MECHANICAL CHARACTERISTICS AND DESICCATION BEHAVIOUR OF BENTONITE-PASTE TAILINGS ENGINEERED BARRIER MATERIALS FOR WASTE CONTAINMENT FACILITIES

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ABSTRACT

Mining plays an essential role in shaping the modern society by providing the necessary raw materials for the development of technology, infrastructure, and other daily conveniences, while also promoting the economic growth of a country. However, this critical industry faces significant environmental challenges, particularly in terms of waste management. The process of mineral extraction generates an enormous amount of waste, known as tailings. Furthermore, a large volume of products made from mined mineral ultimately end up in municipal and industrial landfills before or after their lifecycle. Landfills contain materials ranging from electronic waste and construction debris to discarded clothing, food wastes, etc. As these materials decompose, they generate harmful leachate containing heavy metals and other toxic compounds, as well as greenhouse gases such as methane and carbon dioxide, which contribute to global warming. Such waste needs to be securely contained to prevent environmental contamination and ensure long-term stability.

Engineered barriers systems, such as liners and covers, play a vital role in mitigating these environmental risks. These barriers serve as crucial components in preventing the escape of contaminants into the vadose zone or the atmosphere. Liners are installed at the base and side slopes of waste impoundments and help prevent the toxic substances from seeping into groundwater, surface water, soil, etc. Covers form the topmost layer of waste facilities once they have reached their maximum capacity. Covers aims to prevent ground infiltration of fluids and regulate gas emissions. The efficacy of these barrier systems depends on their material properties, such as hydraulic conductivity, mechanical characteristics, resilience towards natural seasonal stresses such as wet-dry cycles and freeze-thaw cycles, and desiccation cracking behavior.

In alignment with this perspective and to promote sustainability through the reuse of tailings, recent studies have investigated the properties of compacted mixtures of bentonite-paste tailings (BPT) as a potential barrier material. Through the experimental study, it was found that BPT mixtures exhibit very low hydraulic conductivity, which is necessary to fulfill the requirement for barriers in a waste containment facility. This low hydraulic conductivity is further coupled with robust resistance of BPT towards natural stresses such as wet-dry and freeze-thaw cycles. However, mechanical characteristics (consolidation behavior and shear characteristics) of BPT, which are important geotechnical criteria for the design of liner and cover, are not known. No

studies have addressed this research and knowledge gap. Thus, further research is required to address this knowledge deficiency.

This study investigates the mechanical characteristics of bentonite-paste tailings mixtures in terms of consolidation and shear strength. The experimental program evaluates BPT mixtures with varying bentonite contents – 0%, 2%, 4%, and 8% – combined with synthetic tailings. One-dimensional consolidation tests revealed low compressibility and minimal volume change upon addition of bentonite. Moreover, direct shear testing showed improved shear strength and its parameters (cohesion and angle of friction) as bentonite content increases up to a threshold bentonite content (4%), indicating its strength under heavy loading conditions.

However, in reality, barriers are often temporarily exposed to environmental conditions between the time of their installation and placement of waste. Moreover, during the operational phase, the waste placement can be either uniform, covering the entire region, or non-uniform. This can lead to the formation of desiccation cracks, which can significantly reduce the mechanical strength and impermeability, creating preferential pathways for contaminants to seep into the subsurface or escape into the atmosphere. However, no previous studies have examined the desiccation cracking behavior of BPT. Therefore, this study further investigates the desiccation cracking behavior of BPT mixtures, up to one wet-dry cycle, which is critical to ensure its suitable performance. Desiccation crack analysis showed a direct correlation between bentonite content and crack intensity, with increased bentonite content exhibiting more pronounced crack formation.

The experimental program examining the performance of the proposed BPT barrier material reveals a complex interplay between mechanical strength and desiccation behavior. While the BPT mixtures exhibit favorable mechanical characteristics – low consolidation and high shear strength – suited for barrier applications, they also show susceptibility to desiccation cracking at higher bentonite contents, presenting a potential vulnerability to the very same improved mechanical and hydraulic properties. Therefore, the study suggests that optimizing the bentonite percentage needs careful consideration of the trade-off between mechanical performance and crack resistance. The findings from this study significantly contribute to understanding the behavior of BPT mixtures as engineered barriers and encourage further research to ensure their long-term efficiency in waste containment facilities.

DEDICATION

To my loving parents, Anand Verma and Rachana Verma.

This is for you, with all my heart.

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I would like to express my deepest and heartfelt gratitude to my supervisor, Dr Mamadou Fall, for his unwavering guidance and patience throughout my academic journey. Your profound knowledge, approachable demeanor, and the ability to provide constructive feedback have been a source of inspiration and greatly shaped my growth as a researcher. It has been a privilege to work on your research team. Your mentorship will remain a cornerstone of my professional and personal development. Thank you for being an exceptional supervisor.

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Lastly, I would like to lovingly dedicate this work to my beloved parents, whose unconditional love and boundless sacrifices have been the foundation of my journey. Your wisdom has shaped me who I am today, and your belief in me has given me the strength to overcome every challenge. To my father, Anand Verma, for his silent strength and constant encouragement, and to my mother, Rachana Verma, for her nurturing care and unconditional love. I will forever be grateful to you for teaching me the value of perseverance and kindness. All my achievements are a reflection of your love and sacrifices.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

LIST OF SYMBOLS AND ABBREVIATIONS

S. No.	Symbol/ Abbreviated Term	Full Form
1	AMD	Acid mine drainage
2	BOD	Biological oxygen demand
3	BPT	Bentonite-paste tailings
4	CCL	Compacted clay liner
5	CEC	Cation exchange capacity
6	CH_4	Methane
7	CIF	Crack intensity factor
8	CO_2	Carbon dioxide
9	COD	Chemical oxygen demand
10	DDL	Double-diffuse layer
11	EPA	Environmental Protection Agency
12	HDPE	High-density polyethylene
13	GAC	Granular activated carbon
14	GLD	Green liquor dregs
15	GCL	Geosynthetic clay liners
16	GM-GTX	Geomembrane-Geotextile
17	MSW	Municipal Solid Waste
18	PVC	Polyvinyl chloride
19	ST	Synthetic tailings
20	TSF	Tailings storage facility
21	UNEP	United Nations Environment Programme
22	e_f	final void ratio
23	e_0	Initial void ratio
24	Δe	Change in void ratio
25	ΔH	Differential settlement of change in the thickness of sample due to pressure applied

26	H_0	Initial thickness of the sample
27	m_v	Coefficient of volume change or volume compressibility
28	S_c	Consolidation settlement
29	$\Delta\sigma$	Differential pressure
30	H	Thickness of the sample
31	C_c	Compression Index
32	$\Delta \log\sigma$	Difference between logarithmic values of pressure
33	τ	Shear strength
34	σ	Normal stress
35	c	Cohesion
36	ϕ	Angle of internal friction
37	R_{sc}	Surface crack ratio
38	A_{crack}	Total surface area of cracks
39	A_{total}	Total surface area of the drying sample
40	V_c	Crack propagation velocity
41	ΔR_{sc}	Rate of change in surface crack ratio
42	Δw	Change in water content

1 Chapter 1: Introduction

1.1 General Statement

Mining is the process of extraction of valuable or economical metals and minerals from the Earth's geological surface, which are used to suffice the development and demand of modern-day conveniences, including but not limited to high-tech electronics, numerous tools and machineries, infrastructure such as power plants, roads, etc. The mining industry plays a crucial role in enabling a transition to a low-carbon future, since manufacturing of photovoltaic solar cells, windmills, electric vehicles, etc. relies on mined metals and minerals. Moreover, the mining industry serves as the backbone of the economy and society by generating both direct and indirect employment, showing annual growth. In 2022, a total of 694,000 individuals were employed at more than 200 operational mining sites across Canada producing over 60 different minerals and metals. The total value of mineral production in Canada reached $74.6 billion in 2022 (Government of Canada, 2022; The Mining Story, 2024), with the minerals and metals sector alone contributing 6% to the Canadian GDP (The Mining Story, 2024).

However, the conventional process of extraction and processing mined minerals and metals requires substantial amounts of water (Fourie, 2012) and generate an enormous quantity of waste, known as tailings, which pose serious danger to the surrounding environment and infrastructure. Figure 1-1 presents a flowchart illustrating a typical conventional mining process and the stages where waste are generated.

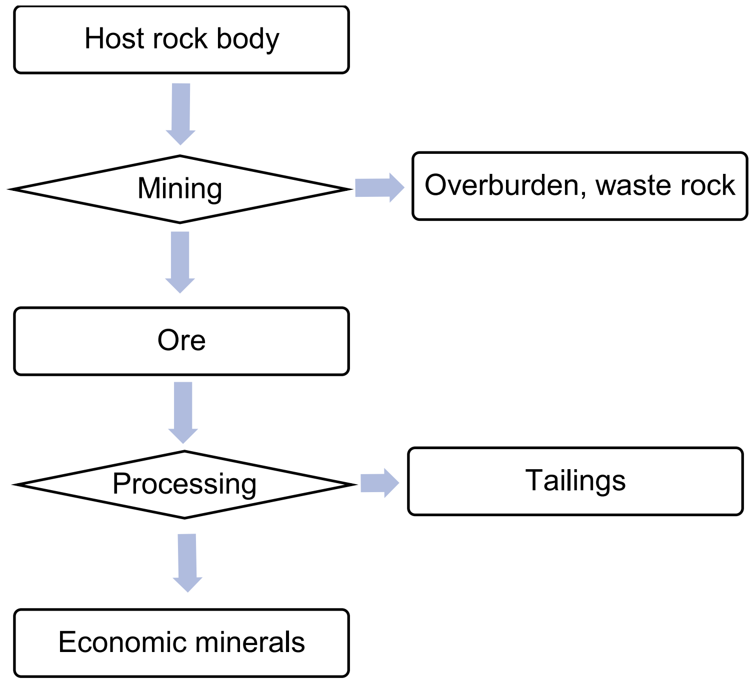

Figure 1-1: Flowchart illustrating waste generation during mining process.

Mine tailings are fine-grained slurry mixtures of crushed rocks and extraction fluids that often contain hazardous substances, depending on their initial chemical composition (Kossoff et al., 2014). In modern mining practices, the most common method of tailings disposal involves storing them in mine tailing dams or impoundments. However, these structures are susceptible to frequent failures resulting in catastrophic damage to ecosystems, human health and nearby communities. Furthermore, leakage from tailings dams leads to contamination of surface water and ground water, causing acid mine drainage (Fourie, 2012; Fall et al., 2009, 2010; Kossoff et al., 2014; Tuomela et al., 2021a).

Concurrently, countless products developed using mined resources are discarded before or after their useful life, and are typically disposed into engineered-landfill. Additionally, engineered landfills also contain unwanted or discarded solid waste from households, industries, and other human activities. According to Government of Canada, the total amount of solid waste generated in the country increased by 19% between 2002 and 2022. In 2022, 72.9% of the total solid waste generated in Canada were sent to landfills (Solid waste diversion and disposal, ECCC, 2024), while only a small fraction was incinerated. The waste stored in landfills decomposes slowly under anaerobic conditions (temperature, moisture and lack of oxygen), releasing leachate and toxic gases such as methane (CH_4), carbon dioxide (CO_2), and volatile organic compounds (VOCs), polluting the air, water, and ground. These emissions also severely affect public and wildlife health in the vicinity. Figure 1-2 provides a flowchart describing a typical process of waste generation, collection, and disposal.

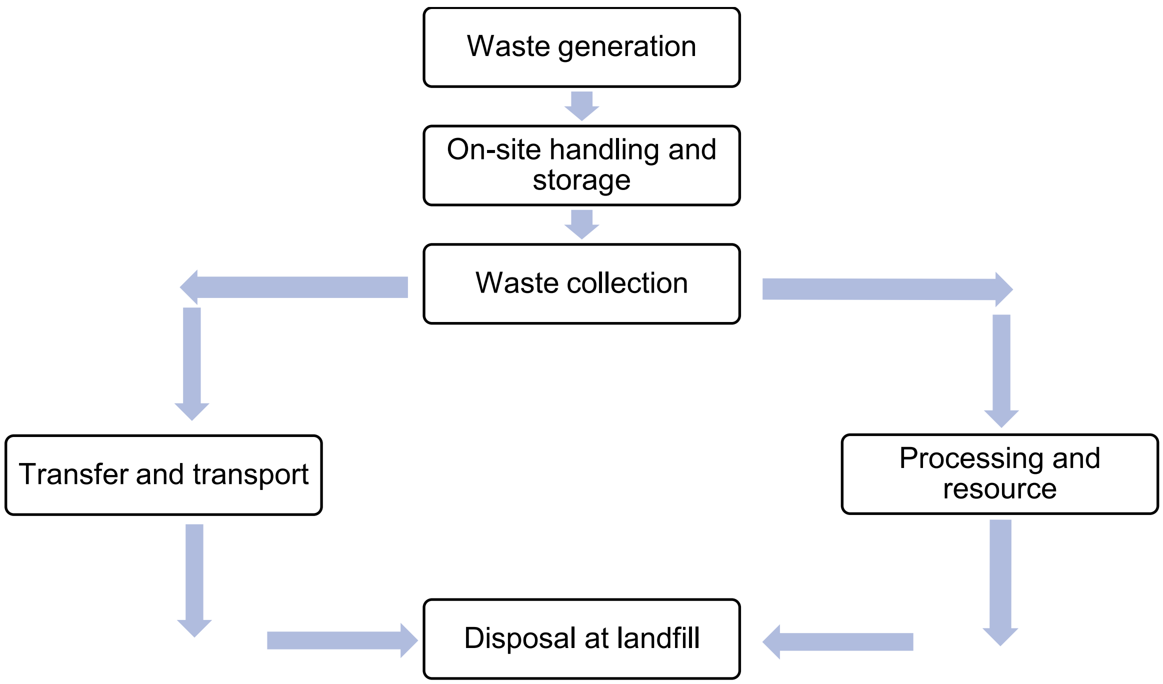

Figure 1-2: Flowchart illustrating waste generation during solid waste disposal.

Both types of waste containment facilities, tailings storage facility and engineered landfills, pose significant risks to environment and nearby communities. Therefore, they require special attention and innovative solutions aimed at reducing their harmful effects. From an engineering perspective, one of the most effective approaches to reduce their environmental impact is by incorporating barriers, such as liners and covers, to seal the waste containment facilities. Liners are laid at the bottom and along the side slopes fully enclosing the waste impoundment region. Waste materials are deposited over these liners, which serve to mitigate the downward flux of contaminants. Once the wastes are poured, the facility is enclosed with covers, which restricts fluid (such as precipitation) accessibility and restrict contact with oxygen (Fall et al., 2009, 2010). In mine tailings dams, the lack of oxygen helps prevent acid mine drainage (AMD), whereas in landfills, it slows the rate of waste decomposition. Both, liners and covers, are together termed as barriers systems, that helps in preventing the contaminants and harmful gases from escaping the containment facilities into the vadose zone.

The barrier system is a multicomponent system serving multiple functions such as restricting fluid infiltration, facilitating drainage, and providing structural reinforcement (Feodorov et al., 2000; Koerner & Daniel, 1997). Figure 1-3 illustrates the multicomponent barrier system used in an engineered waste containment facility. This system primarily consists of geomembranes and geosynthetic clay liners (GCLs) acting as hydraulic barriers, geocomposites for drainage, geotextiles for separation and filtration, and geogrids for reinforcement (Feodorov et al., 2000; Koerner & Bowman, 1994). These layered components work together to isolate the contaminated waste (von Maubeuge, 2018).

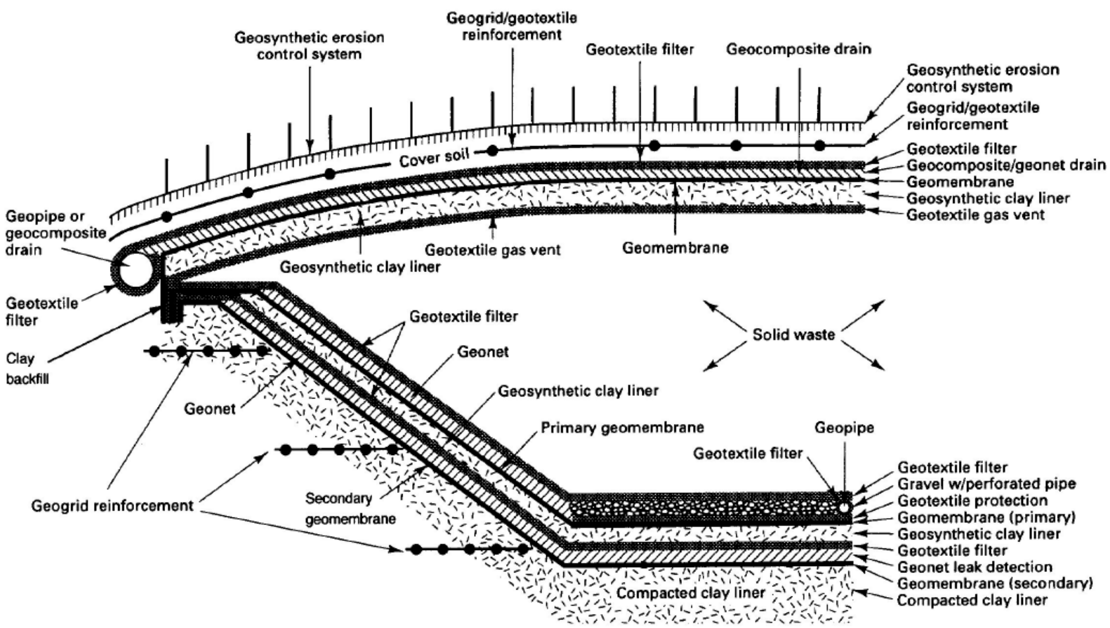

Figure 1-3: Barriers used in a waste containment facility (Koerner & Bowman, 1994).

Compacted paste tailings and bentonite (BPT) is a mixture composed of three main components: non-acid generating synthetic tailings (ST), bentonite clay (primarily composed of montmorillonite) as a binder, and distilled water (Fall et al., 2009). The presence of bentonite significantly influences the overall properties of the mixture. Due to its negative surface charge, bentonite is hydrophilic in nature, develops double-diffuse layer, and displays excellent swelling and shrinking behavior. It also exhibits very high Atterberg limits. Bentonite has been widely used in infrastructure projects to enhance the properties of existing materials, especially as a sealant to reduce water seepage through cracks (Grim & Guven, 1978; Karnland et al., 2006; Oy & Carlson, 2004).

1.2 Problem Statement

In the 1960s, the mining sector released a few tens of thousands of tonnes of tailings per day, which increased to a few hundred thousand tonnes per day by the year 2000 (Jakubick et al., 2003). According to the Global Tailings Review, 12.7 billion metric tonnes of tailings are produced globally each year. Some of the excess tailings can be combined with bentonite as a part of sustainable reuse and reduce strategy to develop innovative materials with enhanced properties to be used as potential barrier materials. In alignment with this approach, the properties of compacted paste tailings and bentonite (BPT) mixtures were investigated for their potential use as a suitable barrier material (Fall et al., 2009). The results indicated that the mixture possessed hydraulic conductivity values lower than 10^{-7} cm/s, meeting a key design criterion for barriers in waste containment facilities. Additionally, the mixture displayed robust resistance to free-thaw and wet-dry cycles. Furthermore, the mixture offers a balanced cost-effectiveness when compared to the alternatives currently used in practice (Fall et al., 2009). In other words, Fall et al., (2009) have demonstrated that compacted BPT mixtures are promising barrier materials for landfill and mine waste containment facilities.

While hydraulic characteristics are vital for the design of barriers for waste containment, an in-depth assessment of the mechanical properties, including consolidation behavior and shear strength, is equally essential for evaluating the effectiveness of the barrier materials. In the engineering design of liners and covers, the selected barrier material should not only satisfy the hydraulic conductivity design criterion, but also demonstrate satisfactory mechanical characteristics in terms of consolidation behaviour and shear strength. For example, since the waste deposited on the liners of landfills and mine waste containments weighs several tonnes (Benson, 1999; Benson & Daniel, 1994b, 1994a; Booker et al., 2004; Bouazza, 2002; Koerner & Daniel, 1997; Rowe & Fan, 2022; Touze-Foltz et al., 2008; Tuomela et al., 2021b), the barriers are subjected to high pressure, which can lead to sudden settlement and shear failure due to loss of strength. Moreover, for liners installed on side slopes, evaluating the shear characteristics (shear strength and shear behavior) is critical for assessing the resistance of the barrier to sliding. Despite the importance of mechanical characteristics (consolidation and shear characteristics) in the design of barrier, no studies have been conducted to investigate the consolidation and shear characteristics of BPT. This knowledge gap needs to be addressed. In addition, once placed in the field, BPT barriers can be exposed to environmental factors (e.g., drying), which may lead to the formation of cracks in the BPT material, primarily due to the presence of bentonite. These cracks can significantly compromise both hydraulic conductivity and overall strength, potentially causing leakages and contamination of surrounding areas. In severe cases, it could also result in collapse of the overall waste impoundment, adversely impacting the ecosystems and nearby communities. However, the desiccation cracking behavior of BPT barriers is not known, and no studies have addressed this critical knowledge gap. Given the significance of crack formation in determining the long-term performance and integrity of waste containment barriers, it is vital to study this phenomenon to ensure the safe implementation of BPT technology.

1.3 Research Objectives

The main objective of this experimental study is to investigate the mechanical characteristics of BPT and to analyze the pattern and extent of crack formation under simulated natural conditions. The sub-objectives are to investigate:

a) Mechanical behavior in terms of:
    (i) consolidation characteristics,
    (ii) shear characteristics.
b) Drying-induced desiccation behavior.

The finding obtained from these investigations will further strengthen the potential use of BPT as a barrier material and bridge the gap between waste disposal practices and sustainable development goals.

1.4 Research Approach and Methodology

The strategy used for the research, from its inception through completion, is illustrated in Figure 1-4. In-depth information on theoretical and technical backgrounds, including but not limited to the properties and scope of bentonite and tailings, various barrier systems, especially Compacted Clay Liners (CCLs), for waste containment facilities, is gathered during the preliminary study. This step helped in establishing the significance of the study and aligning the problem statement with the roadmap for the research.

This is followed by a thorough literature review of previous studies conducted on compacted bentonite-paste tailings (BPT), aimed at their potential application as a barrier material, along with studies conducted on comparable materials. The literature review discusses the past research on BPT, examining its properties related to compaction, hydraulic conductivity, freeze-thaw and wet-dry cycles. Based on this, further scope in research is identified, and the objectives are set into action through the designed experimental program.

The experimental program involves laboratory studies to assess the mechanical properties and desiccation cracking behaviour of BPT. The aim is to evaluate the potential use of BPT as a barrier material provided that these behaviours complement the findings of previous studies. The experimental program is conducted in two phases, with four samples of varying bentonite content (0% (control), 2%, 4%, and 8%) subjected to each test. The first phase focuses on consolidation and shear characteristics of BPT under varying loads. The consolidation test will help to determine the mixtures' compressibility and settlement rate under applied loads, while direct shear tests assess its shear strength and failure parameters (cohesion and friction angle) under increasing normal stresses. The second phase involves analyzing the crack formation, its propagation and extent under controlled conditions. Chapters 3 and 4 discuss these experimental programs at length.

In the final stage, the results obtained from the experimental programs are interpreted and discussed, a conclusion is drawn while considering the findings from previous study, and recommendations for future research is laid down.

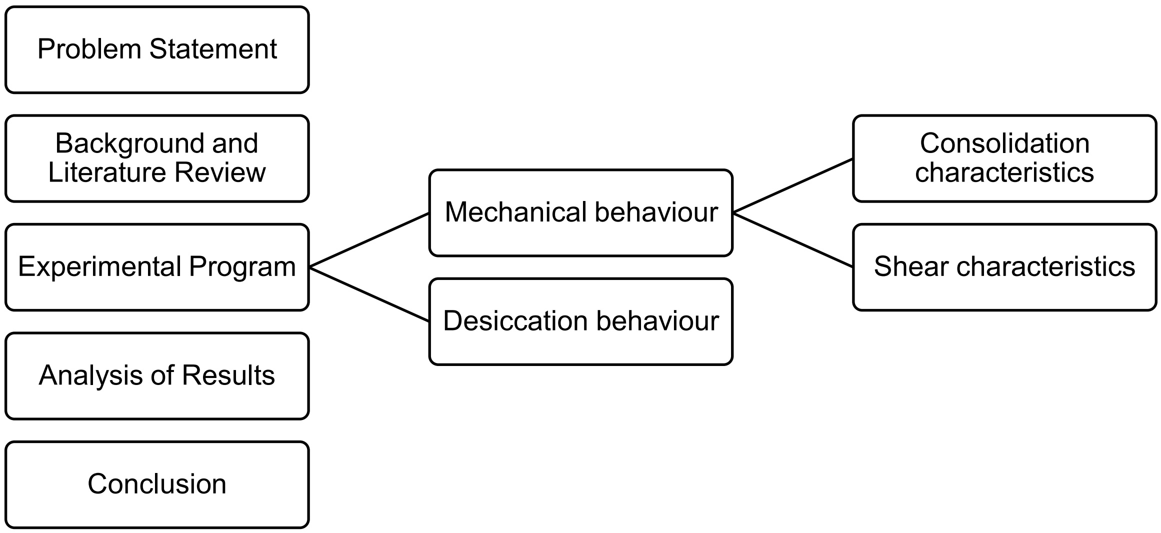

Figure 1-4: Research approach and experimental program.

1.5 Thesis Organization

This thesis manuscript is organized into five chapters, as illustrated in Figure 1-5. The following is a summary of each chapter:

Chapter 1 opens with a general statement providing a brief introduction about the research. It outlines the research scope, establishes the objectives, and lays out the approach and methodology pursued in this research.

Chapter 2 provides a comprehensive literature review, highlighting relevant theories on waste containment facilities, such as mine waste repositories and landfills, along with their associated challenges. It also discusses the existing barriers systems (liners and covers) used in current practices, and the role of bentonite in construction practices. Additionally, this chapter highlights methodologies and key findings from previous experimental studies on compacted bentonite-paste tailings as potential barrier materials as well as laboratory tests conducted on comparable materials. Finally, the review identifies the opportunities for further research, focusing on the mechanical characteristics and desiccation behaviour of BPT.

Chapter 3 contains the first technical paper, titled "Consolidation and Strength Characteristics of Bentonite-Paste Tailings Barrier Materials for Waste Containment Facilities". This paper investigates the mechanical behaviour of BPT by evaluating its compressibility and rate of settlement under various applied loads through one-dimensional consolidation test; as well as its shear strength and failure parameters (cohesion and angle of friction) under different normal stresses through direct shear tests.

Chapter 4 contains the second technical paper, titled "Drying-induced Desiccation Cracking Behavior of Bentonite-Paste Tailings Barrier Materials for Waste Containment Facilities". The paper examines the development of cracks, further analyzing crack geometry, extent of formation, and propagation velocity.

Chapter 5 focuses on the synthesis and integration of results from the preceding technical papers, highlighting the significance of both mechanical properties and desiccation, providing a holistic understanding of performance of compacted bentonite-paste tailings (BPT) as engineered barrier materials, including the novelty and limitations of the research work.

Chapter 6 summarizes the results obtained from both technical papers, discusses them in relation to the initial objectives of the study, and places them in context with the findings of the previous study. Furthermore, this chapter also provides conclusions based on key findings and offers practical recommendations for future research investigations.

Chapter 1: Introduction

Chapter 2: Technical background and literature review

Chapter 3: Technical Paper 1

Consolidation and strength characteristics of bentonite-paste tailings barrier materials for waste containment facilities.

Chapter 4: Technical Paper 2

Drying-induced desiccation cracking behavior of bentonite-paste tailings barrier materials for waste containment facilities.

Chapter 5: Synthesis and integration of results

Chapter 6: Conclusions and recommendations

Figure 1-5: Flowchart illustrating the organization of thesis.

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2 Chapter 2: Technical Background and Literature Review

2.1 Introduction

This chapter outlines the fundamentals of a waste containment facility, with a special focus on mine wastes and landfills (Section 2.2). It provides a detailed discussion on the fundamentals of barriers (Section 2.3) and reviews various types of barriers (Section 2.4) employed in waste containment facilities under current practice. It further explores the properties and use of bentonite in construction projects (Section 2.5). Finally, the concept of compacted bentonite-paste tailings (BPT) mixtures and their application as a potential barrier system is discussed in relation to previous studies (Section 2.5).

2.2 Waste containment facility and associated risks

A waste containment facility is designed and engineered to prevent contamination of the surrounding environment and protect public health by safely storing and isolating hazardous wastes. The practice of isolating and managing waste has been witnessed since 3000 B.C. in the form of landfills (Tammemagi, 1999). Since then, the basic principle and methodologies of containing waste has remained the same; however, the design has evolved to address the emerging challenges (Delmas et al., 2002) due to accelerating demand and supply, as well as technological advancements. In addition to landfills, mining activities have been recorded since prehistoric times beginning with forging hunting tools necessary for survival, and gradually transitioning to making ornaments and currency to mark social status as civilizations developed and expanded. In current generation, nearly all modern-day conveniences are made up of metals or minerals that have been mined from the Earth’s geological surface. The extraction of metals and minerals produces vast quantities of waste, known as tailings, which has significant impact on the environment and public health. The waste from mining operations is generally stored in mine tailings impoundment.

Although waste containment facilities are designed to isolate waste, following are the major risks imposed by them:

a) Contamination of groundwater, surface water, and soil,
b) Generation of harmful gases, leading to global warming and explosions,
c) Accumulation of heavy metals and leachate,
d) Surface runoff,
e) Acid mine drainage (AMD),
f) Collapse of waste impoundment, etc.

Such disasters have long-term impacts on the environment, infrastructure, and human health (Fall et al., 2009, 2010; Koerner, 2002; Kossoff et al., 2014; Tammemagi, 1999). Given the voluminous amount of waste managed by landfills and mining impoundments, it is crucial to highlight the risks imposed by them and explore innovative solutions to mitigate them. The primary goal of waste containment facilities is to protect groundwater quality (Benson, 1999; Koerner, 2002), which would otherwise negatively impact the general ecosystem. In the following sub-sections (2.2.1 and 2.2.2), we will discuss these two types of waste containment facilities in detail.

2.2.1 Mine waste repositories and tailings

Mining refers to the extraction of economic metals and minerals from within the Earth's geological surface (Fall et al., 2009, 2010; Hudson-Edwards, 2019; Islam & Murakami, 2021; Kossoff et al., 2014). Mining operations elevates a country's economy, which, in turn, stimulates further mining activities (Garcia et al., 2024). The current mining practices utilizes water in abundance (Fourie, 2012) and generate enormous amounts of waste, known as mine tailings. Mine tailings are fine-grained slurry mixtures of crushed rocks and extraction fluids that may contain hazardous components (Byrne et al., 2015; Hudson-Edwards, 2019; Hudson-Edwards & Dold, 2015; Kossoff et al., 2014). The chemical composition of the tailings is determined by the minerology of the ore as well as extraction fluids used in the process. These mine tailings are commonly deposited in structures near mining sites, commonly known as tailings dams, ponds, or impoundments, which are constructed using locally-sourced materials, such as soil and tailings themselves (Kossoff et al., 2014).

2.2.1.1 Reasons for tailings dam failure and its environmental impacts

Although tailing dams perform the necessary function of safely storing tailings, they pose a threat to nearby communities and the environment. Due to their fluidic nature, tailings tend to seep through the foundation and side walls, contaminating the immediate surroundings, such as land and water. Tailings also cause air pollution by generating dust (Hudson-Edwards et al., 2011; Nordstrom et al., 2015; Provornaya et al., 2020; Royal Society of Chemistry, 2021; Yurkevich et al., 2017). Mining operations related to copper and gold generate larger quantities of tailings compared to other minerals due to their processing requirements (Baker, 2020). Poor and negligent tailings management of these ores can easily result in overtopping or overflowing, which currently accounts as one of the most commons reasons (17.5%) for dam instability and/ or surface runoff. Moreover, this can also lead to acid mine drainage (AMD), and, in severe cases, catastrophic dam failures (Blight & Fourie, 2003, 2005; Fourie et al., 2022; Garcia et al., 2024; Rana et al., 2021; Roche, 2017). Furthermore, active mining impoundments are more prone to failure than inactive dams (Kossoff et al., 2014; Miller et al., 2004). A historical overview of recorded tailings dam failures spanning over 100 years, from 1910 up till 2020, along with their severity, is illustrated in Figure 2-1.

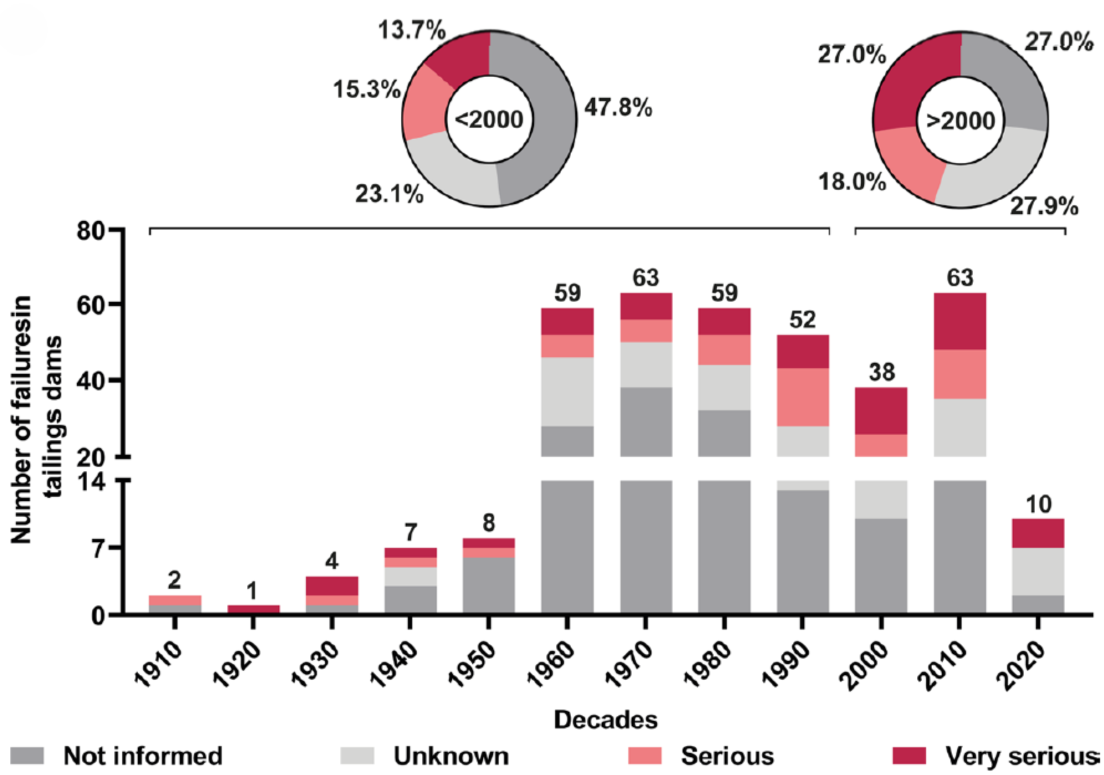

Figure 2-1: Historical overview and severity of tailings dam failures, and the occurrence of failures over time (Garcia et al., 2024).

The Mount Polley copper and gold tailings dam failure in British Columbia, Canada, is regarded as one of the major dam failures. The collapse resulted in release of approximately 25 million m^3 of tailings into three water bodies namely Hazeltine Creek, Quesnel Lake, and Polley Lake. The magnitude and volume of tailings led to expansion of Hazeltine Creek from 2m to 25m in width, washing away trees over a 900 km^2 corridor. Moreover, the water level in Polley Lake rose by 1.7m. These water bodies were contaminated with heavy metals such as copper, gold, arsenic, nickel, manganese, lead, and vanadium, which are likely to cause long-term environmental impacts despite taking remediation measures. Furthermore, the freeze-thaw effect will cause the contaminants to be retained during winter and remobilize in summer, continuing the cycle over an extended period of time (Byrne et al., 2015, 2018; Cuervo et al., 2017; Mcmahen & Hughes, 2016; Pyle et al., 2022; Zabolotnii et al., 2022). Figure 2-2 and Figure 2-3 show aerial images of Mount Polley before and after the dam failure.

Figure 2-2: Image of Mount Polley from 29 July, 2014, before the dam breach. Image Credit: NASA Earth Observatory images by Jesse Allen, using Landsat data from the U.S. Geological Survey.

Figure 2-3: Image of Mount Polley from 5 August, 2014, after the dam breach. Image Credit: NASA Earth Observatory images by Jesse Allen, using Landsat data from the U.S. Geological Survey.

Excessive precipitation and earthquakes may trigger tailings liquefaction (Bedin et al., 2012; Blight & Fourie, 2003; Islam & Murakami, 2021), leach heavy metals (Schaider et al., 2014; Su et al., 2024; Wang et al., 2019; Zhang et al., 2016), and generate AMD (Bussière, 2010; Cheng et al., 2009), even in well-managed facilities (Fourie, 2009). AMD occurs when sulphide-containing minerals, such as pyrite, oxidize in presence of water and oxygen. AMD significantly lowers the pH levels, posing both carcinogenic and non-carcinogenic risks (Su et al., 2024). When such tailings impoundments fail, their adverse impacts can be observed over hundreds of kilometers downstream. Nearby water bodies, such as creeks, lakes, rivers, etc. become overwhelmed with tailings deposits. According to Islam & Murakami (2021), volume and runout are the two crucial parameters in assessing the impact of tailings dam failures. The consequences of such failures can be seen on vegetation, irrigation water, and drinking water, that show elevated concentrations of harmful contaminants and degraded sediment quality (Kossoff et al., 2014).

Buch et al., (2021) conducted an ecological risk assessment of soils affected by the spill of 40m^3 of tailings due to major dam collapse in Brazil, which spread across hundreds of kilometers.

Figure 2-4 shows the magnitude and extent of the disaster. The assessment was conducted over two monitoring periods (2015 and 2018) across 18 contaminated sites. The study revealed long-term environmental impacts, including soil samples exhibiting elevated concentrations of heavy metals, altered pH values, increased bulk density, reduced cation exchange capacity, decreased organic matter content, and altered soil texture.

Figure 2-4: Collapse of Córrego do Feijão mine in Brumadinho, Brazil.

Such adverse environmental impacts require immediate remediation measures such as extensive cleanup of affected areas and surrounding areas, which demands significant resources, time, effort and money. Even the remediation measures can have adverse consequences, such as deviation of river from its natural flow path, leading to an unstable river channel and causing unexpected and frequent flash floods.

From a dam design point-of-view, tailings dam can be classified as upstream, downstream, and centreline (Islam & Murakami, 2021; Kossoff et al., 2014). Figure 2-5 illustrates a schematic diagram of these three types of construction methods. The upstream dam is the most economical as it requires fewer and locally-sourced materials for construction. However, it has historically been the most vulnerable to failure, followed by downstream dam (Islam & Murakami, 2021; Lindolfo Soares, 2000).

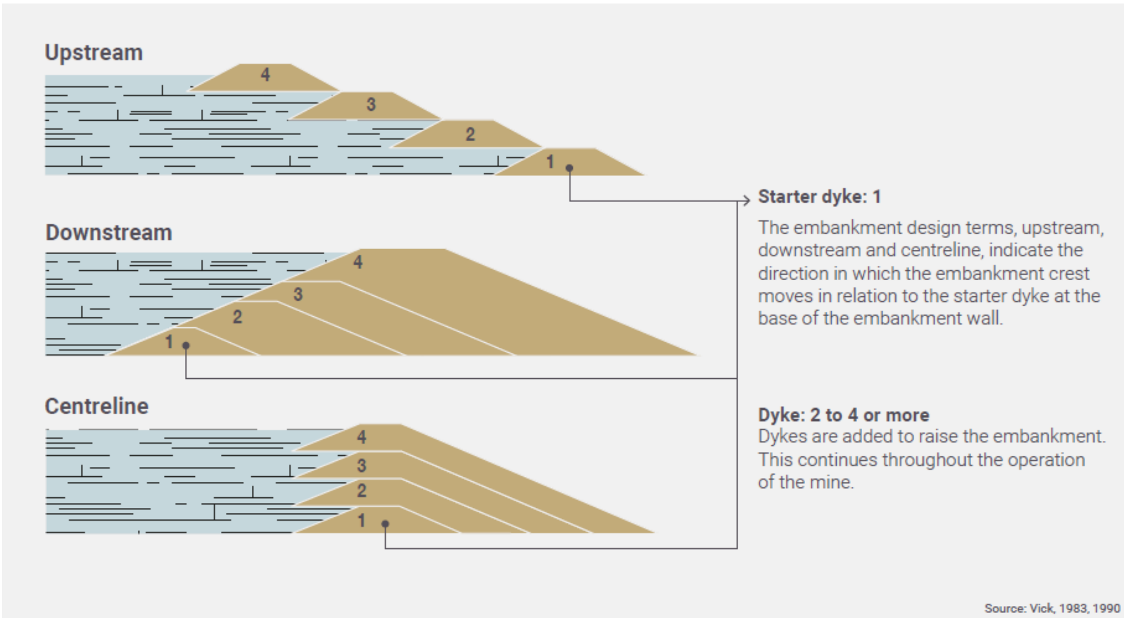

Figure 2-5: Schematic illustrations of upstream, downstream and centreline (Vick, 1990a).

Failures on account of other geotechnical negligence include slope instability (15.9%), seismic activity (13.9%), foundation failure (6.3%), and ground subsidence (0.8%) (Garcia et al., 2024; Stark, 1999). Failures related to slope stability can be categorised based on the materials used. These can be natural materials, such as soil, or geosynthetic materials such as liners or covers. Such failures can occur during the construction of liners, or during and/ or after the placement of waste (Stark, 1999). Figure 2-6 illustrates reported causes of tailings dam failures. This illustration shows that a majority of dam failures go unreported; therefore, the exact cause of failure remains unknown.

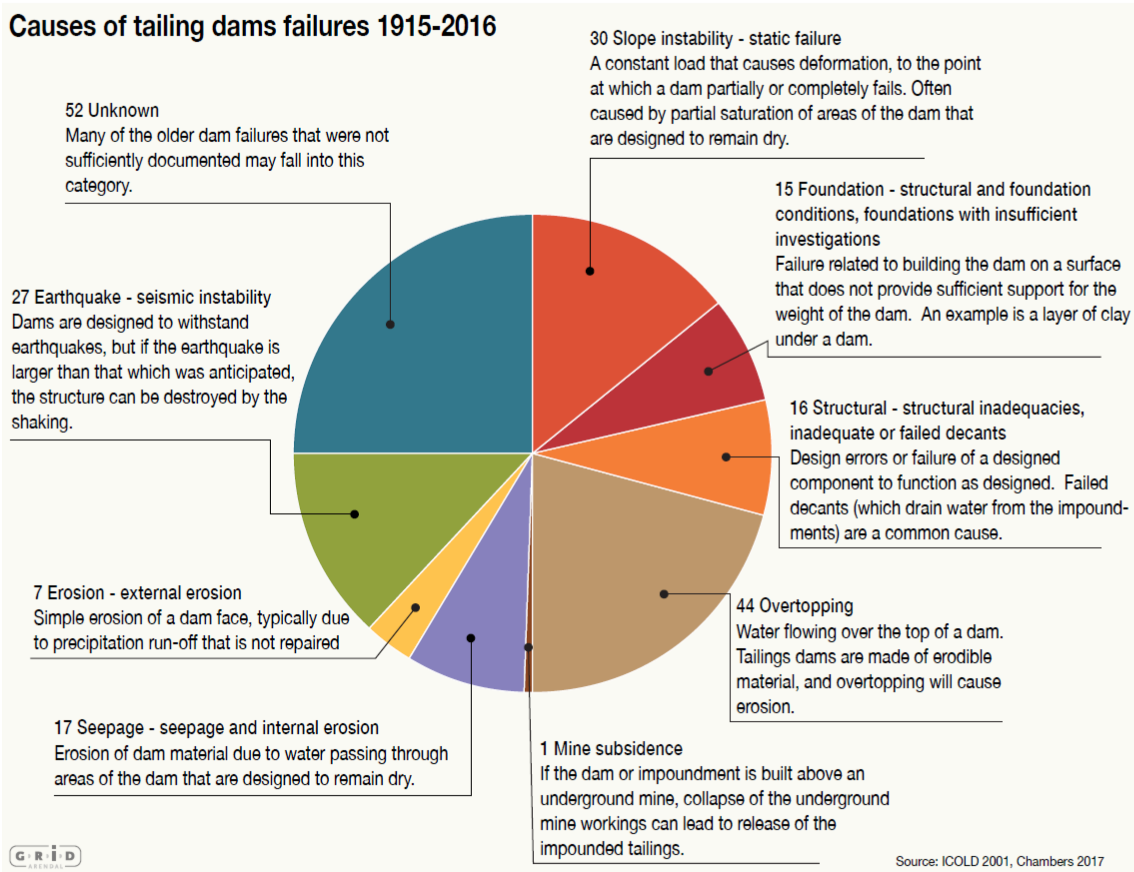

Figure 2-6: Reported causes of tailings dam failures (Roche, 2017).

2.2.1.2 Remediation measures for reducing impacts of tailings with or without dam failure

In the previous section, the reasons for the collapse of mining impoundments were highlighted, along with their impact, citing a few examples of disastrous failures. It was discussed earlier that few mining operations particularly those involving copper and gold, release substantial amounts of tailings. In the current world, gold and copper are two of the most widely used minerals. Therefore, in order to meet the current economic demands and ensure transition to a low-carbon future, a reduction in mining operations, and consequently large volume of tailings, looks highly unlikely and impractical. As a solution, we must look at preventive measures that help reduce the impact of tailings and prevent adverse environmental consequences. This section will discuss a few basic preventive practices and remediation measures.

There are numerous measures implemented in pre-construction, construction and post-construction phases that can help minimize the contamination of the environment through tailings and prevent tailings dam failure. This investigative study specifically examines pre-construction methodologies and their efficacy. In the pre-construction phase, slope stability issues caused by translational failure can be addressed by designing for greater shear strength along the failure surface. To address rotational failure, adequate compaction is essential to ensure uniform settlement and stability before the application of structural loads such as barriers (Stark, 1999).

Incorporating barriers (liners, or covers) and covering the top layer of tailings with water are considered best practices. Barriers help in containing the fluid within the dam region, thus preventing it from seeping into the vadose zone (Fall et al., 2009; Kossoff et al., 2014). Barriers will be covered in more detail in Sections 2.3 and 2.4. A layer of water blocks the tailings from coming in contact with atmospheric oxygen, thus preventing AMD (Bussière, 2010). The use of multilayered cover system impedes AMD by creating a capillary effect, allowing at least one of the layers to maintain high saturation levels while providing stability (Bussière, 2010). While geosynthetics and other clay liners have monopoly in the construction practices, one study demonstrated the potential use of green liquor dregs (GLD), a waste product from sulphate paper mills that is otherwise disposed of in landfills, as a barrier material. However, the study concluded that the material lacks shear strength and needs mechanical improvements (Mäkitalo et al., 2014).

Additionally, it is important to mention process-oriented solutions that make the tailings comparatively less toxic before being deposited into the dam and help settle more quickly. A common practice for this is to treat the mine waste with alkalinizing chemical agents, thickeners, and other flocculating agents to reduce environmental toxicity, balance pH values, improve the contact between tailings and flocculants, and, finally curtail the flow of contaminants (Fourie, 2009; Garcia et al., 2024; Hudson-Edwards & Dold, 2015; Kossoff et al., 2014; Weiler et al., 2016). Technical advancements have made it possible to manufacture flocculants with high molecular weights that efficiently bind ultrafine tailing particles; however, cost remains a consideration (Fourie, 2009). Bussière, (2010) suggests that AMD can also be prevented by allowing secondary minerals to precipitate, which can reduce the reactivity of sulphides and carbonates by forming a coating over them.

Furthermore, attempts have been made to reduce the reactivity of toxic tailings and recover metals by promoting microbial activity. It has been found that some acidophilic and sulphate-reducing bacteria are effective in removing sulphate, arsenic, copper, and zinc by means of precipitation, while other bacteria and fungi can oxidize manganese (Johnson, 2014). Another experiment demonstrated the use of solar thermal desorption to remove mercury from mercury-contaminated mine tailings with an efficiency of 99% when treatment temperature exceeded 400^0C (Navarro et al., 2014).

Finally, in the event of the ultimate dam failure, immediate clean-up of spilled tailings should be conducted as a proactive measure (Kossoff et al., 2014).

2.2.1.3 Sustainable mining practices

Environmental disruption from mining activities is inevitable; therefore, mining and sustainability are often considered contradictory terms. However, environmental disasters can be prevented if mining is practiced sustainably. Sustainable mining practices refers to safe handling and disposal of mine tailings, irrespective of them being toxic or non-toxic. This approach not only aims to reduce the challenges associated with the contamination of surroundings and nearby communities but also addresses the overall stability of mining impoundments. Sustainable mining strategies encompass the entire mine lifecycle, starting from conceptual planning to project closure (Hebblewhite, 2009).

Schoenberger, (2016) argues that the management of tailings storage facilities (TSFs) is more of a political and social challenge than a purely technical one. Therefore, strong policies and regulatory frameworks must be established and enforced to ensure compliance by mining companies. Additionally, mining should be prohibited in areas that are known or predicted to be environmentally vulnerable. There is further evidence that mining companies can meet high standards through strong regulations without discouraging the investors.

With growing demand, there is an increasing recognition of the need to maximize resource utilization by extracting leftover valuable minerals from mine waste (Aznar-Sánchez et al., 2019; Lèbre et al., 2017) driven by both economic and non-economic factors (Suppes & Heuss-Aßbichler, 2021). A few examples of mine waste utilization include its application in underground backfilling and in the manufacturing of construction materials such as bricks and glass-wool products (Edraki et al., 2014; Struthers et al., 1997). Tailings can also potentially be used for carbon sequestration (Assima et al., 2014; Bodénan et al., 2014; Meyer et al., 2014), by leveraging mineral carbonation, especially if the tailings generate magnesium hydroxide (Hitch &

Dipple, 2012). Furthermore, the industry is moving toward increased water efficiency, as conventional methods utilize large quantities of water (Adiansyah et al., 2015).

From a design and construction perspective, liners and covers with low hydraulic conductivity, low consolidation, and high shear strength must be incorporated to prevent the contaminants from seeping through waste impoundment walls, restrict harmful gases from leaking into the atmosphere, and isolate waste from coming in contact with atmospheric oxygen to prevent further reactions (Fall et al., 2009). Another good practice is to design the facility so that the phreatic surface (the level below which soil is fully saturated) remains well below the dam wall in order to minimize the risk of liquefaction during earthquakes (Kossoff et al., 2014; Martin & Mcroberts, 1999). Figure 2-7 illustrates the difference between good and poor practices. Thickened/ paste discharge, dry stacking, and ensuring water removal before discharge are yet another important steps toward environment safety (Schoenberger, 2016).

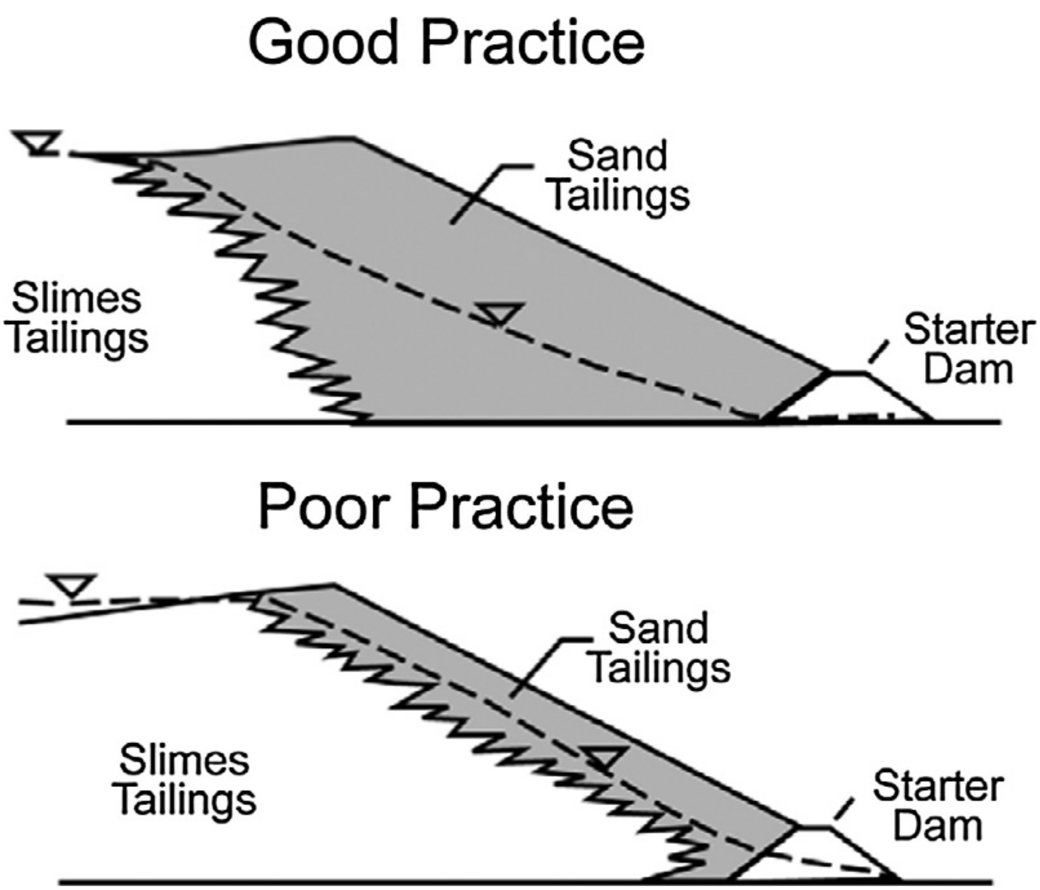

Figure 2-7: Good and poor practice in constructing upstream tailings dams (Kossoff et al., 2014; Martin & Mcroberts, 1999).

2.2.2 Landfills

Municipal Solid Waste (MSW), according to U.S. EPA, refers to discarded everyday items from both, residential and commercial sources (Vergara & Tchobanoglous, 2012; U.S. EPA). They include organic waste such as food scraps, recyclable and non-recyclable materials (plastics, papers, etc.) and hazardous materials (batteries, chemicals, etc.). Figure 2-8 illustrates the national average composition of residual waste disposed of in 2016.

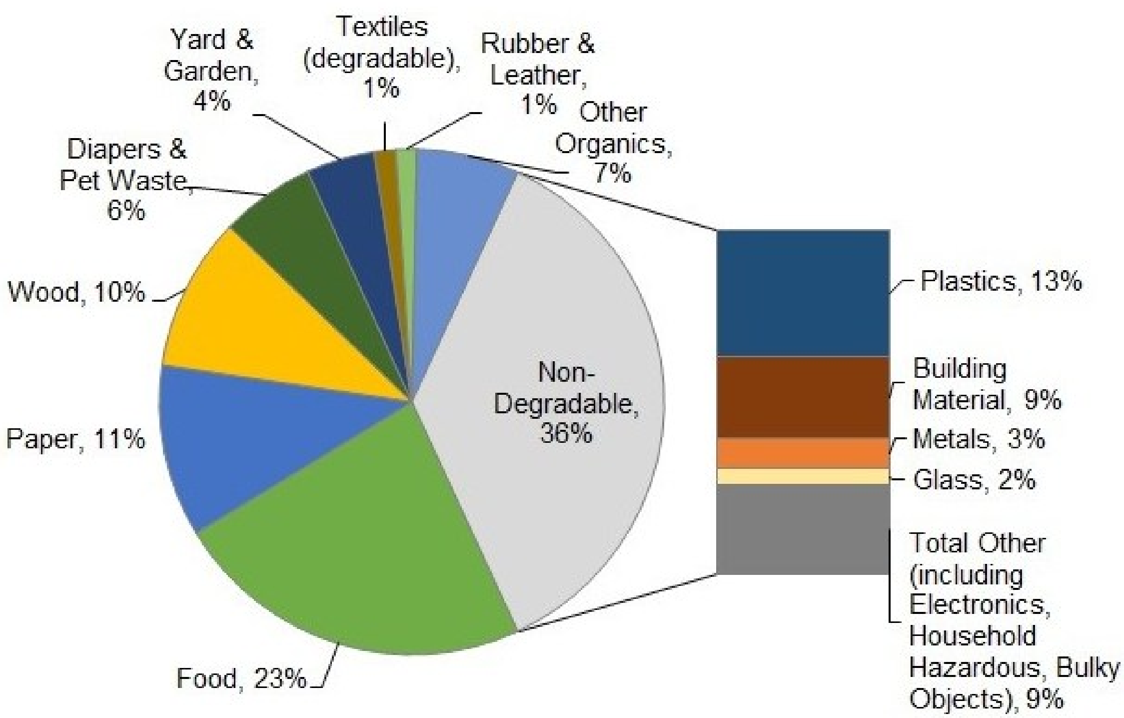

Figure 2-8: National average percentage composition of residual waste disposed (2016) (Environment and Climate Change Canada, 2020).

The United Nations Environment Programme (UNEP) predicts the growth of MSW generation from 2.3 billion tonnes in 2023 to 3.8 million tonnes by 2050. The primary method of MSW disposal in Canada and the rest of the world is landfilling. In Canada, about 97% of the waste is sent to landfills, while only 3% is incinerated (Government of Canada, 2024).

2.2.2.1 Reason for landfill failure and its environmental impacts

Landfilling is the easiest and most widely-used method to dispose of MSW. While landfilling is versatile and cost-effective, it requires careful management of leachate and gas emissions and is often susceptible to failure, depending on the properties of foundation soil, the type and performance of the liner and cover, slope stability, the time and duration of waste acceptance, the weight of waste, etc. (Daniel, 1997; Ya et al., 2023; Yaashikaa et al., 2022).

The waste in these landfills decomposes over time and leads to the formation of harmful gases and leachate capable of polluting the air, water, and soil (Tchobanoglous & Kreith, 2002). The presence of fluids, whether water or leachate, tends to reduce the overall strength of the landfill system. The quantity of fluids, if not managed properly, is inversely proportional to the strength of the landfill. The quality and leakage rate of landfill leachate vary with time, the composition of landfill, and the pattern of infiltration from rainfall or snowmelt (Koerner & Soong, 2000a; Moody & Townsend, 2017; Zhang et al., 2021). Leachate from landfills can be 20 – 100 times more potent than the raw sewage (Rastogi et al., 2015). Both the quality and quantity of leachate are governed by preferential flow, including flow patterns and flow rate (Rosqvist et al., 2005). The concentration of contaminants is higher in the early anaerobic acid phase due to strong decomposition. The following phase, called the methanogenic phase, produces more stable leachate with lower contaminant concentration as well as lower BOD/ COD ratios (Abdel-Shafy et al., 2024). In case of deterioration or failure of drainage pipes collecting leachate, the leachate can accumulate in large quantities and is likely to seep into the surrounding environment, contaminating soil and groundwater with heavy metals, organic matter, and VOCs, and even causing slope instability (Abuabdou et al., 2020; Jucá et al., 2021; Nanda & Berruti, 2021; Škultétyová, 2009). Excess precipitation increases leachate levels and adds to both fluid as well as gas pressures. Figure 2-9 shows a photograph of an exposed MSW landfill with leachate flowing.

Figure 2-9: Leachate flowing from an exposed MSW landfill (Merry et al., 2005).

Landfill waste also generates greenhouse gases, primarily methane (CH_4) and carbon dioxide (CO_2), along with other toxic gases at low concentrations, which contributes to air pollution, climate change and formation of ground-level ozone (Abdel-Shafy et al., 2024; Damgaard et al., 2011; Danthurebandara et al., 2012; Gardner et al., 1993; Vergara & Tchobanoglous, 2012). A photograph of a landfill after a slope failure, from which a smoke plume is emerging is shown in Figure 2-10. Park & Shin, (2001) demonstrated that the surface emission of landfill gases is significantly influenced by seasonal variations. The surface emission increases in the hot season and decreases in winter. Greater landfill depth and higher leachate levels usually correspond to higher gas pressure (Shu et al., 2022). Methane gas is highly flammable, and in extreme cases, high gas pressure can also lead to explosions (Dabrowska et al., 2023; Gendebien et al., 1992; Nanda & Berruti, 2021).

Figure 2-10: Smoke plumes after landfill slope failure in Philippines (Merry et al., 2005).

Stability is yet another concern for landfills. They are susceptible to both translational and rotational slope failures (Koerner & Soong, 2000a; Stark, 1999), especially when inaccurate slope angles are incorporated into design (Ekinci & Arslankaya, 2022). If the failure surface is angled steep enough, the shear resistance will be weaker along this plane, and the translational slide might occur with a greater magnitude than the rotational slide (Stark, 1999). In such cases, precipitation, either in the form of rain or snowmelt, can trigger slope failure as well (Kocasoy & Curi, 1995). A translational failure can also occur due to a weak liner and cover system; therefore, it is an imperative to correctly choose a barrier with suitable shear strength. Figure 2-11 shows an aerial view of a landfill slope failure in the Philippines, and Figure 2-12 shows the aftermath of a landfill failure in Sri Lanka. Both incidents resulted in the loss of human lives, livelihoods, biodiversity, and million of dollars in restoration and cleanup action.

Figure 2-11: Aerial view of 12.7-hectare Payatas landfill, Philippines, with slope failure and homes visible in foreground (photo by S. M. Merry) (Jafari & Stark, 2012; Merry et al., 2005).

Figure 2-12: Aftermath of Meethotamulla MSW landfill failure (Disaster Services, 2020).

Kumar & Reddy, (2021) studied the combined effects of temperature and waste settlement on geomembrane-geotextile (GM-GTX) interface, which has the lowest shear strength and therefore a greater chance of failure under heavy induced stresses. It was concluded from their study that waste placement during summer correspond to higher shear strengths in the GM-GTX interface due to increased temperature, in contrast to colder temperature during winter. Such findings are critical in terms of reducing the chances of shear displacements. Contrastingly, temperature variations affect biological reactivity, which in turn affects the quantity and quality of leachate being formed (Ekinci & Arslankaya, 2022). Keskin & Kezer, (2022) used the finite element method (FEM) and the limit equilibrium method (LEM) to conclude that geogrid reinforcement helps improve slope stability. They also concluded that with the implementation of geogrids, a steeper slope can be designed, allowing the landfill to store larger quantities of waste.

Landfill settlement occurs due to four main mechanisms: (i) Stress-related, where particles are compressed, reoriented, and pore water pressure increases; (ii) Water-related, where pore water pressure dissipates, or soluble materials dissolve; (iii) Physical/ chemical processes, such as corrosion, oxidation, and combustion of inorganic components; and (iv) Biodegradation, where organic matter decomposes and solids are converted into liquids and gases (Ren et al., 2022). Biodegradation alone can account for 40% of landfill settlement (Sivakumar Babu & Lakshmikanthan, 2015).

Furthermore, improper management of landfills also leads to unpleasant odors, insect breeding, spreading of vector-borne disease, and aesthetic issues (Zhang et al., 2022). Pastor & Hernández, (2012), Nai et al., (2021), and Afolabi et al., (2022) showed through their study that multiple closed and abandoned landfill sites have been repeatedly reused for various purposes without specific restoration plans, leading to a heterogenous distribution of pollutants across sites. Such practices instill a need for comprehensive restoration plans addressing contaminants before reuse.

2.2.2.2 Remediation measures for reducing impacts of landfill failure

Proper management of landfills and addressing key challenges are essential to preventing landfill failures and ensuring a long-term balance between waste management and ecology. A crucial step is controlling the amount of organic waste disposed by means of sorting and pre-processing (Kurniawan et al., 2021; Yaashikaa et al., 2022). Choosing sites where the water table is well below the landfill foundation further minimises the risk of groundwater contamination (Ekinci & Arslankaya, 2022; Tchobanoglous & Kreith, 2002). Utilizing natural hydrogeological characteristics and groundwater flow patterns not only helps minimize the migration of contaminants but also reduces the overall project cost (Allen, 2000). A study by Robinson, (2005) shows that, irrespective of varying geographical, climatic, and operational differences, the characteristics of leachate produced in large landfills remain largely the same, especially in the methanogenic phase. This consistency can help standardize best practices for the treatment of leachates. Additionally, an effective drainage and leachate collection system must be installed and regularly monitored (Chen et al., 2022). Monitoring gas pressure is also extremely crucial (Shu et al., 2022). Researchers have suggested levying methods such as physical adsorption using granular activated carbon (GAC) for metal removal (Bove et al., 2015; Foo & Hameed, 2009; Wang et al., 2003) and coagulants to reduce COD concentration (Long et al., 2017; Vaverková, 2019). Leveraging newer and improved remote sensing technologies to monitor gases emitted from landfills is also becoming increasingly popular (Cusworth et al., 2024). Figure 2-13 illustrates a remote sensing image of methane plumes from the River Birch landfill in New Orleans. The rate of methane emission was calculated to be around 48 metric tons per day (Benincasa, 2021).

Example of persistent venting at landfill

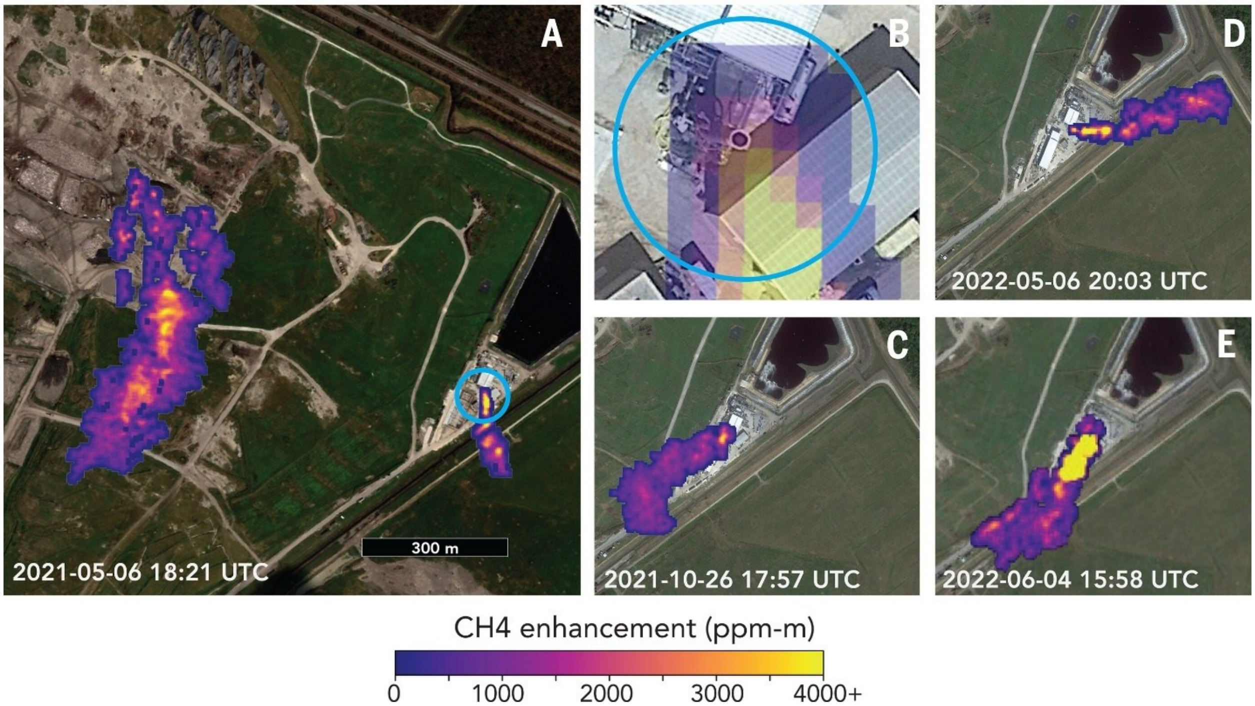

Figure 2-13: Quantification on methane emission from landfill in United States (Cusworth et al., 2024).

In terms of stability analysis, it is crucial to analyse cracks on the surface which can either be settlement-induced or related to slope instability. If a crack reappears within a short duration in the same location, it is more likely due to slope instability rather than settlement (Stark, 1999). Additionally, the factor of safety decreases significantly when gas pressure is taken in account (Shu et al., 2022). Furthermore, leachate is not just an environmental concern but also significantly impacts the stability of landfill. Using higher unit weights and maintaining a safety factor greater than or equal to 1.5 while designing slope is desirable and critical for stability (Koerner & Soong, 2000a).

Careful installation of multilayered barriers (liners and covers) to efficiently seal contaminants is also very essential (Chen et al., 2022; Lisk, 1991; Tchobanoglous & Kreith, 2002). However, the long-term performance of barriers is in question, and researchers are making enhancements to strengthen the integrity of barrier system.

2.2.2.3 Sustainable landfilling practices

The evolution from open dumpsites to closed engineered landfills has improved waste management, but concerns regarding environmental challenges persist. Environmental impacts continue even decades after a landfill has been closed. Gas emissions and transport become negligible after 1-2 decades, whereas leachate generation continues posing a threat to nearby surroundings (Belevi & Baccini, 1989; Iravanian & Ravari, 2020; Vaverková, 2019). These threats can be minimized by practicing sustainable landfilling while improving technologies and materials used in landfill construction. Sustainable landfilling aims at minimizing environmental impact from the inception of the landfill and must not pose threats to human health even after its final closure (Vaverková, 2019). The first step involves source reduction, composting, and recycling which minimize the burden on landfill (Lisk, 1991; Zhang et al., 2022). In order to implement this, a comprehensive approach involving strengthened policies and frameworks, followed by awareness among producers, manufacturers, and the public, must be built (Blair & Mataraarachchi, 2021; Zhang et al., 2022). Laner et al., (2012) emphasizes that utmost care and regular monitoring, specific to the behavior of landfill sites after closure, should focus on waste quality, emission levels, and settlement rates.

Sustainable landfill practices also emphasize on regular monitoring of gas emissions (Yaashikaa et al., 2022). The emerging concept of resource recovery treats landfills as potential future resource repositories (Vaverková, 2019). Integrating gas collection systems with resource recovery can help convert landfill gas into energy while curbing greenhouse gases (Crowley et al., 2003; Danthurebandara et al., 2012; El-Saadony et al., 2023; Warith, 2003; Yaashikaa et al., 2022). Bioreactor landfills aim to accelerate waste degradation process by leveraging enhanced microbiological processes (Lisk, 1991; Mondal et al., 2023; Themelis & Ulloa, 2007).

It is important to identify which leachate treatment method should be applied based on the age of the leachate. For example, ultrafiltration and microfiltration are effective as pre-treatment processes; while biological methods, such as aerobic and anaerobic treatments, suspended-growth and attached-growth biomass systems, are best suited for young leachates (Abdel-Shafy et al., 2024).

Barriers such as liners or covers play an essential role in sustainability. They not only impede contaminants from seeping into the subsurface, but also work in tandem with other components to impart structural stability. When designed carefully, liners can account for the amplification effect of seismic waves (Matasovic et al., 1998). Post closure of a landfill, covers can be repurposed for establishing green energy farms or green spaces.

In conclusion, while the adoption of advance technologies contributes to sustainable waste management, properly managed landfills reduce the risk of contaminants reaching the environment (Podlasek et al., 2021). Therefore, design improvements, better-quality construction materials, early implementation of preventive measures, and regular monitoring are essential to follow sustainable landfilling practices.

2.3 Introduction to barriers (liners and covers) in a waste containment facility

In the previous section (Section 2.2), the role of waste containment facilities, typically mine tailings impoundments and landfill, was highlighted. We discussed the causes of failures common to both types of facilities, such as design flaws, geotechnical failures (e.g., slope instability and liquefaction), the effect of pollutants generated, etc., followed by resulting risks and environmental consequences. Remediation measures, which included adopting and implementing best engineering practices as vital strategies, were discussed. Furthermore, the importance of integrating sustainability into waste management practices to minimize adverse impacts on the environment and ensure long-term effectiveness was emphasized. Among the most effective engineering strategies for enhancing the performance of waste containment systems is the incorporation of barriers – liners and covers. Extending this understanding, this section (Section 2.3) focuses on briefing the basic fundamentals of liners and covers. It will state the primary functions of various components that work in tandem to keep the contaminants from migrating into the subsurface and/ or atmosphere. The following section (Section 2.4) will briefly describe the multicomponent barrier systems currently in use.

Based on the characteristics and potential to contaminate the surrounding environment, the seepage control systems can be broadly classified into the following three categories (Taylor, 1980):

a) Type I System: Uncontrolled seepage from impoundment
b) Type II System: Partially-retained effluent (some seepage loss)
c) Type III System: Maximum restriction of seepage from impoundment

Waste containment facilities are used to store toxic waste that are capable of seeping into the subsurface or escaping into the atmosphere, if not managed properly. To safely secure them within the waste facility, base and top barrier systems, namely liners and covers, respectively, are used. These barriers fall under the Type III seepage control system (Taylor, 1980; Vick, 1990b). These barriers aid in controlling the flow of fluids and/ or gas pressure while also permitting gas recovery by employing liners or covers with very low hydraulic conductivity, preferably of the order 10^{-9} m/s or less (Benson & Daniel, 1994b; Daniel, 2012; Peyton & Schroeder, 1990; Ryan, 2010). More specifically, liners are laid at the bottom and along the side slopes, covering the entire impoundment from end to end. Waste materials are disposed of over the liners, which serve to mitigate the downward flux of contaminants. Once the facility reaches its full capacity, covers are laid to enclose the impoundment, thereby restricting fluid (rainfall or snowmelt) accessibility and preventing ground or subsurface infiltration (Albright et al., 2010; Benson et al., 2011; Fall et al., 2009; Koerner & Bowman, 1994; Koerner & Daniel, 1997; Rowe, 2001; Vick, 1990b). In mining, covers help in restricting the waste from coming in contact with oxygen, thereby preventing acid mine drainage (AMD). In landfills, covers not only help restrict harmful gases, such as methane, from escaping into the atmosphere but also allow recovery of such gases for other purposes. The contamination lifespan ranges from 100 to 300 years for MSW to over a thousand years for mine waste; therefore, the barriers should be designed to ensure long-term performance of the entire system (Rowe & Jefferis, 2022). This makes it an imperative to employ materials with low hydraulic conductivity, as inadequate hydraulic conductivity can lead to development of high seepage forces (Rowe et al., 2000). In the following section, we will briefly describe various kinds of barriers that form the multicomponent system.

2.4 Types of barriers

As the understanding of contaminant transport and the scale of waste generation has increased, many different types of barriers have been developed. Figure 1-3 illustrates the multicomponent barrier system used in an engineered waste containment facility. Each component serves a distinct purpose, not just containing the pollutants safely within a specified boundary but also imparting structural stability to the whole facility.

The first step prior to laying any barrier material is excavation, followed by levelling and ground stabilization to ensure seamlessness. Once this is achieved, the barriers can be installed one by one. The efficacy of a barrier system depends on its material properties, design configuration, location, and installation techniques (Booker et al., 2004; Koerner, 2002). For example, in sub-section 1.2.1.2., we discussed the importance of capillary effect. This occurs when a fine-grained material is enclosed between two coarse-grained materials (Yanful, 1993). The coarser material promotes capillary suction, maintaining the required degree of saturation in the fine-grained material (Benson et al., 1994). Therefore, such barriers are best suited for humid regions (O'kane et al., 2000; O'kane & Waters, 2003). Additionally, incorporating fly ash in a soil-bentonite mix enhances stability and increases contaminant sorption capacity (Edil et al., 1992; Hettiaratchi et al., 1999; Yeheyis et al., 2010).

Following are the various types of barriers (liners or covers) installed in a typical waste containment facility:

a) Compacted Clay Liner (CCL),
b) Primary and Secondary Geomembranes,
c) Geocomposite, geotextile, geogrid, and geonet,
d) Geosynthetic Clay Liner (GCL)

2.4.1 Compacted Clay Liner (CCL)

CCL is the most commonly available and used materials for liner systems (Lake, 2002). It is made up of natural clay, and with correct compaction, hydraulic conductivity as low as 10^{-9} m/s can be achieved, which is the minimum requirement for a liner material. The efficacy of CCL greatly depends on the degree and method of compaction (Vick, 1990a). Similar to ground stabilization techniques, CCLs are compacted in multiple layers and mixed with additives, such as bentonite, to enhance engineering properties and impermeability (Cui et al., 2012; Daniel, 1987, 1993; Fall et al., 2009). Kumar & Yong, (2002) conducted laboratory tests on clay-bentonite mixtures with increasing bentonite content, and found an improvement in Atterberg limits and unconfined compression strength, as well as a decrease in hydraulic conductivity and consolidation properties. Due to this reason, CCLs are less prone to defects such as punctures.

However, clay liners placed on soft or loose foundations will most likely undergo settlement. Moreover, reactions with certain effluents can result in changes in clay minerology (Vick, 1990a). In order to considerably reduce seepage from an impoundment, the permeability of a clay liner must be at least ten times lower than that of the tailings and at least one to two orders of magnitude lower than that of the foundation materials (Vick, 1990a). The minimum thickness recommended for clay liners is 1 metre (Benson et al., 1999; Benson & Daniel, 1994a, 1994b). Furthermore, the performance of CCL is impacted by the configuration of the waste facility. For example, if the impoundment is flat, it will be covered with waste almost immediately, reducing desiccation cracks. In contrast, a sloped impoundment will have exposed liner sections for a longer duration, leading to the development of wider and longer cracks. Desiccation cracks can significantly increase permeability. Moreover, desiccation cracks in CCL can go unnoticed when covered under a geomembrane, especially when the geomembrane is exposed to high temperatures (Rowe, 2018).

In conclusion, the efficacy of CCLs depends on selecting the correct natural material, the appropriate combination for a composite liner system, and implementing good construction practices.

2.4.2 Geomembranes (Primary/ Secondary)

Geomembranes are synthetic polymeric sheets with very low permeability that are installed in contact with CCL or GCL, forming a composite liner to overcome the limitations of CCL and provide greater durability to the liner system (Daniel & Koerner, 2007; Feodorov et al., 2000; Fleming et al., 2006; Rowe, 2001; Rowe & Fan, 2022; Tuomela et al., 2021; von Maubeuge, 2018). Two of the most widely used polymers for manufacturing geomembranes are high-density polyethylene (HDPE) and polyvinyl chloride (PVC). They are relatively cost-efficient, easy to install, and available in smooth, textured, or reinforced types based on their physical appearance (Rowe & Jefferis, 2022; von Maubeuge, 2018). The thickness of geomembranes generally lies between 1mm and 2.5mm (Booker et al., 2004; Bouazza, 2002; Rowe & Fan, 2022; Touze-Foltz et al., 2008; Tuomela et al., 2021). HDPE is commonly used for liners due to its excellent chemical resistance; whereas PVC is common for covers as it offers better ductility at failure than HDPE (Booker et al., 2004; Rowe, 2001). Therefore, selecting the correct material depends on its intended use as a liner or cover.

Despite having good engineering properties, the performance of geomembranes is affected by numerous factors, such as, installation practices, weight of overlying materials, differential settlement of underlying material, and slope instability. These factors can give rise to stress and deformation. Even the protrusion of a small rock can create localized stress points and promote leakage. Therefore, the subgrade must be properly levelled, and field-seaming of the geomembrane must be carried out carefully (Koerner & Daniel, 1997; Rowe & Yu, 2019; Tuomela et al., 2021; Vick, 1990a). HDPE geomembranes have been found to be efficient in restricting the transport of contaminants through diffusion (Rowe, 2018). In standard construction practices, geomembranes develop a considerable number of wrinkles before being covered (Rowe, 2007). Furthermore, temperature fluctuations can cause geomembranes to expand, shrink, and form wrinkles. An increase of approximately 50^0C in temperature can result in wrinkle heights of 0.1m in HDPE geomembranes and 0.01m in PVC geomembranes. These wrinkles can induce tensile stress and initiate cracks, thereby creating a pathway for contaminant migration (Giroud & Bonaparte, 1989; Giroud & Peggs, 1990). Rowe (2018) suggests that proper monitoring should be conducted to ensure that at the time of covering (a) the area beneath wrinkles is less than 8% of the total area to be covered, and (b) the height of wrinkles is less than 50 – 60mm.

Touze-Foltz et al., (2008) suggests two design approaches to prevent damaging of geomembrane from overlying materials, especially gravel. The first approach involves preventing elongation past the yield point of the geomembrane material (Koerner, 2005), while the second approach focuses on limiting local strains caused by the combined pressure forces from the overlying and underlying layers (Bouazza et al., 2002). Moreover, to maintain the integrity of a composite liner system, such as the geomembrane/ CCL interface, Rowe (2018) recommends either covering the geomembrane to protect it from elevated temperatures or using a white geomembrane or a white geotextile protection layer.

2.4.3 Geocomposite, Geotextile, Geogrid, and Geonet

Geocomposites are combinations of two or more geosynthetic materials designed to enhance the performance of barrier systems (Shackelford, 2003). The materials used in these combinations include geomembranes, geotextiles, geogrids, and/ or geonets. Since geocomposites consist of various materials, it is important to check the frictional resistance of one material with respect to the other before applying them on field. This can be assessed from direct shear test.

Geotextiles are woven or non-woven synthetic polymeric fibres used as a means of separation, reinforcement, filtration and drainage (Feodorov et al., 2000; Kettley, 2011; Nicholson, 2015; Rajapakse, 2016). When acting as a filter, geotextiles must be porous enough to permit water to flow through them without increasing pore water pressure (Koerner & Daniel, 1997). It has been demonstrated that a well-designed continuous geotextile layer overlying a drainage layer in a landfill enhances the service life of leachate collection system (Rowe, 2018).

Geogrids are polymeric materials used as reinforcement to enhance the strength of the underlying material. They can be fabricated either through machine or by weaving/ knitting looms (Feodorov et al., 2000; Rajapakse, 2016; Rowe, 2001). Geogrids provide efficient interlocking due to their large openings (Fourie & Fabian, 1987).

Geonets are polymeric materials generally placed between primary and secondary liners to facilitate drainage, serve as a leak detection layer, and minimize strain on the underlying geomembrane, especially on slopes, by allowing movement once the wastes are deposited. In addition, the net-shaped structure prevents any larger particles from entering into the drainage system (Feodorov et al., 2000; Snow et al., 1994; Weeks & Schubert, 1986; Yu & Rowe, 2018).

In conclusion, geocomposites can fulfil a variety of purposes in a waste containment facility. However, proper selection, specification, and manufacturing are critical given the varied nature of waste facilities.

2.4.4 Geosynthetic Clay Liner (GCL)

Geosynthetic clay liners (GCLs) are prefabricated layers of bentonite placed between geotextiles or geomembranes with a total thickness ranging between 5 – 10mm and hydraulic conductivity ranging as low as 10^{-9} to 10^{-11} m/s (Bouazza, 2002; Katsumi et al., 2008; Koerner & Daniel, 1997; Koerner & Soong, 2000b; Mendes et al., 2010; Rowe & Jefferis, 2022; Sobti & Singh, 2017; Whittle & Ling, 2002). The layers can be either needle-punched, or stitch-bonded or bonded using adhesives, providing better internal shear strength, especially on sloped surfaces. However, excessive needle-punching can result in a reduction of hydraulic conductivity in low-stress applications, such as covers that involve exchange of cations (Rowe, 2020). The hydrophilic property of bentonite helps in retarding the flow of fluids and adsorbing contaminants (Whittle & Ling, 2002).

Selecting the appropriate bentonite is critical to the performance of GCLs; therefore Rowe & Jefferis, (2022) suggests conducting a modified swell index test by replacing the water with the actual fluid that will be contained in the facility. The limited thickness of GCLs also means low sorption capacity (Bouazza, 2002; Rowe, 2014). Furthermore, GCLs may be subjected to minor defects such as stress concentration due to wrinkles or small penetrations. Previous studies show that Na-bentonite can effectively seal minor holes, especially those up to 30mm diameter, with only a slight increase in hydraulic conductivity (Bouazza et al., 1996; Didier et al., 2000; Mazzieri & Pasqualini, 2000; Shan, 1991). However, another research shows that the self-healing capacity of bentonite can be impeded by ion exchange during the process (Lin & Benson, 2000). Additionally, hydraulic conductivity deteriorates with an increase in the ionic strength of solutions.

Pre-hydration of GCL with water improves their chemical resistance and the overall performance (Katsumi et al., 2010). Leakage of contaminants through holes can be reduced by ensuring the proper installation of a reasonably hydrated GCL before it comes into contact with leachate in a landfill. This can be achieved by ensuring that the subgrade has suitable moisture content (Rowe, 2018). Temperature variation also affects the service life of GCLs, especially their hydraulic properties. Exposure to elevated temperatures can lead to an increase in leakage rates (Hornsey et al., 2010; Rowe et al., 2023; Rowe, 2014). Therefore, it is advised to minimize exposure time as much as possible before covering.

In summary, the primary objective of a barrier system is to ascertain the maximum efficacy of the system as a whole, not just its individual components. It is recommended to inspect the project on a regular basis, as waste facilities always hold a certain degree of uncertainty. Once a problem has been recognized, suitable measures must be adopted and implemented to fully address the problems.

2.5 Bentonite, its general properties and role in construction industry

Bentonite is a type of very fine-textured, expansive clayey soil formed as a result of the alteration of igneous materials such as volcanic ash and tuff. It belongs to the smectite group of minerals, predominantly comprising either sodium (Na^+) or calcium (Ca^{2+}) montmorillonite minerals and has a crystalline structure. Bentonite is known for its excellent swelling capacity, low hydraulic conductivity, low thermal conductivity, high Atterberg limits, high cation-exchange capacity (CEC), large specific surface area, and high adsorption capacity (Ahmad et al., 2021; Gleason et al., 1997; Grim & Guven, 1978; Melamed & Pitkänen, 1996; Mitchell, 2005; Oy & Carlson, 2004; Pusch, 1982; Wilson et al., 2011; Zelić, 2013).

On the basis of dominant exchangeable cation, bentonite can be classified into two types – sodium (Na^-) bentonite, and calcium (Ca^+) bentonite, each with varying properties. Na-bentonite has higher compressibility, lower hydraulic conductivity, and several times higher swelling capacity, as compared to Ca-bentonite (Athanassopoulos, 2011; Grim & Guven, 1978; Liu et al., 2011).

The crystalline structure of smectite minerals is composed of tetrahedral sheets and octahedral sheets. The tetrahedral sheets consist of oxygen at the corners with cation, predominantly Si^{4+}, in the center. The octahedral sheets consist of cations, predominantly Al^{3+} or Mg^{2+}, located in the center surrounded by OH^- (hydroxyl ions) at the corners. The exchangeable cations help in maintaining the charge balance (Sawyer II, 1984), but the tetrahedral sheets have a lower charge than the octahedral sheets (Karnland et al., 2006). In montmorillonite minerals, the alumina octahedral sheets are located between the two silica tetrahedral sheets, joined by van der Waal forces, and has a net negative surface charge. Therefore, these are also referred to as 2:1-layer structures, as illustrated in Figure 2-14. Bentonite is made up of hundreds of such mineral layers which can extend to several hundred nanometers in length and width, with a thickness of about 1 nm (Karnland et al., 2006; Pusch et al., 1990; Saiyouri et al., 2004).

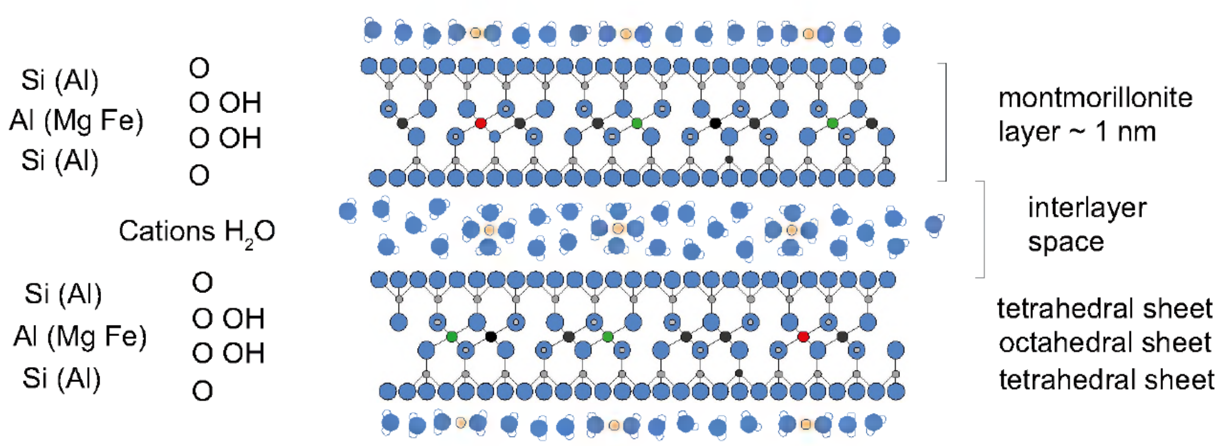

Figure 2-14: Edge view cartoon of two montmorillonite layers with interlayer cations and water molecules (Karnland et al., 2006).

The van der Waals force form a weak bond between the layers and are easily broken, allowing water molecules to replace them upon hydration, forming a double-diffuse layer. Montmorillonite has very high cation-exchange capacity, which forms the fundamental mechanism behind the swelling and expansion of bentonite particles. However, the extent of expansion depends on several factors, such as the exchangeable cation, specific surface area, and concentration in water (Cui et al., 2012; Laird, 2006; Mesri & Olson, 1971; Mitchell, 2005; Pusch et al., 1990). A study by Pusch et al., (1990) reported that Na (9.74 Å) and Mg (9.08 Å) bentonites formed three layers of water molecules, resulting in a thicker double-diffuse layer causing more expansion compared to K (6.15 Å) and Ca (5.64 Å), which formed only two layers of water molecules. The numbers in parentheses indicate their respective thicknesses.

Due to properties such as dry density, swelling ability, and hydraulic conductivity, bentonite is widely used in various engineering applications. For these reasons, bentonite has often been mixed with other materials to enhance its overall properties. It is commonly used as a liner and cover system to restrict the flow of contaminants and gases that might otherwise escape from waste impoundments. In addition, bentonite helps in adsorbing the contaminants due to its effective cation-exchange capacity (Tripathy et al., 2014). Dry density is another important parameter for engineered barrier materials, influencing both swelling behaviour and hydraulic conductivity. Previous studies have shown that as the dry density of compacted bentonite increases, the hydraulic conductivity decreases while the swelling pressure increases (Cho et al., 1999, 2012). Similarly, the initial water content has a significant impact on the swelling pressure of compacted bentonite with high dry density (Fall et al., 2009; Villar & Lloret, 2008). Additionally, compared to other clay minerals, smectites contribute very high compressive strength within mixtures of clay and non-clay minerals (Grim & Guven, 1978).

To conclude, based on the findings from the literature, bentonite offers ideal characteristics to be implemented in various engineering applications, including waste containment facilities, where it serves as a barrier to prevent contaminant migration.

2.6 Tailings and its general properties

Tailings, are very fine-grained, slurry mixtures of crushed rocks and extraction fluids remaining after the extraction of economic minerals from their ore (Benzaazoua et al., 2004; Bernd & Bernd, 2007; Vick, 1990a; Younger & Wolkersdorfer, 2004). Vick, (1990) categorised tailings into four broad groups based on their gradation and plasticity. The first category consists of soft-rock tailings obtained from shale ores. Lead-zinc, copper, gold-silver, molybdenum and nickel are included in the second group called hard-rock tailings. This type of tailings is formed from finely crushed silicate particles. The third category is fine-tailings, which include phosphatic clays, bauxite red muds, fine taconite tailings, and slimes from tar sands tailings. The fourth and final category is coarse tailings, whose characteristics are governed by the percentage of coarse sand or by non-plastic silt. Based on their composition, tailings may or may not contain hazardous acid-generating substances (Kossoff et al., 2014). The fine-grained texture of tailings influences its capability to bind with other materials, such as bentonite, for engineering purposes.

The tailings in a given category share similar physical properties; therefore, the risks associated with waste management are likely to be comparable. Sarsby, (2000) and Bjelkevik, (2005) investigated the physical properties of tailings and concluded that the bulk density of the tailings tested varies with their parent rock, ranging between 1.8 and 1.9 t/m^3, with a specific gravity between 2.6 and 2.8. They exhibit a high friction angle due to their angular structure, and show minimal cohesion. Higher tailings density also leads to an increase in strength (Fall et al., 2004, 2008). On the contrary, the chemical composition of tailings depends not only on the minerology of their parent rock but also on the nature of the processing fluids used in mineral extraction and the efficiency of overall extraction process (Kossoff et al., 2014). Hu et al., (2017) conducted a series of laboratory experiments to investigate the geotechnical characteristics of iron and copper tailings of both, fine and coarse textures. The study found that fine tailings exhibited greater compressibility, lower strength, and lower hydraulic conductivity than coarse tailings. Additionally, iron tailings showed higher compressibility, lower strength, and lower hydraulic conductivity than copper tailings. This study provides crucial data for understanding the behaviour of tailings and concludes that fine tailings require special attention to ensure tailings dam safety. The result of this study is also consistent with the findings obtained by Fall et al., (2005) and Shamsai et al., (2007).

2.7 Compacted bentonite-paste tailings (BPT) mixtures as proposed barrier material

The implementation of engineered barriers, such as liners or covers, is a necessary approach to prevent contaminant transport and to limit fluid infiltration from waste containment facilities. The most commonly used materials are natural-clay barriers or geosynthetics, which can be expensive and not readily available. The shear strength of clay varies with the amount of non-clay components (Grim & Guven, 1978). In this alignment, Fall et al., (2009) introduced a novel type of bentonite-based material, called compacted bentonite-paste tailings (BPT). They investigated compacted BPT for its potential use as an engineered barrier material for waste impoundments. The study evaluated the compaction behaviour, hydraulic conductivity, and resilience towards natural stresses such as wet-dry and freeze-thaw cycles.

The experimental study was conducted in a controlled environment. Synthetic tailings (ST) devoid of acid-generating elements were used for the experiments. The tailings were primarily composed of quartz, as they closely resemble naturally occurring mine tailings. The sodium bentonite used has a high swelling capacity. Various proportions of bentonite (0%, 2%, 4%, and 8%) were mixed with tailings using deionized water.

Compaction tests demonstrated that the addition of bentonite improved the packing density of tailings by reducing voids. The highest dry density was achieved in the 4% bentonite mix (1640 kg/m^3), and decreased thereafter with further additions. The hydraulic conductivity values of the compacted BPT with bentonite content of 2% or more are lower than the minimum value required for barrier design (10^{-7} cm/s). Hydraulic conductivity decreased continuously as the bentonite content increased owing to its high cation exchange capacity, high water sorption, and formation of a double-diffuse layer that promoted impermeability. In terms of wet-dry cycles, the hydraulic conductivity initially increased, likely due to the formation of desiccation cracks, and then decreased thereafter, showing signs of self-healing. Similarly, self-healing ability was observed after the third freeze-thaw cycle, suggesting that BPT materials can successfully maintain their integrity under extreme environmental conditions. Compared to materials comprising other clay minerals, bentonites are comparatively less susceptible to frost heave owing to their low permeability (Grim & Guven, 1978).

Furthermore, the cost-benefit analysis between BPT mixtures and sand-bentonite mixtures showed that BPT mixes yielded higher economic benefits across all compositions, with the 4% BPT mix displaying the highest cost savings of 66%. This study demonstrated that BPT materials possess the necessary properties to serve as an efficient engineering barrier for waste containment facilities.

However, the mechanical properties and behaviour of BPT, including consolidation behaviour and shear characteristics, were not investigated in the studies conducted by Fall et al., (2009).

These mechanical characteristics are also essential for the design of barriers for waste containment facilities, particularly landfills and mine waste containments. To date, no studies have addressed the aforementioned mechanical characteristics of BPT. In addition, the desiccation cracking behavior of BPT barriers remains unknown, and no studies have addressed this research gap.

2.8 Desiccation cracking and its mechanism

Desiccation cracks are a critical concern in geotechnical projects, including engineered clay liners in waste containment facilities. They can significantly impact the material's properties and strength, create preferential pathways for contaminants, and compromise the structural integrity.

Bentonite is susceptible to desiccation cracking due to its hydrophilic nature, high plasticity, high shrinkage potential, and presence of small pores, which lead to gradual moisture loss upon exposure to environmental conditions such as wet-dry cycles, giving rise to negative pore pressure (Tang et al., 2008; Tang et al., 2012; Wei et al., 2020).

When a saturated BPT sample is subjected to drying, surface water evaporates first, pulling water from the layer beneath the surface through capillary suction. This leads to the formation of water-air meniscus between the particles. However, tensile strength is low or unaffected at this stage. As more moisture is lost, more water is pulled upward, increasing capillary suction and, consequently, the curvature of the capillary meniscus further increases. As a result, the particles are drawn closer to each other, causing volumetric shrinkage and development of tensile stress in the upper layer. This phenomenon continues until a point where the tensile stress exceeds beyond the tensile strength of the soil, leading to formation of crack (Abu-Hejleh & Znidarčić, 1995; Corte & Higashi, 1964; Morris et al., 1992; Peron et al., 2009; Tang et al., 2010). A schematic drawing illustrating the crack initiation process is shown in Figure 1-14.

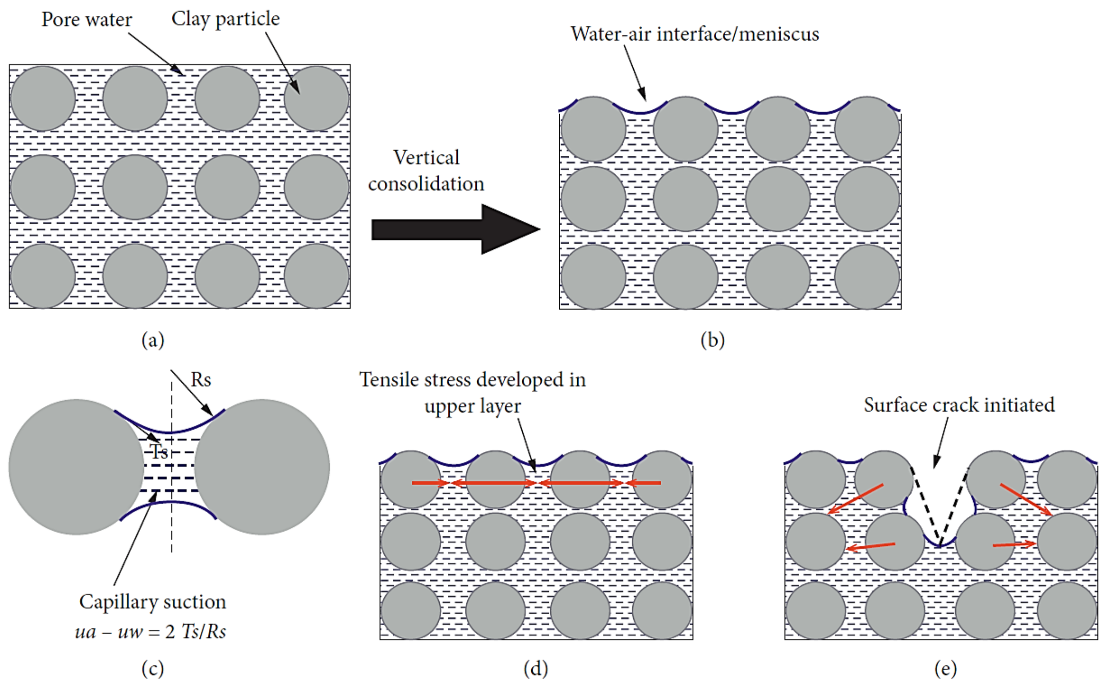

Figure 2-15: Schematic drawing of soil crack initiation process. (a) Initial fully saturated soil; (b) water-air interface meniscus developed between soil particles; (c) capillary suction between soil particles; (d) tensile stress developed in the upper layer; and (e) surface crack initiated (Tang et al., 2011).

Through investigative studies, it was also observed that the extent to which desiccation cracks develop is directly proportional to temperature and relative humidity. Higher temperatures and relative humidity correspond to greater tensile stress, allowing quicker and more extensive cracking (Kayyal, 1995; Tay et al., 2000).

2.9 Conclusion

In this chapter, a comprehensive review of waste management facilities has been conducted, with a special focus on mine tailing impoundments and landfills. The following conclusions can be drawn from the literature review:

a) Waste containment facilities are governed by complex interactions and relationships between various geotechnical, hydrological and chemical parameters, which requires to be dealt with specialized strategies to effectively contain toxic waste within a designated region.

b) Waste containment facilities are susceptible to failures as a result of improper geotechnical design, negligent waste management practices, and other factors. These failures often lead to catastrophic and long-lasting impact on environment such as, but not limited to, subsurface and atmospheric contamination, habitat loss, and economic loss. Such failures, combined with a global shift towards sustainability, underscore the importance of employing robust systems such as engineered barrier systems.

c) Recent technological advancements have led to an evolution from natural clay liner systems to incorporation of multilayered geosynthetics, such as geomembranes, geocomposites, geotextiles, geogrids, geonets, and geosynthetic clay liners. Each system offers specific advantages in terms of mechanical and hydraulic properties, filtration, durability, etc. However, each layer exponentially increases the costs based on its availability and sourcing.

d) Bentonite serves as a valuable material used in various engineering application owing to its high cation exchange capacity, excellent water and chemical sorption properties, excellent swelling capacity, and low hydraulic conductivity. Therefore, bentonite is carefully incorporated as an additive with other materials to enhance their overall mechanical, hydraulic, chemical, and other properties. However, bentonite is also susceptible to drying-induced cracking; therefore, due consideration must be given when optimizing its percentage while combining it with other materials.

e) In alignment with this perspective, a novel approach has emerged in sustainable tailings management in recent years: recycling tailings into barrier materials for waste containment. Recent studies have highlighted the potential of compacted bentonite-paste tailings (BPT) mixtures as engineered barrier materials (Fall et al., 2009).

f) The findings indicate that BPT mixtures exhibit hydraulic conductivity values on the order of 10^{-7} cm/s or lower, coupled with robust resistance to freeze-thaw and wet-dry cycles, while also being cost-efficient at the same time. However, the mechanical properties (consolidation and shear characteristics) and desiccation behaviour of BPT are unknown, and no studies have addressed these critical knowledge gaps.

g) This experimental study aims to investigate the mechanical behavior of BPT in terms of consolidation and shear strength characteristics and to evaluate the drying-induced desiccation behavior. The findings from this study will further enhance the understanding of BPT mixtures as their employment towards barriers for waste containment facilities.

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3 Chapter 3: Technical Paper I – Consolidation and Strength Characteristics of Bentonite-Paste Tailings Barrier Materials for Waste Containment Facilities

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3.1 Abstract

Waste containment facilities, including landfills and mine waste repositories, often contain hazardous contaminants that pose risks of subsurface infiltration and groundwater contamination. To mitigate these risks, engineering barriers such as liners and covers are commonly used — liners reduce contaminant flux, while covers limit fluid access and infiltration. Recent studies have highlighted compacted paste tailings mixed with bentonite (BPT) as a promising alternative to conventional liner and cover materials due to their low hydraulic conductivity. However, their mechanical properties, such as consolidation behavior and shear strength, are unknown. This study investigates the consolidation and shear characteristics of BPT with varying bentonite content (0%, 2%, 4%, and 8%). The results indicate that BPT with 4% bentonite exhibits the best mechanical performance, demonstrating the lowest volume change, compression index, and settlement while achieving higher shear strength. The study also establishes the correlation between bentonite content and shear resistance, showing that excessive bentonite (8%) weakens structural integrity due to increased swelling. The findings provide valuable insights into the mechanical performance of BPT materials, offering a sustainable and effective alternative to conventional barrier systems. These results support the potential implementation of BPT in waste containment infrastructure, contributing to improved environmental protection and long-term stability.

Keywords: Tailings; shear characteristics; consolidation; liner; cover; bentonite; waste containment.

3.2 Introduction

Mining plays a crucial role in driving socio-economic development by supplying the raw materials necessary for high-tech electronics, tools, machinery, and infrastructure such as power plants and roads (Al-Moselly et al. 2022; Xiapeng et al. 2019). In fact, the average electronic device today relies on approximately 60 minerals sourced from Earth, underscoring its indispensable role in modern consumer society (Jenness, 2016; Mining Association of Canada, 2019; Weathers et al., 2001). However, with advancements in technology and accelerating demand, the extraction of valuable materials has intensified, leading to an increase in mine waste generation.

The most significant type of mine waste, in terms of volume, is tailings. Tailings are the finely ground waste materials left over after the extraction of valuable minerals from ore during mining operations. They often contain water, residual chemicals, and finely ground rock particles, making them one of the largest waste streams in mining (Fourie, 2012). Due to their composition, mine tailings typically possess a fine-grained texture and may contain hazardous substances, posing significant environmental risks (Bull and Fall, 2020; Kossoff et al., 2014). Present-day mining operations often deposit tailings in surface impoundments, such as tailings dams or impoundments. Regrettably, these structures are susceptible to failure, leading to immediate and enduring repercussions on human health, ecosystems, and nearby communities. Moreover, the remediation costs associated with such incidents can skyrocket into tens of millions of dollars. Additionally, leakage from tailings dams can contaminate groundwater and surface water, compromising water quality. Furthermore, tailings containing significant amounts of pyrite can induce acid mine drainage (AMD) when exposed to oxygen and water, a reaction that may be catalyzed by microorganisms like bacteria (Aldhafeeri and Fall, 2017; Kossoff et al., 2014). AMD poses a substantial threat to ecosystems and the biosphere, with far-reaching social and economic ramifications for mining operations and the surrounding regions. So, this conventional approach to managing tailings impoundments at ground level has given rise to severe geotechnical and environmental challenges, resulting in adverse effects on the mining industry's reputation, public perception, and financial stability (Fall et al., 2010). Consequently, the mining sector is actively seeking innovative technologies to facilitate more sustainable tailings management practices.

In alignment with this perspective, a novel approach has emerged in sustainable tailings management in recent years: recycling tailings into barrier materials for waste containment (Fall et al., 2009). Designing waste containment facilities, such as solid and hazardous waste landfills, and mine waste repositories, necessitates the implementation of effective barriers, typically in the form of liners and covers. These barriers serve crucial roles in minimizing the downward flux of contaminants and restricting fluid access, thereby mitigating potential environmental impacts on groundwater, surface water, and ecosystems. Barriers typically fall into several categories, including natural clayey deposits, compacted clay and clay–sand mixtures, synthetic materials such as geomembranes, spray-on asphalt, and hydraulic asphalt concrete, as well as natural rock deposits. Studies by Fall et al. (2009) have highlighted the potential of compacted paste tailings-bentonite mixtures (BPT), a compacted mixture of pyrite-free tailings, water and bentonite, as viable materials for liners or covers due to their remarkably low hydraulic conductivity values ($<10^{-7}$ cm/s), meeting the requirements for containment facility design defined by the Environmental Protection Agency (EPA) (Daniel, 1993). Their study found that compacted BPT mixtures exhibit significantly low hydraulic conductivities. For instance, hydraulic conductivities as low as 6.27×10^{-10} cm/s and 9.58×10^{-9} cm/s were observed for BPT with 8% and 4% bentonite, respectively. Furthermore, the research indicated that the proposed BPT barrier demonstrates resilience against environmental stresses, including freeze–thaw and wet–drying cycles (Fall et al., 2009). These promising findings suggest that BPT mixtures hold great potential for application as liner or cover materials in mine waste containment facilities. However, while hydraulic characteristics are crucial, a comprehensive understanding of the mechanical properties, including consolidation behavior and shear strength, is equally essential for evaluating the efficacy of these proposed barrier materials. Waste containment barriers undergo significant stress changes throughout their service life, especially during installation and placement of waste, which makes evaluation of consolidation behavior crucial. These stress change behaviors can induce settlement and changes in void ratio, which directly affects hydraulic conductivity. Additionally, differential settlement can create preferential flow paths through development of cracks further compromising the integrity of barrier systems (Albrecht & Benson, 2001). Waste containment facilities often involve sloped configurations, and the barrier materials must possess adequate shear strength to prevent sliding failures that could catastrophically breach the containment system. Therefore, evaluation of shear strength is equally crucial for slope stability analysis and overall structural integrity of the containment system. Moreover, various US EPA standards (EPA/625/4-89/022, EPA/625/4-91/025, EPA/625/R-94/008, EPA-542-R-98-005) as well as Canadian federal and provincial guidelines (such as Ontario Regulation 347/90) necessitates a thorough geotechnical assessment of waste disposal sites. These standards recognize that barrier failure due to mechanical instability can be catastrophic, making the integrated assessment of both property types essential for reliable barrier design and long-term environmental protection. Unfortunately, no studies have investigated the consolidation behavior and shear characteristics of this new barrier material.

Hence, the primary objectives of this research are:

(i) To conduct experimental investigations into the consolidation behavior of the BPT material.

(ii) To experimentally assess the shear characteristics, encompassing shear strength and shear behavior, of the BPT material.

Both, one-dimensional consolidation tests and direst shear tests are widely used in geotechnical engineering for assessing the performance of barrier materials. One-dimensional consolidation test replicates vertical loading conditions similar to those from overlying waste, allowing prediction for long-term settlement behavior. The direct shear test evaluates the shear strength of the barrier system under various applied normal stresses, representing overburden pressure from continuous waste placement. These tests are crucial for evaluating the potential impacts on the structural integrity and serviceability of the waste containment system, especially as the stress conditions vary with waste depth and time, throughout their operational life.

By addressing these objectives, this research aims to provide valuable insights into the mechanical properties of these promising barrier materials, thereby facilitating informed decisions regarding their suitability for waste containment applications.

3.3 Experimental Program

3.3.1 Materials used

3.3.1.1 Tailings

In this experimental study, commercially available synthetic ground silica tailings (ST) were utilized. Silica is one of the most prevalent elements in natural hard rock mine tailings (Fall et al., 2009; Kossoff et al., 2014). Unlike natural tailings, which may contain reactive minerals such as pyrite, one notable advantage of employing synthetic tailings (ST) is their absence of reactive constituents, which may interact with the bentonite and thus introduce uncertainties into test results. A comparative analysis conducted between tailings obtained from nine eastern Canadian mines and ST is presented in the form of grain size distribution curves in Figure 3-1. As illustrated in Figure 3-1, the characteristics of ST closely resemble those of tailings from Canadian mines. Approximately 40% of particles by weight have a diameter less than 20 micrometers, surpassing the threshold necessary for the development of paste tailings. Furthermore, the tailings exhibit no presence of clay particles and are primarily composed of Quartz (Table 3-2), constituting 99% of the composition (Fall et al., 2009, 2010). The physical properties of the tailings are detailed in Table 3-1, while Table 3-2 provides an overview of their chemical composition. The specific gravity of silica tailings is reported to be 2.66 (Fall et al., 2009, 2010).

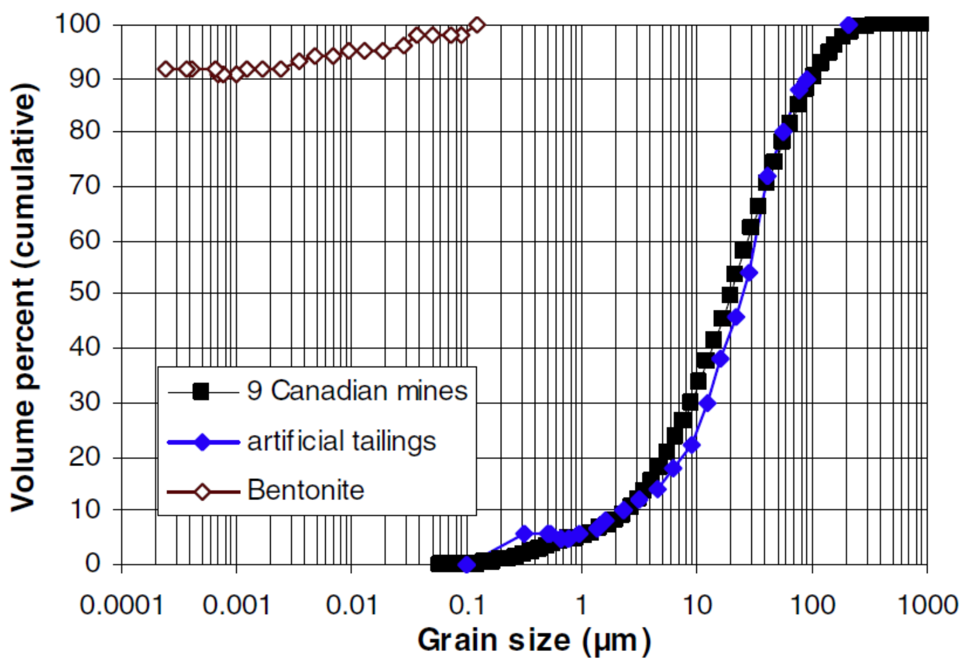


Figure 3-1: Grain size distribution curve depicting comparison between ST and natural tailings from nine Canadian mines.

Table 3-1: Physical properties of silica tailings.

Element Unit	G_s -	D_{10} μm	D_{30} μm	D_{50} μm	D_{60} μm	D_{90} μm
Si	2.7	1.9	9.0	22.5	31.5	88.9

Table 3-2: Chemical composition of silica tailings.

Element Unit	Al wt.%	Ca wt.%	Si wt.%	Fe wt.%	Na wt.%	Pb wt.%	S wt.%	K wt.%
Si	0.1	<0.01	99.8	<0.01	<0.01	0.0	0.0	0.0

3.3.1.2 Bentonite

In this study, commercially available sodium bentonite (Na-Bentonite) is used which is known to possess high swelling potential, thus being expansive in nature. Bentonites are mainly composed of smectites which have good swelling potential as they can trap water within their layers (Oy & Carlson, 2004). In addition, bentonites are already considered to possess the ability to adsorb contaminants (Mukherjee & Mishra, 2019) owing to its surface charge. The expansive nature contributes towards filling up the voids in paste tailings mixture. Owing to this property, bentonites have been extensively used in infrastructures to resist migration of fluids, especially water, through cracks that develop over the period. Figure 3-1 shows the grain size distribution curve for bentonite as well, which was determined using hydrometer test. It can be inferred from Figure 3-1 that bentonite is largely composed of clay mineral, whose percentage is 92%. The specific gravity of Na-Bentonite is 2.58 (Fall et al., 2009). Due to Sodium (Na) being the dominant exchangeable cation, the Atterberg limits are very high; i.e., extremely high liquid limit and high plastic limit. Additionally, bentonites, in general, are known to exhibit high compressive strength (Grim & Guven, 1978). The X-ray diffractogram for the bentonite represented the dominance of sodium montmorillonite mineral (smectite), over other impurities present in lesser quantities (Fall et al., 2009).

3.3.1.3 Mixing water

Distilled water was used for mixing of various samples as it helps in swelling without having adverse chemical effect.

3.3.2 Preparation of the specimens

For both consolidation and direct shear tests, BPT mixtures with different bentonite contents were prepared. The bentonite contents of 0%, 2%, 4% and 8% were selected to maintain consistency with the prior experimental study by Fall et al., (2009) that evaluated hydraulic conductivity of the same BPT mixtures. This allowed direct comparison and deeper understanding of the new proposed engineered BPT barrier material. Additionally, the selected range covers typical range of bentonite used in such engineering applications without exceeding typical design limits (Koerner & Daniel, 1997; Rowe, 2001; Vick, 1990). ST and bentonite were oven-dried separately at 60°C for three days. ST was mixed with varying proportions of bentonite, i.e., 0% (control – no bentonite content), 2%, 4% and 8%, to ensure homogeneity in the BPT mixtures. Next, distilled water was added to the oven-dried BPT batches to match their initial water content to their respective optimum moisture content (OMC). The prepared BPT mixtures were packed in air-tight polyethylene bags and allowed to hydrate for a period of 48 hours in order to reach moisture equilibrium (Fall et al., 2009). The prepared BPT mixes were statically compacted following ASTM D 698-00a for Standard Proctor to their respective maximum dry density (MDD) to prepare samples for consolidation and direct shear tests. For consolidation, a sample with a 60mm diameter and a height of 15mm was extracted; while for direct shear, the sample measured 60mm x 60mm x 16mm (L x B x H) in dimensions. Table 3-3 shows the composition, compaction characteristics (maximum dry density and optimum water content), and coefficient of permeability of the prepared BPT samples.

Table 3-3: Composition, compaction characteristics and saturated hydraulic conductivity of the prepared BPT samples.

Proportions of BPT samples and sample name	Optimum Moisture Content (OMC), W_{opt} (%)	Maximum Dry Density (MDD), $\rho_{d(max)}$ (kg/m^3)	Coefficient of Permeability, k (m/s)
0% Bentonite (control) – 0% BPT	18.2	1602	12.0 x 10^{-8}

2% Bentonite – 2% BPT	18.3	1607	7.0×10^{-10}
4% Bentonite – 4% BPT	19.3	1640	1.3×10^{-10}
8% Bentonite – 8% BPT	20.5	1610	2.0×10^{-11}

3.3.3 Testing Methods and Procedure

3.3.3.1 Consolidation Tests

A one-dimensional consolidation test was performed to understand the stress and volume change behavior under increasing load. Each sample, measuring 60mm in diameter and 15mm in height, was subjected to one-dimensional consolidation in accordance with ASTM D2345 – 03 using a fixed-ring oedometer cell, inundated with distilled water, starting with a seating load of 5kPa for 24 hours. Each loading stage was maintained for 24 hours before adding the next incremental load. Loads were applied via the loading frame with a 10:1 lever arm. Each incremental load was double the previous load and following the sequence – 5, 10, 20, 40, 80, 160, 320, 640, 1280, and 1440 kPa. Upon reaching the final loading stage of 1440 kPa, the sample underwent unloading, which was performed in reverse order. The previously added loads were sequentially reduced to half while maintaining each unloading stage for 24 hours. The sample cell was kept inundated with water until the completion of the experiment. Settlement with respect to time was recorded continuously throughout each loading and unloading stage. The void ratio at each stress level was calculated from the measured vertical deformation and initial sample geometry. Consolidation parameters were derived from the e – log P relationship, including the coefficient of volume change (m_v) for each loading increment, total consolidation settlement (S_c), and the compression index (C_c) determined from the virgin compression portion of the consolidation curve.

3.3.3.2 Direct Shear Tests

The direct shear tests were carried out on BPT samples with planar dimensions of 60mm x 60mm and a height of 16mm following ASTM D6528 – 17. The sample was carefully placed in the shear box and tightened with screws before being placed in the direct shear equipment. The upper part of the shear box remains fixed at the same position throughout the experiment, while the lower part moves at the specified strain rate allowing the sample to shear on a predetermined horizontal plane. Normal stresses of 150 kPa, 250 kPa, and 400 kPa were applied to the test samples via a loading frame with a 10:1 lever arm, and shearing was performed with a strain rate of 0.5 mm/min, consequently providing a longer test duration, up to a maximum shear strain of 12%.

For all tests, vertical and horizontal deformations were recorded during each test stage, and the failure envelope was plotted. Shear strength parameters – cohesion and internal friction angle – were calculated using the Mohr-Coulomb strength failure envelope and the following equation:

$$\tau = c + \sigma * \tan\phi \quad \text{Equation 3-1}$$

Where,

τ = Shear strength

σ = Normal stress

c = cohesion

ϕ = angle of internal friction

3.4 Results and Discussions

3.4.1 Consolidation Characteristics

3.4.1.1 Stress-Strain Behaviour

The results of consolidation tests carried out on each BPT sample are plotted in the form of effective consolidation stress versus (a) void ratio, and (b) shear strain as illustrated in Figures 3-2 and 3-3, respectively. From Figure 3-2, it can be seen that the void ratio decreases as the consolidation stress increases for all samples whether or not they contain bentonite. When the soil undergoes consolidation, the normal stress to which BPT particles are subjected increases, in addition to their self-weight, and is transferred via particle-to-particle contact. Consequently, as pressure increases, the air and water trapped in the pores are expelled, and the particles come closer to each other. As the pores become smaller, the overall void ratio declines. It is crucial to note the extent to which the initial and final void ratios differ as this governs the scale of deformation. Figure 3-2 shows that paste tailings samples without bentonite have larger void ratio, and thus, greater deformation than samples containing bentonite (up to a certain content of bentonite). Furthermore, following the initial loading stages, as the effective stresses increase, the 4% BPTs exhibit the least reduction in void ratio, followed by the 2% BPTs, whereas the 8% BPTs display the most significant decrease. This behaviour can be attributed to the formation of a double diffuse layer over bentonite particles, as a result of swelling upon coming in contact with water (Fall et al., 2009; Grim & Guven, 1978; Karnland et al., 2006; Oy & Carlson, 2004). This behavior represents the varying efficiency of bentonite content. Both, swelling of bentonite due to formation of double diffuse layer and increasing pressure work in tandem to achieve the densest possible state, thereby reducing the pore space and hence, the void ratio. However, 2% bentonite is insufficient, thus develops thin and weak double diffuse layer. The 4% bentonite develops a strong double diffuse layer effective in filling the void spaces, thereby representing optimal bentonite quantity. On the contrary, the 8% bentonite forming thicker but weaker double diffuse layer due to higher specific surface and cation exchange capacity, creating more compressible fabric. In other words, thicker DDL leads to larger swelling potential. However, at lower bentonite contents, the DDL effects are less pronounced.

Table 3-4: Initial and final void ratio of various BPT mixes.

Proportions of BPT Samples	Initial Void Ratio	Final Void Ratio	Difference in initial and final void ratios
0% Bentonite (control)	0.882	0.618	0.264
2% Bentonite	0.697	0.514	0.183
4% Bentonite	0.675	0.555	0.120
8% Bentonite	0.877	0.560	0.317

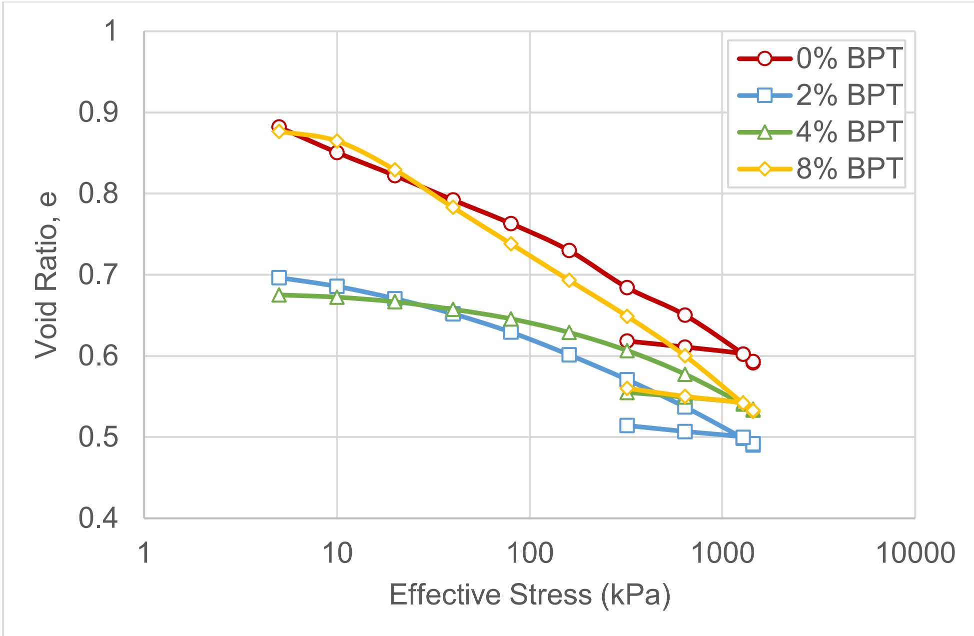


Figure 3-2: Effective consolidation stress vs void ratio.

As the effective stress increases, bentonite particles that fill up the voids are subjected to greater compressive forces. It is important to note that the 4% BPT sample exhibited time-dependent volumetric behavior during the initial loading phase, characterized by swelling that commenced approximately 2 hours following the application of the seating load and persisted for 14 hours before achieving equilibrium. Similarly, the 8% BPT sample started swelling 30 minutes after seating load application and continued swelling for the full 24-hour seating period. Since the consolidation testing procedure maintained each loading stage for 24 hours prior to applying subsequent load increments, the initial void ratios presented in the consolidation curves represent the final equilibrium conditions after the completion of transient swelling and consolidation processes. This increasing force leads to the suppression of the double-diffuse layer and the rearrangement of particles, causing them to pack more closely together (Bohnhoff et al., 2013; Fall et al., 2009; Hong et al., 2012; Vadlamudi & Mishra, 2018). Consequently, the void spaces between particles decrease, resulting in a reduction in void ratio. In the 4% BPT samples, particles are very densely packed and the double-diffuse layer formed is very strong, which counteracts the interparticle compressive forces. Therefore, the reduction in void ratio occurs at a slower rate and is less significant compared to other samples. This is also evidenced by the values of maximum initial dry density presented in Table 3-3. On the contrary, due to excessive bentonite content in the 8% BPT mix, the swelling potential dominates over interparticle forces (Karnland et al., 2006). Therefore, an increase in the differential void ratio is observed, as shown in Table 3-4. Table 3-4 provides a comparative analysis of various BPT mixes by comparing the difference in void ratio changes over the span of the consolidation experiment. The initial void ratio in Table 3-4 are representative of the post-saturation and swelling state under minimal seating load (5 kPa) rather than the as-compacted dry state used in theoretical calculations. Therefore, the transition from partially saturated state achieved at OMC to fully saturated conditions fundamentally alters the stress state allowing unrestrained volumetric expansion under minimal seating load. From Table 3-4, we notice a similarity in the experimentally measured void ratios of the 0% BPT (control) and 8% BPT sample despite their contrasting behavior. This behavior can be attributed their different physical mechanisms. The 0% BPT samples exhibits a higher initial void ratio owing to its loose packing efficiency, lack of cohesion, and the angular shape of the ST particles. Conversely, higher initial void ratio in 8% BPT sample is arises from swelling-induced volumetric expansion upon formation of a thicker double-diffuse layer that exceed the restraining capacity of the minimal seating load, pushing the particles further away. Therefore, while the initial void ratios for 0% and 8% BPT samples are similar to each other, they result from distinct physical processes – low packing efficiency for 0% BPT sample, and swelling-induced expansion for 8% BPT sample – capturing the effect of different microstructure.

Increasing effective stress also leads to the deformation of a sample, which can be measured in terms of strain. It is worth noting that the one-dimensional consolidation test setup constrains lateral deformation through rigid confining rings, therefore the measured strains are primarily vertical (deformation) strains. The consolidation behavior observed reflects volumetric compression under one-dimensional loading conditions, which is representative of field conditions where lateral expansion is restricted by surrounding materials. Densely packed structures reduce the ability of the paste tailings mixture to undergo deformation. Figure 3-3 shows that paste tailings samples without bentonite undergo larger deformation compared to samples containing bentonite. This follows from the fact that silica tailings are granular and naturally exist in a loose state. With an increase in effective stress, the particles rearrange themselves to a considerable extent to achieve the densest possible state. With the addition of bentonite, the bentonite fills the pores between silica particles, providing greater strength to resist the applied stress. Furthermore, Figure 3-3 depicts that among the bentonite-inclusive samples, the 4% BPT mix offers the highest resistance towards strain under increasing consolidation stress as compared to the 2% and 8% BPT samples. Particle size distribution plays a major role in influencing strain behaviour. Figure 3-3 indicates that the particle size distribution in the 2% and 8% BPT samples are similar to each other during the initial stages. However, excess bentonite in 8% BPT mixture attracts more water, leading to the formation of a thicker double-diffuse layer. This excess bentonite also weakens the double-diffuse layer due to the weaker bond between bentonite and tailings particles. Therefore, efficient particle size distribution and a stronger double-diffuse layer provide the 4% BPT sample with much greater resistance against vertical deformation (strain).

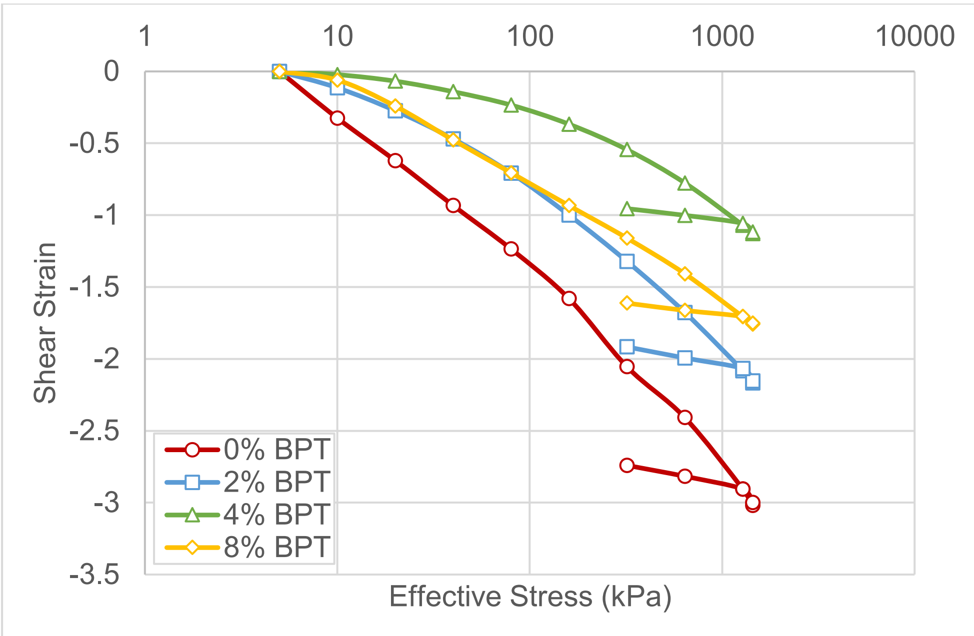


Figure 3-3: Effective consolidation stress vs strain.

3.4.1.2 Coefficients of Volume Change and Compressibility

The trends in volume change and compressibility coefficients are important for further validating and strengthening the results obtained from void ratio and strain. This relationship is represented by the coefficients of (a) volume change, and (b) compressibility as functions of effective consolidation stress during the loading stage, as shown in Figures 3-4 and 3-5, respectively. The coefficient of volume change curves generally exhibits a consistent declining trend across all samples. However, mixtures without bentonite show a more pronounced reduction in volume as compared to those containing bentonite. The extent of volume change in a sample depends on the compactness of its particle arrangement. The control mixture (i.e., 0% BPT) represents a loose particle arrangement, resulting in a sharp decline in volume change. The 2% BPT shows a similar but less pronounced behavior due to the small quantity of bentonite present. In the case of 4% BPT, the volume change is heavily restrained due to its densely packed structure and the formation of a strong double-diffuse layer, leading to a relatively flat curve. However, when the bentonite content increases beyond 4%, the initial behavior is governed by its high swelling potential. This is evident in the 8% BPT mixture, which initially swells, showing an increase in volume under the applied seating load. Since the specimen is inundated with water, the electrically charged surface of Na-bentonite adsorbs water and expands until the voids are fully saturated. Swelling occurs due to formation of a diffuse-double layer on negatively charged hydrophilic bentonite particles (Fall et al., 2009; Vadlamudi & Mishra, 2018). The Na-bentonite used in the experiment develops a thicker double-diffuse layer as compared to Ca-bentonites (Yang et al., 2018). The hydrophilic nature is accounted towards the mineralogy of bentonite (Zelić, 2013). As soon as the load greater than the swelling pressure is applied, the volume change behaviour normalizes, as the weak double-diffused layer is easily compressed.

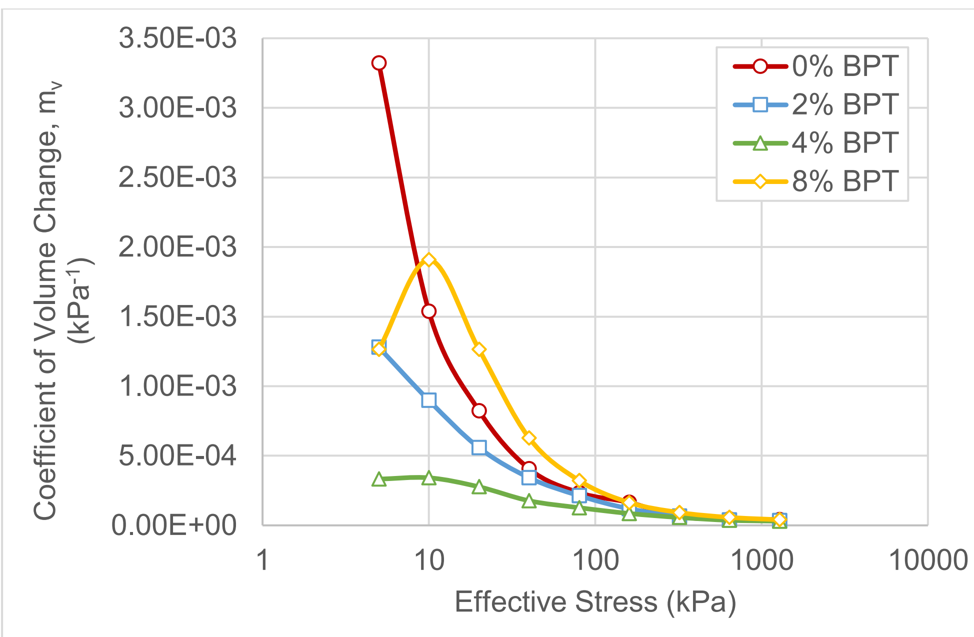


Figure 3-4: Coefficient of volume change as a function of effective consolidation stress during loading.

The coefficient of compressibility shows a similar trend with increasing effective stress. Regardless of the presence of bentonite, the coefficient of compressibility initially decreases and then stagnates toward the end of loading. During the stagnation phase, the samples do not show any notable change, indicating that the sample has reached a state of equilibrium by achieving their densest possible particle rearrangement where the response to increasing stress has almost stabilized. The curves from Figure 3-5 shows a sharp decline in compressibility of the 0% BPT as effective stress increases due to particle rearrangement. In samples containing bentonite, the sample with 2% bentonite content provides minimal improvement due to insufficient bonding between ST and bentonite and less pronounced effect of DDL, while sample with 4% bentonite content achieves optimal performance through efficient filling of voids and formation of strong and unbreakable DDL layer. The 4% BPT mix demonstrates the maximum resistance, which is evidenced by the relatively flat curve and the lower compressibility values. In contrast, at higher bentonite contents, such as in 8% BPT sample, thicker DDL result in larger swelling potential and reduced structural integrity, therefore, resulting in higher compressibility despite increased bentonite content.

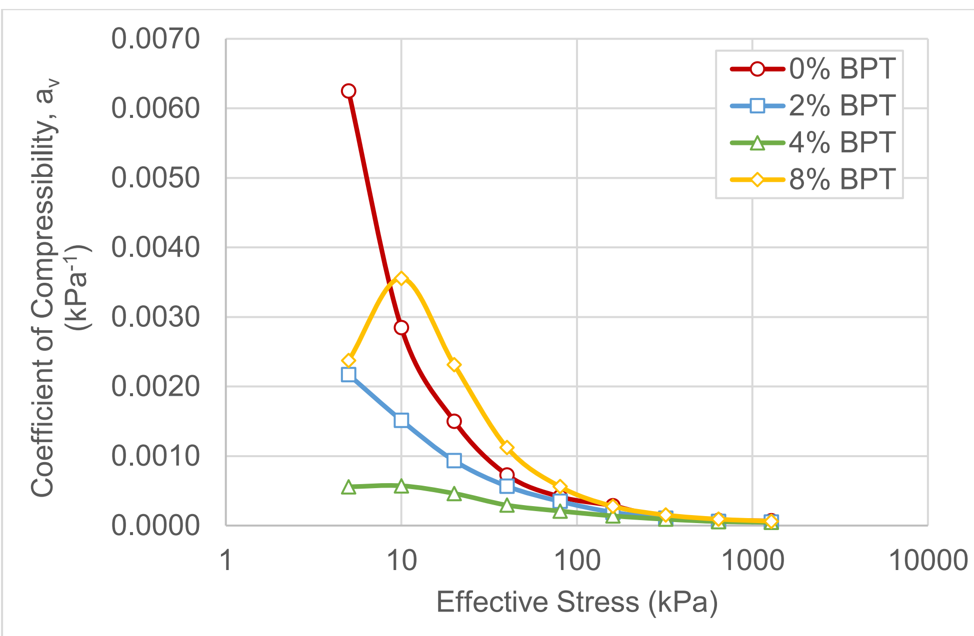


Figure 3-5: Coefficient of compressibility as a function of effective consolidation stress during loading.

Tables 3-5 to 3-8 lists the calculated values of coefficient of volume change (m_v), coefficient of compressibility (a_v), consolidation settlement (S_c), and compression index (C_c), respectively, for the various BPT mixtures. These compressibility parameters were determined by assuming the e – logP curve to be piecewise linear wherein slope corresponding to each stress increment was calculated. This methodology accounts for stress-dependent compressibility characteristics providing enhanced accuracy for predicting consolidation behavior under varying stress levels. It is evident that adding bentonite up to a certain proportion prevents the structure from breaking down easily upon the application of load, reducing the compression index and providing a longer duration for the specimen to consolidate (Bohnhoff & Shackelford, 2014; Sinha, 1998; Vadlamudi & Mishra, 2018).

Table 3-5: Comparison between coefficient of volume change, m_v, for various proportions of Bentonite corresponding to each stress increment.

Effective Stress (kPa)	Coefficient of volume change, m_v (kPa^{-1})			
	0% BPT	2% BPT	4% BPT	8% BPT
5	3.321E-03	1.280E-03	3.325E-04	1.263E-03
10	1.538E-03	8.979E-04	3.419E-04	1.907E-03
20	8.240E-04	5.582E-04	2.771E-04	1.265E-03
40	4.067E-04	3.424E-04	1.769E-04	6.284E-04
80	2.352E-04	2.135E-04	1.269E-04	3.223E-04
160	1.646E-04	1.193E-04	8.549E-05	1.638E-04
320	6.317E-05	6.721E-05	5.674E-05	9.234E-05
640	4.530E-05	3.916E-05	3.659E-05	5.731E-05
1280	4.222E-05	3.379E-05	3.033E-05	4.045E-05

Table 3-6: Comparison between coefficient of compressibility, a_v, for various proportions of Bentonite corresponding to each stress increment.

Effective Stress (kPa)	Coefficient of compressibility, a_v (kPa^{-1})			
	0% BPT	2% BPT	4% BPT	8% BPT
5	0.00625	0.00217	0.00056	0.00237
10	0.00285	0.00151	0.00057	0.00356

20	0.00150	0.00093	0.00046	0.00231
40	0.00073	0.00057	0.00029	0.00112
80	0.00041	0.00035	0.00021	0.00056
160	0.00028	0.00019	0.00014	0.00028
320	0.00011	0.00011	0.00009	0.00015
640	0.00007	0.00006	0.00006	0.00009
1280	0.00007	0.00005	0.00005	0.00006

Table 3-7: Comparison between consolidation settlement, S_c, for various proportions of Bentonite corresponding to each stress increment.

Effective Stress (kPa)	Consolidation Settlement, S_c (mm)			
	0% BPT	2% BPT	4% BPT	8% BPT
5	0.249	0.096	0.025	0.095
10	0.231	0.135	0.051	0.286
20	0.247	0.167	0.083	0.379
40	0.244	0.205	0.106	0.377
80	0.282	0.256	0.152	0.387
160	0.395	0.286	0.205	0.393
320	0.303	0.323	0.272	0.443
640	0.435	0.376	0.351	0.550
1280	0.101	0.081	0.073	0.097

Table 3-8: Comparison between compression index, C_c, for various proportions of Bentonite corresponding to each stress increment

Effective Stress (kPa)	Compression Index, C_c			
	0% BPT	2% BPT	4% BPT	8% BPT
5	0.104	0.036	0.009	0.039
10	0.095	0.050	0.019	0.118
20	0.100	0.062	0.031	0.154
40	0.097	0.075	0.039	0.149
80	0.110	0.092	0.056	0.149

160	0.151	0.102	0.074	0.147
320	0.113	0.112	0.097	0.162
640	0.159	0.128	0.123	0.195
1280	0.212	0.158	0.146	0.195

3.4.1.3 Coefficient of consolidation

Time-rate of settlement analysis were determined by computing the coefficient of consolidation, C_v, using both Taylor's square root of time method as well as Casagrande's logarithm-of-time method for various stress incremental stages. Table 3-9 and 3-10 summarizes the C_v values, and Figures 3-6 and 3-7 illustrates the coefficient of consolidation as a function of effective stress during the loading stage obtained from both Taylor's and Casagrande's methods, respectively.

Table 3-9: Coefficient of consolidation based on Taylor's method for various proportions of BPT samples.

Effective Stress (kPa)	Taylor's Coefficient of Consolidation, $C_{v\ (Taylor)}$			
	0% BPT	2% BPT	4% BPT	8% BPT
10	1.211E-08	1.153E-06	1.464E-07	4.375E-08
20	4.947E-09	3.324E-07	1.616E-07	1.133E-08
40	1.711E-08	4.500E-07	7.188E-07	2.301E-08
80	5.318E-08	6.412E-07	1.163E-07	2.490E-08
160	1.058E-07	1.988E-07	7.385E-07	9.340E-08
320	7.877E-08	1.851E-07	6.232E-07	1.855E-07
640	1.662E-07	5.835E-07	3.953E-07	2.137E-07
1280	2.028E-08	2.170E-07	5.565E-07	2.041E-07

Table 3-10: Coefficient of consolidation based on Casagrande's method for various proportions of BPT samples

Effective Stress (kPa)	Casagrande's Coefficient of Consolidation, $C_{v\,(Casagrande)}$			
	0% BPT	2% BPT	4% BPT	8% BPT
10	7.000E-10	1.517E-08	8.314E-09	5.702E-09
20	9.070E-10	1.347E-08	5.517E-09	2.186E-09
40	1.532E-09	1.749E-08	6.680E-09	3.687E-09
80	2.278E-09	1.099E-08	6.921E-09	6.555E-09
160	2.223E-09	7.859E-09	7.625E-09	1.037E-08
320	4.428E-10	5.782E-09	5.840E-09	1.091E-08
640	4.191E-09	6.485E-09	6.716E-09	1.067E-08
1280	4.028E-09	4.604E-09	5.508E-09	1.103E-08

Tables 3-9 and 3-10 indicate that, in general, the value of C_v derived from the Taylor approach is higher than that derived from the Casagrande method. A similar observation was noted by Bohnhoff & Shackelford, (2014).

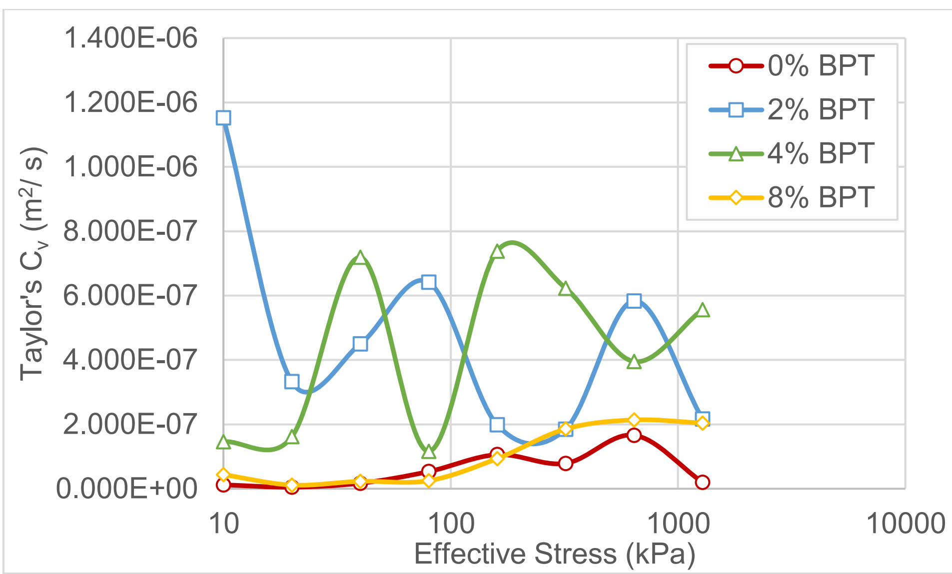


Figure 3-6: Coefficient of consolidation based on Taylor's method as a function of effective stress during the loading stage.

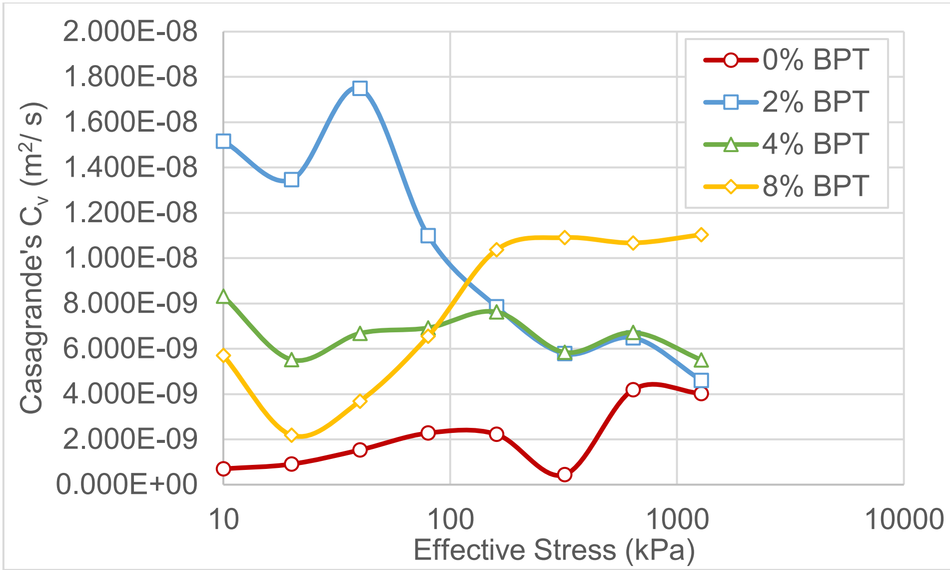


Figure 3-7: Coefficient of consolidation based on Casagrande's method as a function of effective stress during the loading stage.

It can be seen from Figures 3-6 and 3-7 that pure paste tailings exhibit poor consolidation performance indicating severe structural instability. This behavior is attributable to its granular structure and low packing efficiency which makes it prone to sudden and greater particle rearrangement under increasing stress conditions. Contrastingly, addition of bentonite to paste tailings fundamentally alters the consolidation behavior enhancing consolidation efficiency and making it more predictable. This enhance occurs as a result of effective rearrangement of paste tailings matrix as bentonite occupies the voids spaces between the ST particles. Additionally, the bentonite mineralogy plays a crucial role as it governs it high cation exchange capacity and high swelling potential, leading to formation of double diffuse layer further minimizing the void spaces, and providing structural stability.

The 2% BPT mixture demonstrates rapid consolidation at low pressure with exceptionally high C_v values according to Casagrande method. However, this mixture exhibits a clear trend of decreasing consolidation efficiency as the applied pressure is increased indicating that even small amount of bentonite improves particle interaction. The 4% BPT mixtures represents the optimal composition, exhibiting the most stable and consistent consolidation behavior across all stress levels with Casagrande's method. This behavior indicates that this concentration of bentonite (4%) provides adequate structural stability and a robust microstructure. Conversely, the 8% BPT mixture shows significant degradation in performance and with notable variability in C_v values according to Taylor's method, and extended consolidation period at low stress levels according to Casagrande's method. This behavior indicates a threshold effect after which the swelling potential of bentonite dominates the consolidation behavior.

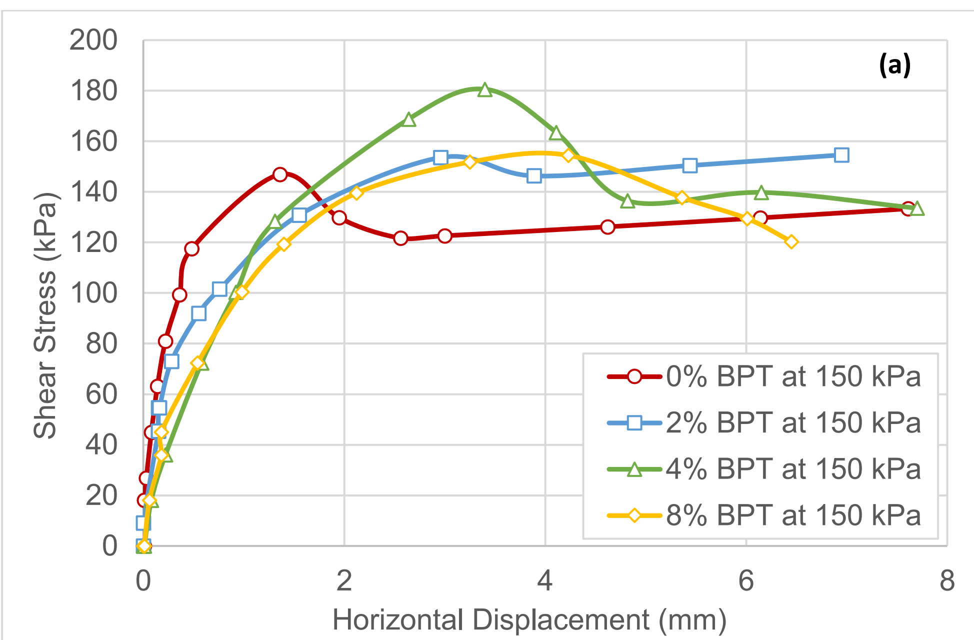
3.4.2 Shear Characteristics

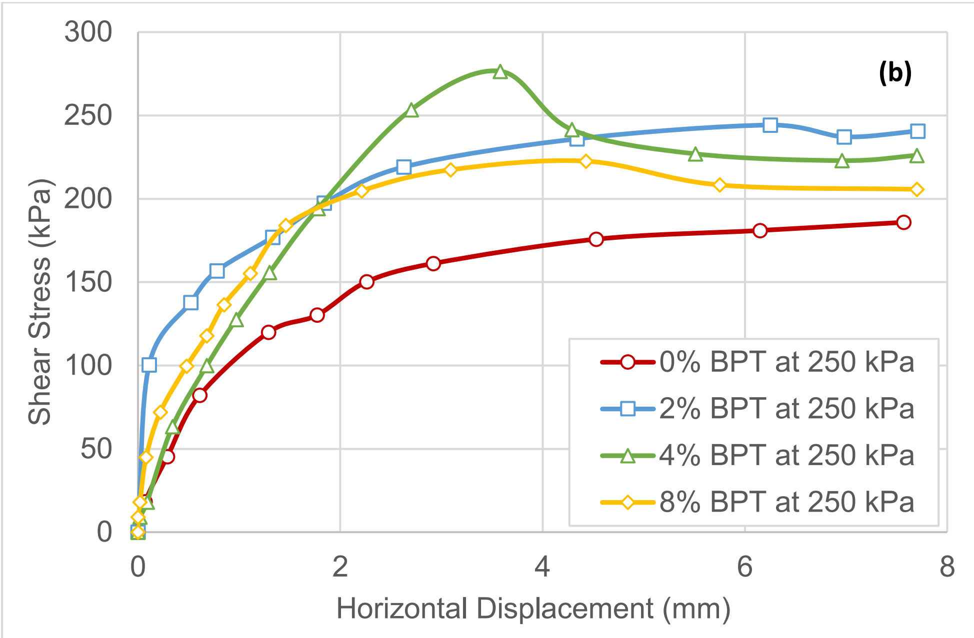
3.4.2.1 Shear stress and displacement relationships

The barriers in waste impoundments can be subjected to high pressures, with shear stresses increasing significantly on sloped terrains, potentially compromising their performance. Therefore, investigating and determining the shear strength and its characteristics for the proposed barrier system is critical for evaluating its ability to resist sliding and deformation under heavy stresses, ensuring structural stability and long-term performance in waste containment facilities under these loading conditions. The results of the direct shear tests for various BPT mixes are presented as relationships between horizontal displacement and (a) shear stress, and (b) vertical displacement, corresponding to normal stresses of 150 kPa, 250 kPa, and 400 kPa, as illustrated in Figures 3-8 and 3-9, respectively. A summary of the peak stresses obtained from the direct shear tests is provided in Table 3-11 and plotted in Figure 3-10.

Figure 3-8 shows a consistent pattern across all samples. As normal stress increases, the contact area and frictional resistance between the particles also increase, facilitating particle rearrangement. Therefore, it can be observed that the peak stress increases with an increase in normal stress, regardless of whether the samples contain bentonite. However, the introduction of bentonite greatly influences the shear behavior of the samples in terms of achieving peak shear stress and post-failure softening behavior. Samples with bentonite initially display a strain-hardening behavior (upward slope) up to the point of peak stress, followed by strain-softening behavior (downward slope) once the sample has failed in shear. In contrast, the shear stress in samples without bentonite increases gradually with horizontal displacement until its maximum stress is reached, after which it either decreases in case of a normal stress of 150 kPa or remains constant for a normal stress of 250 kPa or greater. It can be inferred that the sample without bentonite (0% BPT) did not display any sign of post-failure strain-softening for normal stresses equal to or greater than 250 kPa. Furthermore, peak stress observed in 0% BPT across all normal stresses was lower than in samples containing bentonite. This behavior can be attributed to the granular nature of the tailings, its low maximum dry density, and its larger void ratio. The bentonite, upon addition, occupies the space between the pores to reduce the void ratio and increase the overall performance.

The curves also depict whether the samples are in a loose or dense state. In dense samples, the shear stress initially increases with horizontal displacement as a result of elastic deformation and reaches a peak before decreasing (Dafalla, 2013). This can be witnessed in case of 4% BPT mixture. This is further validated by its highest maximum dry density as indicated in Table 3-3. The quantity of bentonite in this mixture optimally occupies the voids between silica tailings and swells with a strong double-diffuse layer, providing a dense particle arrangement and greater strength in resisting higher normal loads. On the contrary, the 8% BPT mix shows excessive initial swelling, lowering its density. In addition, the double-diffuse layer is weak, making it more susceptible to breaking upon constant loading. Consequently, lower peak stresses are achieved even after attaining a dense state. Moreover, the bentonite quantity in the 2% BPT mix is not sufficient to achieve a dense state which can resist constant loading, thereby impacting its shear behavior. From this, we can infer that a certain threshold quantity of bentonite is responsible for greater strength characteristics. Any quantity of bentonite above or below this threshold value does not have the ability to resist shear under elastic deformation and is unable to provide better strength characteristics which can thus affect the performance of the barrier material.





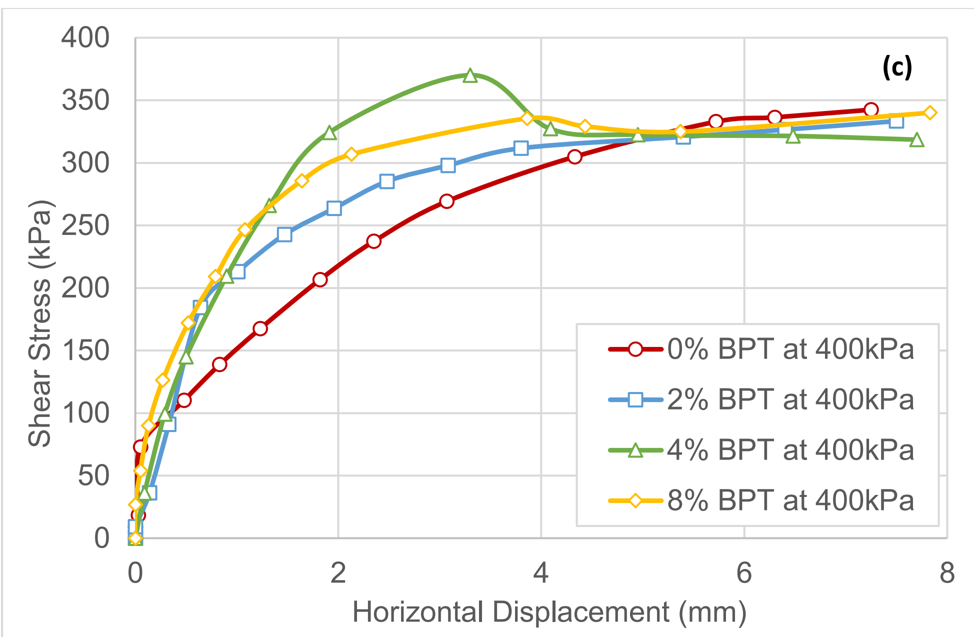
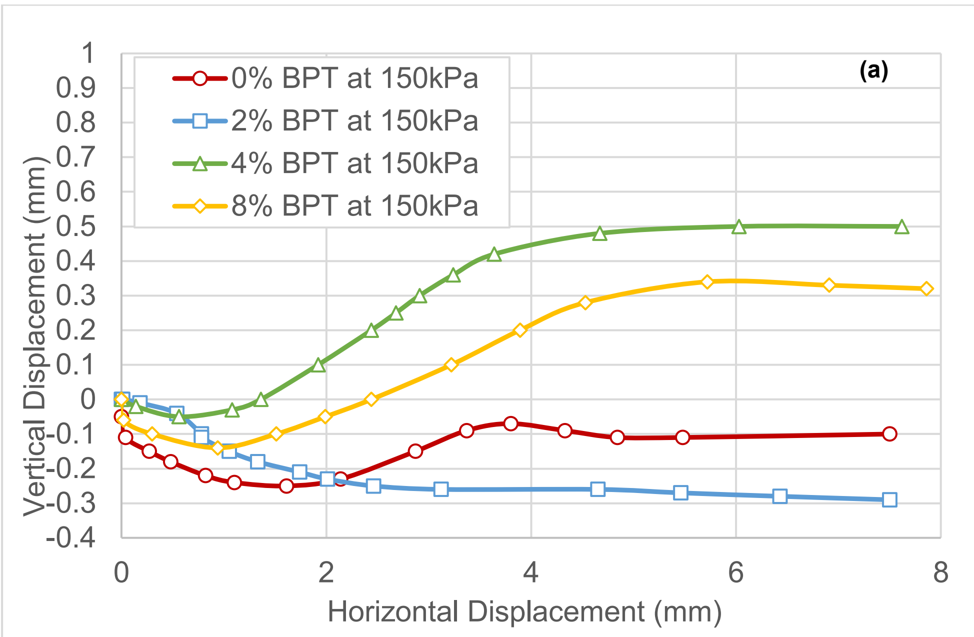
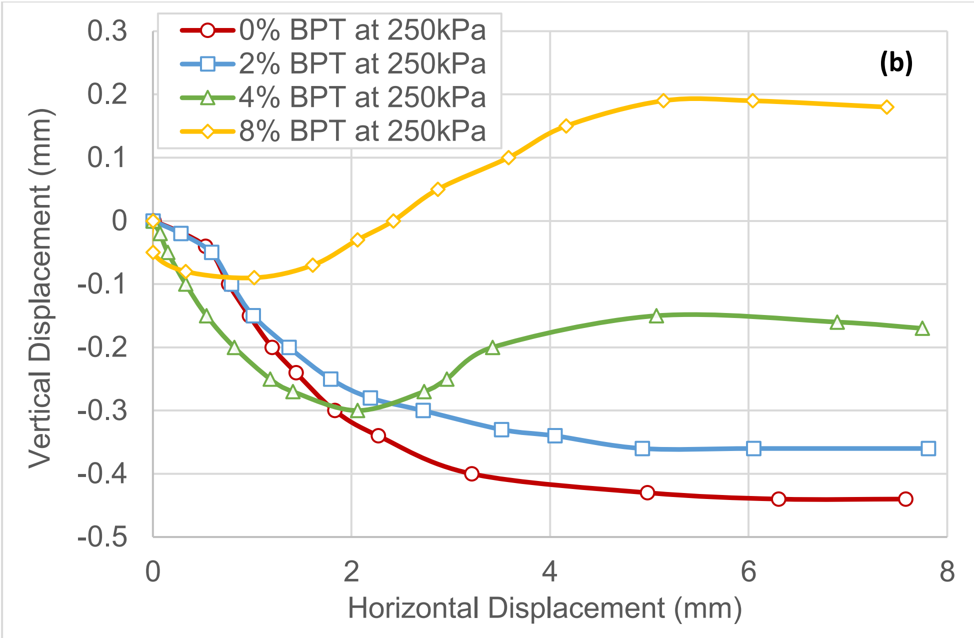


Figure 3-8: Horizontal Deformation vs Shear Stress at (a) 150 kPa, (b) 250 kPa, and (c) 400 kPa.

The observations from Figure 3-8 are in line with the curves illustrated in Figure 3-9, representing vertical deformation as a function of horizontal deformation under normal stresses of 150, 250, and 400 kPa for varying BPT mixtures. Samples without bentonite generally experience only contractive behavior, which is representative of their loose state. This is largely due to their lower dry density and particle size distribution, which results in a failure of interlocking within granular silica tailings particles. On the contrary, samples with bentonite first show a contractive behavior owing to the compressibility of mixtures, followed by subsequent dilation, which diminishes when the normal stress is increased. The dilation is prominently visible in tailings mixed with 4% and 8% bentonite, indicative of their dense state.





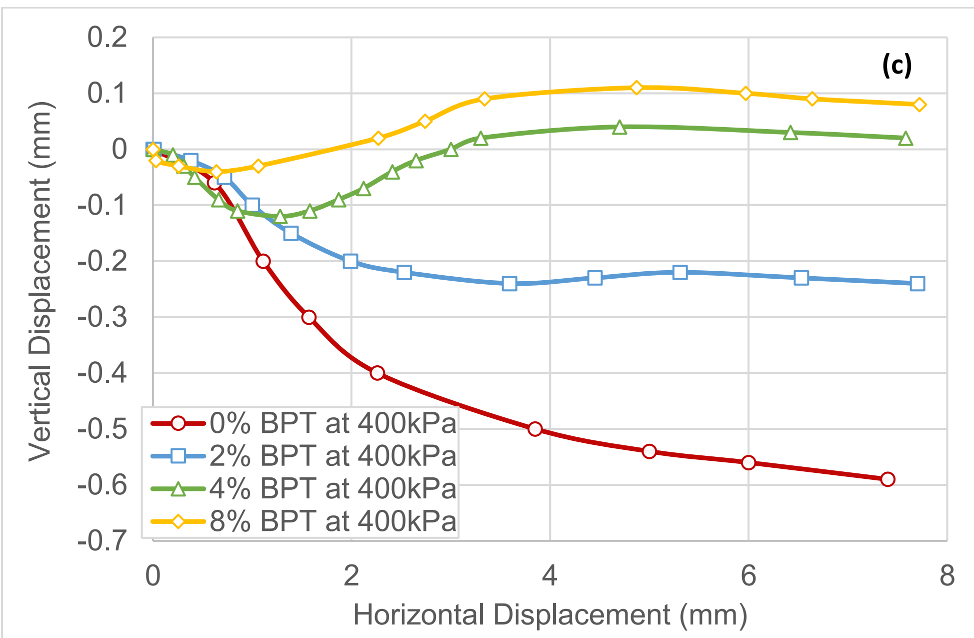


Figure 3-9: Horizontal vs. Vertical Deformation at (a) 150 kPa, (b) 250 kPa and (c) 400 kPa.

3.4.2.2 Shear strength parameters

The peak shear stress values obtained from Figure 3-8 are used to derive the Mohr-Coulomb failure envelope, as illustrated in Figure 3-10. The plot demonstrates a linear relationship with increasing normal stress. These peak shear stress values, listed in Table 3-11, show a consistent increase with rising normal stress across all mixtures, irrespective of the presence of bentonite. The results imply that samples without bentonite (0% BPT) have the lowest peak stress values across the entire normal stress range. This is an indicator of the non-cohesive nature of the granular ST. On the other hand, the highest peak stress across the entire normal stress range is exhibited by 4% BPT, primarily due to its ability to fill the voids effectively and the formation of a resilient double-diffuse layer, further facilitating strong interparticle bonding between ST and bentonite.

Table 3-11: Summary of direst shear tests.

Normal Stress (kPa)	Peak Shear Stress, τ (kPa)			
	0% BPT	2% BPT	4% BPT	8% BPT
150	146.928	153.580	180.619	154.427
250	183.396	244.219	276.537	222.578
400	336.330	348.120	370.092	335.473

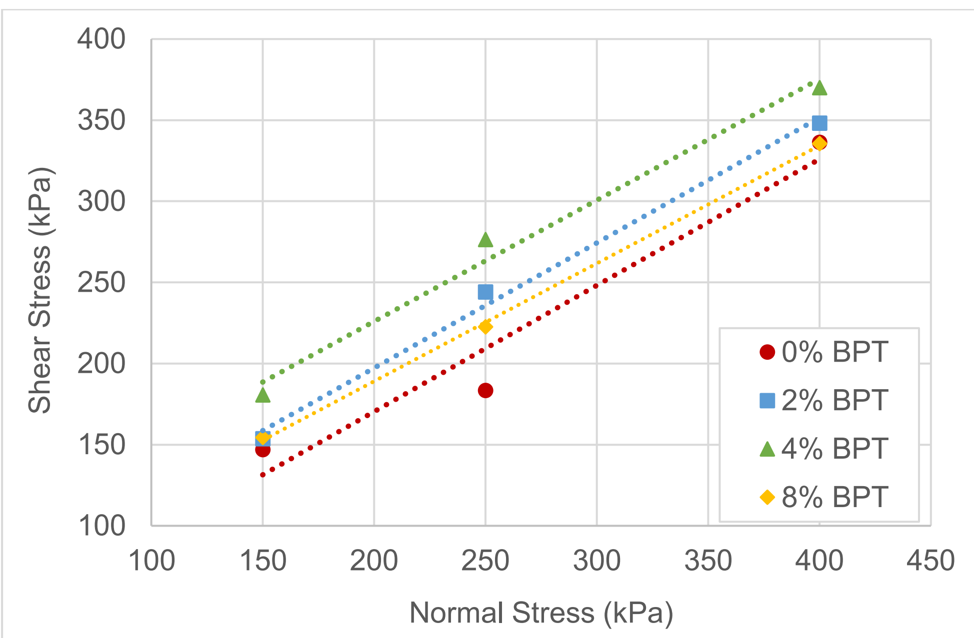


Figure 3-10: Failure Envelope for BPT proportions at various peak stresses.

Furthermore, it is important to assess the relative contribution of shear strength parameters – cohesion and angle of internal friction – which govern the strength characteristics of different mixes. The relationship between these parameters and varying bentonite content in compacted paste-tailings mixtures is illustrated in Figure 3-11 and summarized in Table 3-12. Figure 3-11 reveals that the angle of friction decreases as bentonite content increases, whereas cohesion increases with bentonite content up to 4%, before decreasing with further additions. Additionally, as cohesion increases with bentonite content (up to 4%), the angle of friction simultaneously decreases (Xiang et al., 2021). Beyond 4% bentonite, both cohesion and the angle of friction decline. The reduction in the angle of friction at higher bentonite contents can be attributed to the swelling of clay particles, which pushes the tailings grains farther apart, reducing interparticle friction and thereby decreasing the friction angle.

It can be seen from Figure 3-11 that strength of a sample without bentonite is primarily governed by the angle of friction, as it lacks cohesion and interparticle bonding due to its granular nature. Introducing a small amount of bentonite, as in the case of 2% BPT, increases its cohesiveness slightly by filling the voids and reduces the frictional resistance. This is seen in the increase in cohesion and the decrease in the friction angle. The 4% BPT mix represents the strongest correlation between the shear strength parameters. At this proportion, the property of the mixture is defined by bentonite. This quantity of bentonite helps in building a strong matrix by efficiently filling the voids and developing a strong double-diffuse layer. The interparticle friction is limited. This characteristic makes compacted paste-tailings with 4% bentonite the most mechanically resistant, making it a more suitable barrier material than other BPT mixtures in terms of sliding resistance. When the content of bentonite is increased beyond 4%, the double-diffuse layer weakens as a result of excess water adsorption. The thicker double-diffuse layer pushes the particles away, thus reducing both cohesiveness and the angle of friction. Therefore, we can infer that presence of bentonite, up to a certain proportion, has direct correlation with the BPT shear strength performance parameters.

Table 3-12: Shear strength parameters for different BPT samples.

Proportions of BPT Samples	Cohesion (kPa)	Angle of friction (degrees)
0% Bentonite (control)	4.7	37.9
2% Bentonite	42.9	37.6
4% Bentonite	76.5	36.8

8% Bentonite	43.8	36.0

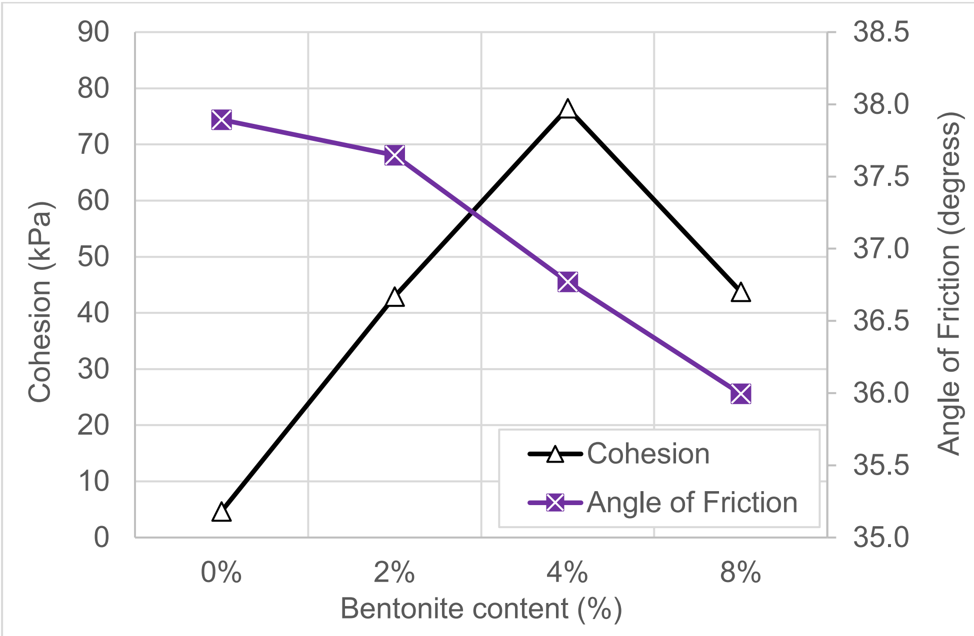


Figure 3-11: Cohesion and Friction Angle for BPT proportions.

3.5 Summary and Conclusion

This study provides critical insights into the mechanical behavior of compacted paste tailings with varying bentonite content (0%, 2%, 4%, and 8%) as potential barrier materials for waste containment facilities. The findings indicate that the inclusion of bentonite significantly enhances the mechanical performance of the mixtures, particularly in terms of consolidation behavior and shear strength characteristics. Among the tested compositions, the 4% BPT mix demonstrated optimal performance, exhibiting the highest resistance to compressibility and deformation, minimal volume change, and superior shear strength parameters.

The findings highlight the role of bentonite in filling voids and forming a strong double-diffuse layer, which enhances interparticle bonding and overall material strength. However, excessive bentonite (8%) leads to reduced performance due to excessive swelling and weaker particle bonds. Conversely, the absence or insufficient inclusion of bentonite (0% and 2%) results in lower shear strength and higher compressibility, rendering those mixes less suitable for barrier applications. The findings underscore the importance of optimizing bentonite content to balance swelling potential and mechanical stability, ensuring the structural integrity of barriers under heavy stress.

By establishing the mechanical behavior of BPT mixtures under consolidation and shear stresses, this study confirms the viability of 4% BPT as a superior material for liners and covers in waste containment systems. These findings align with previous research and contribute to advancing the sustainable management of tailings and waste materials in mining and environmental engineering.

While this study establishes a foundation for understanding BPT mechanical behavior, further research is recommended to: (i) investigate the long-term mechanical behaviour and properties of the proposed BPT barriers under cyclic environmental conditions, such as freeze-thaw and wet-dry cycles. (ii) assess the mechanical and hydraulic performance of the BPT barriers in diverse contaminant environments to ensure reliability under varying chemical exposures.

Data availability

Some or all data used are available from the corresponding author by request.

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4 Chapter 4: Technical Paper II – Drying-Induced Desiccation Cracking Behaviour of Bentonite-Paste Tailings Barrier Materials for Waste Containment Facilities

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(submitted)

4.1 Abstract

The effectiveness of waste containment facilities depends on barrier systems like liners and covers that prevent contaminant migration. However, desiccation cracks can undermine their performance by creating preferential flow paths. Compacted bentonite-paste tailings (BPT) mixtures have been recently proposed as novel alternative liner and cover materials due to their low hydraulic conductivity and favorable mechanical properties, but their susceptibility to desiccation cracking remains unexplored, leaving a critical knowledge gap. This study examines the desiccation cracking behavior of compacted BPT mixtures with 0%, 2%, 4%, and 8% bentonite under controlled drying conditions. Digital image processing (ImageJ) was used to analyze surface crack ratio, crack geometry, total crack length, and crack propagation velocity. Results show that all BPT mixtures develop cracks upon moisture loss, with crack extent and network expansion increasing with bentonite content. Cracks appear earlier in bentonite-containing samples due to its high swelling and shrinkage properties. These findings provide key insights into the cracking susceptibility of BPT barrier systems, highlighting the need for further optimization to enhance their long-term durability and performance in waste containment applications. The study contributes to the broader field of clay-based engineered barriers and supports the development of more resilient waste containment solutions.

Keywords: Tailings; desiccation crack; image processing; liner; cover; bentonite; waste containment.

4.2 Introduction

Waste containment facilities are designed to safely store and isolate hazardous waste that could contaminate the surrounding environment. Barriers, such as liners or covers, are commonly used in a waste containment facility to contain this waste in a sustainable and long-term manner. They act as impermeable layers capable of restricting the accessibility of fluids at underground levels, minimizing external infiltration and preventing gas emissions (Booker et al., 2004). The main types of waste containment facilities that require liners and covers for environmental protection include landfills, mine waste storage (waste rock, tailings) facilities. Landfills are used for municipal, industrial, and hazardous waste disposal, where liners prevent leachate from contaminating groundwater, while covers minimize infiltration and gas emissions (Booker et al., 2004). Mine waste repositories store overburden and waste rock, requiring barriers to control acid mine drainage and heavy metal leaching (Yilmaz and Fall, 2017). Tailings storage facilities contain finely ground waste from mineral processing, where liners and covers help manage seepage, prevent toxic leachate migration, avoid acid mine drainage development, and reduce water loss for sustainable waste management (Sharma and Al-Busaidi, 2001).

The effectiveness of these barrier systems depends on their structural integrity, which is largely determined by their mechanical properties and hydraulic performance. One of the primary challenges in maintaining their integrity is crack formation in liners and covers. Cracks create preferential flow paths, allowing contaminants to seep into the subsurface, increasing leachate production, and compromising the long-term effectiveness of the containment system. This can lead to groundwater and soil contamination, posing significant environmental and health risks. Additionally, structural degradation from cracks increases the risk of barrier failure, leading to prolonged pollution. In mine waste containment facilities, cracks can also allow water and oxygen infiltration, accelerating the oxidation of sulfide minerals such as pyrite. This oxidation process generates sulfuric acid, which leaches heavy metals from waste materials, resulting in acid mine drainage (AMD). If left uncontrolled, AMD can contaminate surface, groundwater and soils, causing severe environmental and ecological damage (Aldhafeeri and Fall, 2017).

Desiccation is one of the primary mechanisms leading to crack formation in liners and covers of waste containment facilities. In practice, desiccation cracks commonly develop due to prolonged exposure to drying and wetting cycles. When clay-based liners or covers lose moisture during dry periods, they shrink, generating tensile stresses that, if exceeding the material's tensile strength, result in crack formation and propagation (Chaduvula et al., 2017). This process significantly weakens the mechanical properties of the barrier, such as shear strength and compressibility, compromising its structural stability and integrity (Chaduvula et al., 2017; Julina & Thyagaraj, 2020; Safari et al., 2014; Tang et al., 2008, 2011, 2012; Tian et al., 2022; Wei et al., 2020). Moreover, the presence of desiccation cracks substantially increases hydraulic conductivity, creating preferential pathways for contaminant transport and release, thereby reducing the effectiveness of the barrier system (Albrecht & Benson, 2001; Li et al., 2016; Tang et al., 2012; Tian et al., 2022). If left exposed for extended periods before waste placement, cracks can widen and deepen, further deteriorating the liner’s ability to contain contaminants (Safari et al., 2014). In extreme cases, crack-induced weakening at slopes can lead to the ultimate failure of waste containment facilities (Tang et al., 2008). In other words, a comprehensive understanding of desiccation crack formation is crucial for ensuring the long-term integrity and stability of waste containment systems.

In recent years, a novel approach to sustainable tailings management has emerged, focusing on recycling paste tailings into barrier materials for waste containment (Fall et al., 2009). Research by Fall et al. (2009) demonstrated that compacted paste tailings-bentonite mixtures (BPT)—formed by mixing paste tailings with various amounts of bentonite and then compacting them—can achieve hydraulic conductivity values below the required threshold for liner or cover design. This indicates that BPT has the potential to serve as an effective liner or cover material for waste containment facilities. Additionally, studies by Abhinav and Fall (2024) found that BPT with 4% bentonite exhibits the best mechanical performance, showing minimal volume change, low compression index, reduced settlement, and higher shear strength. However, the desiccation cracking behavior of BPT barriers remains unknown, and no studies have addressed this critical knowledge gap. Given the significance of crack formation in determining the long-term performance and integrity of waste containment barriers, it is essential to investigate this phenomenon to ensure the safe implementation of BPT technology.

This study experimentally assesses the drying-induced desiccation cracking behavior of BPT with varying bentonite content (0% (control), 2%, 4%, and 8%) under controlled laboratory conditions simulating natural wind. The ImageJ processing tool was utilized to analyze desiccation cracks and evaluate their geometric characteristics. Specifically, this study examines: (i) surface crack ratio (crack intensity factor); (ii) crack geometry and total crack length; and (iii) crack propagation velocity. Understanding the mechanisms of crack development will provide insights into how cracks expand over time in BPT due to moisture loss, which will contribute to the successful implementation of the BPT barrier technology in practice.

4.3 Experimental Program

4.3.1 Materials used

4.3.1.1 Tailings

Quartz is one of the most frequently observed minerals in natural tailings from hard rock mines (Fall et al., 2009, 2010; Kossoff et al., 2014; Bull and Fall, 2020). Therefore, commercially available synthetic ground silica tailings (ST), which are mainly composed of quartz, are used in this experimental study. The advantage of using ST rather than natural tailings is that it does not contain acid-generating compounds such as pyrite, which can lead to significant uncertainties in the results and their interpretation. The particle size distribution curve of ST shows a high degree of similarity to that of natural tailings obtained in nine Canadian mines, and is presented in Figure 4-1. This figure shows that approximately 40% of the particles by weight measure less than 20 micrometers in diameter, which is above the threshold required for the formation of paste tailings. The ST are mainly composed of quartz (~99%) and do not show any trace of clay particles (Fall et al., 2009, 2010). The physical and chemical properties of the ST are listed in Table 4-1 and Table 4-2, respectively.

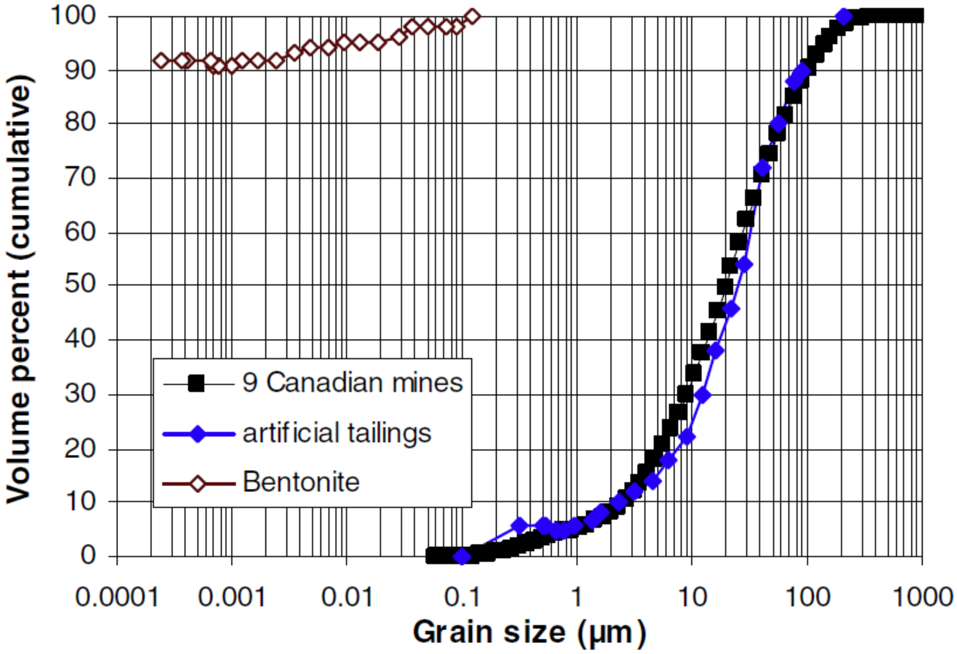


Figure 4-1: Grain size distribution curve illustrating the comparison between ST and natural tailings from nine Canadian mines.

Table 4-1: Physical properties of silica tailings.

Element Unit	G_s -	D_{10} μm	D_{30} μm	D_{50} μm	D_{60} μm	D_{90} μm	C_u -	C_c -
Si	2.7	1.9	9.0	22.5	31.5	88.9	16.2	1.3

Table 4-2: Chemical composition of silica tailings.

Element Unit	Al wt.%	Ca wt.%	Si wt.%	Fe wt.%	Na wt.%	Pb wt.%	S wt.%	K wt.%
Si	0.1	<0.01	99.8	<0.01	<0.01	0.0	0.0	0.0

4.3.1.2 Bentonite

In this experimental study, commercially available sodium bentonite, known for its high swelling capacity and expansive capability, was used to effectively fill and minimize the void spaces between the paste tailings particles. Figure 4-1 also shows the particle size distribution curve of the bentonite, obtained by hydrometric testing, which shows a predominant composition of clay-sized particles (92%). An X-ray diffraction analysis is carried out to identify the mineralogical composition of the bentonite material. The X-ray diffraction analysis for bentonite, as shown in Figure 4-2, clearly highlights the predominance of sodium montmorillonite over other impurities in minor quantities. The predominance of sodium as the main exchangeable cation also results in markedly high Atterberg limits - liquid limit and plastic limit (Fall et al., 2009; Grim & Guven, 1978).

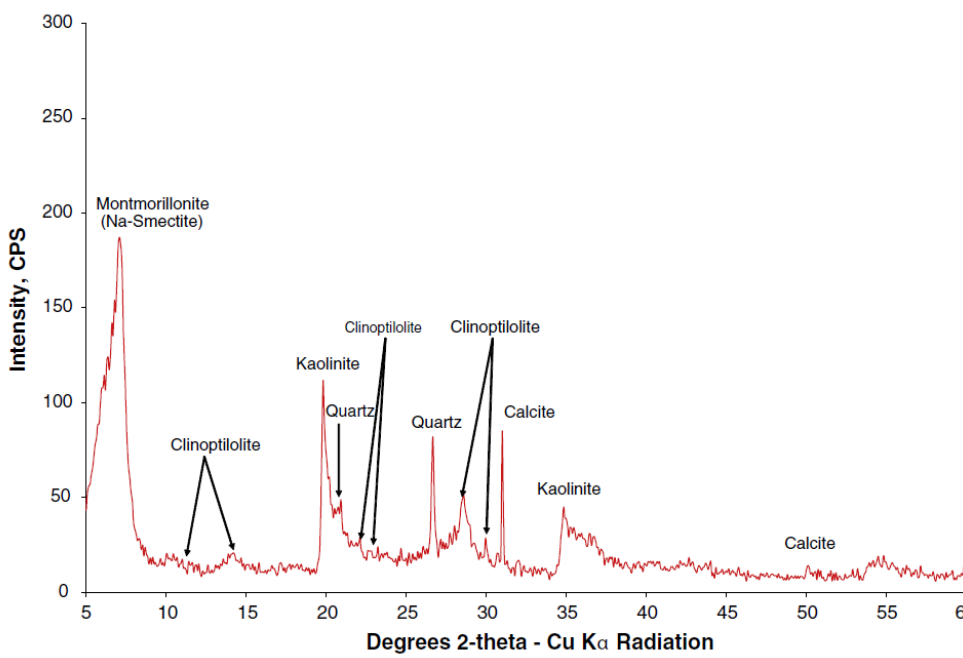


Figure 4-2: X-ray diffractogram for bentonite.

4.3.1.3 Mixing water

Distilled water is free of impurities, has a stable chemical composition and a neutral pH, and allows a controlled environment to be maintained for conducting experiments. Therefore, the samples were prepared with distilled water to facilitate swelling without having negative chemical effects.

4.3.2 Preparation of the specimens

It has been observed that cracks appear along the path of least resistance, so it is very important to achieve homogeneity when preparing samples to study desiccation cracks (Chaduvula et al., 2017). In this experimental study, the ST and the bentonite were oven-dried at 60°C for three days. Then, varying proportions of bentonite, namely 0% (controlled mix, without bentonite), 2%, 4% and 8%, were homogeneously mixed with the ST to form dry BPT mixes. Distilled water was then added to the batches to increase their initial water content to their respective optimum moisture content (OMC). The prepared mixtures were then sealed in airtight polyethylene bags for 48 hours to facilitate hydration and thus achieve moisture equilibrium.

In order to prepare the test BPT samples for desiccation cracking, all samples were subjected to static compaction with a fixed displacement rate of 0.4 mm/minute, in a 16 cm x 16 cm x 1 cm (L x W x H) format. The compaction characteristics and mix design of all prepared BPT samples are summarized in Table 4-3. After compaction, the desired quantity of distilled water was applied uniformly to the compacted samples using a spray bottle to achieve complete saturation (Brian Albrecht & Benson, 2001; Krisdani et al., 2008). The saturated samples were then sealed with plastic wrap for 48 hours to achieve a homogeneous distribution of moisture.

Table 4-3: Composition, compaction characteristics and saturated hydraulic conductivity of the prepared BPT samples.

Proportions of BPT samples and sample name	Optimum Moisture Content (OMC), W_{opt} (%)	Maximum Dry Density (MDD), $\rho_{d(max)}$ (Kg/m^3)	Coefficient of Permeability, k (m/s)
0% Bentonite (control) – 0% BPT	18.2	1602	12.0×10^{-8}
2% Bentonite – 2% BPT	18.3	1607	7.0×10^{-10}
4% Bentonite – 4% BPT	19.3	1640	1.3×10^{-10}
8% Bentonite – 8% BPT	20.5	1610	2.0×10^{-11}

4.3.3 Testing Methods and Procedures

4.3.3.1 Drying Procedure

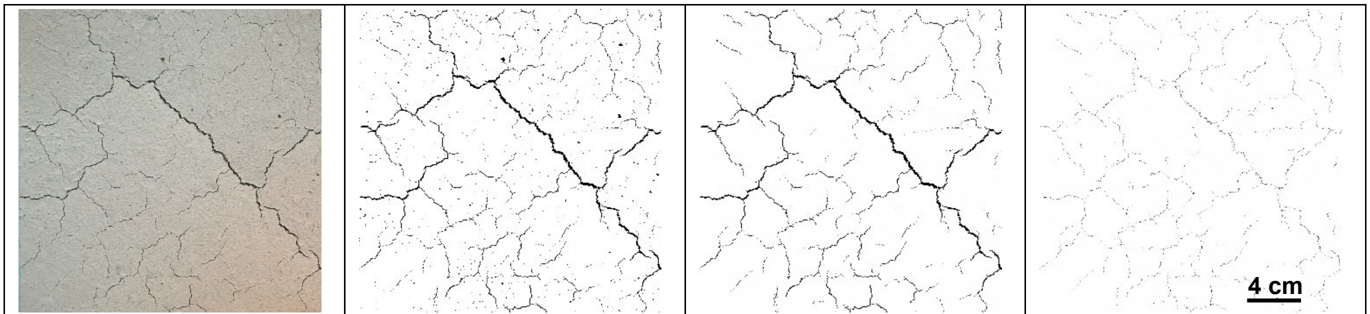
The prepared BPT samples were subjected to a wetting-drying cycle using the air-drying method, after removing the plastic packaging. Since the drying cracking behavior is sensitive to variations in temperature and humidity, the drying procedure was carried out carefully in a controlled environment, at a temperature maintained at 20°C and a relative humidity of 45 ± 5%. The first wet-dry test is considered complete when the mass of the sample remains stable, without variation over a period of two days. In order to closely monitor the evaporation rate and surface cracking, all samples were weighed and photographed at regular 60-minute intervals during the drying phase.

4.3.3.2 Test Apparatus

The surface cracking phenomenon is highly sensitive and minor deviations in environmental conditions, such as light and wind intensity, or camera alignment can lead to inaccurate or unintended results. Therefore, precision in the setup of the test apparatus is essential to ensure the quality of the data collected for the study of desiccation cracks. For this experimental study, a test device similar to those used by other researchers (e.g., Tang et al., 2008; Tang et al., 2011; Tian et al., 2022) was used. The test apparatus consists of an image acquisition system comprising a digital camera with a support frame, a light source and a fan. The recommended resolution for the camera is between 5 and 10 million pixels, and it is positioned orthogonally to capture the entire surface of the soil with a fixed magnification (Shokri et al., 2015; Tang et al., 2008; Tang et al., 2011, 2021; Tian et al., 2022). The light source provides heat to the samples, while the fan simulates natural wind conditions. Under controlled conditions, the fan and light together help promote evaporation. The samples are placed on a digital scale with a high degree of precision of 0.01 gram to continuously record the loss of water during desiccation in real time.

4.3.4 Digital Image Processing and Analysis

Quantitative analysis of images captured for each BPT specimen was carried out using the ImageJ program (Julina & Thyagaraj, 2020; Liu et al., 2013; Tang et al., 2008, 2011, 2012; Tian et al., 2022). The image processing involved the following key steps: (a) *Image Enhancement* – The captured color images were converted to grayscale, and properties such as brightness, contrast, and saturation were adjusted to improve visual clarity. (b) *Image Binarization* – The enhanced grayscale image was converted into a binary image (black and white pixels) to clearly distinguish BPT clods from cracks. (c) *Image De-noising and De-speckling* – Unwanted lines, grainy dots, or minor pixel artifacts that could be misinterpreted as cracks were removed to restore the true image. (d) *Image Skeletonization* – Cracks were reduced to thin lines, allowing for easier identification of crack geometry and intersections. An example of these processing steps is illustrated in Figure 4-3.



(a) Digital image	(b) Binarization and before de-noising	(c) After de-noising	(d) Skeletonization

Figure 4-3: Crack processing procedure for 8% BPT sample using *ImageJ*.

It should be noted that linear measurements, such as crack length, were obtained from the enhanced grayscale image, while crack area measurements were performed on de-noised binary images (Chaduvula et al., 2017; Tang et al., 2012; Tian et al., 2022). A detailed visualization of how surface crack ratio and crack length measurements are illustrated in Figure 4-4. These magnified images illustrates the methodology for precise quantification of crack networks using ImageJ software, including identification of fine microcracks.

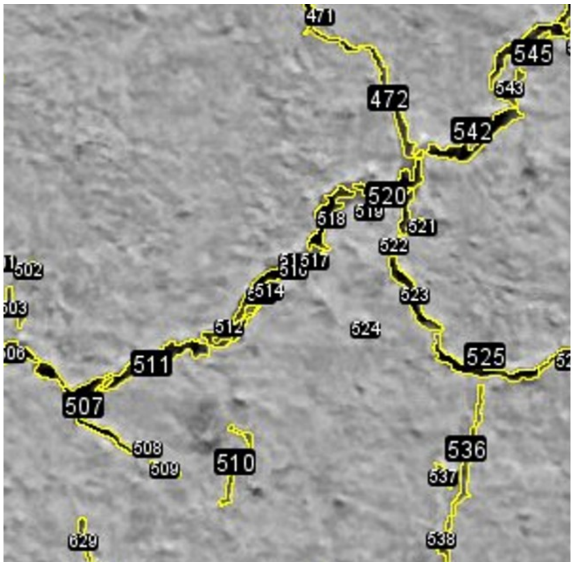
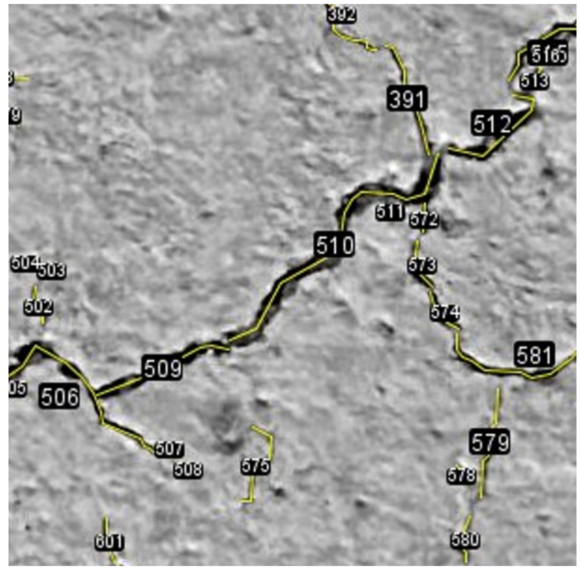
	
(a) Quantification of surface crack ratio	(b) Quantification of total crack length

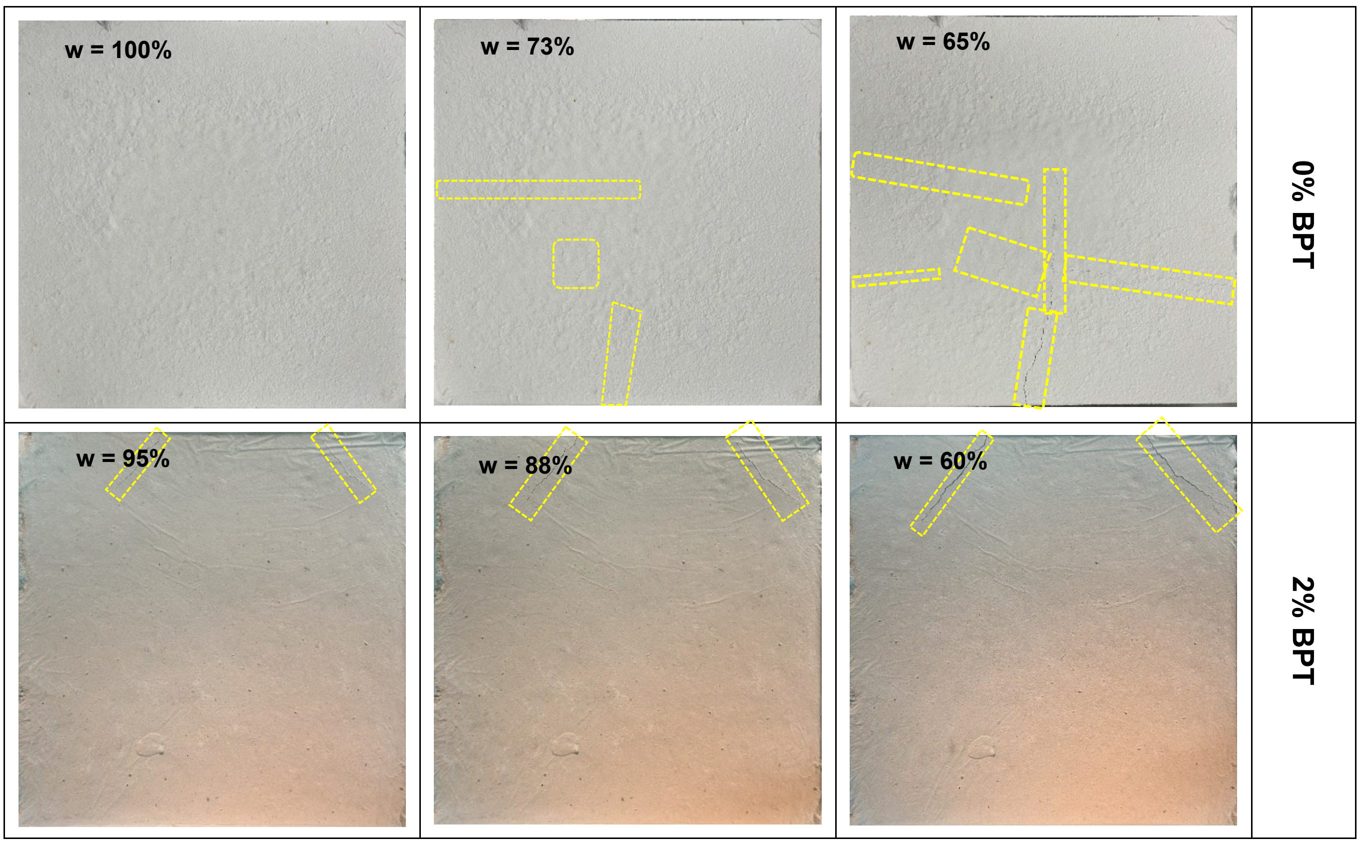
Figure 4-4: Quantification of (a) surface crack ratio, and (b) total crack length for 8% BPT sample using ImageJ.

4.4 Results and Discussions

4.4.1 Crack formation and surface crack area

Bentonite is known for its swelling and shrinking properties. In this experimental study, when a saturated BPT sample is exposed to environmental conditions, drying begins. As water is lost, the sample undergoes volumetric shrinkage. As a result, tensile stresses accumulate, eventually exceeding the tensile strength of the sample. To counter these stresses, cracks appear as a natural response. The overall evolution, geometry and dimensions of the cracks due to moisture loss are determined by the dominant material in the mixture (Chaduvula et al., 2017; Julina & Thyagaraj, 2020; Safari et al., 2014; Tang et al., 2008; Tang et al., 2011, 2012; Tian et al., 2022; Wei et al., 2020). The crack initiation and propagation of each BPT sample were monitored throughout the drying process in this study. Figure 4-5 illustrates the chronological progression of crack development in various compacted BPT samples as moisture loss occurs, captured through digital imaging. The development of major cracks is captured in the yellow dotted boxes for better identification. This figure shows that samples without bentonite (0% BPT) develop fine, almost invisible desiccation cracks after losing nearly 30% of their water. The cracks appear in the middle of the sample, then spread toward the center. The new cracks that appear intersect at right angles.

The cracks start to develop with a significantly lower loss of moisture when a small quantity of bentonite is added. The 2% BPT shows a development of shorter and wider cracks emerging again from the edge of the sample. When the bentonite content was increased to over 2%, the desiccation cracks appeared from the start of drying. With minimal moisture loss, a large network of cracks forms. The main crack forms first, then widens and lengthens. Sub-cracks appear from the main cracks. In the case of the sample containing 4% bentonite, the sub-cracks are orthogonal to the main cracks, while in the sample containing 8% bentonite, they are Y-shaped, i.e. they cross at 120°. The mechanisms driving the observed differences in crack initiation and propagation in BPT samples during moisture loss are explained in the following paragraphs.



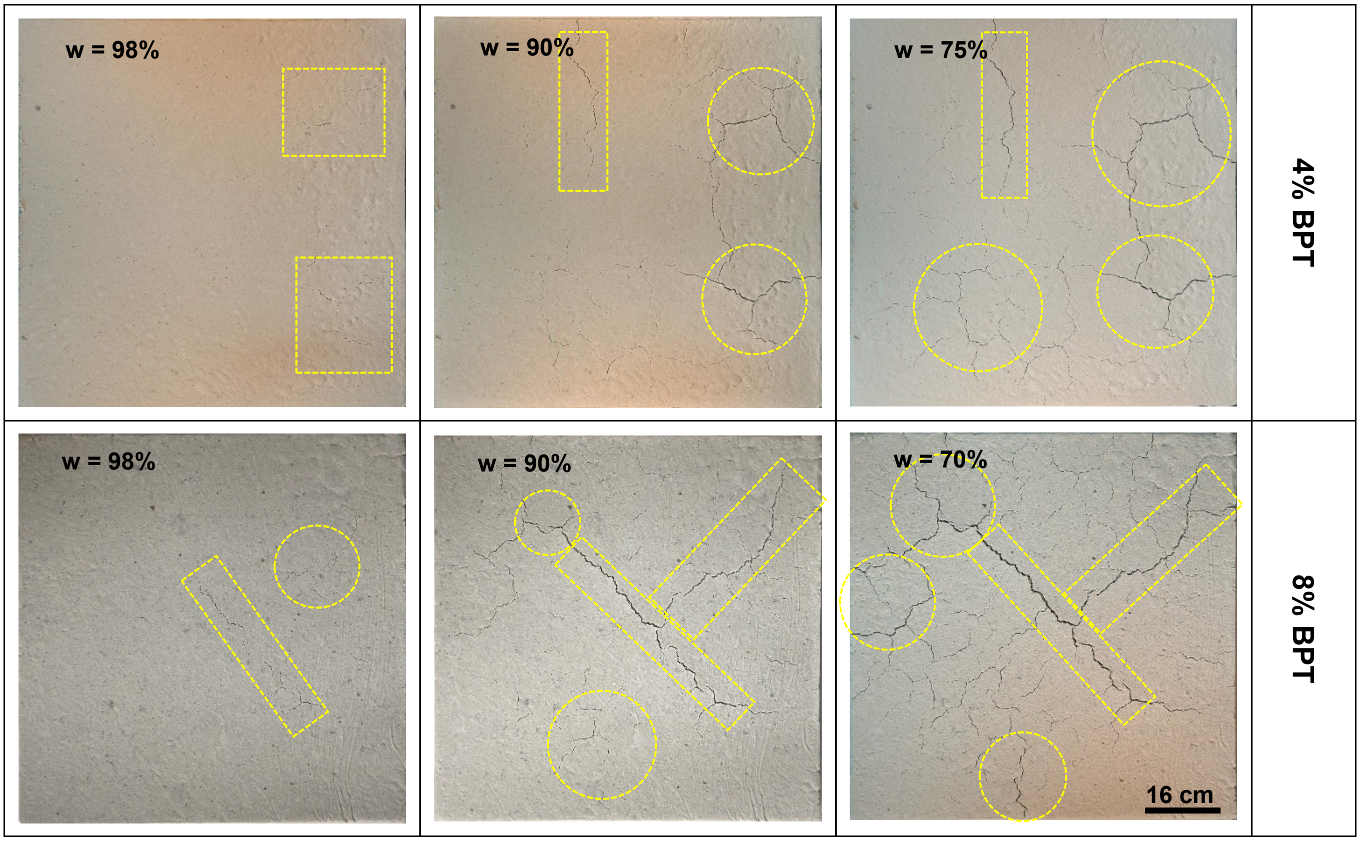


Figure 4-5: Crack initiation and propagation in the compacted bentonite-paste tailings samples with moisture loss.

The generation and development of surface crack patterns in BPT as a function of moisture loss, presented in Figure 4-5, align with the findings from surface crack area evaluations conducted in this study. The evolution of desiccation cracks is a time-dependent progressive drying process caused by moisture loss, leading to shrinkage and stress accumulation within the BPT sample. This process can be analyzed using the Surface Crack Ratio (R_{sc}), also known as the Crack Intensity Factor (CIF). R_{sc} is calculated as the ratio of the total surface area of cracks (A_{crack}) to the total surface area (A_{total}) of the drying sample (Chaduvula et al., 2017; Safari et al., 2014; Tang et al., 2008; Tang et al., 2011, 2021; Tian et al., 2022). Mathematically, this is expressed as:

$$\text{Surface Crack Ratio, } R_{sc} = \frac{A_{cracks}}{A_{total}} \qquad \text{Equation 4-1}$$

The Surface Crack Ratio is a key parameter in determining which samples are more prone to or more resistant to cracking induced by desiccation, and to what extent. Figure 4-6 illustrates and compares the surface crack ratio of BPT samples with different bentonite contents.

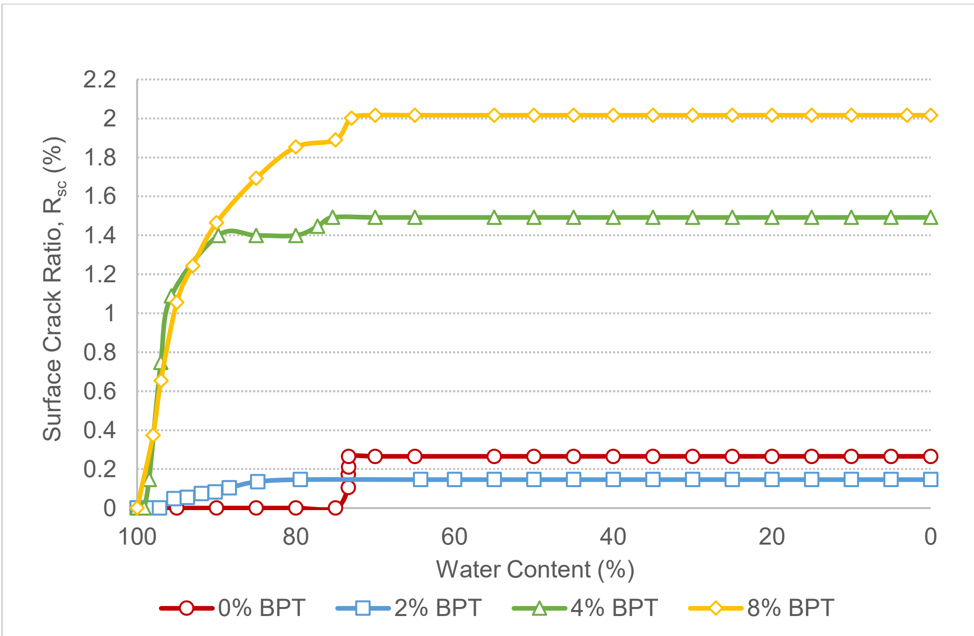


Figure 4-6: Surface crack ratio of BPT samples as a function of loss in moisture.

Figure 4-6 shows that, regardless of the bentonite content, cracks develop as moisture is lost due to air-drying. The extent of crack formation and network expansion increases with bentonite content, primarily due to bentonite's hydrophilic nature, swelling and shrinking behavior, and high plasticity (Tang et al., 2008; Fall et al., 2009, 2010; Safari et al., 2014; Wei et al., 2020). During sample preparation, BPT specimens are saturated with water and covered with plastic wrap to achieve moisture equilibrium. In bentonite-containing samples, sodium montmorillonite absorbs and retains water, forming a double-diffuse layer. As drying begins, moisture loss increases capillary forces, drawing water from deeper layers and weakening the double-diffuse layer, leading to excessive volumetric shrinkage. The resulting tensile stresses counteract the cohesive forces within the material, and once they exceed the specimen's tensile strength, cracks begin to form and propagate (Chaduvula et al., 2017; Tang et al., 2008, 2012; Tian et al., 2022; Wei et al., 2020). The specimen's vulnerability to desiccation cracking is directly related to its surface crack ratio (R_{sc})—higher R_{sc} values indicate greater susceptibility to cracking. Figure 4-6 shows that as bentonite content increases in the BPT barrier material, R_{sc} initially rises, reaching a peak before stabilizing, even as drying continues. Cracks appear earlier in bentonite-containing samples compared to those with only ST.

From Figure 4-6, it can also be seen that in 0% BPT samples, cracks appear later and remain shallow, narrow, and slender, spanning across the sample. However, its peak R_{sc} value is higher than that of the 2% BPT sample. This behavior is attributed to loose particle packing, high void ratio, and lack of cohesiveness, even after compaction (Wei et al., 2020). The non-plastic nature of ST prevents significant swelling and shrinking, leading to low and uneven tensile stress distribution (Fall et al., 2009, 2010; Tang et al., 2008, 2012; Wei et al., 2020), which results in narrow, localized cracks along weaker points in the structure. Adding 2% bentonite leads to wider and deeper cracks over a limited surface area (Figure 4-6). At this low concentration, bentonite fails to create strong cohesion between tailings particles, resulting in minimal shrinkage. However, the weak cohesive forces are easily overcome, leading to localized widening rather than extensive crack propagation (Tang et al., 2008). With 4% and 8% bentonite, cracks appear immediately after drying begins and spread extensively (Figure 4-6). These samples exhibit pronounced swelling and shrinkage, forming an interconnected crack network across the entire surface. The primary cracks are wider and deeper, while branched cracks are shorter and less prominent, leading to higher R_{sc} values in a shorter time (Figure 4-6). The increased water absorption and retention at higher bentonite contents result in greater shrinkage as drying progresses, causing the rapid development of tensile stress beyond the material's tensile strength. As a result, cracks propagate over a larger surface area to release accumulated stress (Chaduvula et al., 2017; Tang et al., 2008, 2021; Tian et al., 2022; Wei et al., 2020). Higher R_{sc} values are also associated with crack widening. However, the crack network in 4% BPT is less dense and extensive than in 8% BPT, as also shown in Figure 4-5. This is due to the strong double-diffuse layer in 4% BPT, which retains water molecules and limits shrinkage potential. In contrast, 8% BPT forms a wide, dense crack network with numerous minor independent cracks across the surface. This occurs because its weaker double-diffuse layer allows for continuous moisture evaporation, leading to prolonged shrinkage and ongoing tensile stress accumulation. Additionally, 8% BPT samples exhibit edge upheaval, further indicating intense shrinkage effects.

4.4.2 Crack geometry and total crack length

The potential for contaminant migration from waste containment facilities into the subsurface can be assessed by analyzing crack propagation over time as drying progresses, as shown in Figure 4-7. Total crack length is defined as the sum of all individual crack lengths, with higher values indicating an increased risk of contaminant migration. Longer and deeper cracks act as preferential flow pathways, making barriers more vulnerable to contaminant transport. According to Wei et al. (2020), crack propagation requires additional energy beyond that needed for initial crack formation. As cracks expand across the surface, they also influence the surface's cracking rate, leading to an increase in surface damage (Tang et al., 2012). Analyzing crack length provides insights into whether cracks remain localized or spread extensively across the material.

From Figure 4-7, it is evident that all samples develop cracks over time, but the extent of crack formation increases with bentonite content, due to its high swelling and shrinking capacity. Swelling and shrinkage occur continuously as desiccation progresses, leading to a steady build-up of tensile stress. Once the tensile stress exceeds the material’s tensile strength, cracks form as a natural response (Chaduvula et al., 2017; Tang et al., 2012). Initially, cracks elongate lengthwise before widening, as stress concentrations develop linearly along the surface (Tang et al., 2012). Once the primary cracks release tensile stresses, secondary branches begin to emerge, eventually widening. Widening first occurs in primary cracks, followed by branches that extend from them. Additionally, some minor cracks develop due to surface defects (Tang et al., 2011).

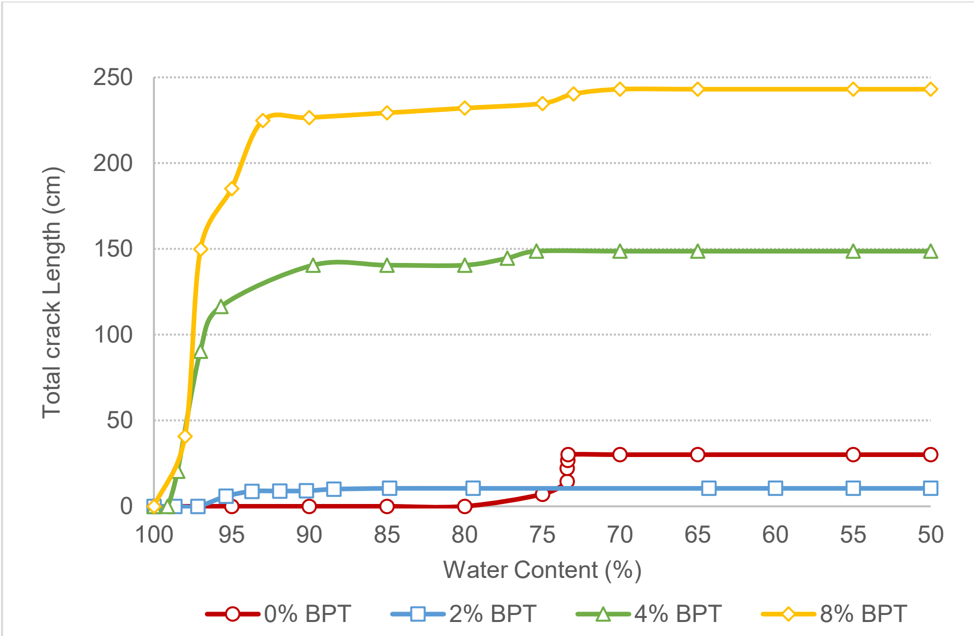


Figure 4-7: Total crack length of BPT samples as a function of moisture loss.

In samples without bentonite (0% BPT), cracks are extremely slender, narrow, and shallow (Figure 4-5). They initiate at the edges and propagate inward, branching orthogonally (90°). Due to poor water absorption and retention, ST undergoes minimal shrinkage during desiccation, resulting in low tensile stresses. With minimal stress buildup, less energy needs to be dissipated, leading to shallow, linear cracks rather than wide ones (Chaduvula et al., 2017; Tian et al., 2022). With the addition of 2% bentonite, water absorption improves slightly, and shrinkage properties are enhanced. However, tensile stresses remain too low to generate large cracks, resulting in isolated, short, and wider cracks compared to the ST-only samples (Figure 4-5). Consequently, total crack length in 2% BPT samples is lower than in 0% BPT samples (Figure 4-7). Similar to ST-only samples, cracks in 2% BPT originate at the edges and propagate inward in a linear fashion, with no secondary branching observed. A dramatic increase in crack length is observed in 4% BPT, reaching peak values in 8% BPT samples (Figure 4-7). The hydrophilic nature of bentonite enhances shrinkage, leading to the accumulation of greater tensile stresses (Wei et al., 2020). As drying progresses, multiple cracks emerge, forming an extensive crack network (Figure 4-5). In both 4% and 8% BPT samples, cracks develop simultaneously at multiple locations, rather than from the edges, as seen in 0% and 2% BPT samples. As water evaporates, the cracks become highly interconnected, longer, wider, and deeper. Secondary, tertiary, and smaller sub-branches emerge from the primary cracks, decreasing in dimension as they spread. Unlike in 0%

and 2% BPT samples, cracks in 4% and 8% BPT samples do not originate at the edges, but rather from stress-concentration points within the sample. In 4% BPT samples, cracks intersect at right angles, whereas in 8% BPT samples, intersections form a ‘Y’ shape at 120°. The 8% BPT samples exhibit a dense network of minor cracks (Figure 4-5), leading to significantly higher total crack length values compared to the other BPT samples (Figure 4-7). Additionally, edge upheaval is observed in 8% BPT samples, further highlighting intense shrinkage effects.

4.4.3 Crack propagation velocity

Crack propagation velocity (V_c) is defined as the rate of change in surface crack ratio (ΔR_{sc}) relative to the corresponding change in water content (Δw) (Tian et al., 2022). Mathematically, it is expressed as:

$$V_c = \frac{\Delta R_{sc}}{\Delta w} \qquad \text{Equation 4-2}$$

Crack propagation velocity provides insight into the rate and extent of surface crack formation as the sample dries and shrinks, helping to predict the vulnerability of a barrier material to contaminant seepage into the subsurface. Since the experiment is conducted under controlled conditions simulating natural wind exposure, V_c can also be used to assess durability response under extreme environmental conditions typical of waste containment facilities. An in-depth understanding of crack propagation velocity can aid in planning the time interval between barrier installation and waste disposal, optimizing operational efficiency and reducing project costs. This concept is illustrated in Figure 4-8 and Figure 4-8. Notably, Figure 4-9 represents the crack propagation velocity of samples containing only bentonite, as the V_c of 0% BPT (control sample) exhibits a sudden high peak, making the peaks of other samples indistinguishable on the given scale.

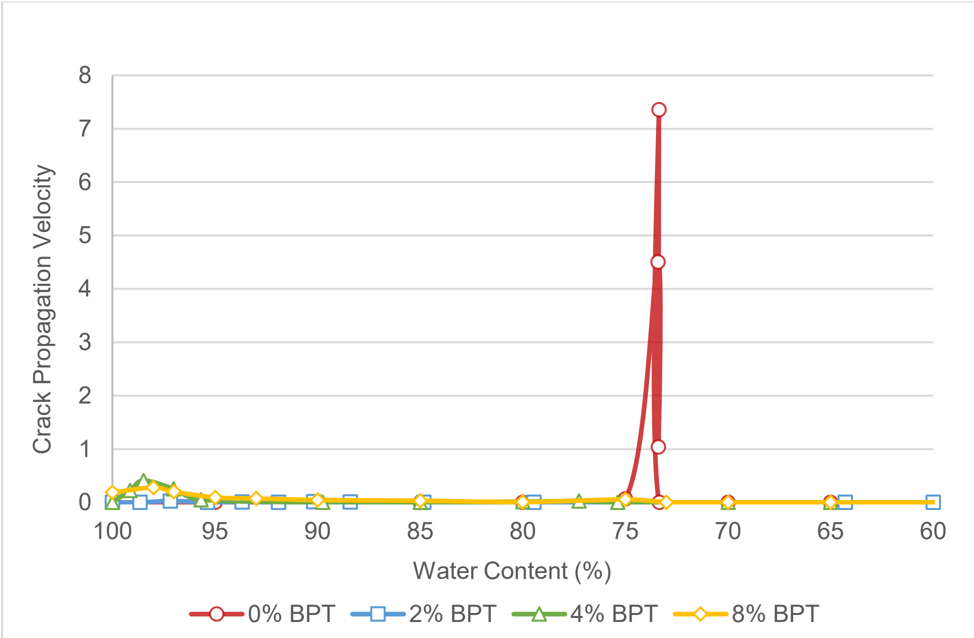


Figure 4-8: Crack propagation velocity versus water content for all BPT samples.

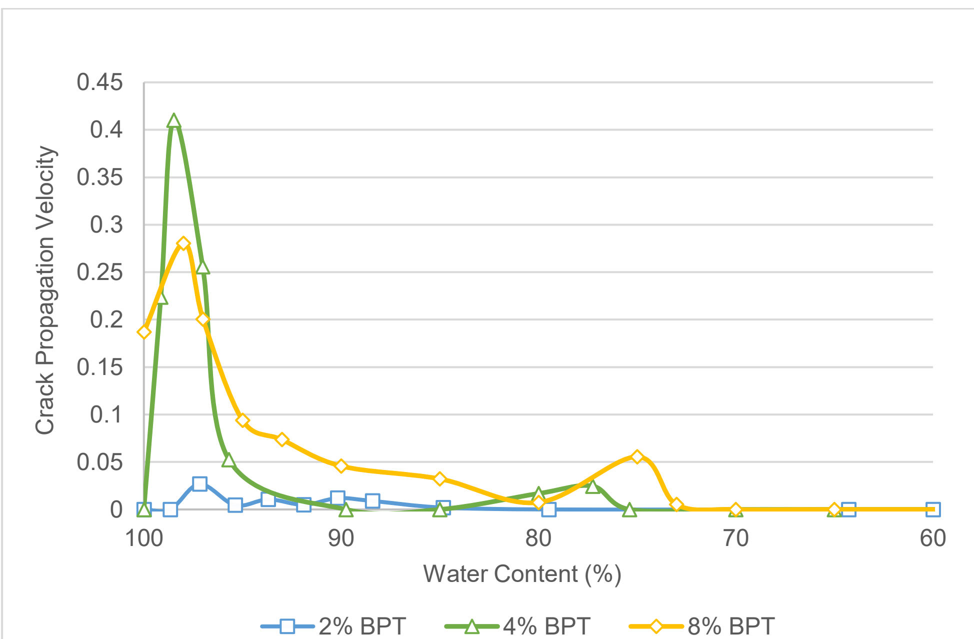


Figure 4-9: Crack propagation velocity versus water content for samples containing bentonite.

Figures 4-7 and 4-8 show that the crack propagation curves resemble a normal distribution, regardless of bentonite content. However, the distribution for samples without bentonite is negatively skewed, while for bentonite-containing samples, it is positively skewed. In all cases, the crack propagation velocity (V_c) increases to a peak before gradually decreasing to zero. Primary cracks tend to propagate more rapidly than secondary cracks, consistent with the findings of Chaduvula et al. (2017). The gradual decline to zero is due to minor crack formation and the widening of existing cracks (Tian et al., 2022). Since ST has marginal water retention ability, samples without bentonite lose water quickly once desiccation begins. This leads to a short-lived tensile stress, which is released almost immediately, resulting in rapid crack formation. This behavior is represented by a sudden peak in crack propagation velocity followed by a steep decline. In the 2% BPT sample, drying occurs more slowly, as cracks first propagate lengthwise before widening. This results in multiple short peaks before stabilization, corresponding to successive phases of tensile stress buildup, crack elongation, and widening. The 4% BPT sample exhibits the highest peak among all bentonite-containing samples, as primary cracks form and widen almost immediately. The peak gradually declines as secondary cracks branch from the primary crack. A smaller secondary peak appears before stabilization, indicating the gradual emergence of additional cracks. The strong double-diffuse layer and high cohesion between particles contribute to the rapid stabilization of the velocity curve. In the 8% BPT sample, cracks appear rapidly after drying begins but form a denser crack network more gradually compared to the 4% BPT sample, due to its higher water retention capacity. This explains why, despite having a greater surface crack ratio than 4% BPT, its peak crack propagation velocity is lower and takes longer to stabilize, as minor cracks continue forming throughout desiccation.

4.5 Summary and Conclusion

Desiccation cracks in barrier systems, such as liners and covers in waste containment facilities, pose significant challenges by compromising their hydraulic and mechanical properties. This study examines the drying-induced cracking behavior of compacted paste tailings (BPT) mixed with varying bentonite contents (0%, 2%, 4%, and 8%) as potential barrier materials for waste containment applications. The research focused on evaluating surface crack ratio, total crack length, and crack propagation velocity using digital image processing techniques.

The findings indicate that all BPT mixtures develop cracks upon moisture loss, with the extent of cracking increasing with higher bentonite content. The swelling and shrinkage properties of bentonite, while beneficial for reducing hydraulic conductivity of BPT, also contribute to higher tensile stress accumulation, leading to more extensive crack formation.

Although previous studies have highlighted 4% BPT as the most favorable mixture in terms of hydraulic and mechanical properties, this study identifies a limitation—increased susceptibility to drying-induced cracking with higher bentonite content. The 8% BPT mixture showed a higher surface crack ratio and more extensive crack propagation, potentially compromising long-term barrier performance. This implies that, in real-world applications, BPT barriers should not be exposed to conditions that promote desiccation cracking, such as moisture loss due to evaporation, temperature fluctuations, wetting-drying cycles, and prolonged exposure before waste deposition.

These findings underscore the need for a comprehensive approach in BPT barrier system design, balancing hydraulic efficiency, mechanical stability and cracking susceptibility. Future research should focus on: (i) Evaluating the potential for crack closure upon rehydration, (ii) Enhancing the self-healing properties of BPT through chemical agents while maintaining hydraulic and mechanical performance. By addressing these knowledge gaps, BPT barriers can be optimized for long-term environmental protection and improved waste containment strategies.

ACKNOWLEDGMENTS

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5 Chapter 5: Synthesis and Integration of Results

5.1 Introduction

This chapter culminates a comprehensive analysis of the findings obtained from both the technical papers and previous research, highlighting the impact and importance of incorporating bentonite into compacted paste-tailings mixtures for engineered barrier materials in waste containment facilities. Section 5.1 of this chapter underscores the significance of a well-optimized design mix and presents an overview of the previous study by Fall et al., (2009), which provides detailed insights into crucial parameters such as hydraulic conductivity, wet-dry cycles, and freeze-thaw cycles of BPT materials, revealing their suitability as potential barrier materials in landfills and mine waste impoundments.

Building upon this foundational research, subsequent studies, articulated in the first and second technical papers, investigate the mechanical characteristics of BPT material in terms of consolidation behavior and shear strength, as well as its proclivity to drying-induced desiccation cracking. Sections 5.2 and 5.3 integrate the findings obtained from the first and second technical papers, respectively. Lastly Section 5.4 explores the implications of implementing BPT-based barrier material in a waste containment facility. A summary of the experimental programs conducted in both technical papers is outlined in Table 5-1.

Table 5-1: Summary of experimental program conducted in technical paper 1 and 2.

Technical Paper	Chapter	Consolidation behavior	Shear behavior	Desiccation cracking behavior
1	3	✓	✓	
2	4			✓

In order to achieve desirable experimental results, a carefully optimized design mix of synthetic tailings (ST) and bentonite plays a vital role (Elkady et al., 2015). For all the tests, non-acid generating synthetic tailings (ST) were mixed with varying proportions of bentonite (0% (control sample), 2%, 4%, and 8%) to synthesize the desired BPT mixtures. Initially, both ST and bentonite are oven-dried at 60^0C for 72 hours in order to completely eliminate moisture. Next, ST was mixed with different bentonite contents i.e., 0%, 2%, 4%, and 8%. Subsequently, distilled water, with a neutral pH and devoid of chemicals, was added to the oven-dried batches of BPT mixtures in order to match their initial water content to their respective optimum moisture content (OMC). The prepared BPT batches were then packed in air-tight polyethylene bags for 48 hours to achieve homogeneity and moisture equilibrium. Finally, the prepared BPT mixtures were statically compacted to their respective maximum dry density (MDD). Samples measuring 60mm in diameter and 15mm in height were extracted from their compacted state for consolidation tests, while samples for direct shear tests measured 60mm x 60mm x 16mm (L x B x H).

Table 5-2 compiles the composition, compaction characteristics (optimum moisture content and maximum dry density) and hydraulic properties of the compacted paste-tailings (BPT) mixtures. It can be observed that the presence of bentonite influences these characteristics, which are crucial for predicting the behavior of BPT material. The data shows that moderate addition of bentonite (2% and 4%) is effective in filling voids, thereby enhancing the properties, but excessive additions (8%) can loosen particle packing efficiency and weaken the enhanced properties. Reduced permeability can be attributed to the increasing bentonite content in various BPT mixtures, which occupies the remaining porous spaces after compaction, leading to further blockage and inhibiting the movement of fluids. Furthermore, the BPT mixtures also displayed signs of self-healing of desiccation cracks after multiple wet-dry and freeze-thaw cycles, demonstrating their robustness against rough environmental conditions and their reliability as potential engineered barrier material.

Table 5-2: Summary of compaction characteristics (OMC and MDD) and hydraulic properties of various BPT samples.

Compaction characteristics and hydraulic behavior	Proportions of BPT samples and sample names			
	0% BPT (control)	2% BPT	4% BPT	8% BPT
Optimum Moisture Content (OMC), W_{opt} (%)	18.2	18.3	19.3	20.5
Maximum Dry Density (MDD) $\rho_{d(max)}$ (kg/m^3)	1602	1607	1640	1610

Coefficient of Permeability, k (m/s)	12.0 x 10^{-8}	7.0 x 10^{-10}	1.3 x 10^{-10}	2.0 x 10^{-11}

5.2 Effect of addition of bentonite on mechanical properties of BPT mixtures

The third chapter, which examines the outcomes of the first technical paper, investigates the effect of bentonite content on the consolidation and shear characteristics of BPT mixes using one-dimensional consolidation tests and direct shear tests, respectively. The summary of results obtained from both tests on various BPT mixes is compiled in Tables 5-3 and 5-4.

All the parameters used for measuring the consolidation behavior of BPT mixes show a similar trend. It can be clearly observed that the difference between the initial and final void ratios decreases with the addition of bentonite up to a certain limit, indicating reduced compressibility, improved resistance to volume change, and enhanced stability.

Table 5-3: Summary of consolidation characteristics of various BPT mixes.

Consolidation characteristics	Proportions of BPT samples and sample names			
	0% BPT (control)	2% BPT	4% BPT	8% BPT
Difference in initial and final void ratios	0.264	0.182	0.120	0.316
Coefficient of volume change, m_v (kPa^{-1})	4.529 x 10^{-5}	3.916 x 10^{-5}	3.659 x 10^{-5}	5.732 x 10^{-5}
Consolidation settlement, S_c (mm)	0.435	0.376	0.351	0.550
Compression Index, C_c	0.132	0.107	0.085	0.155

Similarly, the general trend observed in direct shear tests demonstrates a substantial improvement in shear strength and its parameters – cohesion and angle of friction. The peak shear stress increases with increasing in normal stress, and is highest for the BPT mix with 4%

bentonite content. The shear strength parameters also suggest that as cohesion improves, the angle of friction is slightly compromised (Xiang et al., 2021).

Table 5-4: Summary of shear characteristics of various BPT mixes.

Shear characteristics	Proportions of BPT samples and sample names			
	0% BPT (control)	2% BPT	4% BPT	8% BPT
Peak Shear Stress at 150kPa	146.928	153.580	180.619	154.427
Peak Shear Stress at 250kPa	183.396	244.219	276.537	222.578
Peak Shear Stress at 400kPa	336.330	348.120	370.092	335.473
Cohesion (kPa)	4.7	42.9	76.5	43.8
Angle of friction (degrees)	37.9	37.6	36.8	36.0

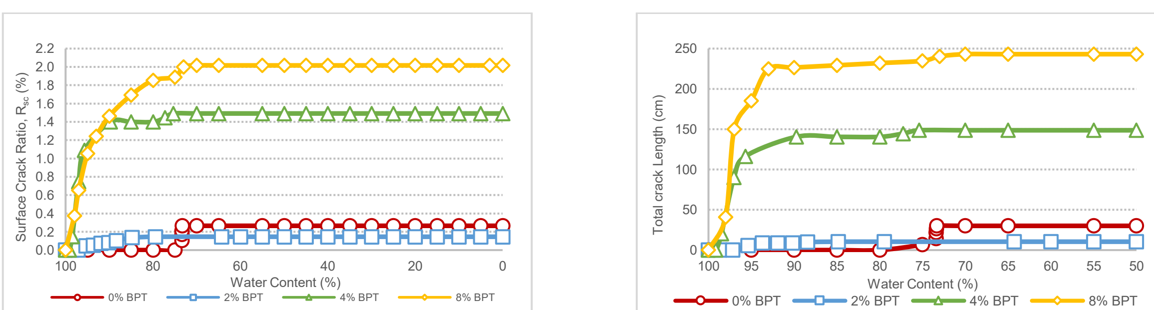
The findings from Table 5-3 and 5-4 indicate improved properties in terms of consolidation and shear behavior upon addition of bentonite up to a threshold quantity (i.e., 4%). Several mechanisms govern this behavior. The particles are rearranged and the voids are significantly reduced during standard proctor compaction. Under compressive forces during the experiments, the particles pack even more closely, facilitating stronger inter-particle bonding. Additionally, the added bentonite occupies the remaining void spaces further reducing the porous spaces. Furthermore, bentonite is known for its hydrophilic nature and high cation exchange capacity. As a result, it swells upon coming in contact with water, forming a resilient double-diffuse layer (Bohnhoff et al., 2013; Dafalla, 2013; Grim & Guven, 1978; Karnland et al., 2006; Li & Fall, 2019; Oy & Carlson, 2004; Vadlamudi & Mishra, 2018). However, higher settlement and reduced shear strength are observed when the bentonite content is either insufficient (i.e., less than 4%), or excessive (i.e., greater than 4%). Therefore, it can be concluded that the amount of bentonite has a direct influence on the mechanical properties of the BPT material.

Based on the findings obtained from the first technical paper, the 4% BPT mixture demonstrates the best mechanical characteristics indicating the best balance between enhanced shear strength, improved resistance to consolidation, and reduced permeability, making it a suitable choice for application as barrier material for waste containment facilities.

5.3 Effect of addition of bentonite on desiccation behavior in BPT mixtures

Conventional geomechanics is primarily focused on the study of compressive forces. However, investigating the tensile strength of the materials is crucial to ensuring their stability and performance. The fourth chapter, which contains the second technical paper, investigates another pivotal factor critical to ensuring the performance of BPT mixtures in terms of drying-induced desiccation behavior, up to one-wet-dry cycle.

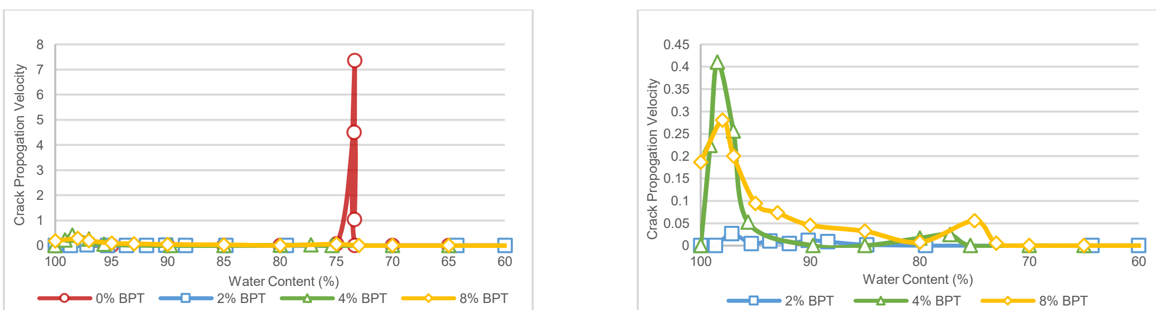
The sample for studying desiccation cracks was prepared by statically compacting BPT mixtures at a fixed displacement rate of 0.4 mm/ min to a dimension of 16cm x 16cm x 1cm (L x B x H). The sample is brought to full saturation by adding distilled water and sealed with a plastic wrap for 48 hours to achieve homogeneity and moisture equilibrium. The experiment was conducted in a controlled environment with a temperature of 20^{0}C, relative humidity between 45 ± 5%, and constant wind and heat forces simulating natural environmental conditions. The sample was subjected to one wet-dry cycle, which is achieved when its mass remained stable for two consecutive days. Cracks were photographed at regular intervals and analyzed using ImageJ software. The suitability of various mixtures was evaluated by comparing the following parameters: (i) surface crack ratio, (ii) total crack length, and (iii) crack propagation velocity, as illustrated in Figures 5-1 and 5-2.



(a) (b)

Figure 5-1: (a) Surface crack ratio, and (b) Total crack length of BPT samples as a function of moisture loss.

From the Figures 5-1(a) and (b), it can be seen that the samples developed cracked upon loss of moisture. Contrary to the mechanical properties, which is governed by a threshold quantity of bentonite, crack development intensifies as the bentonite content increases in the BPT mixtures. The mechanism of crack formation is directly related to an increase in the tensile stress of the sample. Upon saturation, bentonite adsorbs and retains water molecules, forming a double-diffuse layer and swelling. As drying begins, the sample loses moisture, causing the double-diffuse layer to break, leading to volumetric shrinkage. This results in the development of tensile stress. Once the tensile stress exceeds the tensile strength of the sample, cracks form as a natural response (Chaduvula et al., 2017; Julina & Thyagaraj, 2020; Safari et al., 2014; Tang et al., 2008; Tang et al., 2011, 2012; Tian et al., 2022; Wei et al., 2020). Presence of larger quantity of bentonite results into greater water retention, resulting in more pronounced shrinkage upon drying and, consequently, a more intensified crack network.



(a) (b)

Figure 5-2: Crack propagation velocity of (a) all BPT samples, and (b) samples containing bentonite versus water content.

Figure 5-2 illustrates the crack propagation velocity while the drying is under progress. It can be observed that sample without bentonite lose water very quickly, resulting in rapid crack formation. However, in samples with 4% and 8% bentonite content, crack propagation velocity stabilizes more gradually. This can be attributed to a stronger double-diffuse layer that retains water for a longer duration, along with the simultaneous widening of primary crack coupled with development of multiple secondary cracks. Furthermore, the samples showed no signs of self-healing of cracks.

Desiccation cracks can significantly reduce the shear strength of the material and induce large settlements. Therefore, based on the findings obtained from the second technical paper, it is recommended to minimize the exposure of BPT barrier materials in real-world applications to mitigate the effects of desiccation cracking.

5.4 Implications of Implementing of Bentonite-Paste Tailings (BPT) for Design of Barrier Systems in Waste Containment Facilities

Effective waste containment facilities require carefully designed barrier systems (liners and covers) that can maintain their integrity over long periods while preventing contaminant migration. The findings from first and second technical papers provide valuable insights about behavior of BPT material and its potential as an engineered barrier. This section examines the implications of BPT properties for barrier design in waste containment facilities.

The findings indicate that BPT mixtures exhibit reduced permeability and settlement, along with improved shear strength, as bentonite content increases up to 4%. Low permeability is essential for liners to prevent contaminant migration into surrounding soil and groundwater and for the cover system to minimize water infiltration into the waste mass. Moreover, reduced settlement is critical for maintaining liner integrity and preventing ponding over the cover system, which could otherwise lead to increased infiltration. Additionally, higher shear strength provides stability against sliding failure, especially on side slopes or in seismically active regions.

On the contrary, the findings also indicate the formation of cracks, which increases with increasing bentonite content, showing no signs of self-healing when subjected to a single wet-dry cycle. Desiccation cracks can create preferential pathways for contaminant transport and severely compromise the improved mechanical and hydraulic properties. Therefore, construction planning and execution must incorporate measures that minimize drying of the liner material during construction and operation.

Barrier design can also be optimized by incorporating different bentonite contents in a layered configuration in the barrier system to address specific hydraulic and structural stability requirements. Furthermore, BPT materials could be combined with geosynthetics or other materials to address specific weaknesses. For example, combining BPT with geotextiles might mitigate cracking by providing tensile reinforcement.

In conclusion, the properties of BPT mixtures, particularly those with 4% bentonite content, offer promising advantages for waste containment barrier systems. These materials combine low permeability, good mechanical stability, and reasonable resistance to environmental stresses. However, careful attention must be paid to desiccation behavior, which presents the most significant challenge to long-term performance.

5.5 Novel contributions of the research work

This thesis makes several novel and impactful contributions to the field of geoenvironmental engineering, particularly in the development and evaluation of sustainable engineered barrier materials for waste containment applications. The research investigates the potential of bentonite-paste tailings (BPT) mixtures — a sustainable material derived from the reuse of synthetic tailings and bentonite clay — as an alternative barrier system for mining and landfill facilities. It addresses critical knowledge gaps related to the mechanical behavior and desiccation performance of BPT mixtures, which had not been previously explored in the literature.

One of the most significant and original contributions of this study is the comprehensive mechanical characterization of BPT mixtures under conditions relevant to field applications. While prior studies have demonstrated that BPT possesses low hydraulic conductivity and satisfactory resistance to environmental cycles (e.g., freeze-thaw and wet-dry), the mechanical integrity of these mixtures remained unassessed. This thesis is the first to systematically evaluate both the consolidation characteristics and shear strength of BPT with varying bentonite contents (0%, 2%, 4%, and 8%). Through one-dimensional consolidation testing, the study revealed that BPT mixtures exhibit low compressibility and minimal settlement under loading — key performance criteria for barrier materials subjected to the self-weight of overlying waste. In addition, direct shear tests conducted at multiple normal stresses confirmed that BPT mixtures, particularly those with up to 4% bentonite, exhibit enhanced shear strength due to increases in both cohesion and internal friction angle. These findings offer critical insights into the structural stability of BPT when used in liners and covers of containment systems, especially on slopes or under high waste loads.

A second major contribution lies in the first-time investigation of desiccation cracking behavior in BPT materials – an area previously unexplored. Desiccation cracking poses a significant threat to barrier performance by compromising structural integrity and creating preferential flow paths for contaminant transport. This thesis employs an innovative image-based digital analysis approach to quantify crack geometry, surface crack ratio, crack length, and propagation velocity across varying bentonite contents. The results clearly demonstrate that while increased bentonite content improves mechanical and hydraulic properties, it also leads to a higher propensity for crack formation under drying conditions. This trade-off between improved strength and increased crack vulnerability presents a critical consideration for the design and optimization of BPT-based barriers. Notably, this study highlights that a 4% bentonite content may offer an optimal balance between mechanical performance and desiccation resistance.

Furthermore, this research advances the scientific understanding of barrier material behavior under coupled mechanical and environmental stresses, providing a nuanced view of how bentonite addition influences both beneficial and detrimental aspects of BPT performance. By integrating findings from mechanical and desiccation analyses, the study offers a holistic framework for assessing the feasibility of BPT as a barrier material, moving beyond singular property evaluation toward a multi-criteria decision-making approach.

Lastly, the thesis contributes to sustainability in engineering practice by promoting the reuse of tailings in high-value geoenvironmental applications, aligning with global efforts to reduce the environmental footprint of the mining and waste disposal industries. The proposed use of BPT represents a cost-effective, locally available, and environmentally beneficial material alternative to conventional geosynthetics and natural clays.

In summary, this work bridges a crucial research gap by establishing the mechanical robustness and environmental vulnerability of BPT mixtures, offering actionable recommendations for their practical application, and paving the way for future research on long-term field performance, chemical compatibility, and multi-cycle behavior.

5.6 Limitations of the study

Despite the valuable insights gained from this research, several limitations should be acknowledged to guide future investigations. First, the desiccation behavior of bentonite-paste tailings (BPT) mixtures was assessed under a single wet-dry cycle, which may not adequately represent the cumulative effects of repeated or seasonal environmental loading typically experienced in field applications. Moreover, all tests were conducted under controlled laboratory conditions, which do not fully replicate the complex and heterogeneous nature of field environments, including variations in loading, waste placement, and climatic factors. The study was limited to a specific range of bentonite contents (0%, 2%, 4%, and 8%), leaving potential effects of higher or alternative additive proportions unexplored. In addition, while surface crack patterns were analyzed, subsurface or three-dimensional crack propagation, which is critical for understanding barrier integrity, was not examined. Furthermore, long-term durability aspects, such as potential chemical and mineralogical changes in BPT mixtures under interaction with leachates, were beyond the scope of this work but are essential for real-world applications. Addressing these limitations through expanded experimental frameworks, field-scale validation, and long-term performance monitoring will be crucial for optimizing and validating the use of BPT as a sustainable engineered barrier material.

5.7 References

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6 Chapter 6: Conclusions and Recommendations

This section presents a conclusion of the results obtained from the experimental program and suggests recommendations for future research work. This research provides valuable insights into compacted bentonite-paste tailings (BPT) mixtures and their potential use as engineered barriers systems (liners or covers) in the waste containment facilities. The study focuses on the behavior of BPT mixtures in terms of their mechanical characteristics and drying-induced desiccation behavior, building upon previous findings regarding hydraulic conductivity and behavior under natural environmental stresses such as wet-dry and freeze-thaw cycles.

The experimental results demonstrated that BPT mixtures possess favorable mechanical properties – low compressibility and volume change, coupled with high shear strength and its parameters, cohesion and angle of friction. Of all the mixtures that were evaluated, the 4% BPT sample demonstrated the highest resistance to compressibility and deformation and the greatest shear strength parameters, indicating minimal settlement in the long run and adequate structural stability against the expected heavy loading conditions. The results emphasize the efficiency of bentonite in filling the voids between synthetic tailing particles and creating a durable double-diffuse layer, enhancing the interparticle bond and material strength. On the contrary, when the bentonite content is reduced to less than 4% or increased beyond 4%, compromised performance is observed due to excessive swelling and a weaker double-diffuse layer. Therefore, it is important to optimize the percentage of bentonite to maintain the required structural integrity of the barrier system under extreme stress.

The experimental program also investigated the drying-induced desiccation behavior up to one wet-dry cycle, revealing important considerations for practical applications. The study shows that all mixtures are susceptible to the development of cracks, irrespective of the presence of bentonite, as a response to the rising tensile stress due to loss of moisture. Moreover, a direct correlation was observed between increasing bentonite content and the extent of crack propagation. This is due to the high swelling and shrinkage behavior of bentonite. Furthermore, no sign of self-healing of cracks was observed across any BPT mixtures. The development of cracks can severely affect the hydraulic conductivity and mechanical properties. This behavior underscores the significance of careful optimization of BPT composition to balance these unfavorable characteristics.

In conclusion, the results obtained from this study enhance our understanding of the behavior of BPT mixtures under various conditions, in conjunction with previous findings. The findings from this study provide a foundation for future research aimed at sustainably enhancing the properties of proposed BPT mixtures and their potential use as engineered barrier system for waste impoundments. Few recommendations for future investigations include:

a) investigating the long-term mechanical behavior and properties of the proposed BPT barriers under cyclic environmental conditions, such as freeze-thaw and wet-dry cycles,

b) assessing the mechanical and hydraulic performance of the BPT barriers in diverse contaminant environments to ensure reliability under varying chemical exposures,

c) enhancing crack-healing properties by leveraging chemical agents without compromising the hydraulic and mechanical properties,

d) investigating the possibility of crack-healing upon rehydration, and

e) examining the role of vegetation cover in varying climate zones in mitigating cracking behavior.