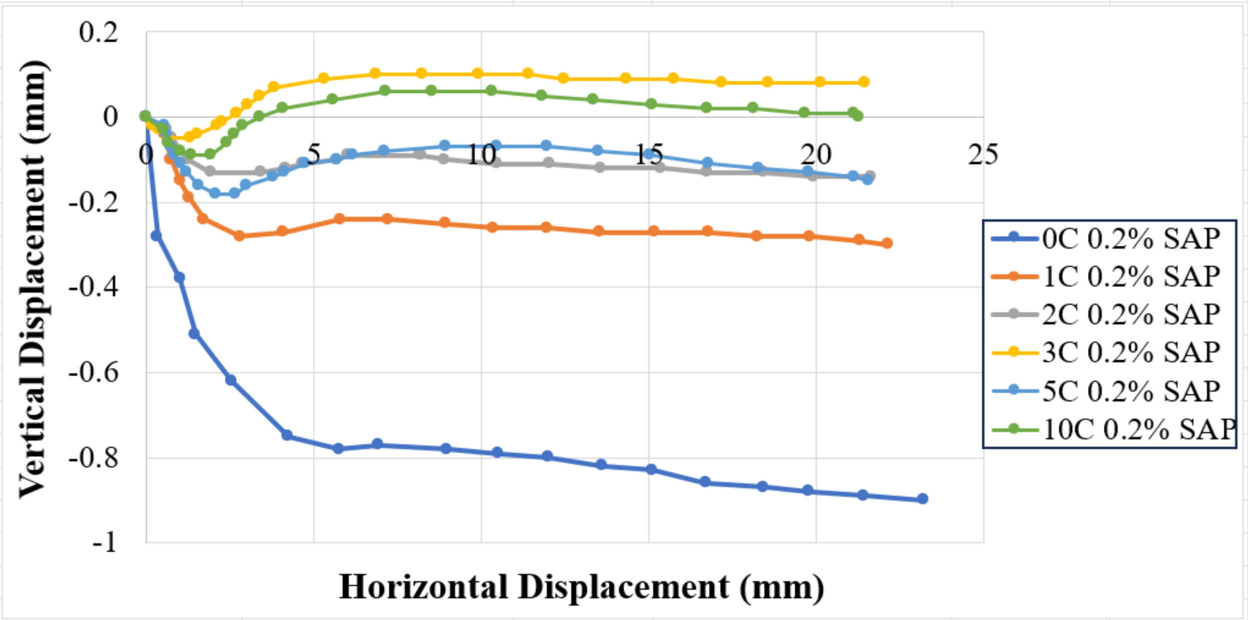
	Casagrande's method	**Taylor's method**	**Casagrande / Taylor method**
Cycles	C_v (x10^{-7} m^2/s)	C_v (x10^{-6} m^2/s)	C_v (x10^{-6} m^2/s)
0 Cycle	0.8270	0.388	1.198
1 Cycles	0.3324	0.2789	1.192
2 Cycles	0.3470	0.2748	1.265
3 Cycles	0.5660	0.1589	2.5619
5 Cycles	0.3512	0.2852	1.2313
10 Cycles	0.2794	0.3808	2.5719

4.4.2 Shear characteristics of PP

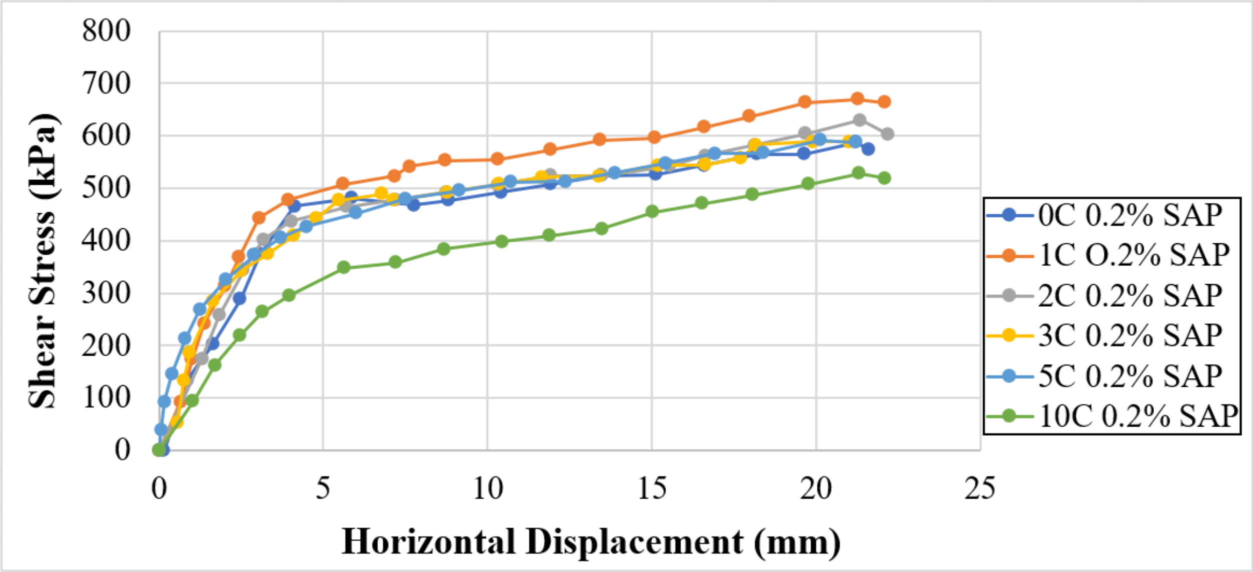
Figure 4.6 (a, b, and c) presents plots showing the relationship between horizontal displacement and shear stress for different freeze-thaw cycle counts (0, 1, 2, 3, 5, and 10 cycles) at applied pressures of 100 kPa, 200 kPa, and 400 kPa, as detailed in Table 4.7. The graphs reveal a consistent pattern where the shear stress increases gradually with horizontal displacement until it reaches a maximum value. Notably, the stress-displacement curves for the PP samples do not display distinct peak shear stresses. According to ASTM guidelines, in the absence of a clear peak, the shear stress at 15% shear strain is considered the peak shear stress or shear strength. Initial observations show that shear stress increases from 0 to 1 cycle, but then decreases at 2 cycles, particularly under higher normal stress (200 kPa). This decline may indicate structural weakening or deterioration within the material, leading to reduced shear stress. However, from the 3rd to the 5th cycle, there is a trend of increasing shear stress, suggesting a partial recovery or stabilization of shear strength, possibly due to the material undergoing restructuring or consolidation. At the 10th cycle, the trend shifts dramatically, with a significant decrease in shear stress observed. This sharp drop in shear strength could be attributed to factors such as accumulated damage or fatigue effects on the material's structure, ultimately leading to failure. Overall, the fluctuations in shear strength during the freeze-thaw cycles reflect the complex interaction between changes in the material's structure, the effects of freeze-thaw cycles, and external loading conditions like normal stress.



a) Horizontal Displacement versus Shear stress for 100 kPa stress



b) Horizontal Displacement versus Shear stress for 200 kPa stress



b) Horizontal Displacement versus Shear stress for 400 kPa stress

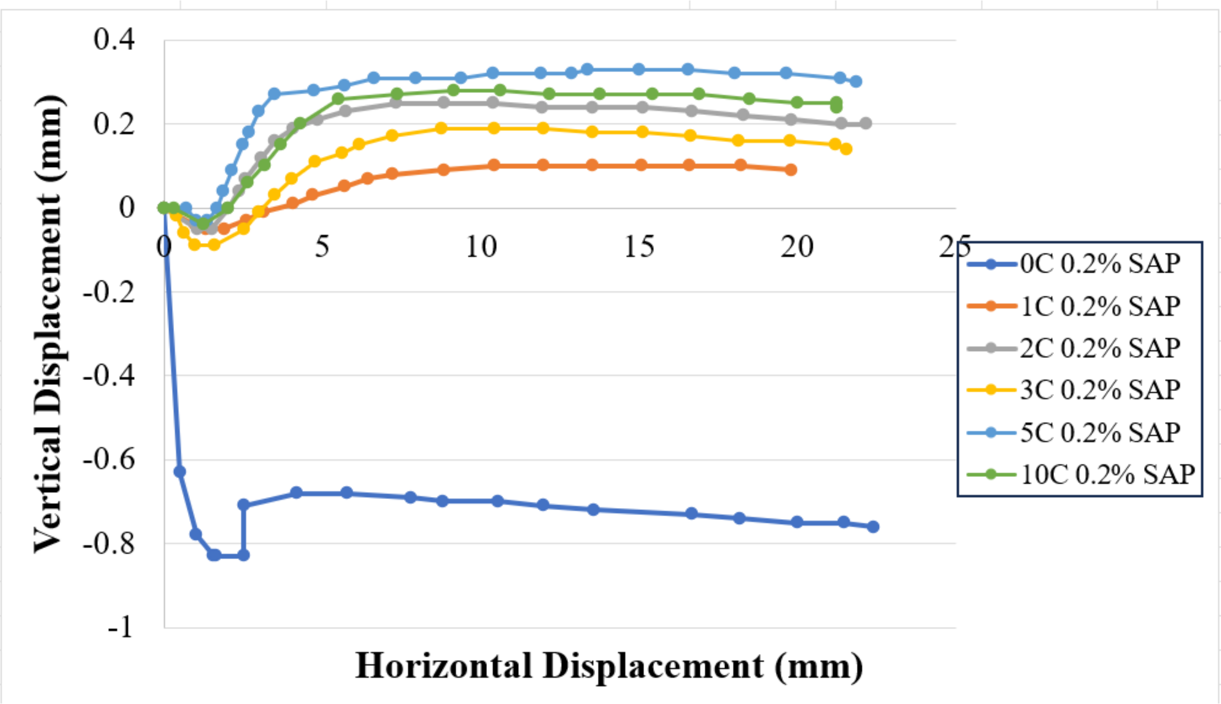
Figure *4*.6 Shear stress-horizontal Displacement for SAP-Pastfill mixture for (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles). (a) 100kPa (b) 200kPa and (c) 400 kPa.

4.4.4 Volume change behavior during shear

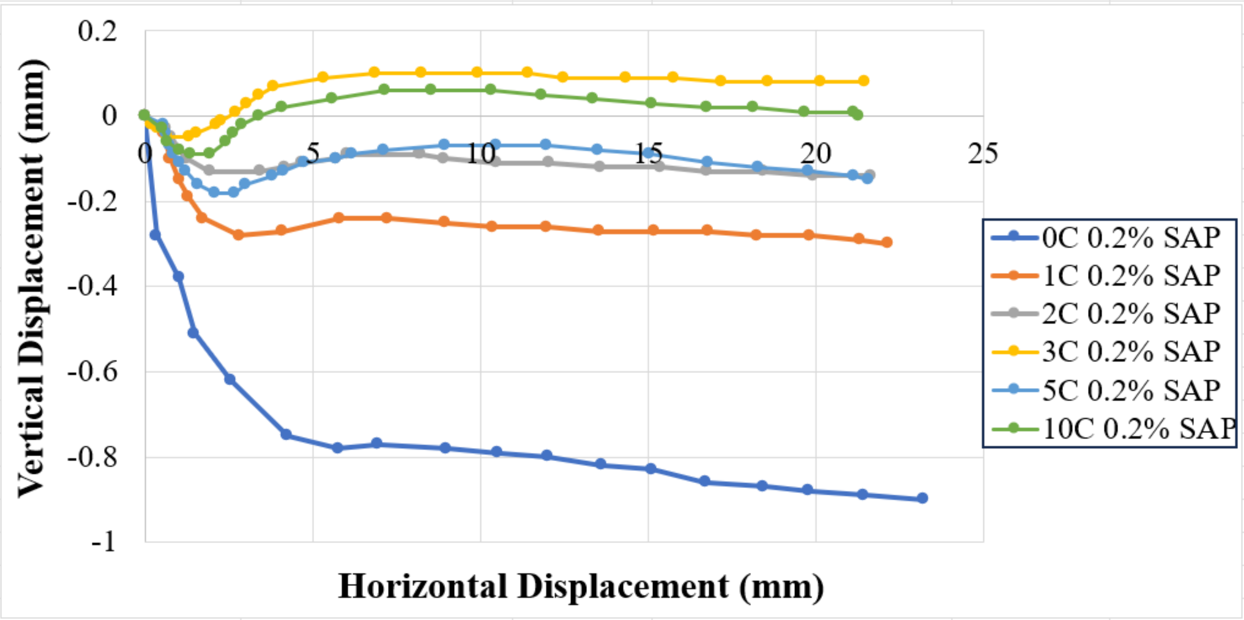
A different representation of the volume change curves, showing the relationship between vertical displacement and horizontal displacement, was observed, as depicted in Figures 4.7 (a, b, and c). The results indicate that the vertical deformation of the interface can be broadly categorized into two distinct stages during shear displacement under applied normal stresses of 100, 200, and 400 kPa. In the **first stage**, under an applied normal stress of 100 kPa, the SAP paste tailing material exhibited vertical contraction accompanied by an increase in shear stress, particularly in the initial cycle with no freeze-thaw exposure. This contraction is attributed to the initial compaction and consolidation of the material under shear stress. At the start of the experiment, the material likely had a loose structure, and as shear stress was applied, the particles reorganized into a denser configuration, causing vertical contraction and an associated increase in shear stress (Nasir & Fall, 2008). This behavior was consistent across specimens subjected to higher normal stresses of 200 kPa and 400 kPa during the initial cycle.

In the **second stage**, as the freeze-thaw cycles progressed (1 cycle, 2 cycles, 3 cycles, 5 cycles, and 10 cycles), the SAP paste tailing specimens began to exhibit expansion due to dilatancy, particularly under the low applied normal stress of 100 kPa. The freeze-thaw cycles likely altered the particle arrangement, leading to either a denser packing or localized loosening, which made the material more prone to dilatancy. Dilatancy occurs when densely packed materials, like the SAP paste tailings, experience shear deformation, causing the particles to attempt to move past each other (Guo & Su, 2007) and create additional void spaces (Nasir & Fall, 2008). This phenomenon was less pronounced at higher normal stresses of 200 kPa and 400 kPa, where the increased compaction restricted particle movement, resulting in minimal or no dilation.

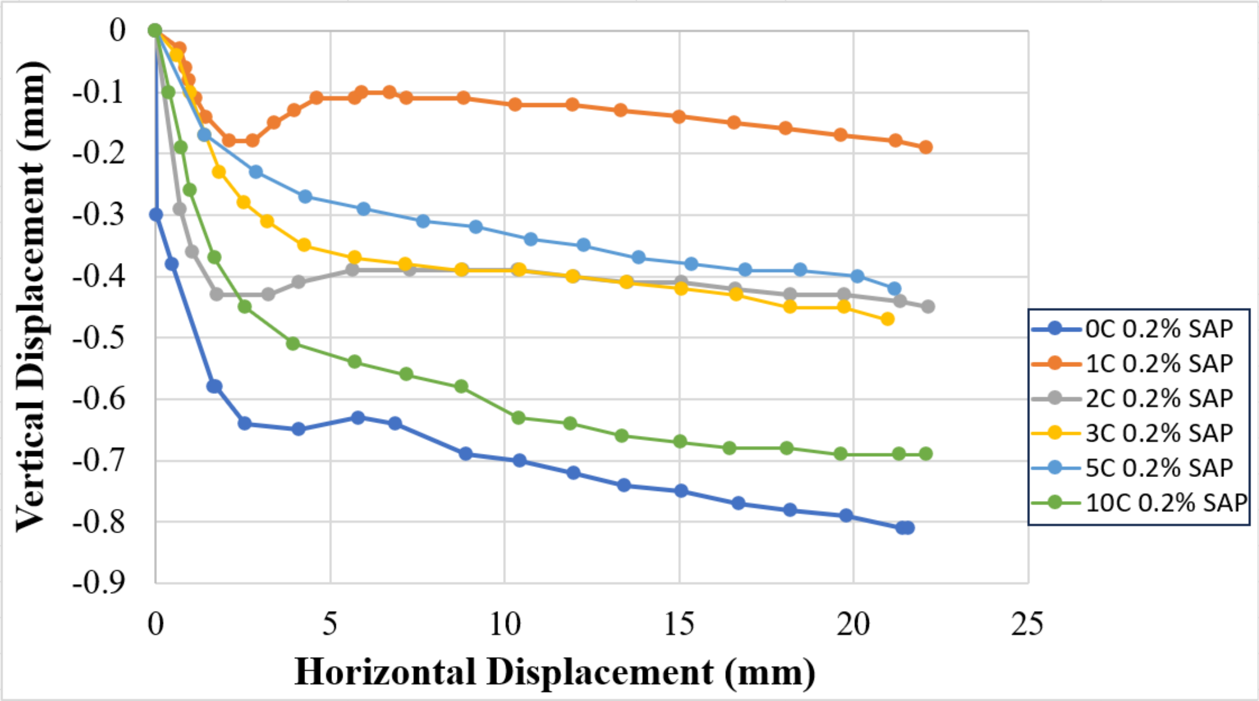
However, it is evident that the extent of dilation at the ultimate stage is significantly influenced by the level of normal stress applied. For example, in figure 4.7 when a normal stress of 200 kPa was applied to the SAP paste tailing material, the observed dilation was minimal compared to the dilation observed at the lower stress of 100 kPa. Similarly, at a normal stress of 400 kPa, the dilation was even more minimal when compared to the dilation at 200 kPa. This behavior can be explained by the balance between the applied normal stress and the internal structure of the material. As the normal stress increases, the material becomes more compact, reducing the space available for particle movement. While at lower stresses, particles can move apart and cause dilation, at higher stresses, the material becomes so compact that particle movement is restricted, resulting in minimal or no dilation (Craig, 2004; Mitchell & Soga, n.d.; Terzaghi et al., 1996).



a) Horizontal Displacement versus vertical displacement for 100 kPa stress



b) Horizontal displacement versus vertical displacement for 200 kPa stress



c) Horizontal displacement versus vertical displacement for 400 kPa stress

Figure 4.7 Volume change behavior-horizontal displacement for SAP-Pastfill mixture with (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles).

Figures 4.8 and 4.9 illustrate the shear strength (τ), cohesion (c), and internal friction angle (φ) of SAP paste tailing samples subjected to different numbers of freeze-thaw cycles (0, 1, 2, 3, 5, and 10 cycles), respectively. Table 4.7 further details the changes in cohesion values for each cycle, which are 54.8 kPa, 38.7 kPa, 15.6 kPa, 46.5 kPa, 54.3 kPa, and 7.8 kPa, respectively. The corresponding internal friction angles (φ) are 47.4º, 51.8º, 51.6º, 48.4º, and 43.9º, respectively. The relatively high friction angle values can be attributed to the angularity of the tailing's particles. As observed by Holubec and D'Appolonia (1973), increased particle angularity typically leads to higher friction angles due to the enhanced interlocking between particles. The peak shear stress versus normal stress curves were accurately fitted using linear regression according to the Mohr–Coulomb failure criterion, with all regression lines showing a high correlation ($R^2 > 0.95$).

The relationship is represented by the equation:

$$\tau = c + \sigma_n \tan(\phi) \quad (1)$$

where τ is the shear strength, c represents cohesion, σ_n is the normal stress, and φ is the internal friction angle.

The results indicate that freeze-thaw cycles significantly affect both cohesion and the internal friction angle, which are essential for evaluating the material’s shear strength and overall stability. Initially, the material shows high cohesion, but this decreases sharply by 29% after the first freeze-thaw cycle and continues to decline by an additional 60% after the second cycle, signaling a progressive weakening of the material's structure. Notably, cohesion temporarily recovers by the third cycle, suggesting possible material reorganization or strengthening, with stability maintained through the fifth cycle. However, after ten cycles, cohesion decreases dramatically by 86%, indicating severe structural degradation due to repeated freeze-thaw cycles.

In contrast, the internal friction angle initially increases by 9% after the first cycle, reflecting improved resistance to sliding. This value remains relatively stable through the second cycle. However, starting from the third cycle, the friction angle gradually decreases, stabilizing by the fifth cycle, but ultimately falling by 15% after the tenth cycle, which points to a reduction in the material’s overall shear resistance. These suggest that freeze-thaw cycles induce significant, albeit initially variable, deterioration in the structural integrity and shear strength of SAP paste tailing mixtures, directly affecting their resistance to shear deformation, a critical factor in the mechanical performance of barriers used in waste containment.

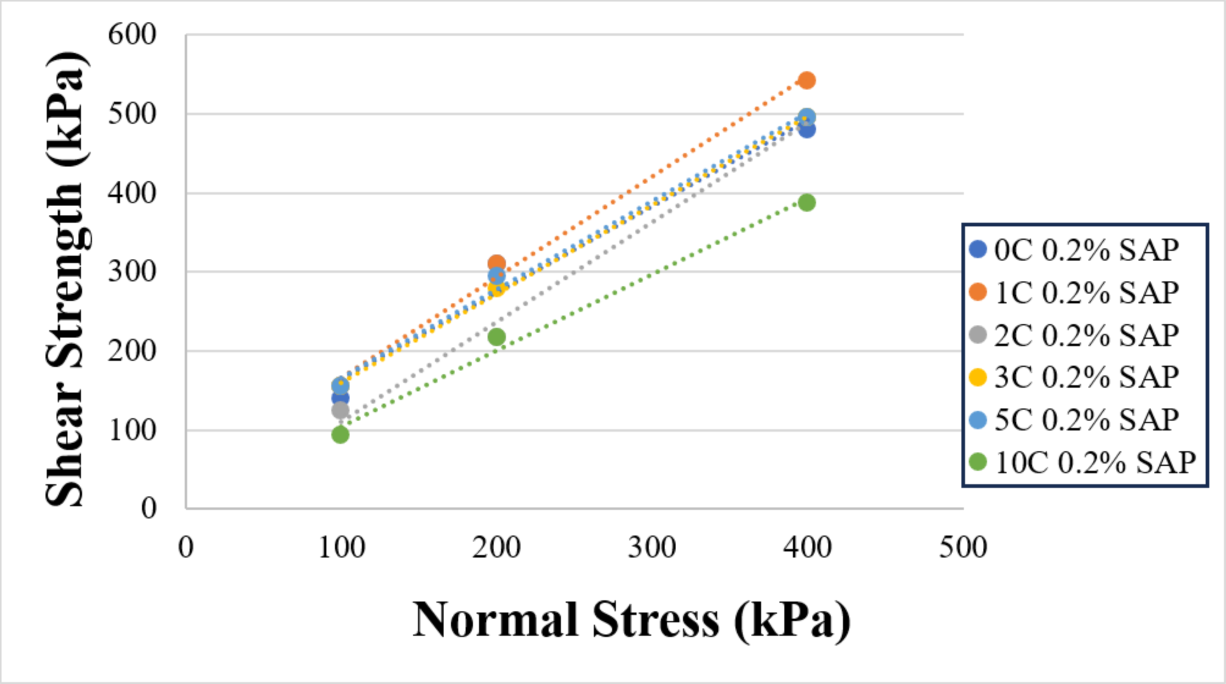


Figure 4.8 Normal stress vs the shear strength of the SAP-Pastfill mixture. (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles). (a) 100kPa (b) 200kPa and (c) 400 kPa.

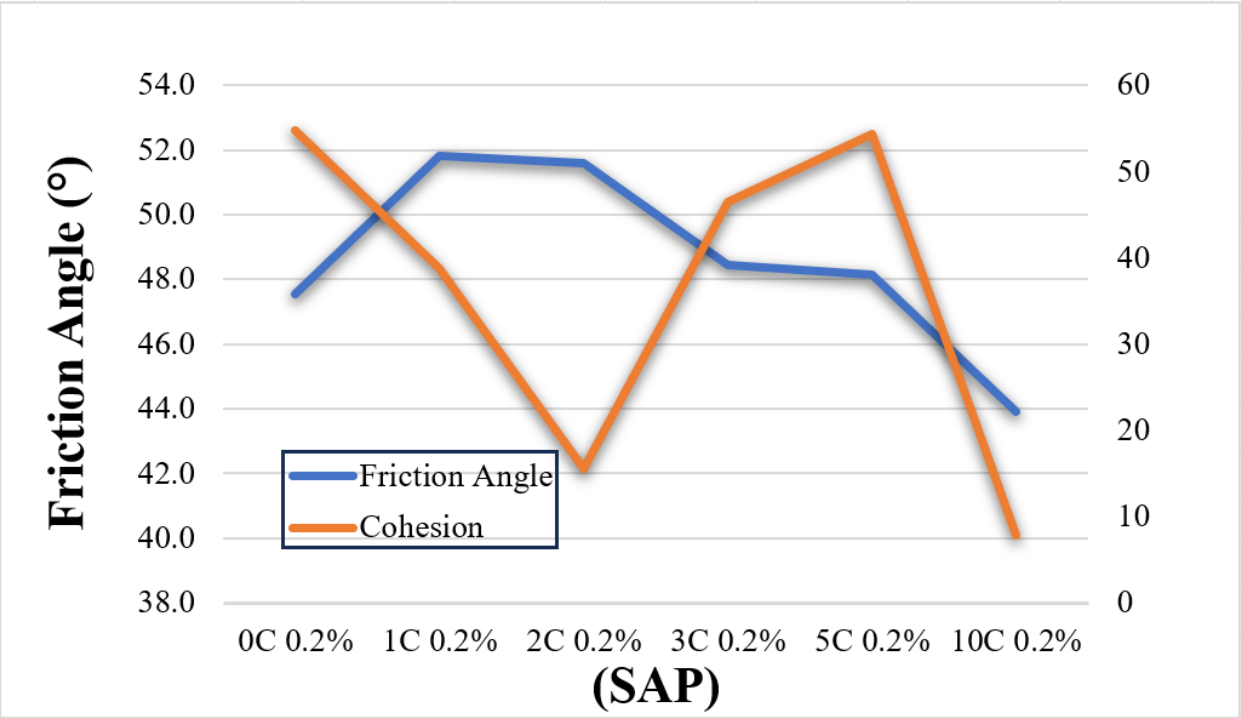


Figure 4.9 Friction angles vs the cohesion angles of SAP-Pastfill mixture. for (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles). (a) 100kPa (b) 200kPa and (c) 400 kPa.

Table 4.7: Cohesion C and Angle of Friction (º)

Cycle	Cohesion, C	Angle of Friction
0 Cycle	54.8	47.5
1 Cycle	38.7	51.8
2 Cycles	15.6	51.6
3 Cycles	46.5	48.4
5 Cycles	54.3	48.1
10 Cycles	7.8	43.9

4.5 Summary and Conclusions

The study comprehensively investigated the behavior of polymer-paste fill (PP) mixtures containing superabsorbent polymers (SAP) under freeze-thaw cycles. The findings shed light on the intricate interplay between freeze-thaw cycles, material composition, and mechanical properties, providing valuable insights for the design and implementation of effective surface tailings disposal facilities, particularly in cold climates. The findings lead to the following Conclusion:

The study revealed that freeze-thaw cycles significantly impact the consolidation behavior of SAP paste tailings. As the number of freeze-thaw cycles increased, there was a noticeable increase in the void ratio. This change, along with alterations in consolidation parameters such as the compression index and swell index, indicates that freeze-thaw cycles influence the material's ability to consolidate effectively.

The shear strength of SAP paste tailings exhibited complex behavior under freeze-thaw conditions and varying confining pressures. Initially, the material showed stability or a slight improvement in shear strength during the first few cycles. However, as exposure to freeze-thaw cycles continued, fluctuations in shear strength were observed, suggesting cumulative damage and potential recovery mechanisms within the material.

The freeze-thaw cycles had a significant effect on both the consolidation and shear characteristics of SAP paste tailings. These cycles led to an increase in void ratio and altered the material's deformation characteristics. Additionally, changes in cohesion and internal friction angle were noted, likely due to modifications in the microstructure and interparticle interactions caused by freeze-thaw cycles.

In conclusion the potential application of compacted SAP-paste fill mixtures as barrier materials shows considerable promise, particularly due to their favorable consolidation and shear strength properties. However, in cold climates, the material's performance may be compromised by the effects of freeze-thaw cycles. Therefore, it is crucial to consider the temperature conditions of the location when using this material as a waste barrier. Engineers working in cold climates should integrate these findings into their waste containment strategies to enhance the performance and longevity of surface tailings disposal facilities. While the results are promising, further research is needed to fully understand the geotechnical properties and durability of the recommended barrier material.

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CHAPTER 5

SYNTHESIS OF THE RESULTS & IMPLICATIONS FOR DESIGN

5.1 Introduction

This thesis examines the mechanical behavior of SAP-paste tailings. Superabsorbent polymers (SAPs) are materials capable of absorbing and retaining large amounts of water relative to their mass. When added to tailings, SAPs can significantly alter the physical properties of the mixture. Chapter 3 focuses on investigating the consolidation behavior and shear strength characteristics of polymer-paste tailings barriers for waste containment facilities. Chapter 4 explores the effects of freeze-thaw cycles on the consolidation behavior and shear strength characteristics of SAP-paste tailings barriers. Table 5.1 summarizes and details the experimental tests conducted as described in Chapters 3 and 4. Based on a comparison of the results, the consolidation and shear strength behaviour of SAP-paste tailings under standard conditions and when subjected to freeze-thaw cycles are summarized in sections 5.2 and 5.3 respectively. SAP paste tailing samples were prepared.

Table 5.1 Summary of laboratory tests

Chapter	Test	% SAP	Tailings	Optimum water content wopt (%)	Maximum dry density, $\rho_{d(max)}$ (kg/m^3)	Coefficient of permeability, k(m/s)
3	**Mechanical strength**	0	ST	18.2	1602	12.0×10^{-8}
		0.2		25.6	1391	2.7×10^{-8}
		0.5		30.7	1191	5.5×10^{-8}
4	**Mechanical strength (freeze-thaw cycles)**	0.2	ST	25.6	1391	2.7×10^{-8}

ST: Selica Tailing; SAP: Superabsorbent polymer

5.2 Mechanical Behaviour (Consolidation and Shear Strength) Characteristics of polymer-Pastefill (PP)

The mechanical behavior, specifically the consolidation and shear strength characteristics, of polymer-pastefill (PP) containing Super Absorbent Polymer (SAP), was thoroughly examined in Chapter 3. Compacted PP samples with different SAP concentrations (0.0%, 0.2%, and 0.5%) were prepared and subjected to consolidation and shear tests. Consolidation behavior was analyzed through oedometer tests, monitoring settlement over time under various stress conditions. Additionally, shear characteristics were assessed using direct shear tests to evaluate the material's resistance to shearing and deformation under different normal stresses. The study revealed significant insights into the stress-strain responses of polymer-pastefill with varying SAP concentrations. Notably, higher SAP content improved resistance to compression and enhanced swelling potential, resulting in more efficient consolidation processes. For instance, the void ratio, as depicted in Figure 5.1, decreased more significantly in samples with higher SAP content, particularly in the 0.5% SAP sample, indicating better consolidation. Further analysis of the coefficients of volume change (mv) and compressibility (av), derived from the slopes of void ratio versus effective stress and strain versus effective stress curves, showed a decrease in mv and av values as effective stress increased, as illustrated in Figure 5.2. This trend correlated directly with SAP content, indicating that higher SAP concentrations resulted in greater initial compressibility due to increased void spaces. However, as effective stress increased, the compressibility effect diminished due to the compression of SAP particles. The coefficient of consolidation (cv) was determined using both the logarithm of time method (Casagrande) and the square root of time method (Taylor). As shown in Figure 5.6, cv values generally increased with higher effective consolidation stress for all PP specimens, reflecting enhanced pore water pressure dissipation and improved soil structure stability.

In conclusion, SAP concentration significantly influences the consolidation behavior of polymer-pastefill. Increased SAP content enhances compression resistance and swelling potential, resulting in more efficient consolidation processes. However, maintaining the right balance of SAP concentration is crucial, as excessive SAP can reduce consolidation efficiency due to over-swelling. These findings are essential for optimizing polymer-pastefill formulations to achieve better consolidation performance in various engineering applications.

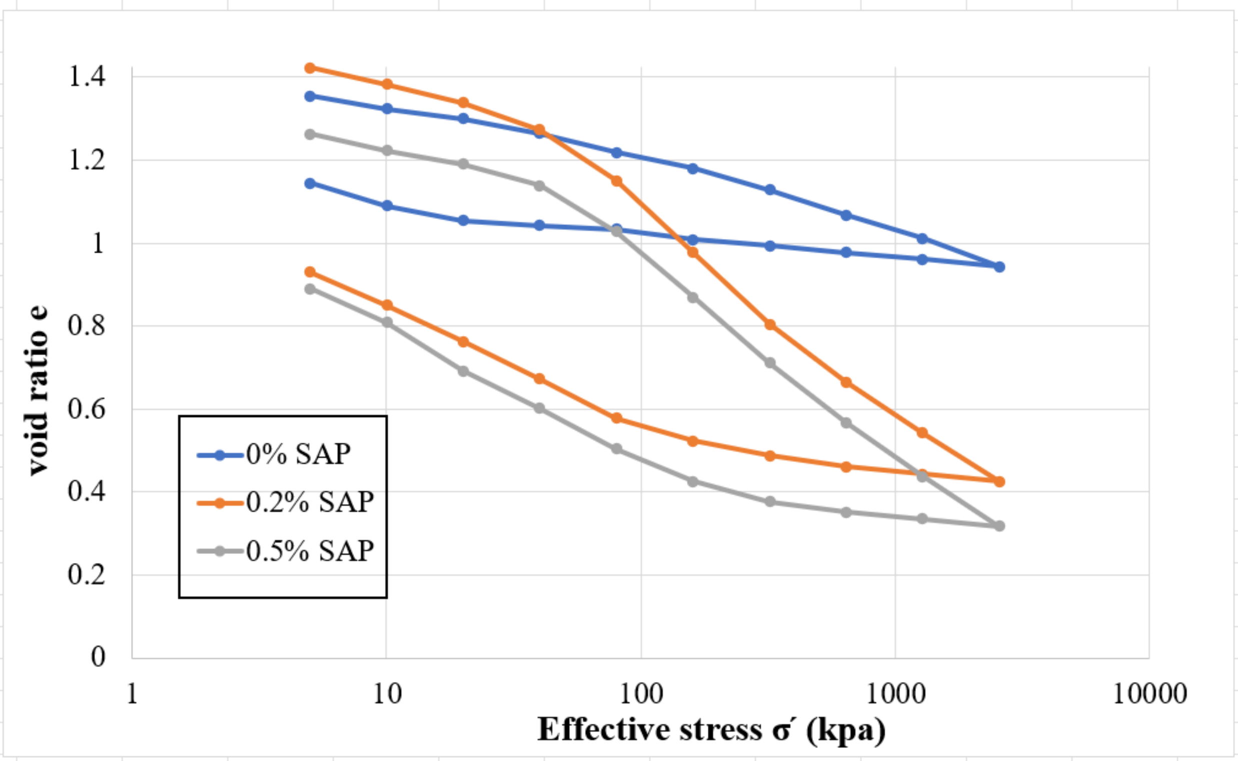

Figure 5.1 Effective consolidation stress versus void ratio

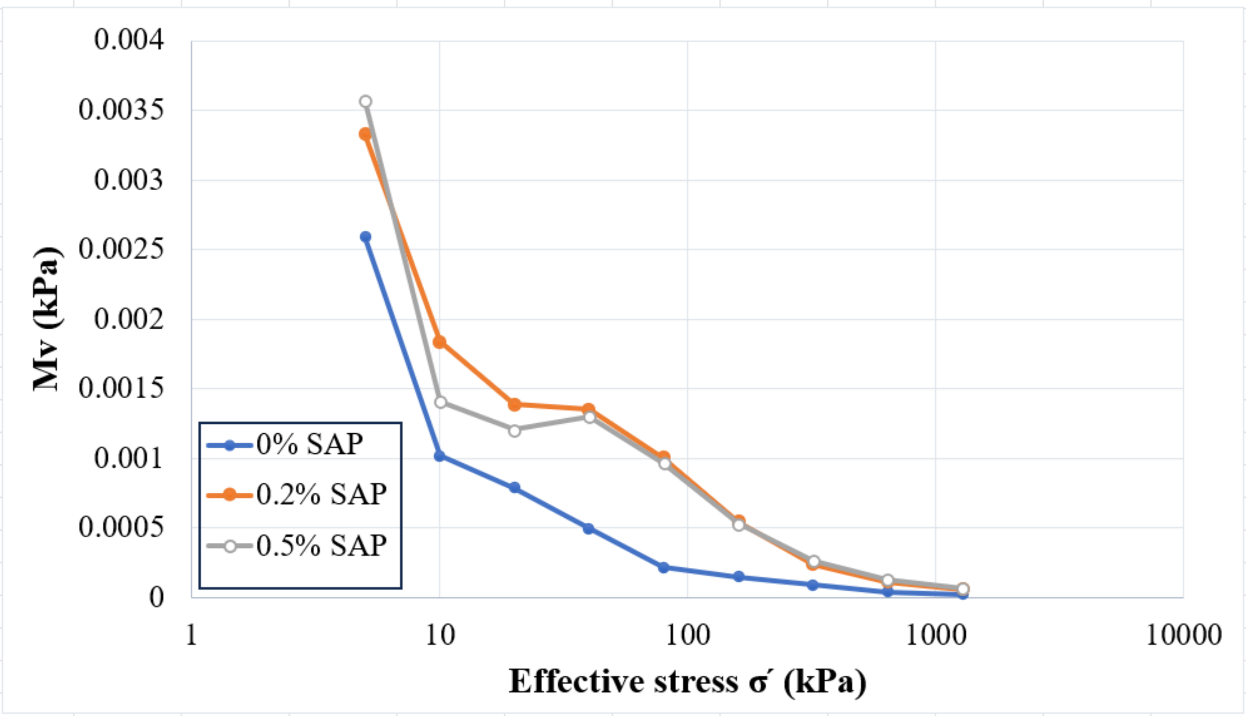

Figure 5.2 Effective consolidation stress versus coefficient of volume change

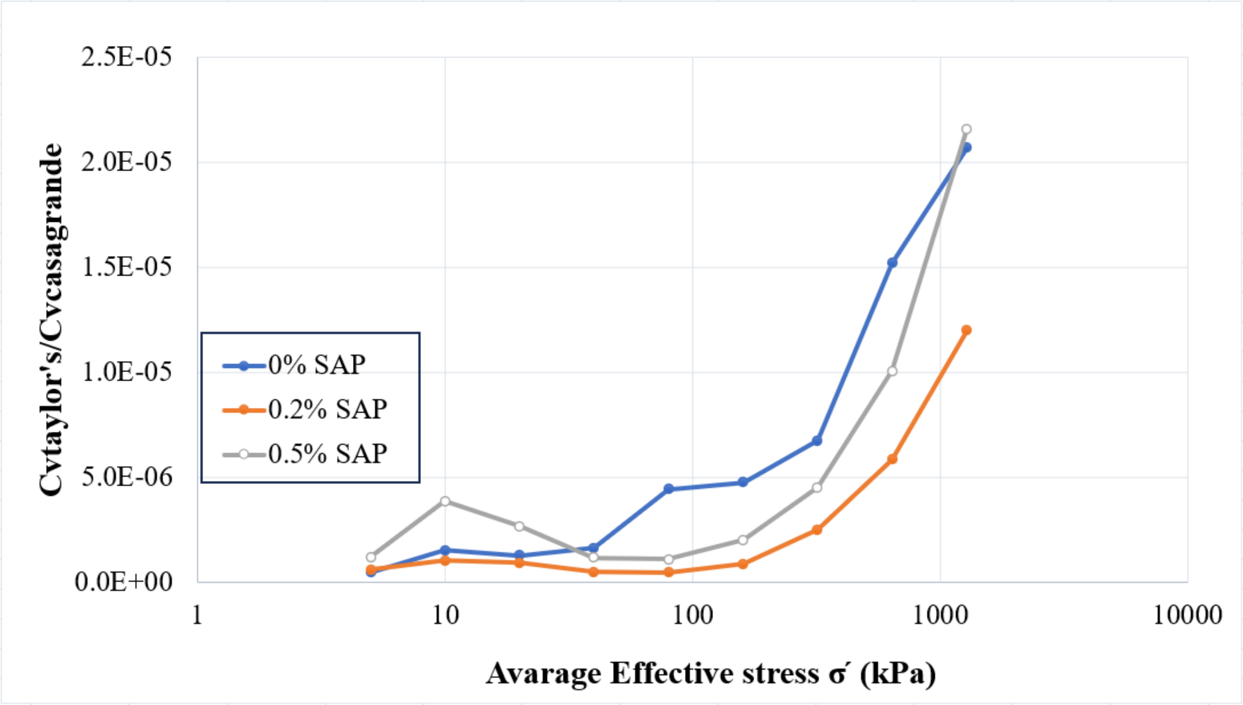

Figure 5.3 Effective consolidation stress versus a ratio of Taylor's method to Casagrande's method.

The shear strength behavior of polymer-pastefill (PP) with varying concentrations of Super Absorbent Polymer (SAP) provides valuable insights into the material's performance under different stress conditions. Experimental tests conducted on PP samples containing 0%, 0.2%, and 0.5% SAP under normal stresses of 100 kPa, 200 kPa, and 400 kPa revealed distinct trends in shear strength, as shown in Figure 5.4. Shear stress increased progressively with horizontal displacement, and in the absence of a definitive peak, the shear stress at 15% shear strain was considered the peak shear stress or shear strength, in line with ASTM guidelines. The results indicated that the maximum shear stress (τmax) was higher for samples with 0.2% SAP compared to 0% SAP, reflecting improved shear strength. However, at 0.5% SAP, a reduction in shear strength was observed, particularly under higher normal stress (200 kPa), attributed to excessive SAP swelling, which disrupted the mixture's integrity by increasing void spaces. Additionally, volume change curves presented in Figure 5.5 delineated two distinct stages of deformation in PP samples, both with and without SAP. In the first stage, vertical contraction occurred as a result of particle compaction, with contraction magnitude influenced by SAP content (0.2% SAP < 0.0% SAP < 0.5% SAP), indicating the presence of a threshold beyond which excessive swelling compromises the structural stability of the mixture. In the second stage, dilatancy was observed at low normal stress (100 kPa) in samples with lower SAP content, while no dilatation was detected at higher normal stresses due to the suppression of void space expansion. Cohesion (c) and internal friction angles (φ) for the samples were evaluated, with 0%, 0.2%, and 0.5% SAP samples exhibiting cohesion values of 30.0, 54.7, and 62.0 kPa, respectively, and internal friction angles of 50.7º, 47.5º, and 38.6º. The relatively high friction angles were attributed to the pronounced angularity of the tailings particles. These results demonstrate that higher SAP content enhances cohesion but decreases the internal friction angle, underscoring the complex interaction between SAP concentration and the material's structural integrity. The Mohr-Coulomb failure criterion, as summarized in Table 5.2, further confirms that increased SAP concentration enhances cohesion but reduces friction angles, primarily due to the water absorption and swelling characteristics of SAP. In conclusion, SAP concentration significantly influences the shear strength of polymer-pastefill, with 0.2% SAP enhancing strength and stability, while 0.5% SAP leads to over-swelling and reduced shear strength. These findings are critical for optimizing SAP concentrations in polymer-pastefill formulations to enhance shear strength and structural stability in engineering applications.

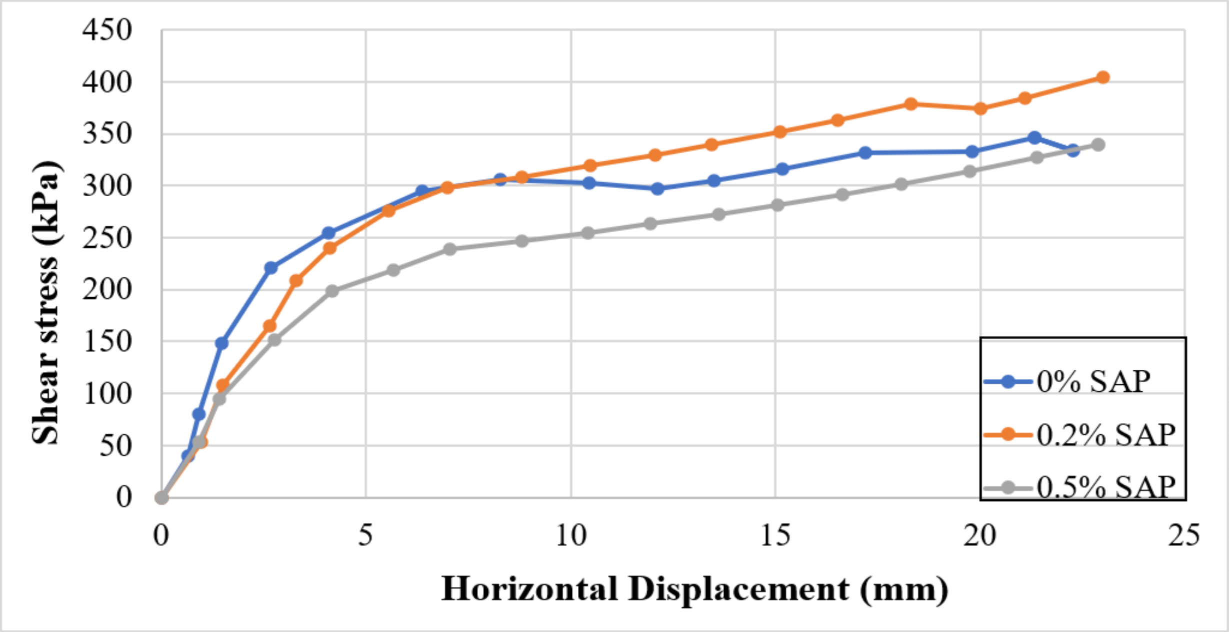

Figure 5.4 Horizontal displacement versus shear stress for 200 kPa stress

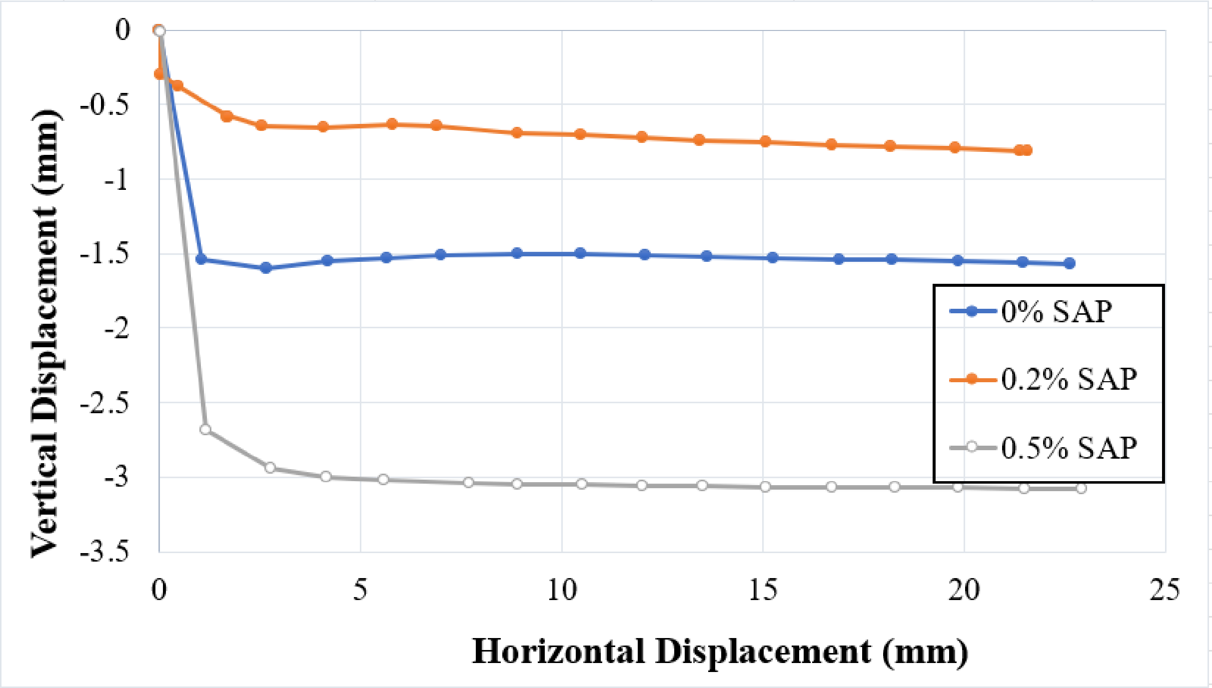

Figure 5.5 Horizontal displacement versus vertical displacement for 200 kPa stress

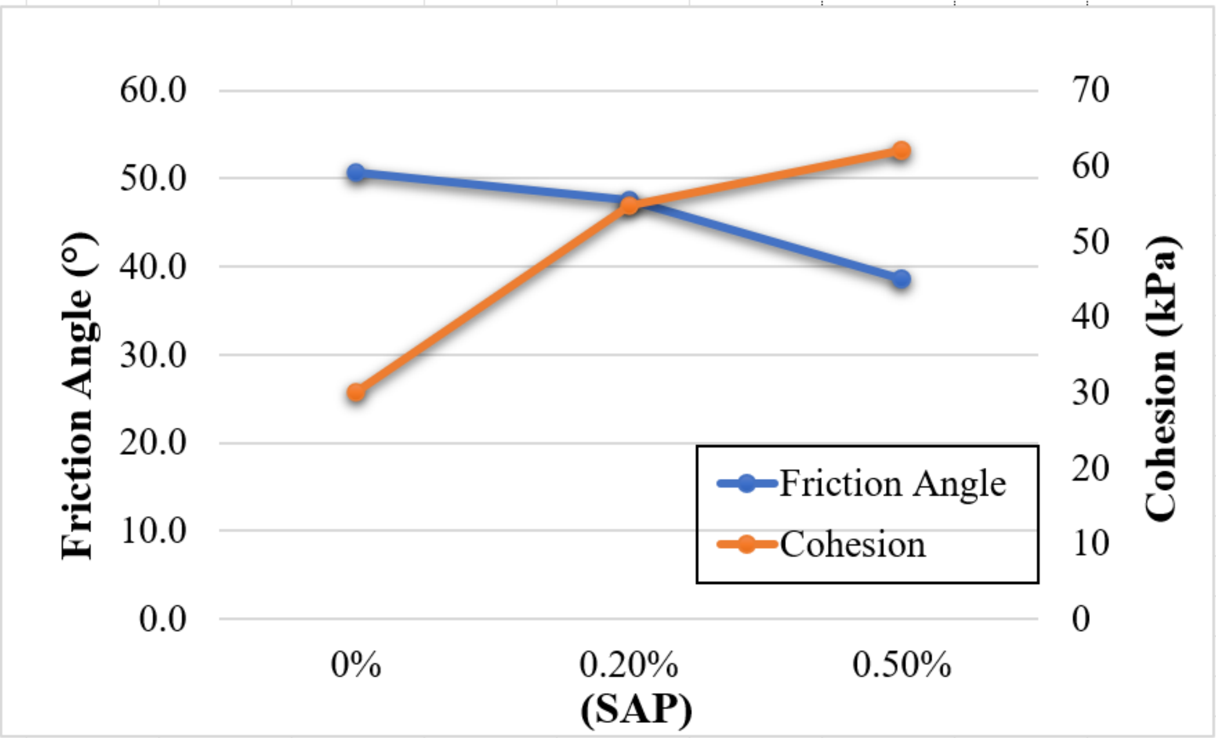

Figure 5.6 Friction angles vs the cohesion angles of SAP-Pastfill mixture. for 0%, 0.2% and 0.5% SAP. (a) 100kPa (b) 200kPa and (c) 400 kPa.

Table 5.2: Cohesion C and Angle of Friction (º)

% SAP	Cohesion, C	Angle of Friction
0%	30.0	50.7
0.20%	54.7	47.5
0.50%	62.0	38.6

5.3 Impact of Freeze-Thaw Cycles on the Mechanical Strength of Polymer-Pastefill

The effect of freeze-thaw cycles on the mechanical behavior, specifically the consolidation and shear strength characteristics, of polymer-pastefill (PP) containing Super Absorbent Polymer (SAP) was thoroughly examined in Chapter 4. This section explores how freeze-thaw cycles, which simulate climate change effects, influence the mechanical strength characteristics of polymer-pastefill. SAP-paste tailings exposed to these cycles exhibit significant consolidation and shear strength changes. These changes highlight the material's resilience and stability under temperature fluctuations, making it a viable option for waste containment applications. Therefore, understanding the behavior of SAP-paste tailings is crucial for researchers developing effective strategies for using this innovative material as liners or covers in mining and industrial waste facilities. This knowledge will ensure waste containment systems' long-term stability and effectiveness in environments prone to freeze-thaw cycles.

In consolidation experiments on PP samples with 0.2% SAP content subjected to varying freeze-thaw cycles (0, 1, 2, 3, 5, 10 cycles), distinct changes in the void ratio were observed. Initially, the void ratio decreased significantly after the first freeze-thaw cycle, but subsequent cycles gradually increased the void ratio (Figure 5.7). This can be attributed to ice crystal formation during freezing, which disrupts particle agglomeration and creates additional void spaces. Moreover, repeated freezing and thawing can also lead to ice lenses or cracks, further increasing void spaces and mechanically disrupting the material's structure.

The compression index (Cc) and swell index (Cs) derived from stress-strain curves show that freeze-thaw cycles affect the compressibility of PP samples. Notably, the 10th cycle showed a higher compression index than the 0-cycle sample, indicating increased compressibility and swelling potential after extensive freeze-thaw cycles. Furthermore, the coefficients of volume change (mv) and compressibility (av), calculated from the slopes of the void ratio versus effective stress and strain versus effective stress curves (Figure 5.8), generally decreased with increasing effective stress. This trend reflects increased initial compressibility due to void spaces formed by freeze-thaw cycles, but eventually decreased with higher effective stress as the material compacted.

Additionally, the coefficient of consolidation (cv), calculated using both the Casagrande and Taylor methods, increased with higher effective consolidation stress for all samples (Figure 5.9). This increase can be attributed to soil densification, improved particle contacts, increased stiffness, and changes in permeability, thereby enhancing the material's ability to consolidate more rapidly under subsequent loads. However, excessive freeze-thaw cycles can cause structural disruption and increased void spaces, potentially reducing consolidation efficiency.

In conclusion, freeze-thaw cycles and the presence of SAP significantly influence the consolidation behavior of polymer-pastefill. The void ratio, compression index, and coefficients of volume change and compressibility exhibit notable changes with varying freeze-thaw cycles, providing valuable insights for optimizing polymer-pastefill compositions and understanding their behavior in environments subject to freeze-thaw cycles.

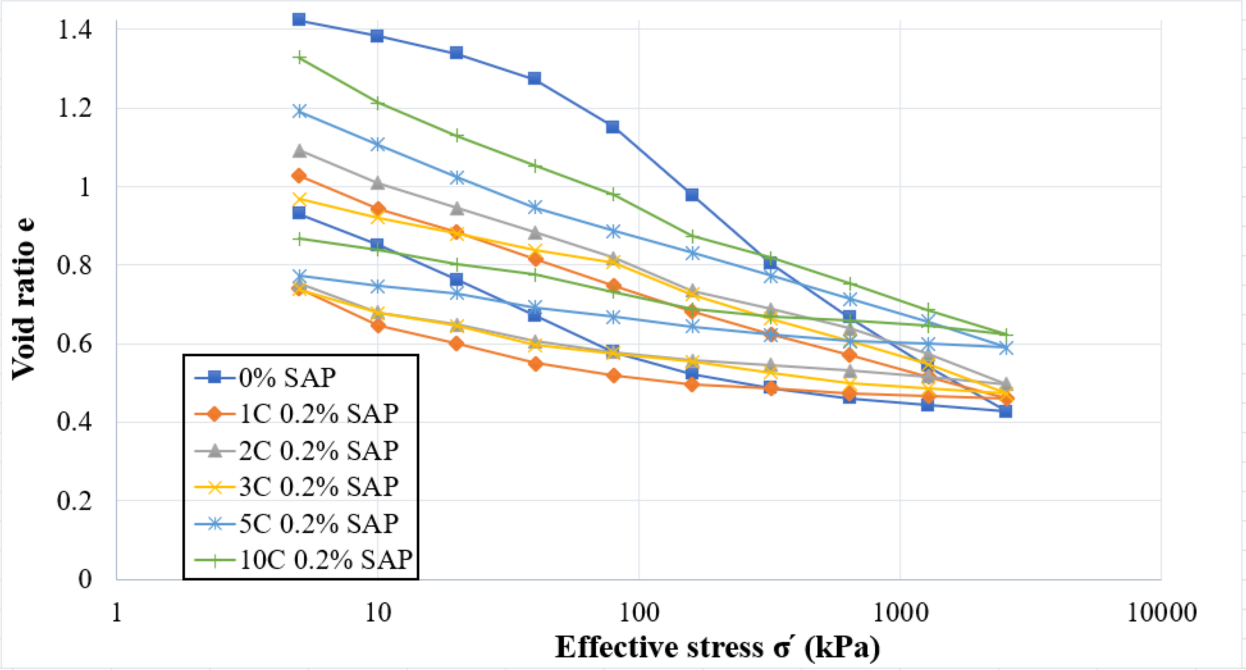

Figure 5.7 Effective consolidation stress versus void ratio

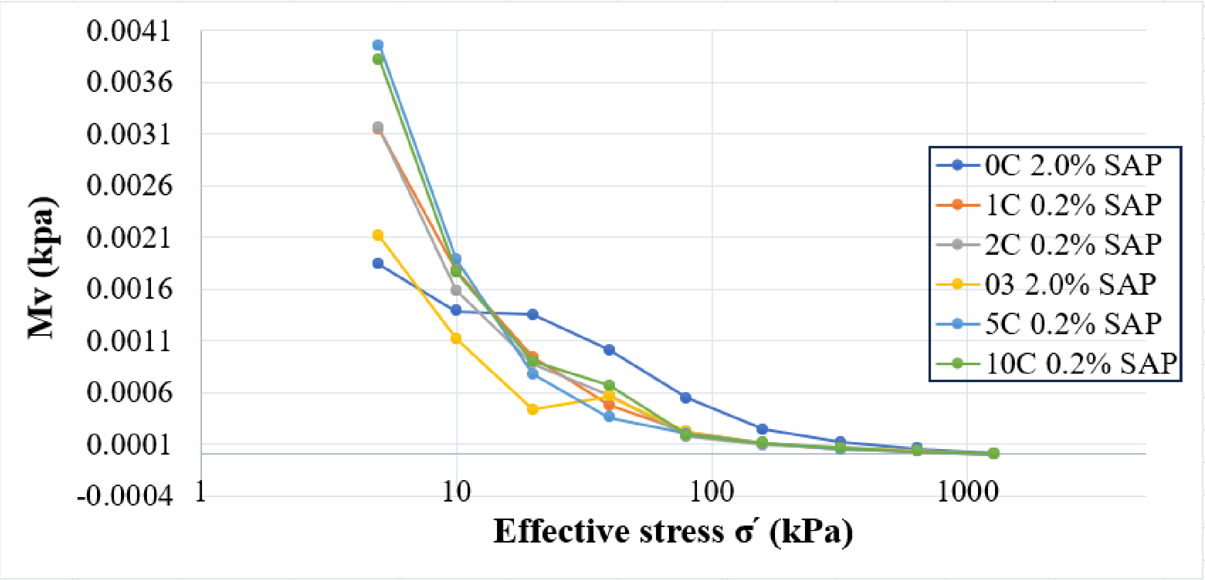

Figure 5.8 Effective consolidation stress versus coefficient of volume change

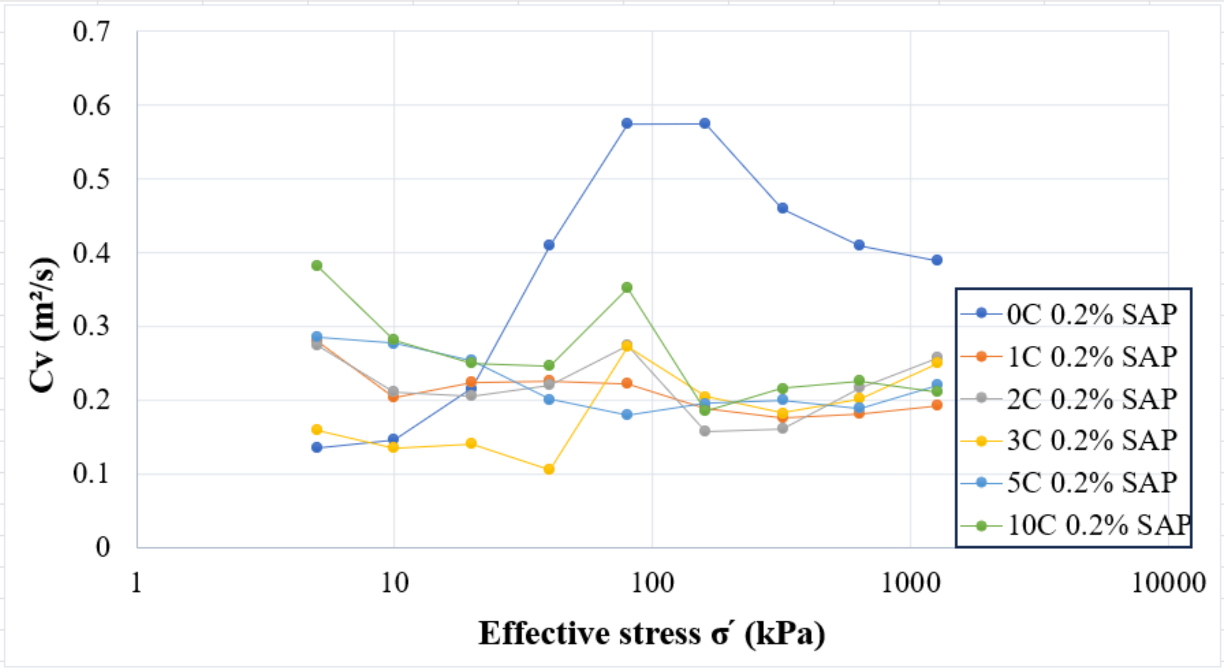

Figure 5.9 Effective consolidation stress versus Taylor’s method

The shear strength behavior of polymer-pastefill (PP) with 0.2% SAP content subjected to varying freeze-thaw cycles (0, 1, 2, 3, 5, 10 cycles) provides valuable insights into the material's performance under different environmental conditions. Figure 5.10 shows plots of horizontal displacement versus shear stress for these freeze-thaw cycles at a pressure of 200 kPa. The shear stress curves rise consistently until reaching a maximum value. Notably, the stress-displacement curves for the PP samples do not display distinct peak shear stresses. According to ASTM guidelines, in the absence of a clear peak, the shear stress at 15% shear strain is considered the peak shear stress or shear strength. Initially the result shows that shear stress increases from 0 to 1 cycle; however, it then decreases at 2 cycles, indicating structural weakening, particularly under high normal stress (200 kPa). From the 3rd to the 5th cycle, peak shear stress increases again, suggesting partial recovery or stabilization due to restructuring or consolidation within the material. Nevertheless, a significant decrease in peak shear stress at the 10th cycle indicates accumulated damage or fatigue leading to failure. These fluctuations highlight the complex relationship between structural changes, freeze-thaw cycles, and external loading conditions.

Moreover, the volume change behavior of SAP paste tailings under varying normal stresses (100, 200, and 400 kPa) during shear displacement follows two stages: initial vertical contraction due to particle compaction and consolidation, particularly under 100 kPa normal stress. As freeze-thaw cycles progress, expansion due to dilatancy occurs at lower stresses (100 kPa), while higher stresses (200 and 400 kPa) limit particle movement, resulting in minimal or no dilation. The degree of dilation decreases with increasing normal stress due to greater material compaction.5.3.1 Impact of freeze-thaw cycles on shear strength

The freeze-thaw cycles significantly impact the shear strength of the SAP-pastefill mixture. As shown in Figure 5.12, the shear strength (τ), cohesion (c), and internal friction angle (φ) for the 0, 1, 2, 3, 5, and 10 freeze-thaw cycles indicate that the 0, 1st, 3rd, and 5th cycles significantly increase cohesion while reducing the internal friction angle. In contrast, the 2nd and 10th cycles decrease cohesion while increasing the friction angle. Additionally, the microstructure and interparticle interactions within the SAP samples change under freeze-thaw cycles as the water present within the material freezes and forms ice crystals, causing microcracks and alterations in particle arrangement. The existence of ice crystals can facilitate particle rearrangement and enhance cohesion, resulting in elevated shear strength and cohesion values. However, excessive freeze-thaw cycles lead to structural disruption, thereby reducing cohesion and increasing the internal friction angle. This non-linear relationship between freeze-thaw cycles and shear strength properties highlights the complex interplay between freeze-thaw cycles, material microstructure, and interparticle interactions.

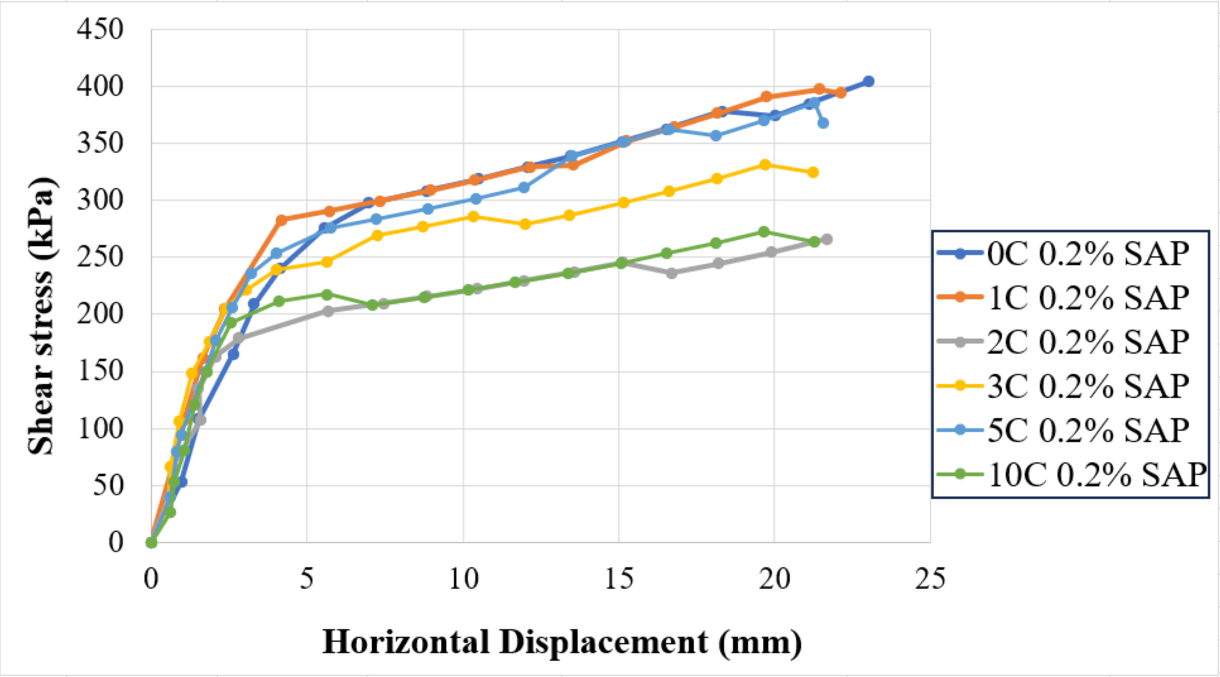

Figure 5.10 Horizontal Displacement versus Shear stress for 200 kPa stress

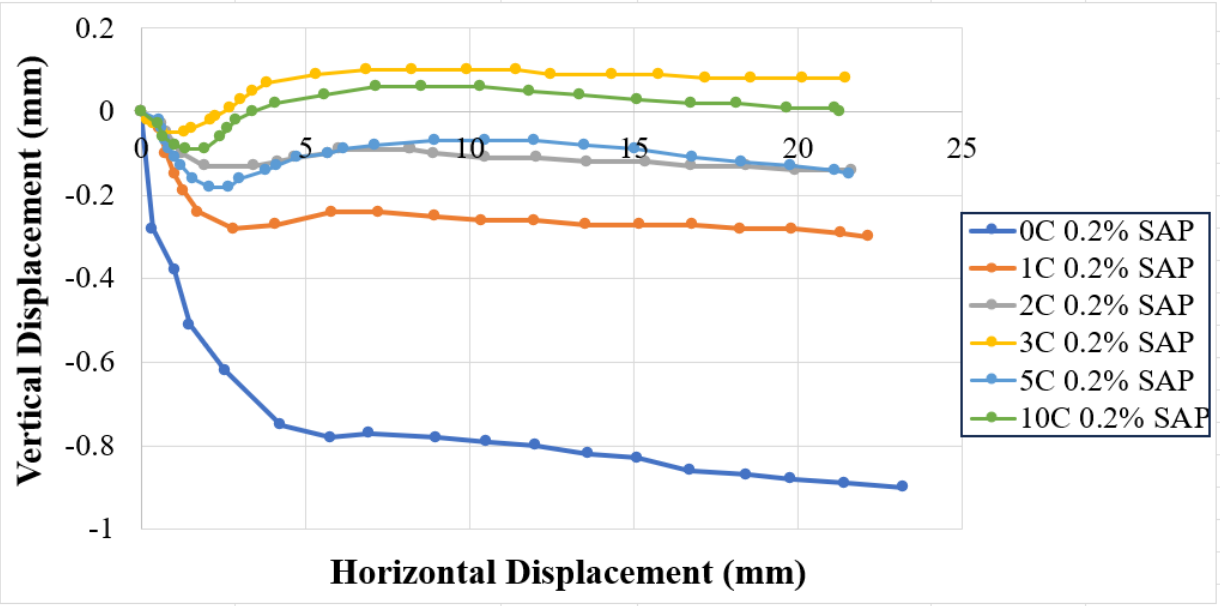

Figure 5.11 Horizontal displacement versus vertical displacement for 200 kPa stress

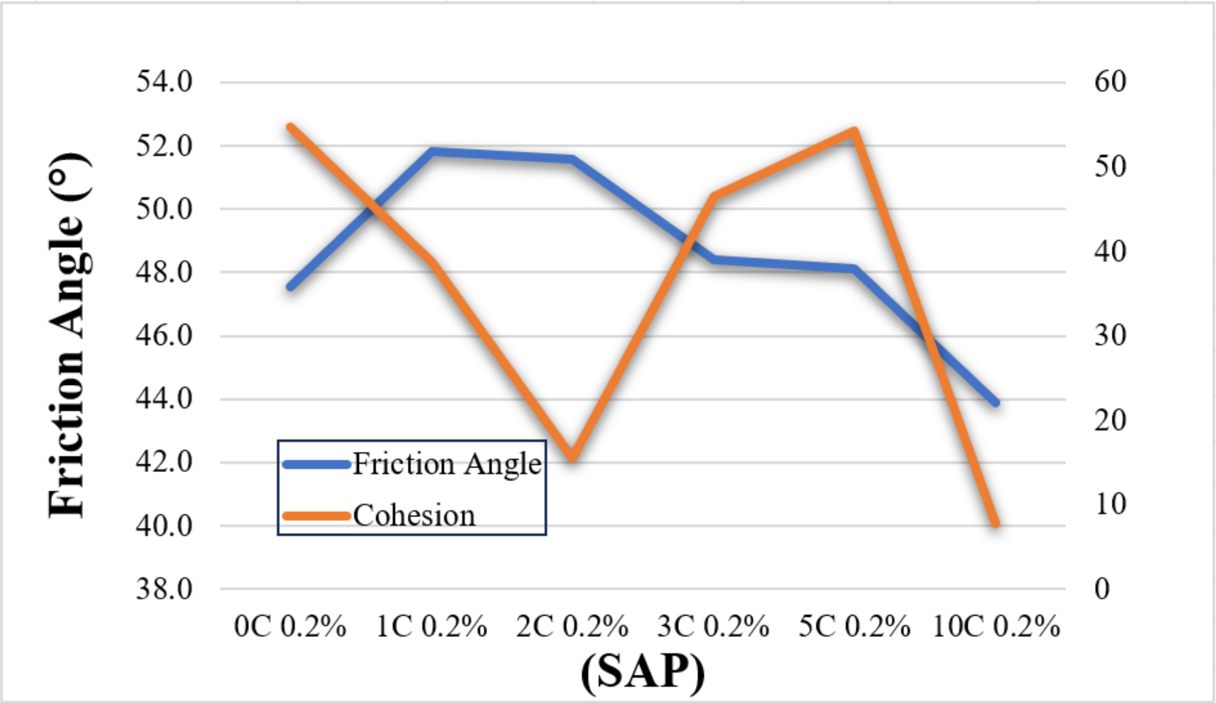

Figure 5.12 Friction angles vs the cohesion angles of SAP-Pastfill mixture. For (0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles) 0.2% SAP. (a) 100kPa (b) 200kPa and (c) 400 kPa.

5.4 Design Considerations of Densified Polymer-Paste Tailings Mixture as Waste Containment Barrier

When designing barriers for waste contamination facilities using SAP-paste tailings, several key considerations emerge from the experimental results, particularly regarding the material's mechanical behavior under varying conditions. Firstly, the concentration of Super Absorbent Polymer (SAP) must be optimized. Experimental results indicated that a 0.2% SAP concentration enhanced shear strength and stability by improving interparticle bonding. However, concentrations above this, such as 0.5%, led to over-swelling, which disrupted the pastefill mixture and reduced shear strength. Consequently, finding the right balance in SAP concentration is crucial to ensure the barrier maintains both strength and stability.

Additionally, freeze-thaw resilience is a significant factor in designing these barriers. The experiments showed that SAP-paste tailings exposed to freeze-thaw cycles exhibited notable changes in consolidation and shear strength. For instance, while initial freeze-thaw cycles might increase cohesion, excessive cycles led to structural weakening and reduced cohesion. Therefore, materials must be selected and tested to withstand repeated freeze-thaw cycles without significant degradation, maintaining structural integrity and resisting the formation of microcracks and void spaces caused by ice crystal formation.

Furthermore, hydraulic properties play a critical role. Fall et al. (2010), who developed the SAP-paste tailing, demonstrated that compacted PP can have hydraulic conductivity values below the minimum required for liner design in compliance with EPA regulations (10^-7 cm/s). Hence, there is still a need to control the permeability of the SAP-paste tailing barrier to ensure it effectively contains contaminants while allowing controlled water passage. Moreover, the swelling potential of SAP should be managed to maintain desired hydraulic conductivity and prevent excessive expansion, which might damage the containment structure.

The experimental results highlight the importance of monitoring consolidation behavior. Higher SAP content improved resistance to compression and enhanced swelling potential, which contributed to more efficient consolidation processes. This indicates that the material's settlement over time under various stress conditions must be minimal to maintain barrier effectiveness. Additionally, understanding the material's shear strength behavior under normal stresses is vital, particularly in ensuring that the barrier remains stable under varying environmental conditions.

Environmental impact and long-term performance are also crucial considerations. The SAP materials chosen should be eco-friendly to minimize environmental impact and ensure the sustainability of the containment facility. Moreover, the SAP-paste tailings must be chemically compatible with the surrounding environment and the tailings material to prevent adverse reactions that could compromise the barrier's integrity. The design should also account for durability, ensuring that the barrier can withstand long-term exposure to environmental stressors, including freeze-thaw cycles, water flow, and chemical exposure.

Lastly, implementing regular maintenance and monitoring programs is essential to assess the barrier's performance and address any issues promptly. Pilot testing in real-world conditions can provide valuable insights before full-scale implementation, ensuring the solution is economically viable and effective for the specific waste containment application. By carefully considering these design factors, SAP-paste tailings can be effectively utilized to create robust and reliable barriers for waste containment facilities, ensuring long-term environmental protection and structural stability.

5.5 Practical Implications for Waste Containment Facility Design

The practical implications for designing waste containment facilities, especially in areas prone to freeze-thaw cycles, are substantial. For polymer-paste barriers, incorporating optimal SAP content enhances stability and shear strength, making them suitable for regions with stable or moderate temperature variations. However, in areas with significant temperature fluctuations, SAP-paste barriers must be designed with freeze-thaw resilience in mind. This can be achieved by incorporating additives and design features that mitigate the effects of temperature changes. Additionally, regular monitoring and maintenance are crucial to address potential structural weakening due to freeze-thaw cycles, ensuring the barriers' continued effectiveness and durability. Therefore, these findings underscore the importance of tailored design strategies that consider local environmental conditions to achieve safe and sustainable waste containment solutions.

5.6 Novel Research Contributions of the Thesis

The research presents several novel contributions to the field of waste containment using tailings as a material. The key novel research contributions of this thesis include:

1. The thesis investigates the integration of Superabsorbent Polymer (SAP) into paste tailings to create a densified polymer-paste material. This study is the first to explore the mechanical behavior of such materials, particularly with respect to their performance as barriers in waste containment facilities. The novel use of SAP can enhance the low hydraulic conductivity and mechanical characteristics of the paste, making it an effective barrier for containing hazardous waste, which is a significant environmental concern in mining operations.
2. The research presented in this thesis is the first one conducted to gain insight into the consolidation behavior and shear strength characteristics of SAP-modified tailings. It presents a thorough examination of how varying concentrations of SAP (0%, 0.2%, and 0.5%) affect these properties. The study demonstrates that the incorporation of SAP influences both consolidation rates and shear strength, revealing that increasing SAP content accelerates consolidation but only enhances shear strength up to a certain threshold before it declines. This detailed analysis is crucial for optimizing SAP content for barrier materials in waste containment.
3. Another novel aspect of this research is its evaluation of the effects of freeze-thaw cycles on the performance of SAP-modified paste tailings. Given the potential exposure of waste

containment facilities to extreme climatic conditions, especially in cold regions, this study is essential for understanding how these materials behave under repeated freezing and thawing. The findings suggest that while freeze-thaw cycles initially increase the strength and solid content of the SAP-paste tailings, prolonged exposure leads to a decline in strength, which could influence the long-term stability of waste containment barriers.

4. Another key contribution is the identification of an optimal SAP concentration (0.2% in this study) that balances both consolidation efficiency and mechanical strength. This provides a clear guideline for the use of SAP in paste tailings to achieve maximum performance in practical applications, offering mining engineers a new approach to designing waste containment barriers.
5. The study provides significant insights into the potential for using non-acidic, cement-free paste tailings with SAP for constructing barrier systems in waste containment facilities, which include liners and covers. By proposing an alternative to traditional materials, this research contributes to more sustainable and environmentally friendly practices in mining and industrial waste management.

5.7 References

Fall, M., Célestin, J., & Sen, H. F. (2010). Potential use of densified polymer-pastefill mixture as waste containment barrier materials. *Waste Management*, *30*(12), 2570–2578. https://doi.org/10.1016/j.wasman.2010.07.016

CHAPTER 6

CONCLUSIONS AND RECOMMENDATIONS

This section provides a summary of the findings and suggestions for future research. The primary aim of this study is to explore the effect of superabsorbent polymer (SAP) on the performance of tailings barriers, with a focus on consolidation behavior, shear characteristics, and the influence of freeze-thaw cycles. This involves examining how SAP influences consolidation over time, evaluating shear characteristics under various conditions to assess stability and resistance to shear forces, and identifying the optimal SAP concentration for maximum benefit. Additionally, the study emphasizes the importance of understanding the effects of freeze-thaw cycles, especially in the Canadian context, on consolidation and shear strength behavior, considering settlement patterns and overall trends. The investigation is conducted in two phases. The first phase involves preparing compacted PP samples with varying SAP concentrations (0.0%, 0.2%, 0.5%) and subjecting them to consolidation and shear tests. The second phase subjects 0.2% SAP paste tailings to multiple freeze-thaw cycles (ranging from 0 cycle (i.e. no freeze-thaw cycle), 1 cycle, 2 cycles, 3 cycles, 5 cycles, 10 cycles, between 20°C and −20°C), followed by consolidation and direct shear testing according to ASTM standards. Consolidation behavior is examined using oedometer tests, which monitor settlement over time under different stress conditions. Shear characteristics are assessed through direct shear tests to determine the material's resistance to shearing and deformation under various normal stresses. The key findings from both phases are presented in the following sections:

Phase 1

i. Densified polymer SAP-pastefill mixtures show potential as barrier materials due to their favorable consolidation and shear strength characteristics. However, identifying the ideal SAP concentration is crucial for optimal performance.

ii. Higher SAP content in PP intensifies the consolidation process, with 0.5% SAP demonstrating greater consolidation compared to 0.2% and 0% SAP. This is likely due to the superior water-absorbing capacity of SAP at higher concentrations, facilitating faster consolidation.

iii. The SAP-pastefill mixture shows higher strength at 0.2% SAP, suggesting enhanced cohesion and internal bonding at this concentration. However, at 0.5% SAP, the shear strength decreases, likely due to increased void spaces and reduced friction between particles from the polymer's water absorption.

iv. The optimal SAP concentration in pastefill will depend on specific project requirements, including stability considerations, construction timelines, and long-term performance expectations. Engineers and designers must carefully evaluate these factors when determining the appropriate SAP dosage.

Phase II

i. Compacted polymer SAP-paste fill mixtures, with an appropriate percentage of SAP, show considerable promise as barrier materials due to their favorable consolidation and shear strength characteristics. However, in cold climates, these materials may be affected by freeze-thaw cycles, making it important to consider the location's temperature when using this material as a waste barrier.

ii. Freeze-thaw cycles significantly impact the consolidation behavior of SAP paste tailings. An increase in the freeze-thaw cycles leads to a higher void ratio, indicating changes in consolidation parameters such as compression index and swell index.

iii. The shear strength of SAP paste tailings varies under freeze-thaw cycles and different confining pressures. Initial cycles may show stability or slight enhancement in shear strength, but prolonged exposure results in fluctuations, suggesting cumulative damage and potential recovery mechanisms within the material.

iv. Volume change behavior during shear tests highlights the material's response to freeze-thaw cycles and loading conditions. Freeze-thaw cycles influence deformation characteristics, potentially affecting material hardness and deformation processes.

v. Changes in cohesion and internal friction angle of SAP paste tailings were observed with varying freeze-thaw cycles. These changes are due to modifications in microstructure and interparticle interactions induced by freeze-thaw cycles, impacting the material's shear strength properties.

vi. Engineers working on surface tailings disposal facilities, especially in cold climates, should consider these insights when developing waste containment strategies. Integrating these findings will enhance the performance and longevity of surface tailings disposal facilities, advancing the understanding of material behavior and improving engineering practices.

In conclusion, the thesis contributes to the growing body of knowledge on innovative materials for waste containment, offering practical solutions for improving the environmental impact of mining operations. The use of SAP-modified paste tailings holds great promise for creating more effective barriers in waste containment facilities, especially in challenging environmental conditions. However, further research is essential to fully understand the performance attributes and qualities of the proposed barrier material, specifically focusing on its geotechnical properties and the durability of the pastefill material. This involves examining how the material behaves under various stress conditions, its long-term stability, and its resistance to environmental factors. In particular, the impact of wetting and drying cycles on the material's consolidation and shear strength must be thoroughly investigated. In addition, the development of mathematical and numerical models to evaluate the performance of the developed SAP-paste tailings barriers under different field loading scenarios would be important for a better understanding of the characteristics of the barrier and its cost-effective design. While initial findings are promising, ongoing studies are crucial to gain a comprehensive understanding of the material's performance. This continued research will ensure that the barrier material meets the requirements for different applications, by providing detailed insights into its behavior over extended periods and under realistic conditions.