EXPERIMENTAL EVALUATION OF CEMENTED TAILINGS BACKFILL STRENGTH CHARACTERISTICS AND ACID MINE DRAINAGE POTENTIAL

By

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Abstract

Following the research & development of Sustainable Mining by Drilling (SMD) technique in the narrow vein mineral deposits, a conceptual framework for backfilling large-diameter drilled holes has been developed, utilizing a mixture of cemented tailings paste. In the paste mixture, the tailings constitute 75% to 85%, the binder makes up 3% to 9%, and the water content represents 15% to 25% of the total weight of dry materials. This thesis contains a comprehensive assessment of various aspects related to cemented tailings backfill (CTB), including the strength characteristics, measurement of dynamic elastic properties using the ultrasonic method, rheological analysis, and evaluation of acid mine drainage potential. To minimize the cement cost in backfill operation, comparative analysis was conducted in the laboratory for the samples of 6% and 4% cement content by weight along with the concerned proportional mixture of tailings and water to achieve the design strength of 1 MPa. The strength characteristics were evaluated following the compressive strength test, stress-strain behaviour and dynamic elastic properties measurement through ultrasonic wave velocity method. Moreover, on the collected backfilled samples from field location, strength measurement and particle size distribution were conducted to understand the effect of particle gradation on strength development. Then, comparative analysis has been described from lab experimental results to evaluate the acid mine drainage potential. From the static test of tailings, the experimental results shows that the tailings has high potential of acid generation. The long-term kinetic test of cemented tailings mixture with variable cement percentage showing the neutralization behaviour of acid generating tailings for the presence of cement components.

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Table of Contents

List of Figures

List of Tables

Nomenclatures

AMD	Acid Mine Drainage
AP	Acid Potential
ASTM	American Society for Testing Materials
Cc	Coefficient of Curvature
CCS	Confined Compressive strength
CGS	Canadian Geotechnical Society
CPA	Curing Under Pressure System
CPB	Cemented Paste Backfill
CTB	Cemented Tailings Backfill
Cu	Coefficient of uniformity
CUAPS	Curing Under Applied Pressure System
DAQ	Data Acquisition System
DTL	Drilling Technology Laboratory
EC	Electrical Conductivitiy
FFT	Full-Field Trial
LDH	Large Diameter Hole
LVDT	Linear Variable Displacement Transducer
MDT	Mine Design Technologies Inc.
mS	Milli Siemens
MUN	Memorial University of Newfoundland
NNP	Net Neutralization Potential
NP	Neutralization Potential
NPR	Neutralization Potential Ratio

OPC	Ordinary Portland Cement
PSD	Particle Size Distribution
PVC	Polyvinyl Chloride
R&J	Romeo and Juliet
SEM	Scanning Electron Microscopy
SG	Specific Gravity
SMD	Sustainable Mining by Drilling
SSD	Saturated Surface Dry
UCS	Unconfined Compressive Strength
UPV	Ultrasonic Pulse Velocity
Vp	Primary wave (P-wave)
Vs	Shear Wave (S-wave)
XRD	X-ray Diffraction

Chapter 1: Introduction

1.1 Background of the Research

Billions tons of tailings are generated annually worldwide from mineral extraction operation. According to the 2020 study of world mine tailings failure association, every year the global production of 18-20 billion tonnes of minerals results in the generation of approximately 80-90 billion tonnes of waste rock and 8 billion tonnes of tailings. At present, for each one million tonnes of mined mineral product, there is a requirement to manage 4.9 million tonnes of waste ore, waste rock, and tailings. Sustainable management of tailings remains an ongoing challenge for the mining industry and regulatory bodies worldwide. The sheer volume of tailings produced poses challenges in terms of their management, long-term stability, and potential environmental impacts.

Conventional tailings storage involves creating traditional tailings ponds or impoundments to store waste materials from mining operations. The process includes constructing a pond along with a dam near the mining site and depositing the tailings slurry into the pond. Over time, water drains or evaporates, causing the tailings to consolidate and dry. Excess water is managed through overflow systems and some water may be recycled. When the mining operation ends, the site goes through closure and rehabilitation to restore the land to its original state or a beneficial use. Modern tailings dam structures are built to store and permanently dispose of the waste materials from mining and milling activities. At some projects, the tailing dams cover several square miles. The dams face difficulties in maintaining stability due to the large volumes of water and tailings they handle, with the mixture consisting of 85% water and 15% solids by weight. Managing stability becomes particularly challenging under various conditions, such as static and dynamic loads (seismic events, blasting vibrations), floods, and seepage. Around hundred of mine tailing storage dams have disastrously failed so far around the world causing devastating damage.

Surface Paste Disposal (SPD) is an innovative technique used in mining operations to manage and dispose of mine tailings effectively. Unlike traditional tailings storage methods, which often involve constructing large dams, SPD involves dewatering the tailings before deposition. This process can be achieved through thickening or filtering, which reduces the moisture content of the tailings and results in a paste-like material with a higher solids concentration. However, the main challenge with SPD is the cost associated with the filtration or thickening process to achieve the desired paste consistency.

Cemented tailings backfilling (CTB) or cemented paste backfill (CPB) is a technique, which utilize tailings for filling underground voids and supporting mining operations. It is a carefully designed combination of tailings, a hydraulic binder, and mixing water. The tailings make up 75-85% of the mixture by weight, while the binder constitutes 3-9% of the total dry materials weight. The inclusion of a binder is necessary to ensure the strength and stability of CTB. It is also important for CTB to have an appropriate water content to achieve the desired consistency, enabling it to be efficiently transported from the paste plant to the underground openings.

Here, the objective is to develop the backfilling concept utilizing the tailings for the SMD technology. The focus of SMD is on steeply dipping narrow-vein mineral deposits where ore recovery is more economic, sustainable and safer than conventional selective mining methods. The SMD technique consist of narrow vein deposit imaging, large diameter drilling after the drilling of pilot holes along the veins, and backfilling of the large diameter boreholes.

Understanding the properties of CTB is important for designing backfill structures that are cost-effective, safe, and long-lasting. CTB has various characteristics related to its physical, mechanical, hydraulic, chemical, and microstructural aspects. These properties can be influenced by different factors. Internal factors are the components of CTB, such as: binder, tailings, and water. It's also crucial to understand how they change over time due to processes like self-consolidation and cement reaction. External factors include environmental aspects like acid mine drainage and stability of the backfill. These factors and their interactions affect how CTB performs. Having a good understanding of CTB properties is crucial for designing safe and cost-effective CTB structures.

Wave propagation has proven to be an effective method in geotechnical laboratories for assessing the dynamic small-strain engineering properties of geotechnical materials. These properties include Poisson's ratio, bulk modulus, shear modulus, and Young's modulus. When compressional (P-waves) and shear (S-waves) waves travel through a sample, they encounter variations in the density and mechanical properties. One of the primary parameters measured using this method is the velocity of those waves through the geotechnical material. P-wave velocity is the speed at which compressional waves travel and S-wave velocity is the speed of shear waves. By measuring the time it takes for these waves to propagate through the material and knowing the distance they travel, the velocities can be calculated. In this thesis, approach was taken to investigate wave propagation and its applicability in determining the elastic properties of cemented tailings paste during the hydration process.

Determining the rheological properties of materials is crucial for understanding their behavior in various industries and applications. The presence of tailings particles, cement, water, and additives affects the flow characteristics of the paste and understanding its rheology helps to determine suitable transportation parameters. The consistency of cemented paste backfill during transportation is essential to ensure cost-effective and efficient operations. The physical, chemical, and mineralogical properties of the components significantly impact its flow ability and overall performance.

Proving the benefits of the paste backfilling approach has presented a major industry challenge, particularly in assessing the operational and long-term effects on mine and groundwater quality. The oxidation of sulfide minerals within paste backfill can lead to acid mine drainage (AMD), lowering pH levels in soil and water, release of toxic heavy metals. To address these issues, reclamation plans must include strategies to minimize oxygen exposure, effective monitoring, and swift remediation measures to mitigate environmental damage. One of the key advantages of paste backfilling is the reduction in the volume of tailings that need to be stored on the surface that leads to smaller environmental footprint. Furthermore, in underground backfilling, the risk of AMD generation is significantly diminished, leading to improved environmental management. To properly assess potential environmental issues, it's essential to thoroughly examine the paste mixture's characteristics such as its mineral composition, acid generation capacity, potential for generating acid, speed of reactions, and ability to release metals. This analysis allows for predicting the short and long-term effects on the quality of surface and groundwater.

The movement of air and water within and around paste backfill is crucial for assessing potential oxidation and metal release during and after mining operations. Factors such as paste grain size, mineral composition, density, saturation, permeability, binder chemistry, and engineering properties impact this movement. Additionally, host rock characteristics, paste placement, and storage conditions also affect air and water flow through the paste backfill. Understanding these dynamics is essential for predicting environmental impacts on groundwater and surface water quality.

1.2 Research Objective and Motivation

The concept of backfilling from cut and stope mining method is being utilized in the SMD technology. The cut and stope mining method is used in underground mining to extract minerals from ore bodies. It involves creating horizontal tunnels called drifts and vertical tunnels known as stopes to access the ore. Once the ore is removed, the resulting vertical or inclined voids created by the extraction process are called stopes. To provide support and prevent collapses, these stopes are filled with a suitable materials and the whole process is called backfill. The backfill is typically a mixture of cemented tailings or waste rock combined with water, which forms a stable paste or slurry. The stopes are mined in primary and secondary phases. The ore from the primary zones are extracted utilizing the spaces of secondary stopes as working ground. Then those primary zones are backfilled. When the primary backfilled stopes are cured and stabilized, then ore recovery from the secondary zone occurs utilizing the primary backfilled zone as the working ground. After that, the secondary stopes are backfilled following the same process of primary backfilling. In the backfilling operation, the major concerns are related to achieving designed strength with optimized binder cost, consistency of paste transportation and reliability of the waste materials utilization following the environmental issues. So, in this thesis some aspects of these concerned are investigated through comprehensive literature review and experimental process. The aspects of the research for this thesis are the following:

- Optimization of cement content to achieve the design strength and reduce the cement cost for cemented tailings backfilling operation using the cement as binder, water and tailings.
- Development of non-destructive experimental set-up and procedure through the ultrasonic wave measurement equipment to evaluate the dynamic elastic properties of CPB samples.
- Understanding of rheological behavior of cemented paste tailings following the yield stress measurement from slump test to understand the consistency in paste transportation through the pipeline and settling behavior after pouring them.
- Investigation on particle size distribution of tailings and aggregates following it effects on strength development for backfilling. From the collected field samples of backfilling, an experimental assessment of strength variation was conducted for different batches of mixtures.
- Evaluation of acid mine drainage potential for acid generating tailings and cemented tailings mixture. Through acid base accounting test, acid generating and acid

neutralizing capacity was evaluated for the tailings. Then in laboratory set-up, long-term evaluation of acid mine drainage potential for cemented tailings samples has been conducted to analyze the contamination behavior of ground water and environmental impacts. The purpose is to understand the acid neutralization capacity of cement in the acid generating tailings.

1.3 Thesis Outline

This thesis consists of six chapters. The content of each chapter are the following:

Chapter 1 is the introduction. It describes brief idea about the research topics that are listed in this thesis. This chapter includes an overview of the tailings properties and research ideas and a summary of research motivation.

Chapter 2 is a detailed literature review that includes broad concepts of each segment of this thesis work. It includes properties of cemented tailings backfill, strength measurement, elastic properties measurement, particle size distribution analysis, rheological properties, and acid mine drainage potential evaluation.

Chapter 3 represents the experimental work of strength, elastic properties and rheological properties evaluation. It describes methodology, materials and equipment that were used for conducting the experiments. Then, finding of those experimental results are described subsequently in this chapter.

Chapter 4 presents the publication of a technical paper at 75th Canadian Geotechnical Conference, GeoCalgary 2022. This chapter investigate the effect of particle gradation on strength development for the backfilling samples collected from the 2021 field trial of SMD project.

Chapter 5 is a technical paper of a proceeding of Tailings and Mine Waste Conference 2023. This paper provides short-term and long-term experimental findings about the acid mine drainage evaluation of tailings and cemented tailings samples in the laboratory set-up.

Chapter 6 provides a conclusion and recommendation for the study presented as well as future work related to strength properties, paste consistency for transportation, acid mine drainage evaluation following the cemented tailings backfilling projects of SMD.

Chapter 2: Literature Review

2.1 Properties of Cemented Tailings Backfill

Cemented tailings backfill (CTB) is a technique used in mining and resource extraction industries to manage and safely dispose of waste materials generated during the mining process. It involves mixing the tailings which are the finely ground rock particles left over after extracting valuable minerals from the ore. Those tailings are mixed with cement and water to create a solidified material that can be used for underground mine backfilling. Here, Cemented paste backfill (CPB) and Cemented tailings backfill (CTB) both terms have been simultaneously mentioned as the same concept of cemented tailings paste mixture.

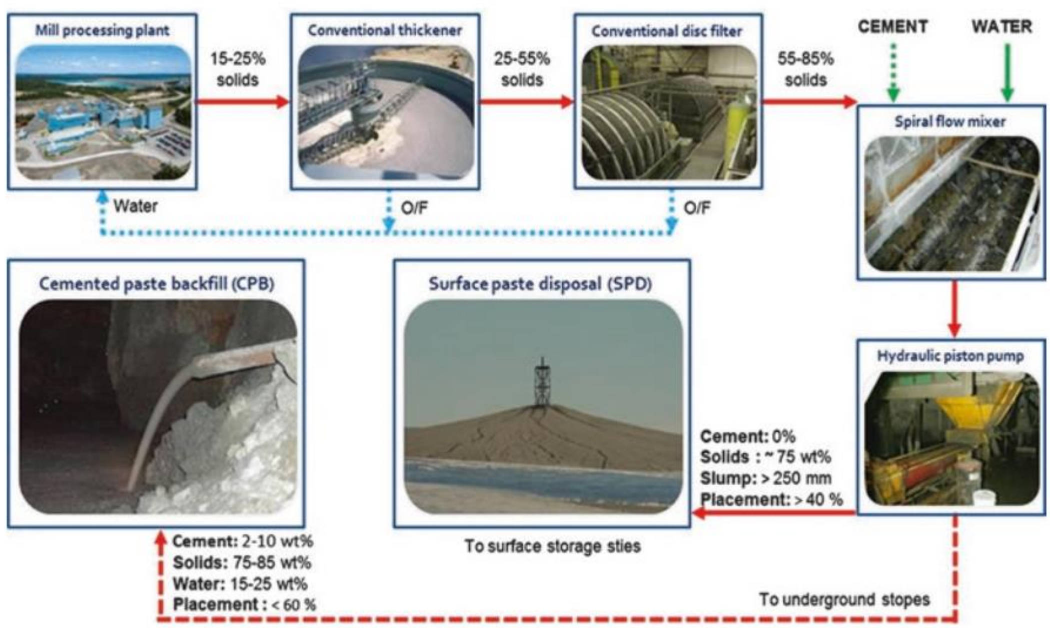


Figure 2-1: Schematic view of integrated paste tailings technology (Yilmaz et al. 2017)

Having a good understanding of CTB properties and the factors that affect them is crucial for designing safe and cost-effective CTB structures. This chapter provides a comprehensive review of the current knowledge on the physical, mechanical, microstructural, and rheological properties of CTB, as well as the factors that influence them. It also addresses the properties used to assess the transportability of CTB, such as yield stress. Figure 2-1 illustrates a schematic view of integrated paste tailings technology process for hard rock mining operations.

2.1.1 Physical Properties

The physical properties of cemented tailings backfill (CTB) such as specific gravity, density, water content, porosity, degree of saturation, moisture content, void ratio, absorption have a significant impact on its behavior and performance. Previous studies have investigated these properties in laboratory settings by several researchers (e.g. Fall et

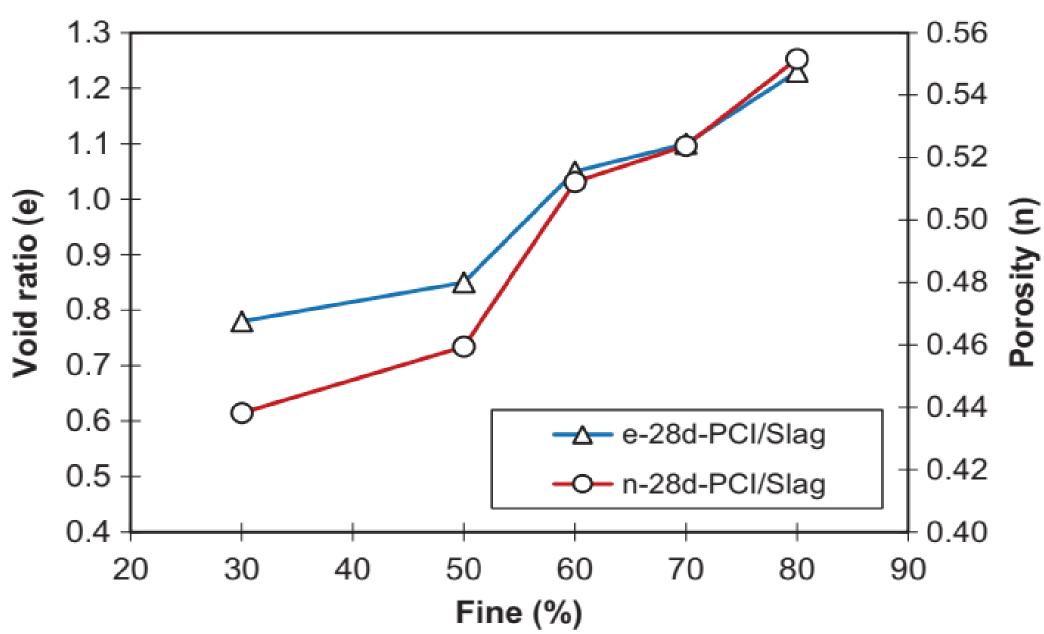


Figure 2-2: Effects of fine content of tailings on void ratio and porosity of CPB (Fall et al. 2004)

al. 2005; Belem et al. 2006; and Yilmaz et al. 2009). However, information about the in-situ physical properties of CTB in real mining conditions is limited in the available literature. This scarcity is primarily due to challenges associated with sampling and testing CTB in the actual mining environment, including restricted access to backfilled areas, interruptions in mining operations, high costs, and safety considerations.

The physical properties of cemented tailings backfill (CTB) are influenced by the physical characteristics of the tailings, particularly the particle size and fine content. The presence of fine tailings (particles smaller than 20 μm) has a notable impact on the porosity (or void ratio) and distribution of pore sizes in CTB. This relationship is illustrated in Figure 2-2 by Fall et al. (2004). When the proportion of fine particles in the tailings is higher, the void ratio of CPB also increases. Additionally, the reduction in porosity is more significant when the fines content decreases in CPB samples made with fine (fines <60%) or medium (fines = 35–60%) fine tailings compared to samples made with coarse tailings (Fall et al. 2004).

2.1.2 Strength Characteristics

The unconfined strength of cemented paste backfill (CPB) is determined based on its specific function in underground stopes. For instance, to prevent risks of liquefaction and barricade collapse, a minimum strength of 0.15 MPa is required during the early stages of curing (Roux et al. 2004). In mining operations that employ cut-and-fill or sublevel methods, CPB is used to ensure stability in adjacent stopes as shown in Figure 2-3. For this purpose, CPB is recommended to have a minimum strength of 0.7 MPa after 28 days of curing (Landriault 1995). Additionally, CPB serves as a sturdy working platform for

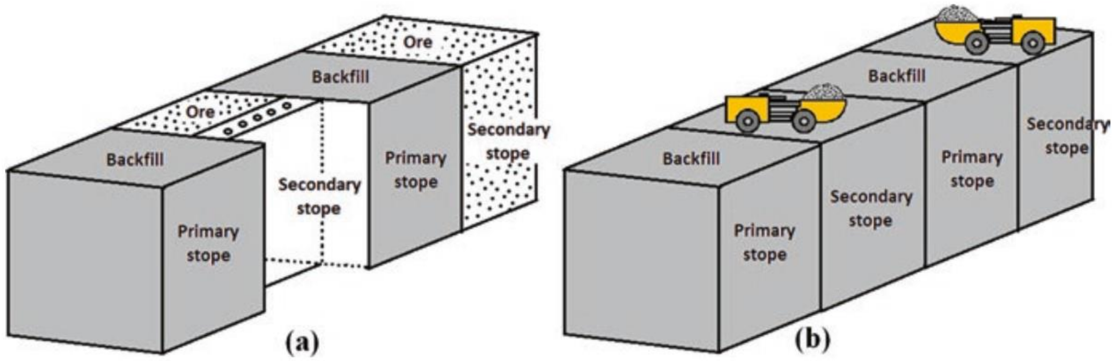


Figure 2-3: Function of paste backfill in underground mining voids (Belem and Benzaazoua 2008, Yilmaz 2017)

equipment and workers, which requires high early strength development (Belem and Benzaazoua 2008).

Consequently, a uniaxial compressive strength (UCS) value of ≥4 MPa is necessary for reliable roof support (Grice 1998). The rate at which the desired strength is achieved helps to reduce downtime between successive mining activities. Therefore, meticulous engineering design is essential to ensure that CPB attains the intended strength requirements.

UCS of CPB

The mechanical strength of cemented paste backfill (CPB) can be influenced by various factors related to the tailings, including their mineralogy content, chemical properties (such as sulphide amount), fine content, density, and grain size (Fall et al., 2005). The type and amount of binder used, as well as the blend ratio of different binders and their chemical properties, can also have an impact on the development of the CPB's mechanical strength (Kesimal et al., 2005). Moreover, the water content in relation to the water-to-cement ratio (w/c) and the chemistry of the mixing water (e.g., sourced from mining processes, lakes, or saline environments) are additional factors that can affect the mechanical properties of CPB.

The impact of the fine content in tailings on the stress-strain behavior of cemented paste backfill (CPB) is depicted in the Figure 2-4. The data demonstrates that as the fine content decreases, both the peak stress and modulus of elasticity increase. The failure modes of samples prepared with varying fine content exhibit similar patterns. However, reducing the fine content to less than 50% does not significantly alter the peak stress and modulus of elasticity. The influence of fine content can be attributed to the fact that CPB containing finer particles necessitates a higher water-to-cement (w/c) ratio to maintain the desired consistency or slump, consequently leading to lower strength of the CPB (Fall et al., 2007).

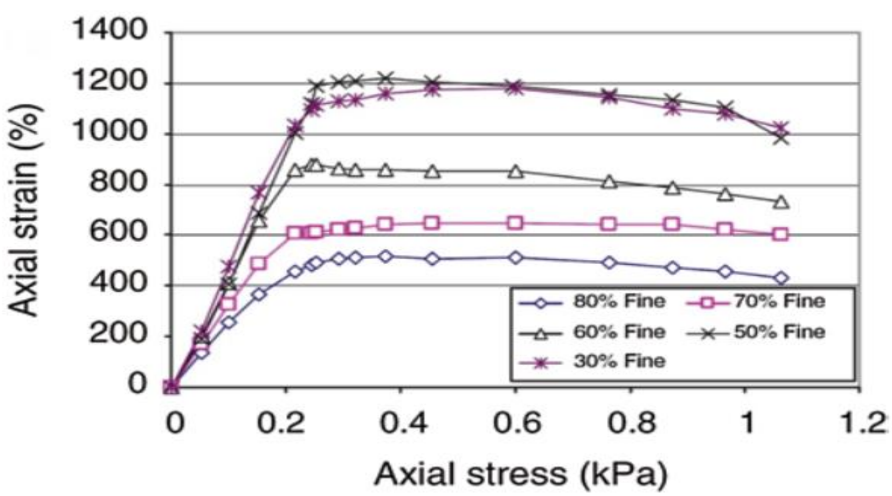


Figure 2-4: Effect of fine content of tailings on the stress–strain behaviour of 28-day CPB samples with 4.5% PCI/slag (Fall et al. 2007)

Stress-Strain Behaviour of CPB

Fall et al. (2007) conducted a study on the compression behavior of CPB to examine how various factors influence its stress-strain behavior and modulus of elasticity. These factors included aging, confinement pressure, and the properties of the main components of CPB (cement, tailings, and water). Stress-strain response of CPB depends on curing time. The impact of cement content on the stress-strain behavior of CPB is illustrated in Figure 2-5. The graph demonstrates that increasing the binder content leads to higher peak stress and modulus of elasticity in CPB samples at a given curing time. Samples with higher binder content exhibit a distinct peak stress and softening after failure, whereas those with lower binder content tend to undergo relatively ductile failure (Fall et al. 2007).

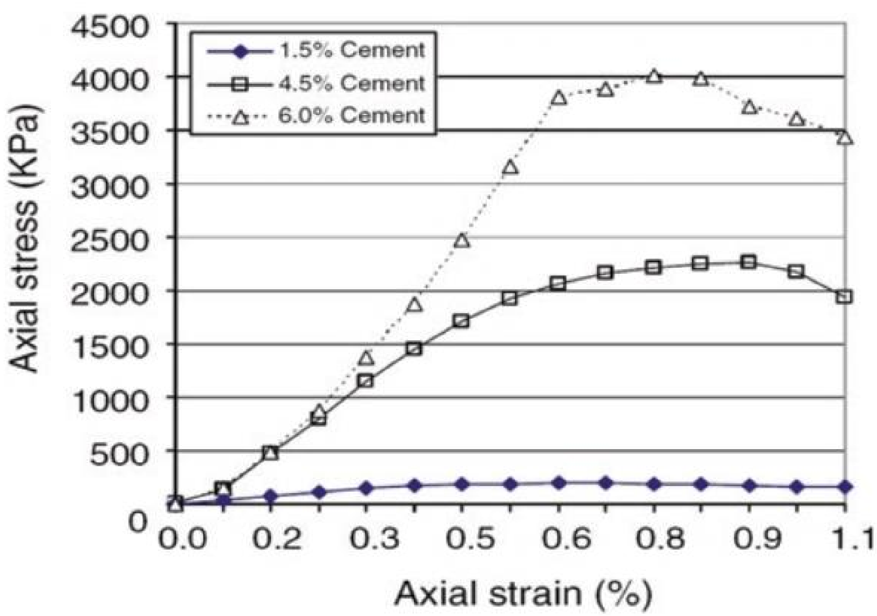


Figure 2-5: Effect of binder content on stress–strain behaviour of 28-day CPB samples with PCI (Fall et al. 2007)

2.1.3 Cement and Alternative Binding Agents

Binders are used to hold solid particles together under specific conditions. There are two main types of binders: hydraulic and non-hydraulic. Portland cement have the capability to undergo a chemical reaction known as hydration, resulting in setting and hardening with the combined of water. In contrast, non-hydraulic binders such as lime and gypsum plaster can harden without water involvement. Among the hydraulic binders, Portland cement type I (PCI) in accordance with ASTM standards is widely utilized. Portland cement (PC) falls into the category of hydraulic cement, as it achieves its setting and hardening characteristics through chemical interactions with water.

By increasing the strength of the backfill, it becomes possible to conduct mining activities in close proximity to the backfilled areas and reduce the need for ore dilution during blasting or excavation near these regions. The impact of the water-to-cement (w/c) ratio and binder content on the compressive strength of cemented paste backfill (CPB) is illustrated in Figure 2-6. The data reveals that for a given binder content, reducing the w/c ratio leads to higher values of unconfined compressive strength (Fall et al., 2008). This effect is primarily attributed to the decreased overall porosity of the backfill resulting from a lower w/c ratio, thereby increasing the UCS (Fall et al., 2008). Similarly, increasing the binder content contributes to higher UCS values. A higher amount of cement encourages more hydration products, which enhances cohesion, reduces porosity and packing density,

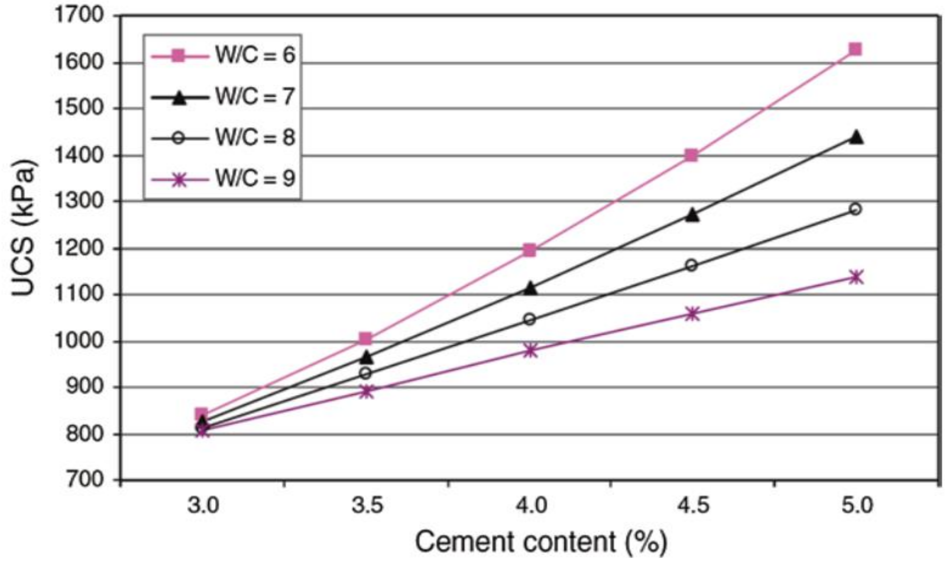


Figure 2-6: Effect of w/c ratio on UCS of 28-day CPB samples with different binder contents (Fall et al. 2008)

ultimately resulting in increased UCS. Furthermore, the presence of fine particles (smaller than 20 µm) in the tailings can significantly influence the strength of CPB. Typically, a granular material needs to have a minimum of 15% by weight of finer particles smaller than 20 µm in order to retain enough colloidal water. This allows the material to form a paste with the desired flow characteristics for efficient transport through particles smaller than 20 µm in order to retain enough colloidal water. This also allows the material to form a paste with the desired flow characteristics for efficient transport through a borehole or pipeline (Ercikdi et al. 2013).

Chemical Composition of Portland Cement

Usually, modern PC primarily contains clinker, which makes up about 95% of its weight. Additionally, a small proportion of gypsum (3%-7% by weight) is added to regulate the

Table 2-1: Chemical Composition of Ordinary Portland Cement. (from Bertrand, 1998)

Principal components of dry cement	Typical Portion	Principal hydration products	Function
Tricalcium silicate: C_3S Ca_3SiO_5(alite) Rapid hardening, early strength development	~50%	1) $2C_3S + 6H_2O \rightarrow Ca_3Si_2O_7 \cdot 3H_2O^{(a)} + 3Ca(OH)_2^{(b)}$ 70% reacted in 28 days	a) Tobermorite gel: principal binding agent of cement. b) Portlandite: no cementing properties
Dicalcium silicate: C_2S Ca_2SiO_4 (belite) Slow hardening, later stage strength development (after one week).	~25%	2) $2C_2S + 4H_2O \rightarrow Ca_3Si_2O_7 \cdot 3H_2O^{(a)} + Ca(OH)_2^{(b)}$ 30% reacted in 28 days; 90% in one year	Same as above
Tricalcium aluminate: C_3A $Ca_3Al_2O_6$ Consumes $Ca(OH)_2$, produces a high heat of hydration.	~10%	3) $C_3A + 12H_2O + Ca(OH)_2 \rightarrow Ca_4Al_2O_6(OH)_2 \cdot 12H_2O^{(c)}$ 4) $C_3A + 10\ H_2O + CaSO_4.2H_2O \rightarrow Ca_4Al_2(SO_4) \cdot 12H_2O^{(d)}$ 5) $C_3A + 26H_2O + 3CaSO_4 \cdot 2H_2O \rightarrow Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O^{(e)}$	c) Tetraclacium aluminate hydrate: some early strength development d) Monosulfoaluminate and e) Ettringite: expansive minerals produced from the reaction of dissolved gypsum with C_3A
Tetracalcium aluminoferrite: C_4AF $Ca_4Al_2Fe_2O_{10}$ Manufacturing purpose to reduce clinkering temperature; responsible for colour effects in cement.	~8%	6) $C_4AF + 50H_2O + 2\ Ca(OH)_2 \rightarrow Ca_6Al_2Fe_2O_{14} \cdot 12H_2O^{(f)}$ 7) $C_4AF + 12H_2O + 6CaSO_4.2H_2O + Ca(OH)_2 \rightarrow Ca_6Al_2(SO_4)_3(OH)_{12} \cdot 26H_2O^{(e)}$	f) Calcium aluminoferrite hydrate: rapid hydration but little strength contribution. Slow hydration reaction to produce ettringite.
Gypsum: $C\underline{S}H_2$ $CaSO_4$*$2H_2O$ Very rapid dissolution, slows the rate of C_3A hydration to avoid flash setting.	~5%	Dissolved gypsum may participate in reactions (4), (5), (6) and (7), depending on the local pore water chemistry.	Too much gypsum may favour the formation of ettringite over portlandite.
Fe, K, Mg Present in clays used to make Portland cement.	Few %		May be included in any cement phase in solid solution.

initial setting time of the cement. Table 2-1 describes the various elements that make up Normal or Ordinary Portland Cement (OPC) typically used in cemented paste backfill, along with the principal hydration reactions involved in the curing of cement mixtures.

Hydration Stages of Cement

Figure 2-7 visually demonstrates the sequential stages of hydration that occur in individual cement compounds, as explained by Taylor et al. (2006). These stages are a result of both thermal and physical transformations taking place within the cement particles throughout the entire hydration process. The main reactants involved in this process include alite, belite, aluminate, ferrite, gypsum, and water. Additionally, there are minor reactants, such as alkali sulfates and free lime.

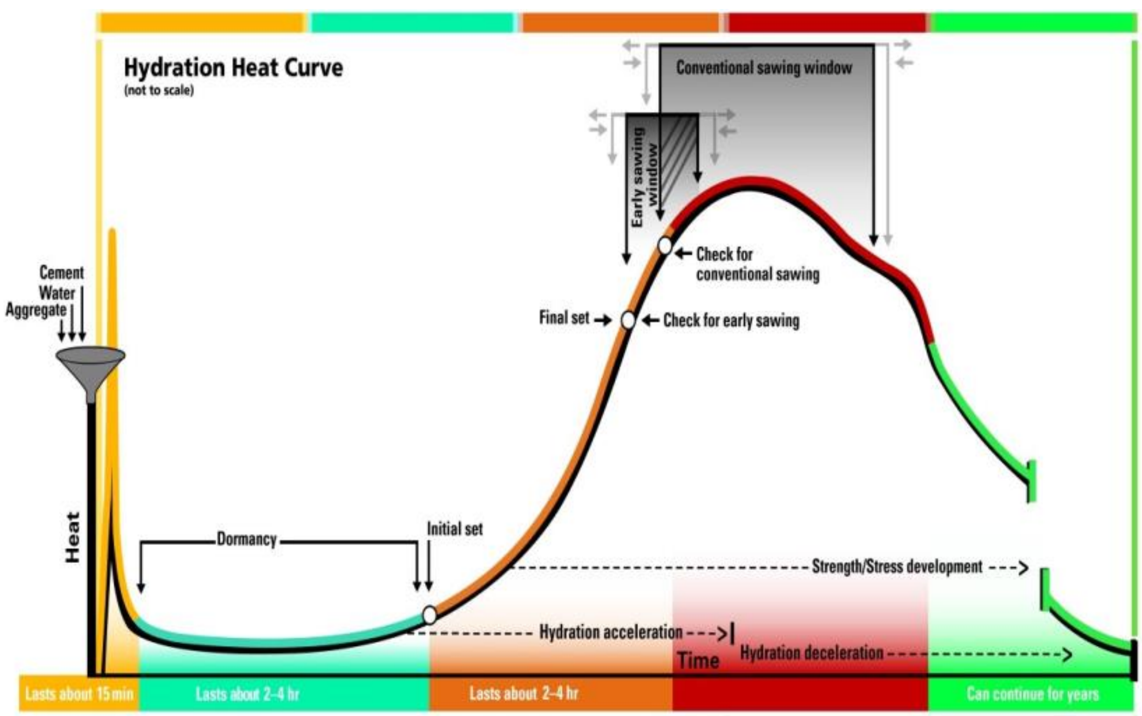


Figure 2-7: Thermal and physical changes in cement particles during all stages of cement hydration (Taylor et al., 2006)

Alternative Binding Agents

These alternative binders aim to provide similar or improved performance compared to cement while addressing certain limitations or environmental concerns associated with cement production. One common alternative binder is fly ash, which is a by-product of coal combustion. Fly ash possesses pozzolanic properties, meaning it can react with calcium hydroxide in the presence of water to form cementitious compounds. By incorporating fly ash into cemented paste backfill mixtures, it is possible to enhance the strength and durability of the backfill while reducing the reliance on cement. This can lead to improved sustainability and reduced carbon footprint.

Another alternative binder is slag, a by-product of the iron and steel industry. Similar to fly ash, slag also exhibits pozzolanic properties and can contribute to the development of strength in cementitious systems. Using slag as a binder in cemented paste backfill can offer advantages such as enhanced long-term stability and reduced permeability. Other alternative binders being explored include industrial by-products such as silica fume, metakaolin, and rice husk ash, as well as geo-polymers. Different types of alternative binding additives and their effects are presented in the Table 2-2. These materials offer potential benefits such as high early strength development, improved chemical resistance, and reduced environmental impact. The selection of alternative binders for cemented paste backfilling depends on various factors, including the specific application, desired performance properties, availability of materials, and economic considerations.

Table 2-2: Replacement Components of Portland Cement to Improve Sulphate Resistance of Concrete (from Bertrand, 1998)

Additive	Effect
Fly ash: Coal combustion residue; low calcium (Torri et al., 1995) (Djuric et al., 1996)	Lower air and pore volume, reduced permeability, increases resistance to sulphate absorption into concrete
Silica fumes: Silicon, silicon alloy smelting ash residue; minimum 75% silicon, very low calcium and aluminium oxides (Aköz et al., 1995)	Lower air and pore volume, very reduced permeability, decreases gypsum and ettringite formation, increases electrical resistivity (corrosion protection)
Blast furnace slag: Glassy iron smelting residue; calcium silicates and aluminosilicates may be high (13 – 15%) Al_2O_3 slag or low (3 – 5%) Al_2O_3 slag (Irassar et al., 1996)	Lower air and pore volume, reduced permeability, may increase mixture strength in the end

The presence of sulphides or sulphate in mine tailings can have detrimental effects on the setting ability and long-term durability of cement and concrete mixtures. The high sulphate concentrations in residual process water and the surrounding environment further contribute to the weakening of the concrete's physical strength. These sulphates react with the hydrated cement, resulting in the formation of expansive minerals like gypsum, which leads to cracking and loss of strength. To mitigate these effects, additives such as slag are used to reduce reliance on portlandite as a binder and enhance resistance to sulphate solutions. While the addition of cement provides some neutralization potential, careful consideration is needed to ensure that the ratio of neutralization potential to acid generating potential (Neutralization Potential Ratio or NPR) is sufficient to alter the acid generating classification of the backfill material.

2.1.4 Particle Size Distribution and Particle Shape

Particle size distribution (PSD) is a critical factor in cemented paste backfilling (CPB) that significantly influences the performance and properties of the backfill material. It impacts workability, strength, permeability, and stability, as well as the hydration process of cement. Optimizing particle size distribution ensures better packing, reducing void spaces and enhancing density and strength. It promotes improved cohesion, stability, and flowability, facilitating transportation and placement of the mixture. Proper management of particle size distribution enables efficient void filling, reduced dilution of ore, and controlled rheological properties that lead to successful underground mining operations and increased productivity. Figure 2-8 shows PSD examples in the literature and Table 2-3 summarises their corresponding PSD parameters (Qi et al. 2019).

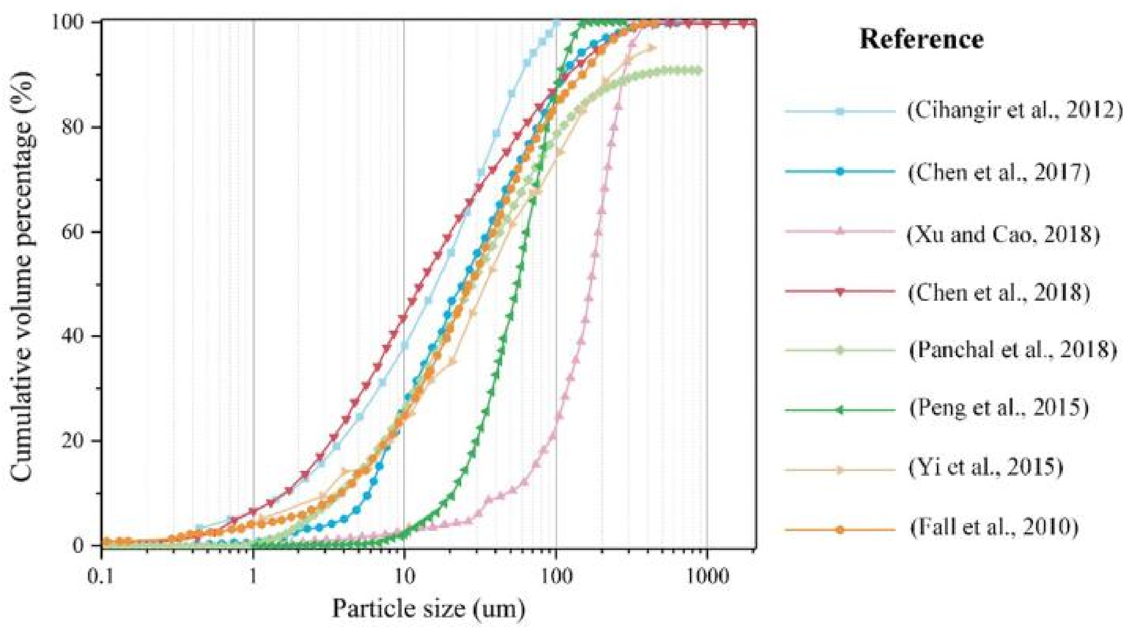


Figure 2-8: Typical PSD examples of tailings from the literature (Qi et al. 2019)

Altering the particle size distribution of tailings material can enhance the effectiveness of paste backfill. Hydro-cyclones have long been employed to achieve this by generating distinct grain size categories, such as fine, medium, and coarse tailings. The selection of appropriate hydro-cyclone sizes and control of operating variables enable the production of desired particle size classes, facilitating improved performance of the paste backfill mixture. The development of blended or composite fills emerged from efforts to engineer and optimize uniformly graded fine or coarse materials for the purpose of creating a structurally sound product. These innovative fill materials, also referred to as "aggregate" fills, aim to achieve an optimal combination of properties through the careful blending and composition of different materials. The goal is to create a cohesive and well-graded mixture that exhibits enhanced structural integrity and performance (Annor B.A. 1999).

Table 2-3: PSD Properties of Tailings in Figure 2-8 (Qi et al. 2019)

Reference	Minerals	Country	D_{10} (μm)	D_{50} (μm)	D_{60} (μm)	C_u	C_c
Cihangir et al. (2012)	Copper-zinc	Turkey	1.70	16.25	22.83	13.41	1.18
Chen et al. (2017)	Copper	China	5.16	24.20	35.40	6.86	1.03
Xu and Cao (2018)	Copper	China	46.38	170.13	190.80	4.11	1.62
Chen et al. (2018)	Phosphate	China	1.50	13.00	20.50	13.67	0.98
Panchal et al. (2015)	Uranium	India	3.45	22.65	32.76	9.44	0.96
Peng et al. (2015)	Tungsten	China	20.77	55.24	64.80	3.12	1.07
Yi et al. (2015)	Nickel	China	3.12	34.32	48.45	15.53	1.27
Fall et al. (2010)	Polymettalic	Canada	3.70	22.40	32.50	8.70	4.00

The particle shape of tailings in cemented paste backfill is an important factor that influences the flow ability, packing density, and mechanical properties of the mixture. Tailings with irregular and angular shapes enhance interlocking and improve strength, while rounded or spherical particles promote flow ability. Achieving a balanced distribution of particle shapes is crucial for optimizing the performance of cemented paste backfill, ensuring both adequate strength and ease of placement. Factors such as ore processing methods and geological characteristics impact the particle shape, and understanding and controlling this distribution can help optimize the design and effectiveness of cemented paste backfill in underground mining operations (Hassan and and Archibald 1998)

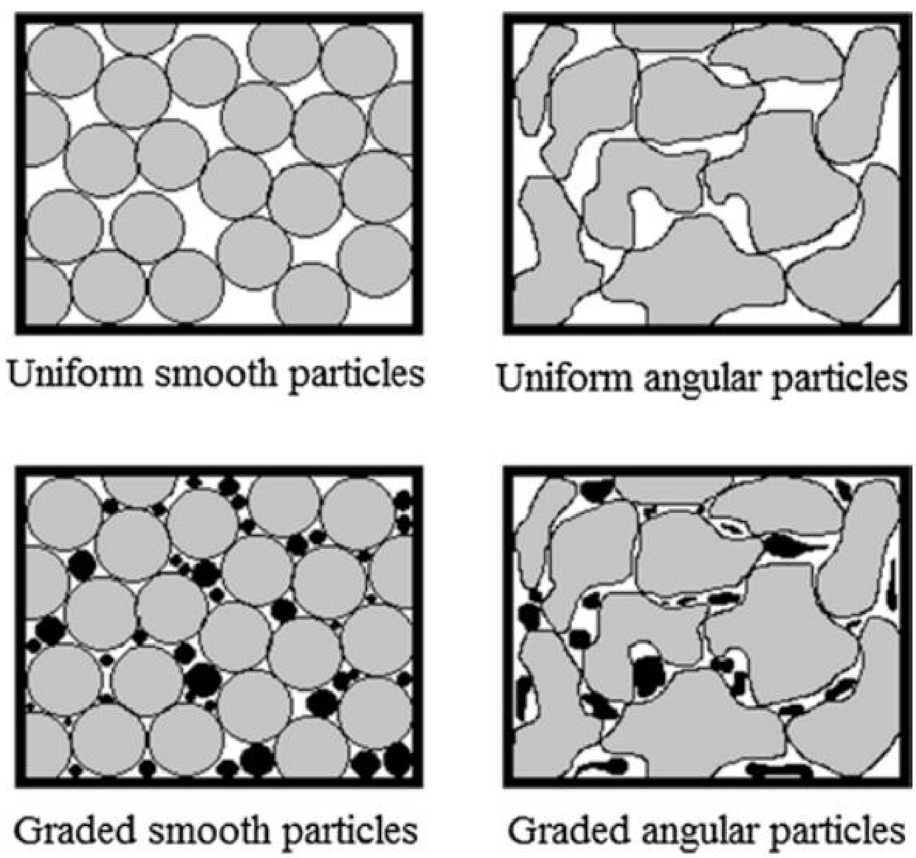


Figure 2-9: Effect of particle shape on interconnection of tailings in backfill (Hassan and Archibald 1998)

2.1.5 Mineralogical Analysis

Mineralogical analysis of tailings and cemented paste backfill involves the identification, quantification, and characterization of minerals present in these materials. Techniques such as X-ray diffraction, scanning electron microscopy, and mineral liberation analysis are utilized to understand the mineral composition and potential chemical reactions. This analysis provides crucial insights into the behavior and performance of cemented paste backfill. This also helps in the selection of suitable binders and additives, optimizing strength development, settling characteristics, and long-term stability. By examining the mineralogical properties, engineers can enhance the design and efficiency of cemented paste backfill systems, contributing to more sustainable mining practices.

Microstructural analysis techniques, such as scanning electron microscopy (SEM), are commonly used to examine the surface and subsurface structure of materials. In the context of cement chemistry and cemented paste backfill, microstructural analysis helps to understand the hydration process and its progression over time. Figure 2-10 presents an example of microstructural analysis conducted on tailings using scanning electron

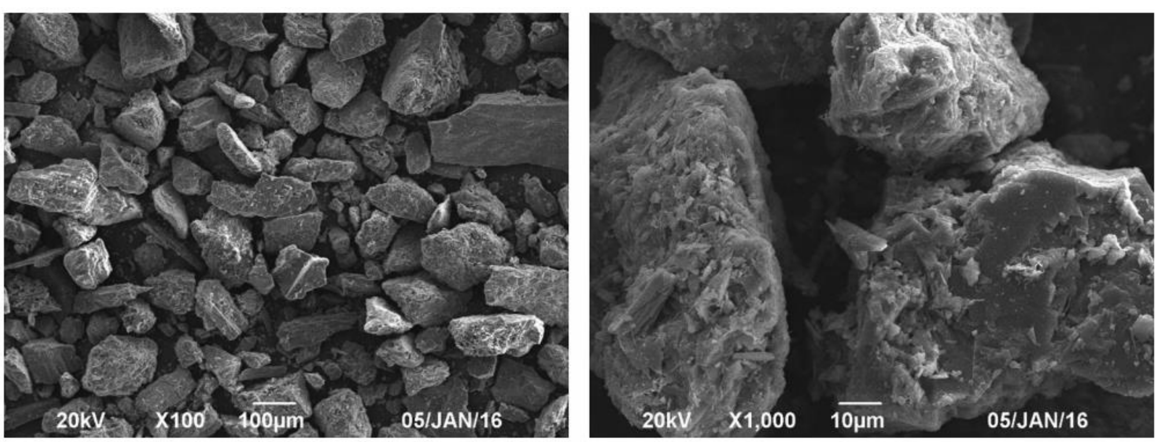


Figure 2-10: SEM images of tailings showing the typical angular particle shape (Qi et al., 2019)

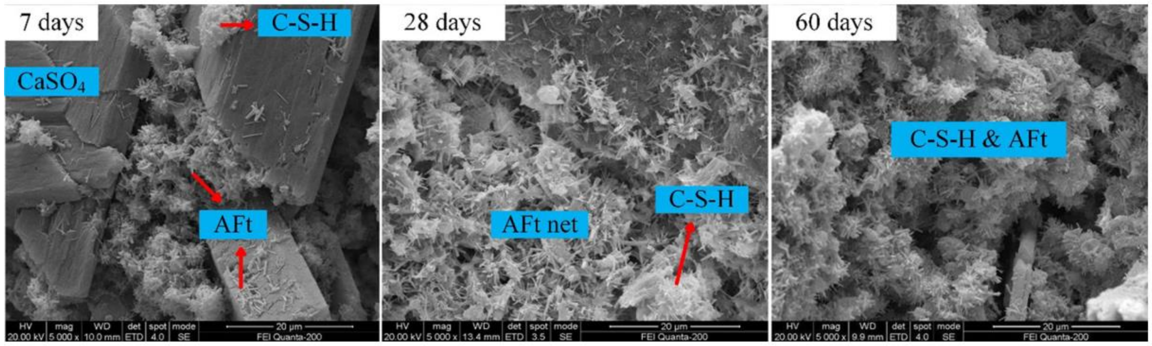


Figure 2-11: SEM images of CPB samples after curing for 7, 28, and 60 days (Chen et al., 2018).

microscopy (SEM). Other alternative techniques, such as environmental scanning electron microscopy (ESEM), transmission electron microscopy (TEM), scanning transmission electron microscopy (STEM), and Cryo-electron microscopy, can also be employed for detailed analysis. These techniques provide valuable insights into the microstructure and can contribute to the optimization and understanding of cemented paste backfilling. Figure 2-11 presents an example of microstructural analysis conducted on cemented paste backfill (CPB) using scanning electron microscopy (SEM). The image demonstrates the progression of cement hydration over time during the curing process (Chen et al., 2018).

2.2 Ultrasonic Properties Measurement

Ultrasonic properties measurements are commonly employed to assess the physical and mechanical characteristics of cemented paste backfill (CPB). These measurements utilize high-frequency ultrasonic waves to investigate the properties of the backfill material. Ultrasonic properties measurements offer a non-destructive and efficient means of evaluating the strength properties. One of the key parameters measured using ultrasonic techniques is the ultrasonic pulse velocity (UPV). UPV represents the velocity at which the ultrasonic waves propagate through the CPB sample. The UPV is influenced by various factors: such as the binder type and content, the density, porosity, composition and the presence of any defects or discontinuities within the material.

By measuring the UPV, valuable information can be obtained about the integrity, homogeneity, and quality of the CPB. Changes in the UPV can indicate variations in the internal structure, density, and stiffness of the backfill material, providing insights into its mechanical properties. Ultrasonic techniques also enable the determination of other properties, including the elastic modulus and Poisson's ratio of the CPB. These parameters provide insights into the material's ability to withstand stress and strain, its deformation behavior, and its overall stiffness. Typical values of P-wave and S-wave of different earth materials is depicted in the figure 2-12.

Ultrasonic measurement setups for characterizing the elastic properties development in hydrating mine backfill typically involve the use of ultrasonic transducers

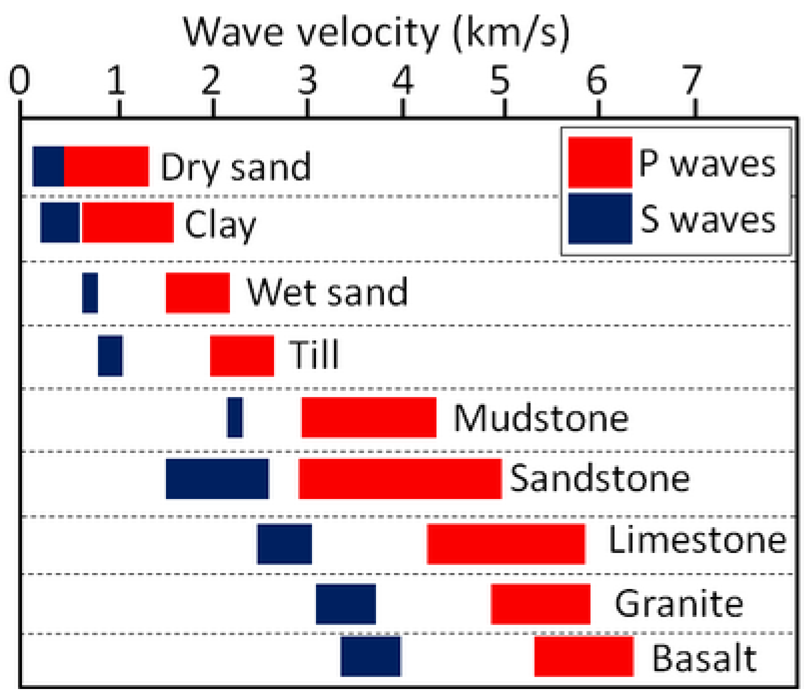


Figure 2-12: Typical velocities of P-waves (red) and S-waves (blue) in sediments and in solid crustal rocks (US EPA 2003)

and instrumentation. The transducers emit high-frequency sound waves into the backfill material, and the reflected waves are detected by the transducers. By analyzing the time it takes for the waves to travel through the material and the amplitude of the received signals, various properties can be determined. These properties may include the velocity of the waves, which is related to the stiffness of the backfill and the attenuation of the waves. The measurement setup often includes positioning the transducers at specific locations within the backfill and recording the ultrasonic signals over time to monitor the development of stiffness during the hydration process.

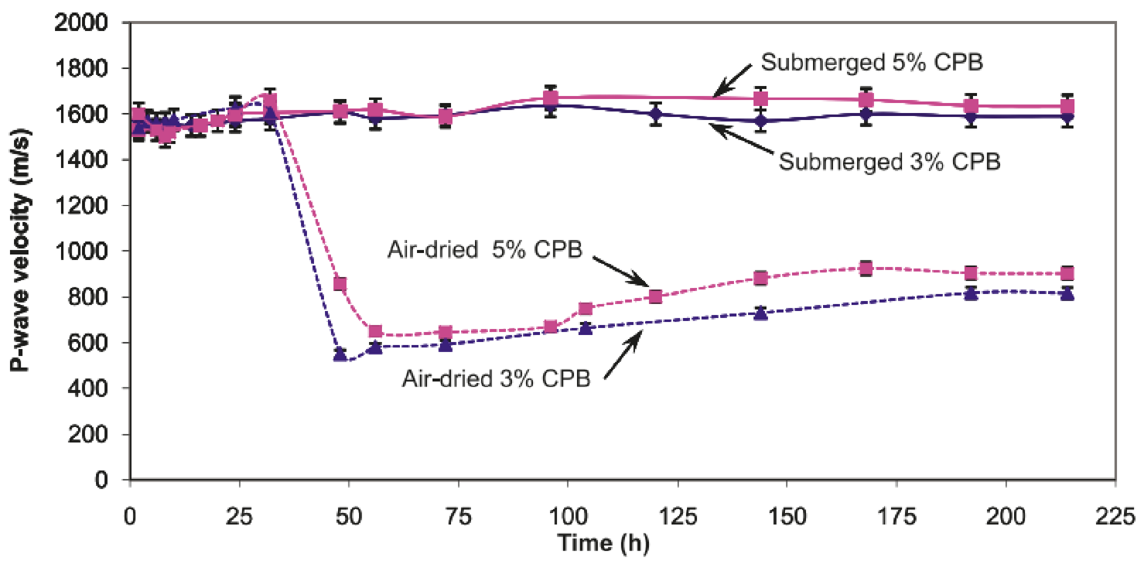


Figure 2-13: Development of P-wave velocity with time for drying and submerged CPB samples containing 3% and 5% binder (Galaa et al. 2011).

Galaa et al. (2011) conducted a pioneering study on ultrasonic properties measurement for cemented paste backfilling samples. Their CPB samples comprised with Portland cement and mine tailings from the Williams mine in Hemlo, Northern Ontario. The objective of the test was to measure the velocities of P-waves (Vp) and S-waves (Vs) in the samples over a period of one week after the mixing. Initial measurements were

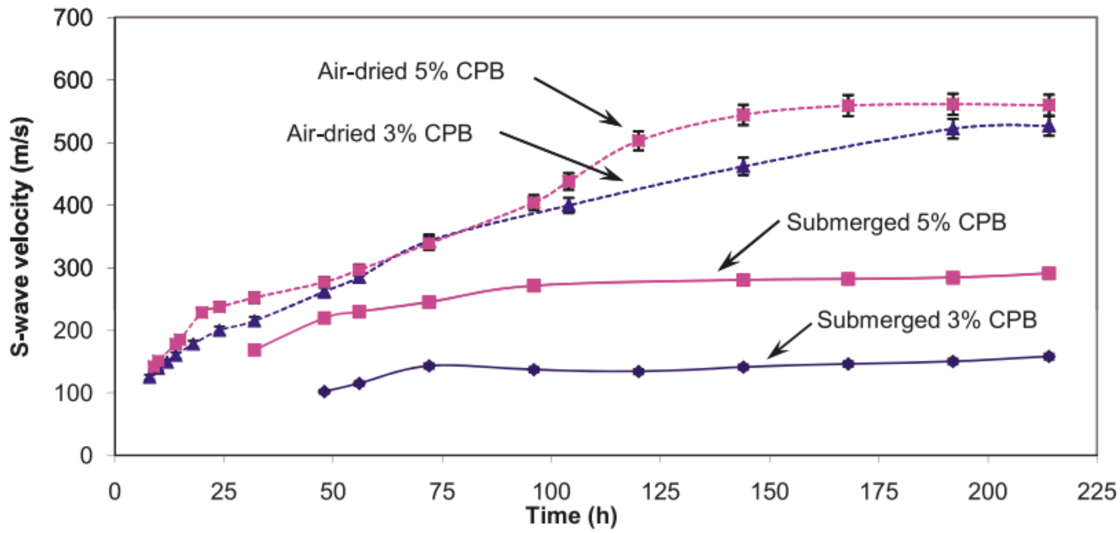


Figure 2-14: Development of S-wave velocity with time for drying and submerged CPB samples containing 3% and 5% binder (Galaa et al. 2011).

conducted within the first 24 hours while the CPB was still in its soft state containing in their molds. Two sets of samples were tested, one stored in air and the other submerged in water. The measurements of P-wave velocities were recorded for the entire duration of the testing, considering both binder contents and different relative humidity (RH) conditions. P-waves were found to propagate through CPB in both its fluid and solid states. The results for P-wave and S-wave velocities are presented in Figure 2-13 and Figure 2-14. The S-waves were detected after 8 hours in the drying CPB samples, with velocities of approximately 120 m/s for 3% CPB and 140 m/s for 5% CPB, with an error range of ±4 m/s. From their experiment, it's found that the S-wave velocities in the 5% CPB were slightly higher than those in the 3% CPB (Galaa et al. 2011).

2.3 Rheological Properties

Significant amount of tailings are generated in the mineral processing phase of the ores after mining operation. Disposal and safety of tailings and their environmental effects are concerning matter for the mining industry. The most conventional way of managing tailings are disposal into tailing dams or discharging into available water reservoir zone. Backfilling into underground mine has become popular nowadays as a form of sustainable management of tailings. The rheological analysis of tailings paste, cemented paste backfilling has been developed due to the engineering requirements of mineral processing, thickening, paste mixing, pipeline transportation, deformation of the filling body.

2.3.1 Paste Rheology in Metal Mines

Rheology is a field focused on understanding and mathematically describing the flow behaviors of materials. In the context of metal mining, rheological studies aim to develop constitutive equations that can predict the behavior of pastes used in processes like

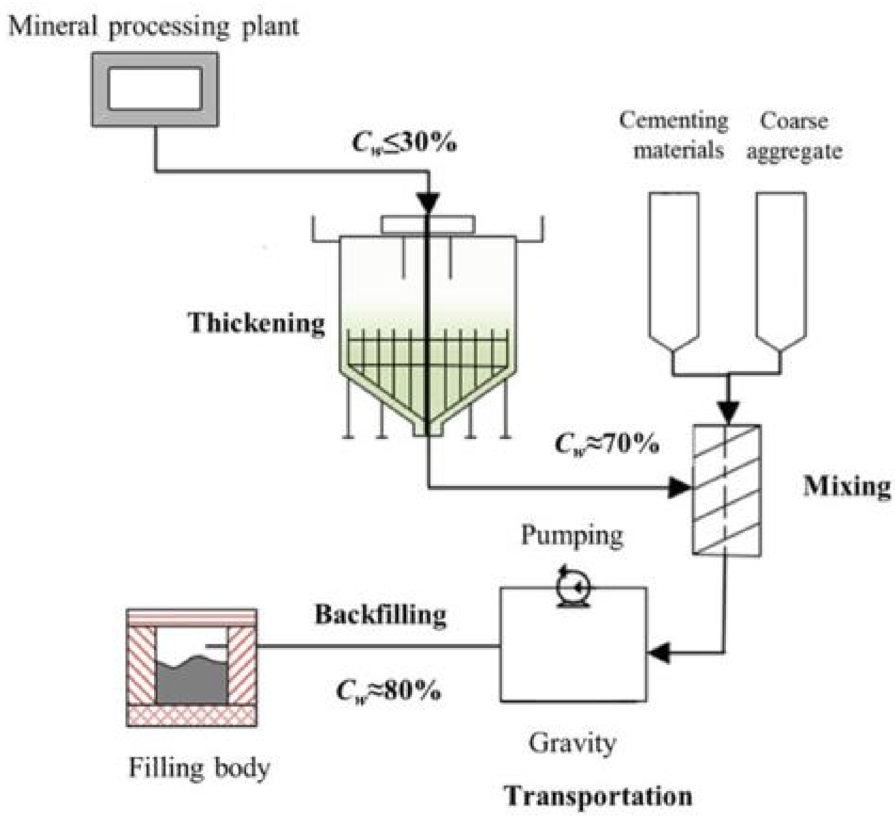


Figure 2-15: Flow Chart of Cemented Paste Backfill in Metal Mines (Wu, 2022)

thickening, mixing, transportation, and backfilling. Experimental methods are used to measure physical properties and validate these equations. Once the mathematical equations are determined, they can be used to analyze the flow properties and deformation of the paste materials. Numerical solutions are typically employed due to the complexity of non-Newtonian fluids. The goal is to meet the engineering needs of metal mining processes by applying rheological principles and developing models to describe material behavior.

Rheological analysis focused on understanding and mathematically describing the flow behaviors of materials. In the context of metal mining, rheological studies aim to develop constitutive equations that can predict the behavior of pastes used in processes like thickening, mixing, transportation, and backfilling. Experimental methods are used to measure physical properties and validate these equations. Once the mathematical equations are determined, they can be used to analyze the flow properties and deformation of the paste materials. Numerical solutions are typically employed due to the complexity of non-Newtonian fluids. The goal is to meet the engineering needs of metal mining processes by applying rheological principles and developing models to describe material behavior.

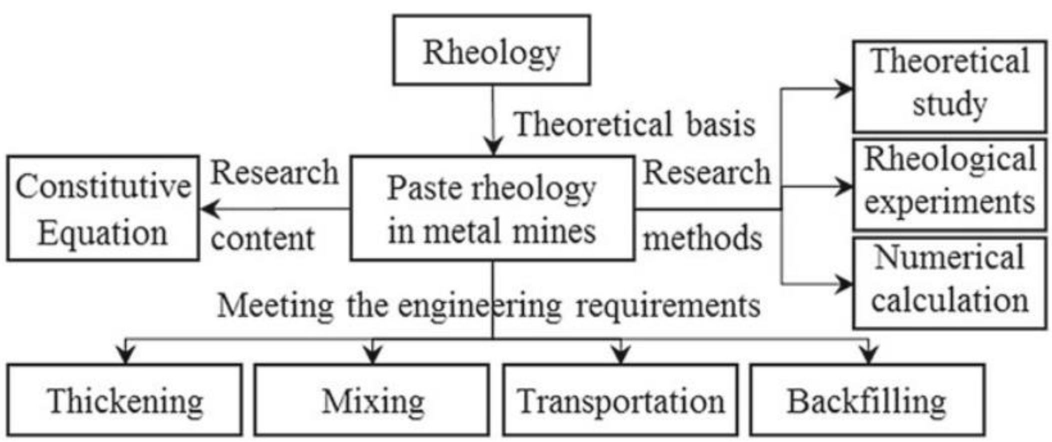


Figure 2-16: Framework of Paste Rheology in Metal Mines (Wu, 2022)

2.3.2 Flow Properties of Tailings

Rheological analysis is crucial in understanding the flow and deformation of tailings paste and cemented paste backfilling materials. The focus is on establishing constitutive equations that mathematically express the rheological behavior of the paste, including its flow and deformation under specific shear and flow conditions. Rheology explores the deformation and flow of various materials, ranging from fluids to solids and suspensions. By combining experimental and theoretical approaches, the goal is to develop a comprehensive understanding of how materials deform and flow, leading to the establishment of mathematical models that describe their behavior, known as constitutive equations.

In South African platinum mining, tailings slurries consist primarily of either Merensky or UG2 reef. The flow characteristics of these tailings types in each mine can vary due to factors such as particle size distribution, solids concentration, and rheological properties. The effect of slurry density (solid concentration) on the energy requirements for pumping can be illustrated by considering the change in flow behavior at different densities. Specifically, for a Merensky tailings system at Mine A, the flow behavior transitions from 1.55 to 2.10 t/m^3. Typical slurry properties for Merensky (Mine A) and UG2 tailings (Mine B) at these densities are provided in Table 2-4. At a density of 2.10 t/m^3, the Merensky tailings are likely to exhibit a paste-like flow behavior, while UG2 tailings still have a relatively low yield stress and behave more like thickened tailings (Paterson, 2004).

Table 2-4: Comparison of Tailings Flow Properties from Two Mines (Paterson, 2004)

Parameter	Mine A: Merensky			Mine B: UG2		
Slurry density (t/m^3)	1.55	1.70	2.10	1.55	1.70	2.100
Solids density (t/m^3)	3.15–3.24 (3.20 average)			3.47–3.51 (3.49 average)		
Solids concentration	51.6%m	59.9%m	76.2%m	49.7%m	57.7%m	73.4%m
Solids concentration	25.0%v	31.8%v	50.0%v	22.1%v	28.1%v	44.2%v
Mean particle size, d_{50}	65–100 μm			50–70 μm		
Bingham yield stress	1.51 Pa	4.55 Pa	102.53 Pa	1.05 Pa	3.06 Pa	45.41 Pa
Plastic viscosity	0.0046 Pa.s	0.0088 Pa.s	0.4093 Pa.s	0.0041 Pa.s	0.0071 Pa.s	0.1162 Pa.s
Flow regime	Conventional	Thickened	Paste	Conventional	Thickened	Thickened

2.3.3 Yield Stress of Different Materials

The study of rheology primarily involves two aspects: (i) converting the flow behavior observed in experiments into mathematical equations, and (ii) developing a constitutive equation that can predict flow behavior not yet observed, creating a mathematical representation of mechanical behavior. Fluids that require a minimum stress to initiate flow and exhibit a solid-like response with small deformation before flowing are known as yield-stress. These fluids behave similarly to Newtonian or pure-viscous non-Newtonian fluids when the applied shear stress exceeds the threshold. Although they continue to display viscous behavior after yielding and flow initiation. Some classify them as pure-viscous non-Newtonian fluids (generalized Newtonian fluids). Examples of yield-stress non-Newtonian fluids include mud, toothpaste, and concrete paste.

Table 2-5: Yield Stress of Different Materials (Yilmaz, 2017)

Tomato Sauce	15 Pa
Salad Dressing	30 Pa
Toothpaste	110 Pa
Mayonnaise	100 Pa
Peanuts Butter	1500 – 1900 Pa
Thickened Tailing Disposal	30 - 100 Pa
Mine Stope Fill	250 – 800 Pa

The Bingham fluid is a type of non-Newtonian fluid with yield stress, commonly found in high-concentration suspensions, drilling fluids, toothpaste, and certain paste in mines. The flow behavior of a Bingham fluid is determined by whether the applied shear stress exceeds its yield stress, with flow only happening when $\tau > \tau y$ (Wu, 2022). Examples of yield-stress for non-Newtonian fluids include substances like mud, toothpaste, tailings paste shown in table 2-5. Clayton et al. (2003) experimentally showed that two mixtures having the same slump value can exhibit varying yield stresses. Mixtures with a yield stress that is excessively low may result in lower strength values for a specific binder dosage. Table 2-6 provides the yield stresses for materials having the same slump value but different densities.

Table 2-6: Slump and Yield Stress Values of Different Mixtures (Clayton et. al, 2003)

Parameters	Coal Tailings	Gold Tailings	Lead-Zinc Tailings
Specific gravity (kg/m^3)	1450	2800	4100
Solids concentration (%)	36	75	75
Slurry density (kg/m^3)	1120	1930	2310
Slump height (mm)	203	203	203
Yield stress (Pa)	160	275	330

Figure 2-17: Slump Test with (a) a high value, (b) a normal value and (c) and a low value (Yilmaz, 2017)

2.3.4 Yield Stress Measurement

The slump height is commonly used to assess the consistency of materials. However, this measure can be influenced by various factors such as chemical composition, particle properties and changes in density. In the mining context, relying solely on slump height for consistency assessment can lead to problems. Therefore, yield stress is a reliable measurement. If a relationship between slump height and yield stress can be established, the slump test would be a convenient on-site method for measuring yield stress. The fluidity of paste backfill is influenced by multiple factors, including solid ratio, water-to-cement ratio, binder type and proportion, additives, particle characteristics, density, surface area, and chemical properties. Increasing the water content in a paste backfill mixture results in higher slump values and facilitates easier transportation through pipelines. However, excessive water can extend the curing time, reduce the strength and durability of the mixture.

Several models have been created to link the slump value to a corresponding yield stress and predict the slumping behavior of the material. These models are based on fundamental principles and use dimensionless variables, making them a material-independent and unique representation of the relationship between yield stress and slump height. However, some uncertainty remains about the yield stress measurement techniques used in these studies, so it is difficult to make definitive conclusions about the accuracy of the models.

2.4 Consolidation of Cemented Tailings Backfill

There has been a developed consensus found from the literature that the strength of the cemented paste backfill (CPB) sample made in the laboratory is different from the mixture poured in the in-situ place. It is widely acknowledged that CPB samples produced in the laboratory exhibit consistently lower mechanical strength compared to CPB samples placed in the actual mining site. The underlying reason for this disparity lies in the gradual development of effective stresses within the stope, resulting from self-weight or time-dependent consolidation loads in the in-situ backfill material. These stress conditions contribute to the progressive development of final strength. However, replicating the precise in-situ CPB placement and properties using conventional molds in the laboratory considered as a major constraint. This is primarily due to the inability to replicate the exact in-situ conditions and the lack of suitable laboratory equipment and procedures (Servant, 2001).

2.4.1 CPB Consolidation Effect

When a load is applied to a saturated mass, the energy initially affects the pore water pressure. This consolidation process takes time and is influenced by the permeability of the materials. Coarse-grained materials with higher permeability consolidate more quickly, while fine-grained materials with lower permeability take longer. The rate of consolidation depends on factors such as fluid viscosity, pore-size distribution, grain-size distribution, void ratio, mineral particle roughness, and saturation.

The strength differences between laboratory-prepared cemented paste backfill (CPB) samples and in situ backfill material are influenced several factors (such as scale effects, placement methods, and in situ curing conditions). It is important to accurately measure and understand the properties of field materials to optimize CPB recipes. Studies have shown that the unconfined compressive strength (UCS) of CPB placed underground can be significantly higher (4 to 6 times) than laboratory-prepared samples of the same CPB recipe cast in conventional molds (Belem et al., 2002; Yilmaz et al., 2006). In-situ strength also indicates that laboratory-made CPB samples underestimate the strength of in situ CPB by a significant margin of 50% to 200%. (Grabinsky et al., 2008).

From literature, it's also found that curing cemented materials under effective stress enhances their mechanical strength, depending on the type and proportion of binders used (Belem et al., 2002). The timing of applying the effective stress relative to the curing process is crucial for CPB strength development. Applying the effective stress immediately

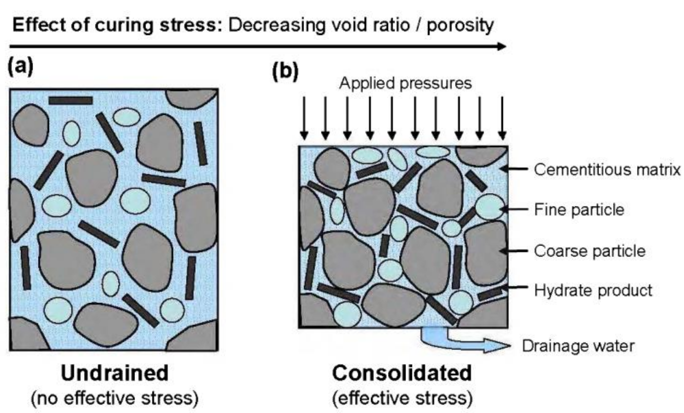


Figure 2-18: Schematic representation of the effect of curing stress on the paste backfill performance: a) undrained CPB sample; b) consolidated CPB sample (Yilmaz et al., 2010)

before curing leads to higher strength due to the formation of cement bonds during hydration (Fourie et al., 2006). However, if curing stress is applied after a few days of hydration, the forming cement bonds may break down which leads to reduced material strength and stiffness (Yilmaz et al., 2010). Understanding these factors is essential for improving the performance and reliability of CPB in practical applications.

2.4.2 Curing Under Applied Pressure System (CUAPS)

As the CPB mixture is placed and hardens in a stope, its own weight and pressure create a downward force that compresses the paste from the top to the bottom. This process aids in the consolidation of the lower layers at an early stage. Yilmaz et al. (2009) did comprehensive research on the effect of curing under pressure on compressive strength development of CPB. The design of the curing under applied pressure system (CUAPS) apparatus (figure 2-19) was influenced by a previous consolidation setup used by Belem et al. (2002). CUAPS apparatus built to assess the in-situ strength performance of CPB under loading by applying pneumatic pressure (up to 600 kPa) to the upper portion of sample. The operating principle of CUAPS consists of one-dimensional compression of CPB sample in a pressure vessel (Perspex cylinder) by vertical pressure application. The applied pressure enables the excess pore water to escape from CPB material through a drainage port located at the bottom of the unit. The CUAPS tool consists of three main component. A rigid top plate with an axial loading piston that applies a pneumatic pressure and with a dial gauge and pressure valve. A rigid Perspex mould protected by a metal cylinder to hold

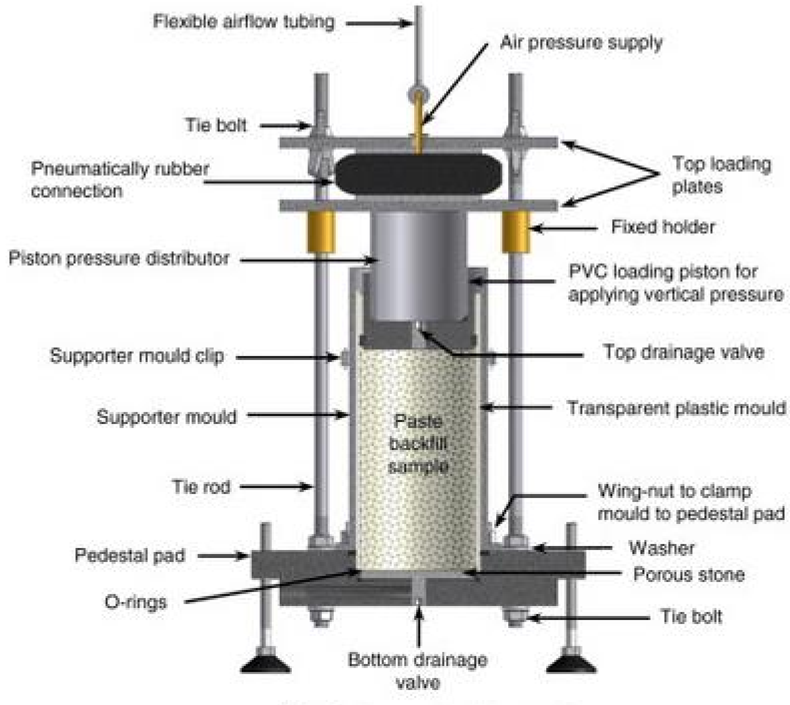


Figure 2-19: Schematic Diagram of CUAPS Apparatus (Yilmaz et al., 2009)

CPB specimen and a bottom plate with a central port equipped with a ceramic plate and drainage port to drain the CPB sample excessive pore water.

From figure 2-20 it can be observed that consolidated CPB samples develop better compressive strength than undrained ones, regardless of the curing time. This difference in the mechanical strength development is presented mainly as a result of the consolidation that reduces the porosity of the CPB compared to the undrained backfill sample (Belem et al., 2002). For ordinary Portland cement, consolidated CPB samples provided a 37.1% and

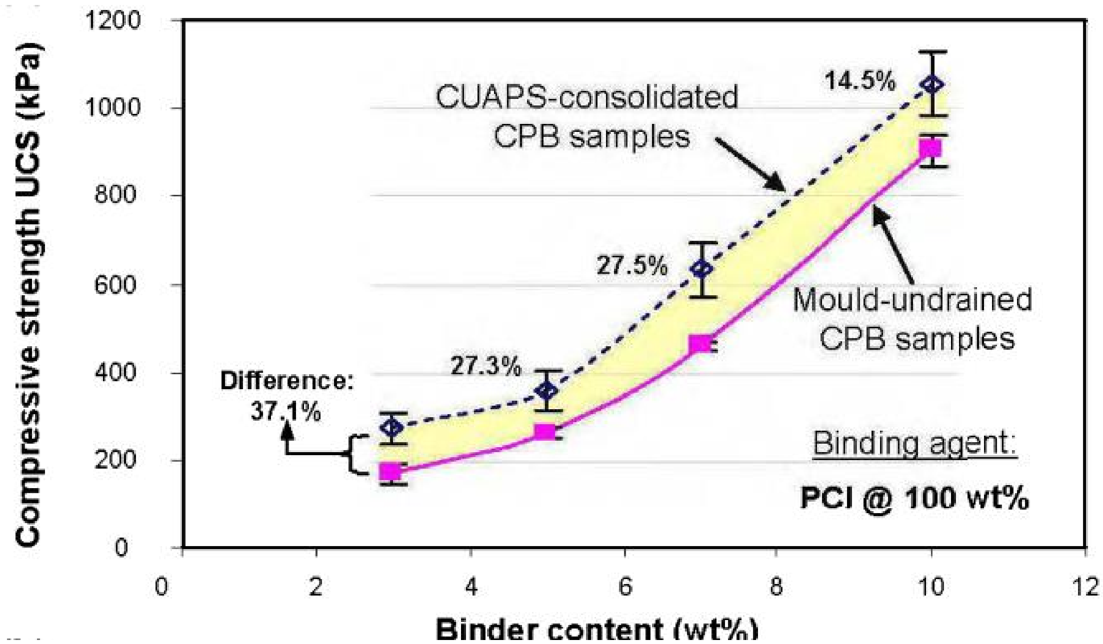


Figure 2-20: Variation in UCS with binder content for all CPB samples prepared using ordinary Portland cement (Yilmaz et al., 2009).

14.5% higher UCS than undrained ones at 3 wt% and 10 wt% binder contents respectively. CPB material prepared using coarse-grained tailings generates higher UCS than CPB made of fine-grained tailings due to lower void ratio or porosity impacts. The experimental findings indicate that CUAPS consolidated backfills generally produce better UCS strength than the samples with mould-undrained backfills. That could explain the CPB strength differences observed between laboratory-prepared samples (using conventional moulds) and in situ backfill materials (Yilmaz et al., 2009).

However, a limitation of the CUAPS apparatus is that the pressure loading system can apply a maximum pressure of 600 kPa which simulates a stope height range of only 25-30 m, depending on the tested material's unit weight and a diameter-to-height ratio of 0.5 (Yilmaz et al., 2009).

2.4.3 Curing Under Pressure Apparatus (CPA)

In the CUAPS apparatus, the maximum applied pressure during curing was limited to 600 kPa which represent the simulated depth of 20 m. The 600 kPa stress does not describe CPB samples from in situ condition as the maximum depth of CPB stope could be 100 m or more. Zhao et al. (2021) conducted an experiment with axial load application up to 3.6 MPa considering the stope depth up to 150 m. The Curing under Pressure Apparatus (CPA) shown in figure 2-21, was developed to simulate the in situ pressure experienced by a cemented paste backfill (CPB) sample during the curing process in a stope. It is based on a previous system designed by Yilmaz et al. (2009) which utilized a single convoluted air spring with a maximum pressure capacity of 600 kPa. In contrast, the CPA setup employs a hydraulic pump capable of providing up to 6 MPa of axial stress. The hydraulic pump applies the axial load which is then transferred to a piston on top of the CPB sample during

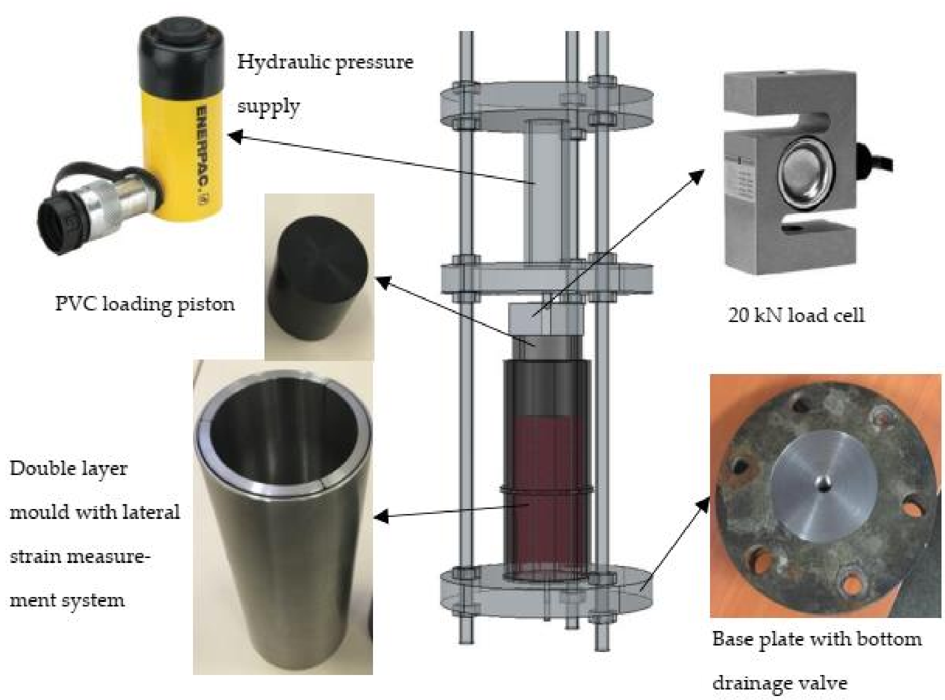


Figure 2-21: Curing Under Pressure Apparatus (Zhao et al., 2021)

curing. A load cell records the applied load. To maintain continuous axial pressure during CPB curing, six screw nuts above and below the center plate are tightened once the desired load level is reached.

Experimental findings Zhao et al. (2021) are illustrated in the figure 2-22 that represent the stress–strain curves for samples under 12 curing conditions in the unconfined compressive test. With the same 7-day curing time the four applied stress are 0 MPa, 1.2 MPa, 2.4 MPa and 3.6 MPa. CPB samples provided a UCS increase of 38.3%, 57.6%, and 130.2% for 1.2 MPa, 2.4 MPa, and 3.6 MPa consecutively applied stress at 7 days of curing (figure 2-21a). Following that, the increase in UCS was found 29.6%, 105.4%, and 206.1% for 1.2 MPa, 2.4 MPa, and 3.6 MPa consecutively applied stress after 14 days of curing (figure 2-21b); and similarly 60.3%, 234.5%, and 390.7% for 1.2 MPa, 2.4 MPa, and 3.6

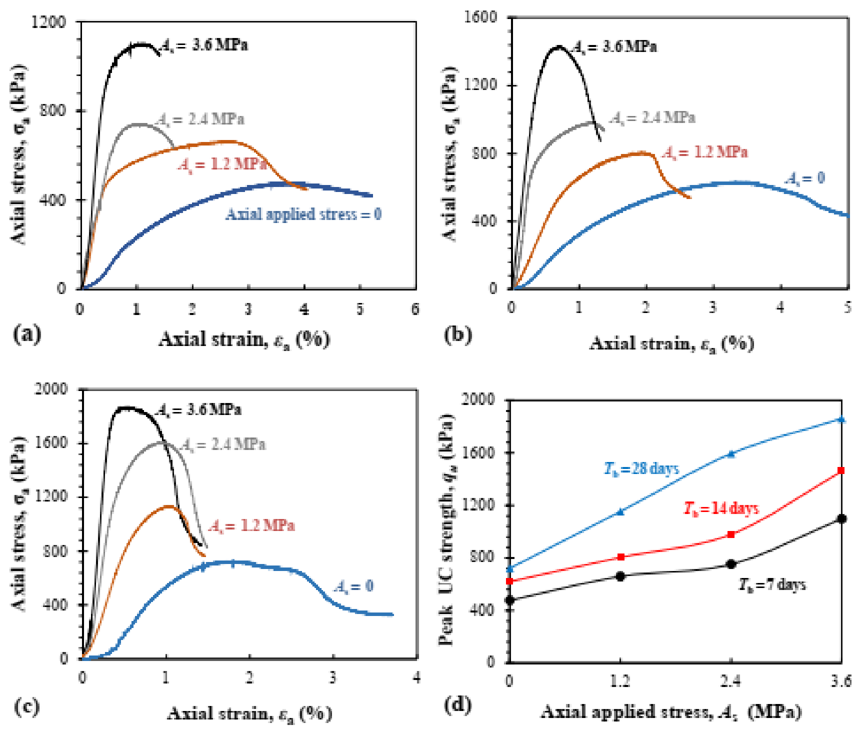


Figure 2-22: Uniaxial compression test results for CPB under CPA Apparatus (Zhao et al., 2021)

MPa applied stress after 28 days of curing (figure 2-21c). Overall, as shown in figure 2-21d, the increase in applied stress during curing leads to the higher resultant peak strength. With the increase in curing time, especially after 28 days, the influence of applied stress during curing becomes more pronounced; UCS increased by 390.7% when comparing samples from no applied stress to 3.6 MPa axially applied stress on 28 days cured samples. Moreover, as the stress applied during curing increases, the influence of curing time on CPB UCS becomes more increasing as well.

2.5 Acid Mine Drainage of Cemented Tailings Backfill

Acid mine drainage (AMD) is a significant environmental concern that occurs when water and oxygen comes into contact with sulfide minerals present in mining activities or abandoned mine sites. As shown in figure 2-23, AMD releases highly acidic water through chemical reactions with elevated concentrations of heavy metals and other contaminants into the surrounding environment. This acidic water can have devastating effects on aquatic ecosystems, damaging fish and other wildlife, degrading water quality, and impairing the overall ecological balance. AMD poses a long-term environmental challenge, requiring comprehensive management strategies to mitigate its impacts and prevent further degradation of affected areas.

The first step involves the oxidation process of sulfide minerals which leads to production of acid. Subsequently, when rainwater or snowmelt enters the waste piles, the oxidized materials are leached. If there is a lack of enough alkaline minerals to neutralize

Figure 2-23: The formation of acid mine drainage as a result of mineral processing (Yilmaz et al., 2017)

the acid, the leach water becomes acidic. The process involved in the AMD generation, can be represented by the following reactions using pyrite as the example.

$$FeS_2\ (s) + 7/2\ O_2\ (g) + H_2O \rightarrow Fe_2^{+} + 2SO_4^{2-}\ (1) + 2H^{+} \quad (2\text{-}1)$$

$$Fe_2^{+} + 1/4\ O_2\ (g) + H^{+} \rightarrow Fe_3^{+} + 1/2\ H_2O \quad (2\text{-}2)$$

$$FeS_2\ (s) + 14\ Fe_3^{+} + 8H_2O \rightarrow 15\ Fe_2^{+} + 2SO_4^{2-}\ (1) + 16H^{+} \quad (2\text{-}3)$$

$$Fe_3^{+} + 3H_2O \rightarrow Fe(OH)_3\ (s) + 3H^{+} \quad (2\text{-}4)$$

The overall sulphide to sulphate oxidation is summarized as follows:

$$FeS_2\ (s) + 15/4\ O_2\ (g) + 7/2\ H_2O \rightarrow Fe(OH)_3\ (s) + 2SO_4^{2-}\ (aq.) + 4H^{+} \quad (2\text{-}5)$$

According to MEND report 10.2 (2006), the potentiality of AMD generation reduces significantly in underground backfill because:

- Less free water that reduces leachate generation.
- Less available oxygen for having the higher degree of saturation.
- Preferential flow of ground water around backfill, rather than through it due to the lower hydraulic conductivity of the paste backfill.
- The addition of cement that provides extra neutralization potential (NP) and decreases effective porosity.
- The potential for flooding at closure which reduces sulphide oxidation in long-term.

2.5.1 Air Permeability and Degree of Saturation

Higher saturation levels typically lead to a decrease in available oxygen, resulting in reduced sulphide oxidation and reactivity within the tailings. The pore geometry influences the amount of water present in the pores, known as the degree of saturation. Materials with smaller pore spaces tend to retain more water under drained conditions due to higher capillary suction. In the case of backfill, the degree of saturation can exceed the residual level if water continues to infiltrate from the surrounding rock. If the influx of water is sufficient, the backfill can become fully saturated, limiting the entry of oxygen to only the dissolved amount in the incoming groundwater (MEND 10.2, 2006).

2.5.2 Water Permeability

The backfilling of underground workings with any material is expected to reduce permeability and decrease long-term oxidation and contaminant release. The addition of cement further lowers permeability by isolating the pores and reducing effective porosity. Water flow through cemented backfill behaves similarly to fractured porous rock, with intact backfill and secondary cracks having different relationships regarding air permeability and degree of saturation. Under dry conditions, partial oxidation may occur in the intact backfill, while full oxidation can happen on fracture surfaces. Under wetter conditions, flow through larger openings or cracks increases, reducing the available surface area for oxidation. When the backfill is flooded, flow primarily occurs through secondary openings or cracks, limiting oxidation. However, the formation of shrinkage cracks and gaps during drainage under relatively dry conditions can increase oxidation (MEND 10.2, 2006).

2.5.3 CTB in Underground Environment

In underground mining, the conditions are different from laboratory or surface settings. These conditions affect things like how the tailings and surrounding rock react, the quality of subsurface water, the flow of underground water, and the air quality. During mining operations, paste backfill is typically used in areas that are not flooded when the water table is kept below the working areas. When mining operations end, the paste backfill can either remain above the water table. This can be affected by a fluctuating water table or be permanently flooded below the water table. The paste backfill is exposed to groundwater and mine water which helps wash away soluble components on its surfaces. Metal mines often have sulphate in the groundwater or wastewater which can lead to AMD with sulphide minerals oxidize. The availability of oxygen plays a role in the amount of soluble oxidation products that are produced. If oxygen ingression is limited, the production of AMD may be reduced, but not entirely eliminated (MEND 10.2, 2006).

Chapter 3: Evaluation of Strength, Ultrasonic and Rheological Properties for Cemented Paste Backfill

3.1 Abstract

The cement (or binder) cost is a significant part of the operating costs in the backfilling operations. Hence, optimization of cement or binders content is crucial by maintaining the design strength parameters. High-quality backfill should use minimum cement or binder content to maintain stability while the adjacent pillars are being recovered. The mechanical strength properties of paste backfill are usually related to the uniaxial compressive strength (UCS), stress–strain behavior and elastic properties.

In this study, the optimized strength parameters are measured during the curing periods of CPB samples prepared with tailings, water and cement as a binder. The uniaxial compressive strength (UCS) testing has been applied to evaluate the strength of CPB samples mixed with 6% and 4% cement content by weight to achieve the design strength of 1 MPa. Despite challenges due to the porous microstructure of CPB, the ultrasonic wave propagation velocity (both P-wave and S-wave) has been successfully determined in the laboratory following the ASTM Standard D2845 to monitor CPB hydration along different curing time on the samples prepared with the same mixture recipe of UCS samples. Moreover, procedure of yield stress measurement through analytical model from the slump test is described for evaluating the rheological aspects of the tailings paste transportation.

3.2 Introduction

The strength characteristics of CPB play a crucial role in determining its effectiveness and long-term stability. It involves a combination of cement hydration and particle interlocking mechanisms. Material properties, curing conditions, particle characteristics, and optimization of the strength properties of CPB are the specific technical features of underground backfilling operations.

The hydration of cementitious materials within the paste results in the formation of a hardened matrix, providing structural integrity to the backfill. The curing conditions, such as temperature and moisture, significantly affect the rate and extent of hydration, thereby influencing the strength gain of the CPB. To assess the strength characteristics of CPB, various laboratory tests are conducted, including unconfined compression tests, shear tests, ultrasonic test. These tests measure the resistance of the CPB to compression, shear and elastic behaviour. The obtained strength values are used to evaluate the stability and load-bearing capacity of the backfill mass.

There are three modes in which the ultrasonic test can be conducted: through transmission, pulse echo, and pitch catch. Gaala et al. (2009) recorded the P-wave and S-wave signals of CPB samples in oscilloscope using the Panametrics model V103 and V153 piezoelectric transducer, pulsing unit (Panametrics 5055UA) at 340V and pre-amplifier. Chotard et al. (2001) employed the pulse echo method using 1 MHz parametric transducers with low energy for testing cement mortars. Abo-Qudais (2005) utilized a PUNDIT pulser-receiver capable of generating 1.2 kV, along with low-frequency piezoelectric transducers (54 kHz) to test concrete at both 3 days and later after mixing.

Determining the flow properties of CPB is a crucial step in understanding how they behave in different settings. In the mining industry, paste slurry used for backfilling can have varying properties due to the presence of tailings particles, cement, water, and chemical additives. The consistency of CPB mixture should be appropriate during its transportation through pipeline systems into mined-out underground openings to ensure efficient and economical transportation. Therefore, the flow ability properties should also be taken into account when designing the CPB mixtures. The physical, chemical and mineralogical characteristics of the paste backfill components have a significant impact on the consistency of the paste material.

3.3 Materials and Methodology

3.3.1 Physical Properties Measurement

Physical properties of tailings are important parameters to properly design the mixture recipe and for the backfilling mixture as well as pouring process. Here, bulk density, specific gravity, absorption, void content, moisture content has been determined in the lab experiment following the ASTM standards for the tailings on the collected samples from anaconda mining site. The sample of the tailings while determining the bulk density are shown in the figure 3-1.

Figure 3-1: Cylindrical Measure for Determining Bulk Density

Bulk Density

Bulk density of the tailings from Anaconda has been determined by following the "ASTM C29 – Standard Test Methods for Bulk Density and Voids in Aggregate". The experiments has followed both loose and compacted condition. The tailings dried in the oven at 110 degree Celsius temperature for 24 hours. There are two types of cylindrical container has that been used to calculate the volume of the measuring equipment. The average value of measured loose bulk density is 1491.5 kg/m^3 and the compacted bulk density is 1748 kg/m^3.

Specific Gravity

Relative density (Specific Gravity) of the tailings from Anaconda has been determined by following the "ASTM C128 – Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate". As shown in Figure 3-2, specific gravity is

Figure 3-2: Specific Gravity Determination using Pycnometer and Le Chateliar Flask

determined with the Pycnometer following the gravimetric procedure and Le Chatelier flask following the volumetric procedure. Both oven dry tailings and saturated surface dry (SSD) tailings has been used in the experimental procedure. Following the gravimetric procedure, the average measured specific gravity on oven dry samples is 2.501 and specific gravity on saturated surface dry (SSD) sample is 2.549. Following the volumetric procedure, the average measured specific gravity on saturated surface dry sample is 2.68. The average value of measured absorption is 1.92%. The moisture content of SSD sample is 5% and water soaked tailings sample is 24%.

3.3.2 Testing Frame

A uniaxial compression test-loading frame is a mechanical device used to apply a unidirectional compressive force to a specimen during a uniaxial compression test. The loading frame typically consists of study materials and is designed to withstand high forces without deformation. It consists of two main components: the fixed platen and the moving platen. The loading frame provides precise control over the applied force, allowing for accurate measurement of the specimen's mechanical properties under compression. It is often equipped with load cells or strain gauges to measure the applied force and deformation of the specimen. This data is crucial for analyzing the stress-strain behavior, strength, and other mechanical characteristics of the material being tested.

Instron’s electromechanical testing systems are used to conduct the uniaxial compression test following the ASTM standard C39 on the CPB samples. Schematic drawing of Instron frame has shown in the figure 3-3. Instron electromechanical load frames are built to apply force to a sample through the moving crosshead. The system

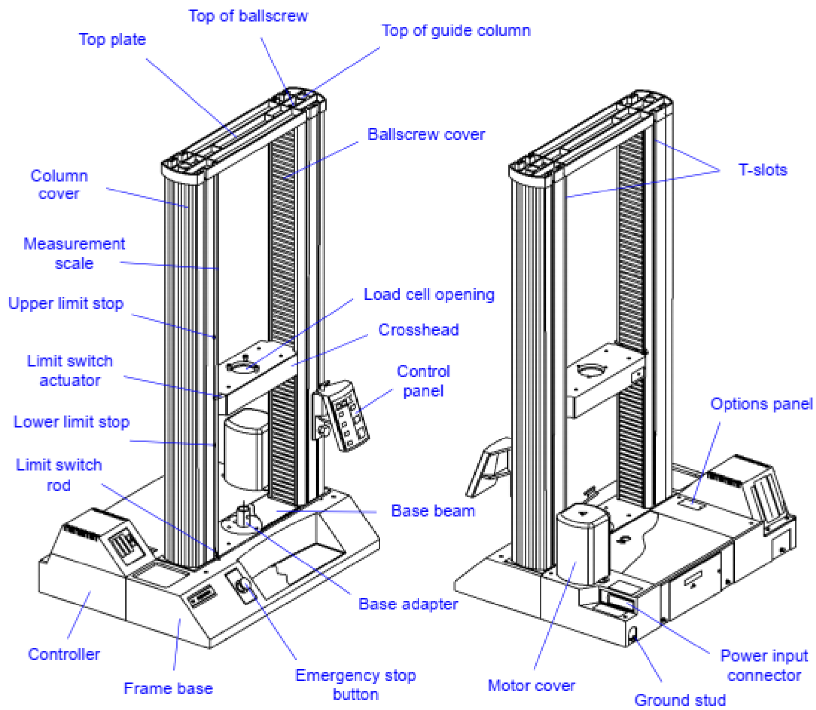


Figure 3-3: Instron 5560H Loading Frame for UCS Testing

moves the crosshead upward to exert a tensile force on the sample or downward to apply a compressive force on the sample. The applied load is measured by a transducer (load cell) that is positioned in line with the specimen. The load cell changes the load into an electrical signal, which is monitored and shown by the control system. The load cells can be substituted with others of varying capacities, offering a variety of load measuring capacities that are only limited by the maximum capacity of the load frame. The systems can also utilize strain transducers (extensometers) to measure strain. The advantage of this loading frame is to have the customized loading rate and displacement rate. The applied pressure can be controlled either through the loading or through displacement rate. In our testing, the set loading rate is 0.5 KN/min and the set displacement rate 0.005 mm/sec.

3.3.3 Mixture Properties

CPB is designed by combining cement, water, and various additives to form a mixture with specific properties. The compressive strength of the mixture can be tailored to meet project requirements by adjusting the cement content and curing conditions. The mixture should have suitable rheological properties to allow for easy pumping through pipelines or underground placement. In this study, the mixture recipe consists of majorly tailings from anaconda mining site, cement and water. After mixing the materials, 4 inch and 2 inch cylindrical mold were prepared for UCS testing in the Instron loading frame. The size of the cylindrical molds are 4 inch diameter x 8 inch length and 2 inch diameter x 4 inch length. The ratio of the mixture properties is mentioned in the following Table 3-1. The percentage of the mixture mentioned here are the weight percentage of total mixture.

3.3.4 Equipment Set-up of Ultrasonic Measurement

The equipment setup for ultrasonic properties measurement of cemented paste backfill (CPB) typically involves ultrasonic pulser/receiver, transducers, coupling medium, data acquisition and interpretation system, sample holder. Ultrasonic pulser/receiver device

Table 3-1: Mixture Properties of CPB Samples

	4 % (By Wt.) Cement	**6% (By Wt.) Cement**
Proportional Ingredients of CPB Mixture	76% Tailings 4% Cement 20% Water	74% Tailings 6% Cement 20% Water
Wet Density of CPB Mixture	2007.87 kg/m^3	2019.43 kg/m^3

generates the ultrasonic pulses and receives the signals. It provides the electrical energy to the transducers and amplifies the received signals for analysis. Transducers emit and receive ultrasonic waves. For CPB measurements, typically piezoelectric transducers are used. They convert electrical energy into mechanical vibrations and vice versa. A pair of transducers is used—one as a transmitter and the other as a receiver. A coupling medium is used to ensure efficient transmission of ultrasonic waves between the transducers and the CPB sample. It is typically a gel or a liquid that helps in reducing signal loss at the transducer-sample interface. A sample holder or container ensures proper alignment of the transducers with the sample and helps in achieving consistent and accurate results. A data acquisition system is used to capture and process the signals received from the transducers. Data interpretation system display the received signals and perform interpretation of the measurements. It may provide features for signal processing, waveform analysis, and calculation of ultrasonic properties such as pulse velocity.

Here in the laboratory set-up, P-wave and S-wave wave velocity were measured on 2 inch x 4 inch cylindrical samples by using a TDS 1002B Two Channel Digital Storage Oscilloscope, Panametrics Square Wave Pulser/Receiver Model 5077PR, and two

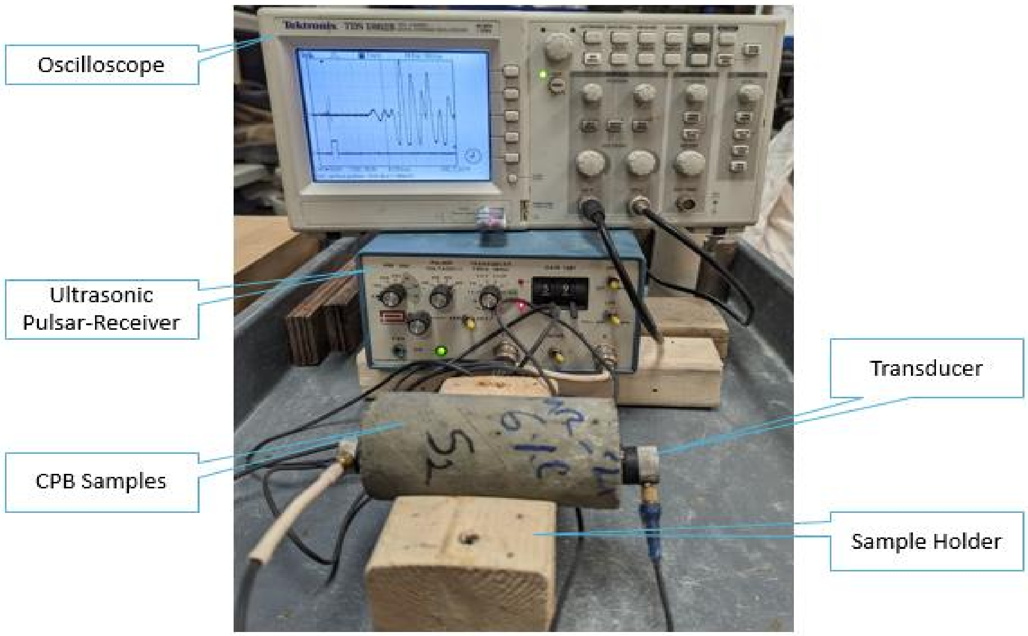


Figure 3-4: Equipment Set-up of the Ultrasonic Testing of CPB Samples

Panametrics transducer. The pulser/receiver model has an in-built amplifier and the amplification frequency was 59 dB. Shear wave couplant was used to ensure complete contact between sensors and rock samples. Recorded data is stored and later processed for P-wave velocity (Vp) and S-wave velocity (Vs) determination. The equipment set-up is depicted in the figure 3-4. The waves are detected at the receiving transducer and the travel time through the sample of length is used to calculate velocity. From the data interpretation of oscilloscope the travel time is determined for each sample. Then, using the velocity = length/travel time formula, the Vp and Vs was calculated. For each samples, several measurements of travel time was recorded in order to ensure the accuracy of measurements. Following the "ASTM standard D2845 – laboratory determination of pulse velocities and ultrasonic elastic constant of rock", mean values of Vp, Vs and density together were used to calculate the shear wave modulus (G), elastic modulus (E), bulk modulus (K), and Poisson's ratio (υ).

3.3.5 Development of Slump Model

Following the study of Clayton et al. (2003), analytical models for the slump test has presented in the figure 3-5 and figure 3-6 for both the cone and cylinder tests. The cylindrical model can be applied to cylinders with the diameter to length ratio 1:1, but the cone model is specific to cones with a base diameter double that of the top diameter (Clayton et al., 2003). To allow for comparison with the cylinder model, a generalized cone model was created. It is assumed that removing the slump cylinder or cone will not change the material's shape. The material is believed to be a perfectly cylindrical or conical shape before it is disturbed. This can only happen if the inner surface of the slump cylinder or cone has perfect slipping. It is assumed that stress exerted on the material is only the vertical stress resulting from the gravitational force acting on the material itself. Therefore, the pressure (P) in the material at some height (z) below the top surface can be expressed as the weight of material above position z.

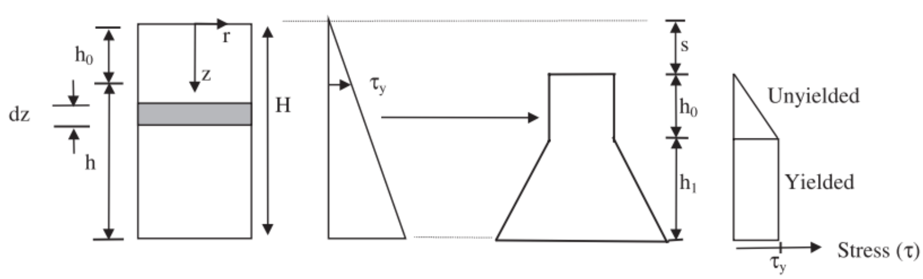


Figure 3-5: Schematic diagram of the cylinder slump test, showing initial and final stress distributions (Pashias et al., 1996)

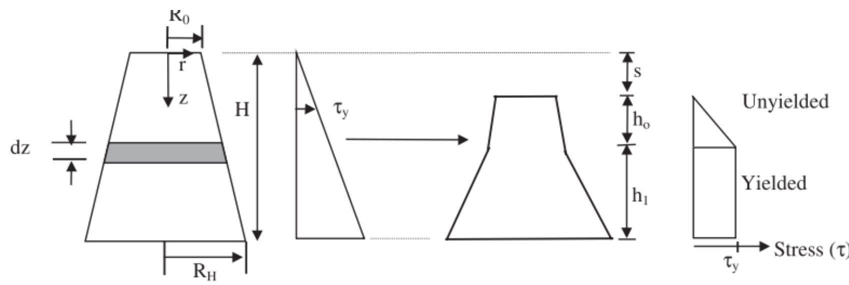


Figure 3-6: Schematic diagram of the conical slump test, showing initial and final stress distributions (Schowalter and Christensen, 1998)

Cylinder: $P\,|_z = \rho g z$ (3-1)

Cone: $P\,|_z = \frac{\rho g z}{3}\left(\frac{R_0}{R_H - R_0}\right) \times (1 + \frac{z}{H}\left(\frac{R_H - R_0}{R_0}\right) - \frac{1}{(1+\frac{z}{H}\left(\frac{R_H - R_0}{R_0}\right))^2})$ (3-2)

Here, H is the height of the un-deformed mixtures, ρ is the density, g is the acceleration due to gravity. The material is assumed to behave as an elastic solid, for which the maximum shear stress that can act on a body when a pressure (P) applied to it in a normal direction is equal to half of the pressure (Hibbeler, 1997). For the dimensionless form (denoted by '), the stress is scaled with ρgH and the height with H.

Cylinder: $\tau\,|_{z'} = \frac{1}{2}\, z'$ (3-3)

Cone: $\tau\,|_{z'} = \frac{\alpha}{6}\,(\left(1 + \frac{z'}{\alpha}\right) - \frac{1}{(1+\frac{z'}{\alpha})^2})$ (3-4)

Where, $\alpha = \frac{R_0}{R_H - R_0}$

The results are expressed in terms of dimensionless variables to enable generalisation of the slump model for different-sized slump moulds and different yield stress materials. The dimensionless variables are defined as follows:

$\tau'_y = \tau_y/\rho gH$ = dimensionless yield stress,

$s' = s/H$ = dimensionless slump height,

$h'_o = h_o/H$ = dimensionless height of un-deformed region,

$h'_1 = h_1/H$ = dimensionless height of deformed region.

Final expressions relating dimensionless slump height and dimensionless yield stress results to cone and cylindrical models. In a standard experiment, the height of the slump is measured, transformed into a dimensionless value, and subsequently the dimensionless yield stress is determined. The actual yield stress is then calculated by multiplying the dimensionless yield stress with ρgH**.**

3.4 Results and Discussion

3.4.1 Experimental Results of UCS Testing

The experimental testing for the uniaxial compression test were conducted in the instron frame following the ASTM C39. That frame is capable to compress the testing sample based on the customized loading rate or displacement rate. In this phase of testing, the set loading rate was 0.5 kN/min and the set displacement rate was 0.005 mm/sec. During the testing of the samples on loading rate controlled, the testing was stopped immediately after the peak strength (i.e: breakage) of the samples. On the other hand, the testing samples that used the displacement rate controlled loading, the samples were allowed to continue loading even after breakage to understand the post-failure behavior of the samples. From the Figure 3-8, it can be overserved that the strain length on the testing samples of displacement rate is higher than the samples that were tested through the loading rate.

Figure 3-7: Cylindrical Samples of CPB for UCS Testing in the Instron Loading Frame

The Figure 3-7 shows the tested sample after breakage in the testing frame. There, the left sample is four inch cylindrical mold and the right samples is two inch cylindrical mold. The UCS test were conducted on 14 days and 28 days of cured samples for four inch and two inch diameter cylindrical mould samples. On each curing days and for each cement percentage, three samples were prepared to conduct the UCS testing. The tested average results from all experiments are shown in the Table 3-2. The observed strength in the Figure 3-8 shows the average data from three tested samples after 28 days of curing in the moisture

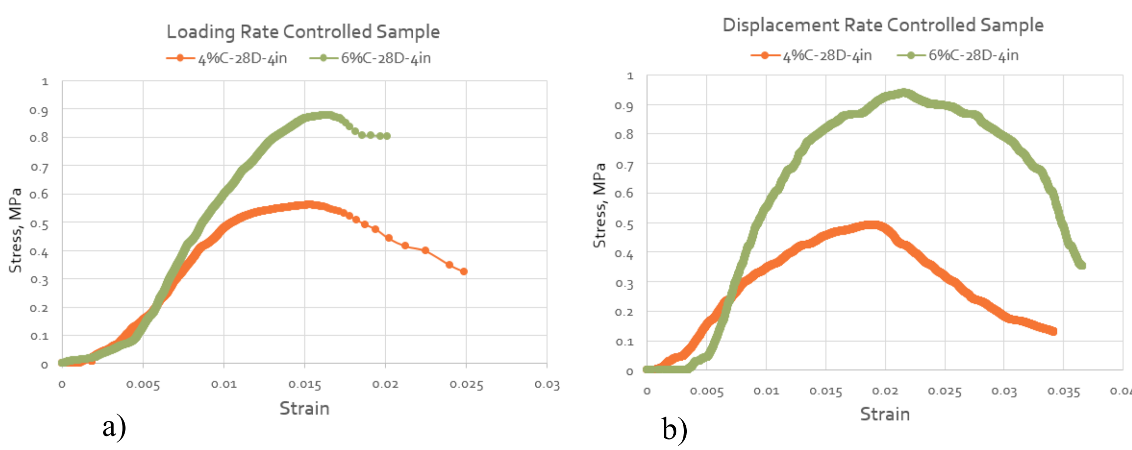


Figure 3-8: Stress-Strain curve showing the results of CPB samples:

a) Loading Rate Controlled; b) Displacement Rate Controlled room. On each testing day, three samples from 4% and 6% cement (by weight) specimen was taken for testing. The UCS testing in the instron frame is providing good quality stress-strain curve for the low-strength CPB sample. In both loading and displacement rate controlled testing, after 28 days of curing the uniaxial compressive strength results ranges around 0.5 MPa for 4 wt% cement samples and around 1 MPa for 6 wt% cement samples.

Table 3-2: Summary of Average UCS Results from Experimental Testing with CPB

4 inch Samples Loading Rate Controlled - 0.5 KN/min		
	4% (Wt.) Cement	6% (Wt.) Cement
Curing Time	UCS, (MPa)	UCS, (MPa)
14 Days	0.506	0.945
28 Days	0.571	0.971
2 inch Samples Loading Rate Controlled - 0.5 KN/min		
	4% (Wt.) Cement	6% (Wt.) Cement
Curing Time	UCS, (MPa)	UCS, (MPa)
14 Days	0.427	0.85
28 Days	0.441	0.952

4 inch Samples Displacement Rate Controlled - 0.005 mm/sec		
	4% (Wt.) Cement	6% (Wt.) Cement
Curing Time	UCS, (MPa)	UCS, (MPa)
28 Days	0.492	0.943
2 inch Samples Displacement Rate Controlled - 0.005 mm/sec		
	4% (Wt.) Cement	6% (Wt.) Cement
Curing Time	UCS, (MPa)	UCS, (MPa)
28 Days	0.447	0.963

3.4.2 Elastic Properties

Ultrasonic wave propagation in cemented paste backfill (CPB) involves a dynamic load regime, characterized by cyclic loading with strain rate and frequency considerations. When transmitting the ultrasonic wave, the CPB skeleton undergoes deformation. The velocity of the wave is linked to the deformation characteristics of internal structures, allowing for the calculation of elastic properties. Compression waves (P-wave) induce deformation in the direction of propagation, while shear waves (S-waves) cause deformation perpendicular to it. This provides two distinct measures of CPB deformability. Using both compression (Vp) and shear velocities (Vs) elastic properties are calculated

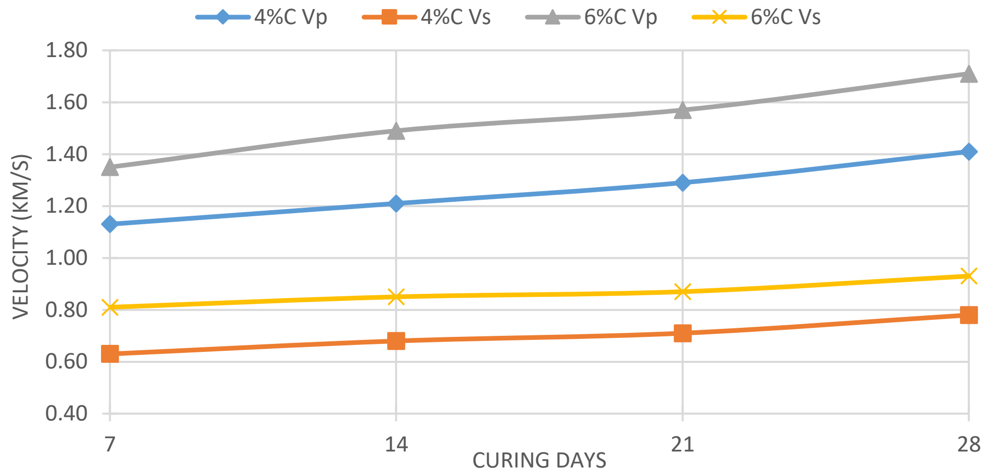


Figure 3-7: P-wave and S-wave velocities of CPB samples on different curing days.

following the equations from ASTM D2845. For each percentage of CPB samples on each testing days, three samples were used to conduct the non-destructive ultrasonic testing. After completing the measurement, the samples were put into the moisture room for consecutive curing. Figure 3-9 shows the average data of P-wave velocity (Vp) and S-wave velocity (Vs) on the tested 4 Wt% and 6 Wt% cement content samples on 7, 14, 21 and 28 days of curing.

Table 3-3: Average Elastic properties of 6% cemented samples on different curing days

Curing Days	Vp (km/sec)	Vs (km/sec)	Shear Modulas, μ (GPa)	Young's Modulas, E (GPa)	Bulk Modulas, K (GPa)	Poisson's Ratio, ν	P-wave modulas, M (GPa)
7 Days	1.35	0.81	1.33	3.44	2.05	0.25	3.96
14 Days	1.49	0.85	1.48	3.83	2.27	0.21	4.38
21 Days	1.57	0.87	1.56	3.73	2.50	0.23	4.50
28 Days	1.71	0.93	1.64	3.85	2.79	0.21	4.75

In the table 3-3 and 3-4, the experimentally measured value of elastic properties for 6% and 4% CPB samples are presented respectively. On each curing days on each samples, five consecutive measurements were conducted to get the Vp and Vs. From that five measurement, using the average Vp and Vs values the elastic properties were calculated. Then, average values of all the measurement for each cement percentage samples have been presented the listed data tables.

Table 3-4: Average Elastic properties of 4% cemented samples on different curing days

Curing Days	Vp (km/sec)	Vs (km/sec)	Shear Modulas, μ (GPa)	Young Modulas, E (GPa)	Bulk Modulas, K (GPa)	Poisson's Ratio, ν	P-wave modulas, M (GPa)
7 Days	1.13	0.63	0.90	2.21	1.61	0.28	2.82
14 Days	1.21	0.68	1.09	2.74	1.94	0.26	3.40
21 Days	1.29	0.71	1.20	3.05	2.35	0.27	3.94
28 Days	1.41	0.78	1.24	3.27	2.20	0.23	3.81

3.4.3 Slump Test

Usually, a higher slump height suggests a lower yield stress and more fluid-like behavior. A lower slump height suggests a higher yield stress and more solid-like behavior. While slump height alone does not provide a direct measurement of yield stress or rheology, it can serve as an indicator or qualitative measure of the flow behavior and consistency of cemented paste tailings. Slump test is an empirical measure dependent on yield stress, density, chemical composition, particle specific gravity, and particle size.

Table 3-5: Average calculated yield stress from slump test with CPB

Solid & Binder Concentrations (Wt%)	Conical Slump	Cylindrical Slump
Average Slump Height	7 cm	2.5 cm
6% Cement, 74% Tailings	569 Pa	434 Pa
4% Cement, 76% Tailings	618 Pa	462 Pa

Figure 3-8: Representation of Conical (Left) and Cylindrical (Right) Slump Test

A series of experiments were conducted to compare the cylinder and cone slump tests and the models associated with them. The experiments were performed with the anaconda tailings at two different cement concentrations as described in the Table 3-1. The slump models for the cone and cylinder tests are derived from principles of dimensionless form. As a result, the models offer a material-independent singular relationship between the yield stress and slump height. The height and diameter of the cylindrical slump is 10 cm. The length to diameter ratio is 1:1. The size of the conical slump and height-diameter is followed accordingly the ASTM C143. Comparatively, cylinder model provides a mathematically simpler representation, which is advantageous for measurement. Table 3-5 shows the measured yield stress properties from slump test for two different kind of mixture ingredients. Clayton et al. (2003) stated that for paste fill transport, the expected slump value is 20 cm. Here, the data of Table 3-5 showing high yield stress and low slump value for the CPB mixtures in both cylindrical and conical slump test. In both type of CPB mixtures as per Table 3-1, the paste has low flow ability. This kind of high yield stress and lower slump value mixture could plug in the pipeline that may lead to disruption in operation. To develop the transportability of that CPB mixture through pipeline further optimization of CPB mixture is necessary while maintaining the design strength.

3.5 Conclusion

The UCS testing in the Instron frame provides good quality stress-strain curve for the low-strength backfilling sample. The uniaxial compressive strength results range around 0.5 MPa for 4 wt% cement samples and around 1 MPa for 6 wt% cement samples in both loading and displacement rate controlled testing. Displacement controlled testing is a method that allows to examine the post-failure behavior of a sample by controlling the rate of deformation.

The ultrasonic wave velocities were measured throughout the testing period for both binder contents (6% & 4%) in the CPB samples. To have good quality wave in ultrasonic equipment, pre-amplifier and acoustic coupling is needed. The CPB samples exhibited the ability to transmit P-waves, with velocities ranging from 1.13 to 1.71 km/s. Similarly, the S-wave velocities ranged from 0.63 to 0.93 km/s. The 6% CPB samples consistently showed slightly higher P-wave and S-wave velocities compared to the 4% CPB samples during the entire experiment. Following the Table 3-3 and 3-4, it can be observed that the 6% CPB samples has the higher elastic values than 4% CPB samples. Capturing the P-wave and S-wave in the ultrasonic equipment can be a challenging task where it takes experience and proper skill to identify the wave categories. The differentiation between the P-wave and S-wave sometimes can be convoluted because of their interference on each other.

The data in Table 3-5 shows that the CPB mixtures have thick consistency and don't flow well in both cylindrical and conical slump tests. This kind of mixture could clog the pipeline without any external operational support. To make it easier to transport through the pipeline while maintaining its strength, there is a need to improve the CPB mixture. However, the yield stress can vary due to factors like chemical composition and particle characteristics. Relying solely on slump height for consistency evaluation in mining waste disposal systems can be problematic. The yield stress is preferred as an indicator of consistency.

Chapter 4: Effect of Particle Gradation on the Strength Properties of Cemented Paste Backfill (CPB)

This chapter discusses the published technical paper titled "Effect of Particle Gradation on the Strength Properties of Cemented Paste Backfill (CPB)". The authors of this paper are Mohammad Shafaet Jamil, Zijian Li, Dr. Abdelsalam Abugharara and Professor Stephen Butt. The paper was published in the proceedings of GeoCalgary 2022 on October 2 - 5, 2022 - at the 75th Canadian Geotechnical Conference (CGS), Calgary, Alberta, Canada. The author's dedicated contributions are described as follows:

- Mohammad Shafaet Jamil: Conceptual analysis, literature review, experimental design, experimental work, data analysis, and manuscript preparation.
- Zijian Li: Planning on sample collection, XRD analysis, manuscript proof reading.
- Dr. Abdelsalam Abugharara: Co-ordination for purchase of materials, Laboratory support in sample preparation, experimental testing, manuscript proof reading.
- Professor Stephen Butt: Research and experimental guidance. Overall supervision, manuscript review and approval of all stages throughout the whole work process.

4.1 Abstract

A comprehensive laboratory study was performed on CPB samples collected from backfilling operations to investigate the influence of particle gradation variation on developing strength at different curing times. Two different locally sourced aggregates were used to prepare the backfill mixtures. The measurement of strength was evaluated by the uniaxial compressive strength (UCS) test on the collected specimens. The particle size distribution of each source material was determined by dry sieve analysis which showed

that one material is classified as well-graded and the other as poorly graded. The observed strength after 28 days of curing is around 1 to 2 MPa for samples using the well-graded aggregates. Conversely, the UCS results are less than 1 MPa for the poorly graded aggregates. Moreover, a comparative analytical data of tailings and aggregates are represented from the strength values and particle size distribution parameters.

4.2 Introduction

In underground mining, backfilling method is used in both cut and fill mining and open stoping mining to fill completed production openings to stabilize hanging wall formations and to facilitate mining ore adjacent to backfilled openings. Backfilling provides improvement in safety support to the engineering structures by controlling subsidence and movement of structures. It also provides sufficient workspace for mining equipment and workers, leading to an increase in ore body production.

The backfilling process should provide a feasible and economical solution for preparing the material into a competent structural product, which would be depended on the availability of abundant sources of quality materials near the mining areas. Hence, to match the engineering, economic and sustainable criteria of the backfilling operation, it is essential to make a careful selection of locally available backfilling materials from tailings, waste rock, aggregates, and metallurgical by-products (Petrolito et al. 1998; Bloss and Greenwood 1998)

In the mining industry, tailings management is one of the biggest challenges. It is increasingly common to utilize tailings as the principal constituent in Cemented Paste Backfill (CPB) for backfilling operations to reduce surface tailings storage requirements.

This takes advantage of already available source material and improves the overall long-term sustainability of the mining operation.

Developing good quality backfill materials depends on the range of strength build-up as a function of particle size gradation, binder and moisture contents, curing environment and time. Among the conventional backfilling methods, paste backfill gives better support and early stabilization which often leads to high strength and stiffness (Bissonnette, 1995). Aref et al. (1989) have reported that paste fill has fast consolidation and uses less binder, usually between 2 and 7 percent. Ouellet et al. (1998) suggested that sufficient cohesion from the cement bond should be there to prevent the mining induced loading and improve the liquefaction resistance of the fill mass to ensure stability. Hedley (1995) reported that compressive strength and deformation modulus of paste fills are primarily influenced by the cement or binder content and to a less extent by porosity. Binder/water ratio and moisture content influence the development of strength properties more than particle size gradation for backfilling mixture (Chen et el, 1995). Thus, the reduced binder content and early development of strength of the CPB method lead to higher productivity and lower operating costs.

Particle size ranges and the gradation characteristic of the CPB tailing material plays a crucial role in the mechanical properties of backfill materials (Espley et al., 1970). In terms of mine backfill, the primary purpose for optimizing particle size distribution is to achieve a well-graded aggregate distribution to obtain optimum porosity which leads to reduction in binder consumption and mine operating cost (Thomas et al., 1979). Ross-Watt (1989) reported that when the fine materials increases, the strength of the paste backfill increases. Contrary, Clark (1988) experimentally showed that the presence of fine particles decreased the compressive strengths of total tailings paste backfill.

The experimental findings of Annor (1999) reported that timely improvements in compressive strength happened when the mixtures were well-graded, having wider range of particle size gradation. Then, Boldt et al. (1993) suggested that binder content and moisture control, fine portion in tailings considered to have more influence on strength development than aggregate gradation alone. They further stated that optimum water/cement ratio and grain size gradation influenced the strength development in tailings paste. At higher water/cement ratios (7 to 11), particle size gradation seems to have minor effect on compressive strength development (Boldt et al., 1993).

Generally, the backfill design is based on the capability of sustaining both the gravitational loading of the roof material and preventing subsidence. The unconfined compressive strength (UCS) test is one of the most important parameters to be considered for strength measurement when dealing with cemented backfill system. In this study, UCS test was conducted on three different days of curing with the collected backfilling sample from field operation. Particle size distribution analysis was conducted on the collected aggregates samples and tailings which were used as major constituents in preparing the backfilling mixtures. An approach is taken here to identify the differences in strength of different backfilling samples by comparative data analysis from the particle size distribution results.

4.3 Materials and Equipment

The backfilling mixture samples were collected from the field operation into cylindrical molds. After being hardened enough and curing in the cold temperature, those molds filled with backfilling mixture and some aggregates samples were transferred into the lab for testing. In the lab, the cylindrical molds were transferred to the moisture condition for curing and test was conducted on different curing days. Compositional analysis using the X-ray diffraction (XRD) method was conducted in the lab for analyzing the components in the aggregates and tailings.

Backfilling ingredients were mixed in the concrete mixing truck. Here, the mixing operation of each truck is mentioned as a batch. Around five to seven cubic meters of backfilling mixer were prepared in each batch. From the each batch mixture, samples were collected into the cylindrical molds for lab testing. The backfilling mixture were poured into the excavated zone. Batch one to batch six were prepared with the SL aggregates.

Figure 4-1: Two Different Aggregates.

Batch seven to batch thirteen were prepared with the BR aggregates. From batch one to batch thirteen, the mixture proportion by weight percentage are approximately 85% aggregates, 8% water, 5% cement, and the water to cement ratio (w/c) is around 1.47 and anti-washout additive used 1 litre/m^3. In batch one to ten, the mixing quantity of calcium chloride is about 3% by weight of the cement. But in the batch eleven to batch thirteen, the calcium chloride used around 10% by weight of the cement content. The moisture content was around 8% in all samples.

4.3.1 Backfill Materials

The aggregate is an extracted material from nearby sources like rivers, excavation areas, etc., which is composed of rock and mineral particles. Aggregates from natural sources are suitable backfill materials based on the availability, grain size and reserves. There are two types of aggregates and tailings have been used for preparing the backfilling mixtures in the field. The aggregates are collected from the local sources nearby the excavated area. The first one is named SL aggregates, has included in the top of Figure 4-1 and the second one is named BR aggregates shown in the bottom of Figure 4-1. The tailings are collected from the nearby mining operation area. The objective is to utilize the tailings for the

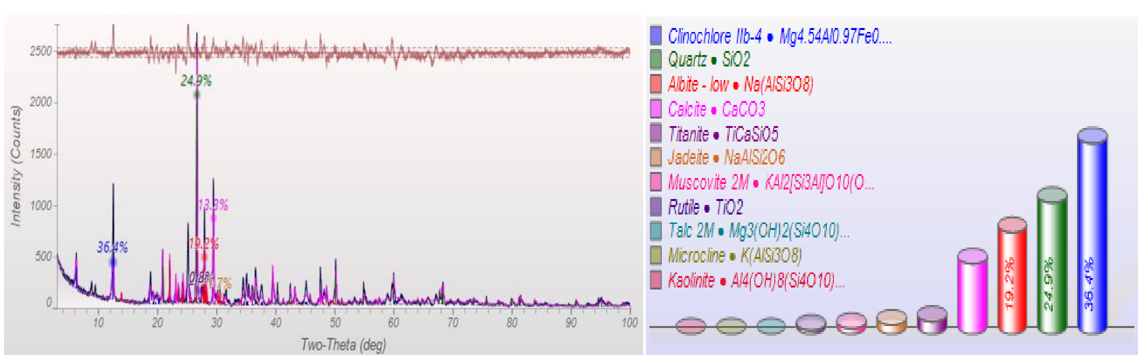


Figure 4-2: XRD Results of SL Aggregates

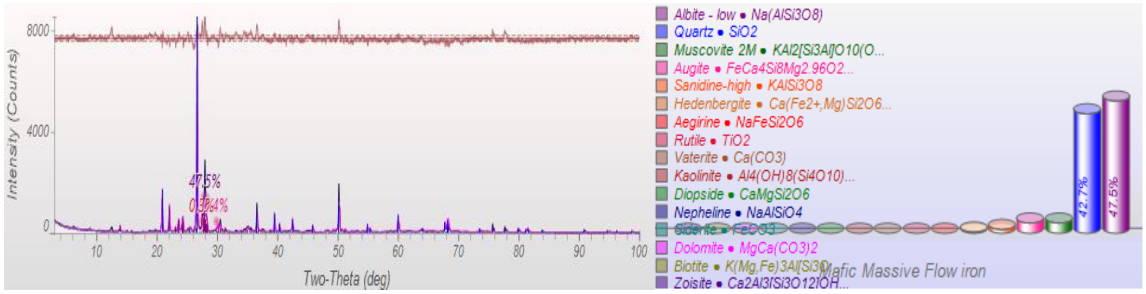


Figure 4-3: XRD Results of BR Aggregates

backfilling operation and compare the results with the aggregates or a combination of aggregates and tailing to achieve adequate strength with minimum cost.

X-ray diffraction (XRD) analysis for the aggregates has been conducted to determine the chemical composition. As shown in Figure 4-2 and 4-3, the major components for SL aggregates are Clinochlore, Quartz, Albite containing 36.4%, 24.9%, 19.2% respectively. The major components for BR aggregates are Albite, Quartz, Muscovite containing 47.5%, 42.7%, 3.8% respectively. The XRD results of the tailings collected from the concerned gold mine is shown in the Figure 4-4. Quan et al. (2021) reported that the major component of the tailings is Quartz. The amount of silica and calcium contents are 31% and 5.5%, respectively. Some other minor components are Calcite, Albite, Muscovite, Clinchlore.

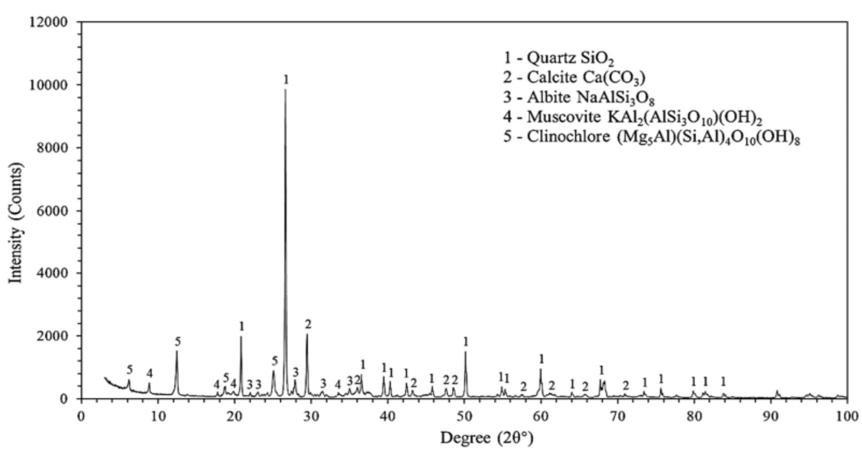


Figure 4-4: XRD Results of Tailings Sample (Quan et al. 2021)

4.3.2 Binders

For efficient backfill preparation, the evaluation of binder composition and the curing environment is important factor. Most commonly used cementitious materials such as Ordinary Portland Cement (OPC) have been utilized here. Type of binder and composition, moisture content, and water/binder ratio tend to regulate the development of strength properties in backfill material preparation. Among the backfilling mixture properties, the cost of binders/cement constitutes a significant portion compared to the other materials. The objective is to minimize the cost of cement/binders by developing the aggregates or tailings mixture to an extent where adequate strength would be gained within the required curing time.

4.3.3 Anti-washout Additive

The excavated zone where the backfilling mixture has been poured is filled with water. When the cement mixture is poured into the water without adding any specific additives, it affects the binding ability of the cement with aggregates. In that case, the underwater concrete method would minimize this effect. The underwater concrete method is widely used in offshore construction, bridges, and foundations in soil with the water level. The underwater concrete is highly flowable concrete that can spread into place under its own weight and get good compaction without vibration. The anti-wash additives mixture provides the resistance to washout, segregation, bleeding in case the concrete is washed out during the placement. The anti-washout additive is substantially influential in enhancing the cohesiveness and rheological properties of backfilling mixture that is poured in water.

4.3.4 Accelerator

Usually, the accelerator in the concrete admixture shortens the curing time and increases the rate of early strength development. The cold weather influences the concrete's slow curing and delays the setting process. Due to cold temperature, water in the concrete is prone to freeze and expand, cracking and weakening the strength of the concrete. Adding an accelerator makes the hydration process of the concrete faster and the set time can be reduced significantly. In the concrete mixture industry, calcium chloride as an accelerator has been very popular. During backfilling operation in winter, the temperature was cold there and there was no concern of rebar corrosion which makes the calcium chloride convenient considering the cheap cost and availability. During the mixture of backfilling, calcium chloride in different batches with varying percentages has been used as the accelerator.

4.3.5 Particle Size Distribution Analysis

Particle size distribution analysis is an analytical procedure to determine the range of the coarse and finer aggregates. The analysis is followed by arranging several layers of sieves with different grades of sieve opening sizes. Particle size distribution can influence the properties like the strength of concrete, solubility of mixture. Among all the available sieve analysis procedures, the dry sieve analysis has been conducted in this study. Particle size distribution has been conducted using the two widely used ASTM standards. The first one is ASTM D6913 – particle size distribution (gradation) of soils using sieve analysis, then ASTM C136 – sieve analysis of fine and coarse aggregates.

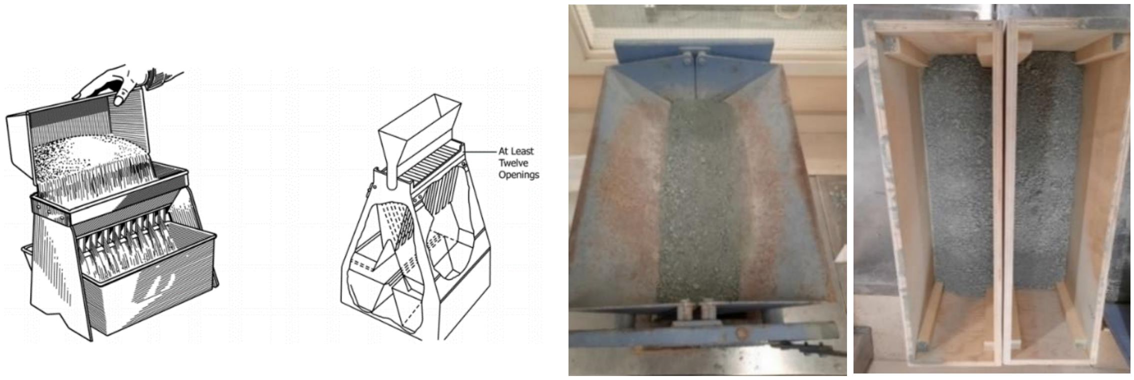


Figure 4-5: Sample Splitters (Riffles) – ASTM C702

Sample splitter has been used to obtain a representative portion of the materials. This procedure is followed by according to the ASTM standard C702 – reducing samples of aggregates to testing size. In the Figure 4-5, the sample splitter has an even number of equal width chutes. The splitter is equipped with two receptacles to hold the two halves of the samples following splitting. Samples are fed to the hopper at the top portion and fed to the chutes at a controlled rate. The sample needs to flow smoothly without restriction or loss of materials.

4.4 Experimental Analysis

4.4.1 Slump Test

The slump test measures the consistency of the freshly mixed concrete batches before it is set to maintain the standard of quality and strength. It measures the workability of the concrete and determines how easily the concrete will flow when it is poured into the site. It provides a good indication of the water-cement mixture ratio. Annor (1999) reported that the workable limits for paste fill mix design and stabilization were found to be between 176 mm and 228 mm slump. The standard was followed for measuring the slump of the mixer using the method stated in the ASTM standard C143 – slump of hydraulic cement

Figure 4-6: Slum test for the backfilling mixtures using SL aggregates

concrete. The slump test was conducted immediately after the mixer occurred in the concrete mixing truck. The measured average distance of the slump is around 9.43 inches (239 mm).

4.4.2 Uniaxial Compressive Strength (UCS) Test

From the collected samples, samples were categorized for testing on different days during the curing process to observe strength development over time. The samples were collected in the 2" x 6" molds. The UCS test was conducted using the geomechanics loading frame assembled with load cell, linear variable differential transformer (LVDT) and the data acquisition system (DAQSys). The UCS test was conducted on the 10, 17, and 28 days of curing using the geomechanics loading frame. In the Figure 4-7, the left side picture shows the collected backfilling sample made from SL aggregates and the right picture shows the sample made with BR aggregates. From each batch, three samples were tested for each testing phase and the average result is represented in the following section of result analysis. As the batch one to batch six made with SL aggregates, the average UCS results are shown in a specific figure 4-9. Then, batch seven to batch ten made with BR aggregates

Figure 4-7: Backfilling sample in UCS testing

and the average UCS results are shown in the Figure 4-10. For having different accelerator percentage in batch eleven to batch thirteen, the average UCS results are shown in the Figure 4-11. According to the ASTM standard C39 - compressive strength of cylindrical concrete specimens, the length, and diameter ratio of the samples were measured as 2.2. The samples were cut by a saw cutter to maintain the length to diameter ratio specified by standard and prepared for the UCS test. The average diameter of most samples was around 50.5 mm and the average length of most samples was around 115 mm.

The frictional forces between the ends of a compression specimen and the loading plates influence the specimen's measured compressive strength and failure type. During concrete compression testing, it is essential to reduce frictional forces. The presence of friction affects the stress-strain curve development significantly. According to the annual book of ASTM standards 2003, volume 4.02 “manual of aggregate and concrete testing”, the fracture type may help to determine the reason for the compressive strength of a tested cylinder being less than anticipated. Following ASTM C39, the most observed fracture pattern is Type 2 and Type 3 in the UCS test. Only a few samples produced Type 1 fracture. Type 4, 5 and 6 fractures have not been observed in any sample.

4.4.3 Sieve Analysis

The tailings and aggregates are collected from the local mining operation area. For the SL aggregate, the maximum size is passing 100% through the 12.5 mm sieve. Also, in the 11.2 mm and 9.5 mm sieve size, the weight percentage retained on the sieve is less than 1%. From the BL aggregates the maximum aggregate size is passing 100% through the 11.2 mm sieve. In the 9.5 mm sieve size, the weight percentage retained on the sieve is less than 1%. Hence, the single set sieve analysis was conducted for this aggregate. Those samples were dried in the oven for around 12 to 14 hours. Then they were put in the sample splitter by following the proper sampling procedure according to the ASTM standard C702. Among the two receptacles of the splitter, samples from the one receptacle was taken for the sieve analysis. In the following Figure 4-8, the particle size distribution curve of aggregates and tailing has been shown along.

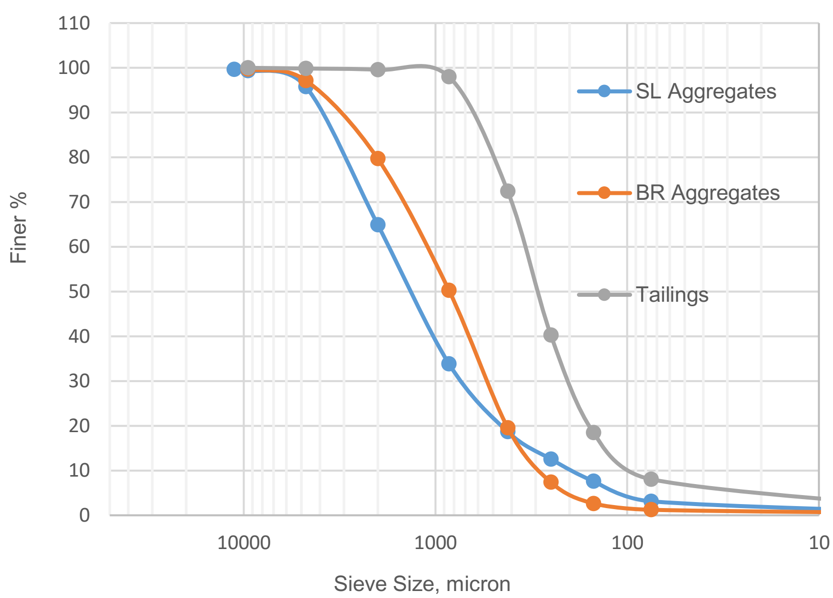


Figure 4-8: Particle size distribution curve of aggregates and tailings.

4.5 Results and Discussion

4.5.1 UCS

The observed range of UCS on all the samples of batch one to batch six has shown in figure 4-9. After 10 days of curing, from all the tested samples the minimum UCS is 0.96 MPa and the maximum UCS is 2 MPa. The average value is 1.32 MPa. For the samples of 17 days of curing, the minimum UCS is 1.03 MPa and the maximum UCS is 2.05 MPa. The average value is 1.4 MPa. Moreover, for the samples of 28 days of curing, the minimum UCS is 1 MPa and the maximum UCS is 2.21 MPa. The average value is 1.5 MPa. The green line indicates the average values which is a progressive increase of strength over the curing period.

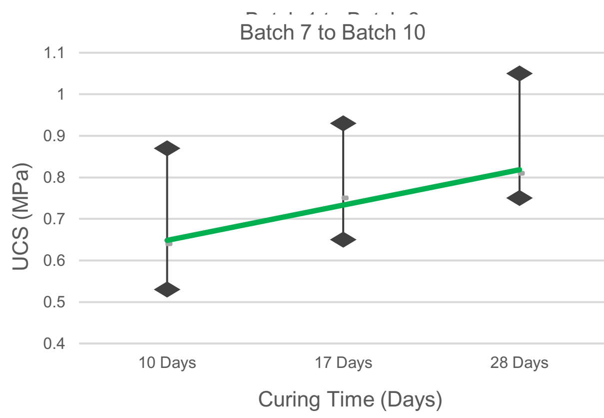


Figure 4-10: Range of UCS values for the samples from batch 7 to 10 on different days of curing, green line representing the average values.

For batch seven to batch ten, the observed range of UCS on all the samples has shown in figure 4-10. After the 10 days of curing, the minimum UCS is 0.53 MPa and the maximum UCS is 0.87 MPa, then the average value is 0.64 MPa. For the samples of 17 days of curing, the minimum UCS is 0.65 MPa and the maximum UCS is 0.93 MPa, as well as the average value is 0.75 MPa. Moreover, for the samples of 28 days of curing, the minimum UCS is 0.75 MPa and the maximum UCS is 1.05 MPa, as well as the average value is 0.81 MPa.

From batch eleven to batch thirteen, the observed range of UCS value on all the samples is shown in figure 4-11. After the 10 days of curing, the minimum UCS value is 0.62 MPa and the maximum UCS value is 0.73 MPa, then the average value is 0.69 MPa. For the samples of 17 days of curing, the minimum UCS is 0.73 MPa and maximum UCS is 0.87 MPa, as well as the average value, is 0.80 MPa. Moreover, for the samples of 28 days of curing, the minimum UCS is 0.80 MPa and maximum UCS is 0.92 MPa, as well as the average value is 0.86 MPa.

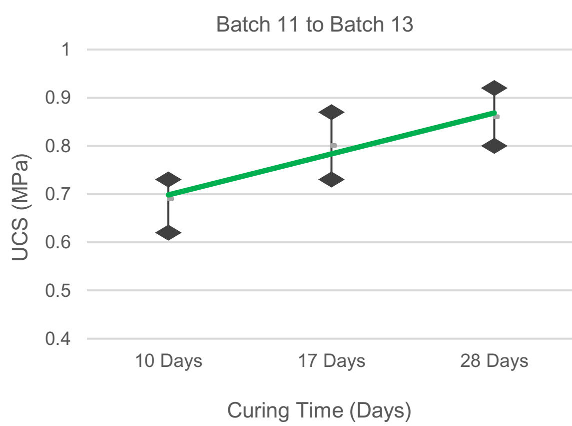


Figure 4-11: Range of UCS values for the samples from batch 11 to 13 on different days of curing, green line representing the average values.

Quan et al (2021) did the experimental analysis of UCS of CPB samples made from tailings and cement. The mixture recipe of solid content, cement water ratio was almost same as the mixture recipe of CPB samples made from aggregates. Using the binder content of 6% by weight, the samples were prepared in the two-inch molds and the length to diameter ratio was 2.1. The average UCS after 14 days is around 1.20 MPa and 28 days of curing is nearly 1.35 MPa.

4.5.2 Gradation of Aggregates

A renowned relationship available between compressive strength and sizes of aggregate materials in the concrete mixing technology. The proper selection of particle size distribution leads to optimum design of concrete mixes and minimization of cement requirements (Neville, 1987).

Well-graded aggregates have different particle sizes from coarser to finer in an adequately distributed manner. On the other hand, in the poorly graded aggregates, the particle sizes have an excess of specific particle sizes or deficiency of a certain range of particle sizes. The gap-graded particle sizes also have missing of different ranges of particles. It may have a few certain ranges of excessive particles compared to the wide range of balanced particles like the well-graded. In the following Figure 4-12, a depiction of the typical aggregate gradation drawing has been shown.

Thomas et al. (1979) reported that adequate fine particles in well-graded backfilling materials tend to fill the void between larger particles which leads to a reduction in the porosity and cement usage. On the other hand, the poorly graded aggregates have a high void ratio and require excess cement to fill the voids. Moreover, if there are too many fine particles, then those aggregates may consume more cement. An excess amount of fine will reduce the strength.

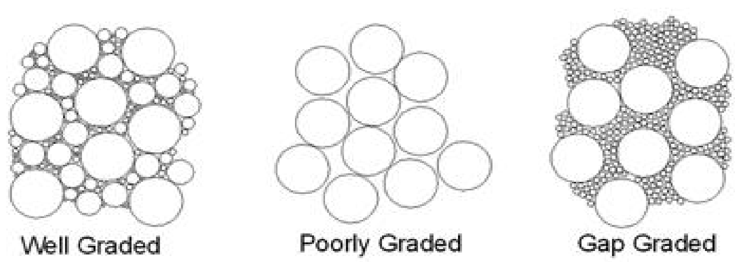


Figure 4-12: Conceptual drawing aggregate gradation (Courtesy of CCI)

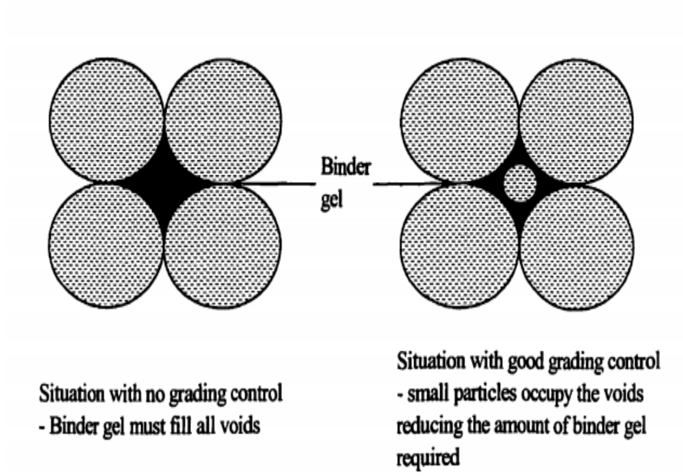


Figure 4-13: Model demonstrating the benefit of the good grading in particles distribution and required binder content (Thomas et al, 1979)

According to Holtz and Kovacs (1981), the analytical approach for the aggregate gradation was conducted by coefficient of curvature (C_c) and uniformity coefficient (C_u) using certain grain diameters D, which refers to equivalent percent passing on the particle size distribution curve. For example: D_{60} is the sieve size through which 60% of soil will pass through them, i.e.: 60% of the particle size is finer than this size. D_{30} is the sieve size through which 30% of soil will pass through them, i.e.: 30% of the particle size is finer than this size. D_{10} is the sieve size through which 10% of soil will pass through them, i.e.: 10% of the particle size is finer than this size. The Uniformity Coefficient and The Coefficient of Curvature is defined by following equation 4-1 and 4-2:

$$C_u = \frac{D_{60}}{D_{10}} \qquad [4\text{-}1]$$

$$C_c = \frac{(D_{30})^2}{D_{10}\ x\ D_{60}} \qquad [4\text{-}2]$$

The aggregates are considered to be well-graded with coefficient of curvature (Cc) between 1 to 3 as long as the uniformity coefficient (Cu) is also greater than 4 for gravels and 6 for sands (Holtz and Kovacs, 1981). According to the gradation theory, the SL aggregates is well-graded since it meet the criteria Cu > 6 and 1 < Cc < 3. But the BR aggregates and tailings are considered poorly graded as they don't meet either of the criteria Cu > 4 and 1 < Cc < 3. For the SL aggregate from the total weight, 5%, 4.5%, and 3% were retained on 150, 75 microns, and Pan consecutively. For BR aggregate from total weight 4.75%, 1.4%, and 1% retained on 150, 75 microns, and Pan consecutively. There is a higher percentage of large size particles in the BL aggregates compared to the finer size particles. The SL aggregates have a well-balanced distribution of large and finer size particles compared to the BR aggregates. On the other hand, the D values of the tailings compared to the aggregates represent that the tailings had significant finer particles than both aggregates.

Table 4-1: Data Analysis of Particle Size Distribution

	SL Aggregates (micron)	BR Aggregates (micron)	Tailings (micron)
D_{10}	198	286	88
D_{30}	741	566	202
D_{60}	1817	1230	354
C_u	9.50	4.30	3.98
C_c	1.60	0.91	1.30

4.6 Conclusion

Appropriate particle size distribution facilitates achieving the optimized strength characteristic of the cemented paste backfill (CPB) structure. Well-graded materials minimize the porosity, increase the contact area between particles, and decrease the use of cement that fills the voids, thus reducing the cost of cementing materials for producing the required UCS strength. Also, early comprehensive strength achievement occurs for CPB mixture with a broader particle size distribution range.

Moreover, the optimum strength development of CPB depends on water-cement ratio, moisture content, binder composition, particle gradation, curing conditions. In the backfilling operation, the cement/binder cost constitutes the most. To minimize that, a combined and correlated investigation approach requires for feasible backfill mixture development. In this study, both the C_c and C_u values have been utilized to categorize the particle characteristics. The findings from experimental analysis refer that the SL aggregates meet the gradation criteria well and produce required strength, around 1 to 2 MPa along their different curing periods. On the other hand, the BR aggregates doesn't meet the gradation criteria and developed strength is less than 1 MPa over different curing durations. Hence, being poorly graded and considering the safety criteria comparatively, the developed average strength for BR aggregates and tailings is lower than SL aggregates.

Further study and experimental analysis can be conducted on the composite material with mixes of tailings and aggregates maintaining a balanced mixture recipe. Modification of tailings by removing or adding different range particles can be done to make it well-graded material. The use of non-standardized aggregates and tailings together can produce a composite mixer to achieve an optimized well-graded particle size distribution. Following that, controlling moisture content and optimizing water/cement ratio can be another approach to develop the required strength.

Chapter 5: Experimental Evaluation of Acid Mine Drainage Potential for Cemented Paste Backfill

This chapter discusses the technical paper titled "Experimental Evaluation of Acid Mine Drainage of Cemented Paste Backfill (CPB)". The authors of this paper are Mohammad Shafaet Jamil, Michael Marsh, and Professor Stephen Butt. This paper has been accepted in the proceeding of Tailing and Mine Waste Conference 2023, which will be happening on November 5-8, 2023 at Vancouver, BC, Canada. The author's dedicated contributions are described below:

- Mohammad Shafaet Jamil: Conceptual analysis, literature review, experimental design, experimental work, data analysis, and manuscript preparation.
- Michael Marsh: Co-ordination for procurement, technical support in experimental set-up, manuscript review.
- Professor Stephen Butt: Research and experimental guidance, overall supervision, manuscript review and approval of all stages throughout the whole work process.

5.1 Abstract

Environmental management of the sulfide-bearing tailings material safely is a significant concern for the mining operation. Iron sulphides (mostly pyrite and pyrrhotite) are the most common in sulfide-bearing mining waste materials. Surface disposal of these waste materials will lead to oxidation in the presence of air and water, eventually generating acid mine drainage (AMD). The utilization of tailings in cemented paste backfilling method eliminates the necessity of storing most of the tailings on the surface, reducing the

environmental footprint. In this study, static and kinetic testing were conducted on the tailings and cemented past backfill mixture to evaluate the potentiality of acid mine drainage.

From the performed static test on the tailings sample through the Acid-Base Accounting (ABA) method, the results of the net neutralization potential and the ratio of neutralization potential to acid potential show that the tailings material will be acid generating. The X-Ray diffraction (XRD) test was conducted on the tailings sample for composition analysis. Kinetic tests measure the dynamic performance or reactivity of excavated and exposed materials over time. The column leach testing setup in the laboratory is designed to observe the weekly wet-dry and leaching cycles of CPB mixtures. The 6-inch diameter by 12-inch long cylindrical PVC columns are filled with CPB materials. The mixture ingredients are mixed with tailings, Portland cement and water. There test set-up designed with a components matrix, where six column contained CPB mixtures, and two columns contained tailings only.

The columns are wetted by applying the deionized water from the top of the surface and the leachate water is collected for measurement in a container located at the base. To simulate the drying environment of natural weather, heat lamps on the top are used to ensure sample drying between test solution applications. Typically, the test solution applied weekly and the leachates were collected every week. For over forty weeks, the pH and electrical conductivity have been measured and analysed weekly on the percolated water for potential AMD evaluation. In the controls column, it is observed that the pH value transitioned towards acidic within the first few weeks of measurements. During the initial week of measurements on cemented columns, the compacted samples showed higher pH values than the uncompacted samples. Initially, the cemented columns in the first few weeks showed pH values around 10 to 12. Then on later weeks, the pH values started to stabilize gradually around 6 to 8.

5.2 Introduction

Cemented paste backfill (CPB) is an essential technique in the mining industry that involves using a mixture of tailings, cement, and water to create a solid backfill material. The significance of CPB lies in its capacity to provide support to underground mining operations while simultaneously utilizing mine waste, such as tailings, as a valuable resource. CPB plays a role in preserving the stability of underground openings, preventing ground subsidence, and enhancing overall operational efficiency. While typical concrete has water/cement ratios around 0.5, CPB applications involve higher ratios ranging from 5 to 10. The unconfined compressive strength values vary between 0.05 and 3.5 MPa, which differ from conventional concrete strength levels of 25 to 35 MPa. The properties of tailings are influenced by various factors, including the composition of the original rock, the method used for mineral extraction, and the methods employed for transporting and placing the tailings materials (James et al. 2003). The CPB is generally transported either by gravity or through pumping to fill the desired underground stope (Yilmaz, 2010).

The use of CPB has gained popularity as an alternative method for managing mine waste in Canada and other countries worldwide over the past two decades (Ercikdi et al. 2017). CPB not only has practical benefits but also contributes to environmental mitigation. The inclusion of cement in CPB results in improved strength, decreased permeability, and reduced acid mine drainage (AMD) formation by enhancing the capacity to neutralize acid

(Ercikdi et al 2017). During mining activities, it is possible for minerals in the tailings and binder to undergo oxidation or chemical reactions, resulting in the creation of soluble contaminants. Pyrite is a common sulphide mineral found in mine waste which plays a significant role in acid mine drainage (AMD). Initially, pyrite undergoes oxidation in the presence of water and molecular oxygen, producing sulfate ions, ferrous ions, and hydrogen ions (Lu et al. 2013).

These contaminants have the potential to affect the quality of water within the mine during operations and can continue to pose a risk to groundwater and surface water quality even after the mine is closed. Evaluation of potential environmental issues requires characterization of the paste mixture in terms of the mixture's characteristics like mineralogy, acid generating capacity, kinetic reactions and potential for leaching metals is crucial (Benzaazoua et al. 2008). This assessment helps to predict the impact on water quality and ensures proper management strategies are in place.

The use of CPB technology has the ability to decrease the chemical reactivity of tailings and the movement of pollutants by combining and consolidating the tailings with an alkaline substance like cement (MEND 2006, Kesimal et al. 2005). Although there have been notable advancements in integrating sulphide-bearing tailings into CPB systems, the environmental behaviour is still an unexplored area. While numerous studies have examined the mechanical characteristics of CPB, there is limited research on how the chemical reactivity affects the performance of CPB systems (Ouellet et al., 2003). In this study, acid-base accounting test were conducted as a static method to evaluate the potential acid generation and neutralization capacity of the tailings material. Column leach test were conducted on the cemented past backfill mixture containing variable cement percentage by weight to evaluate the potentiality of acid mine drainage.

5.3 Materials and Methodology

5.3.1 Tailings Properties

Tailings are the waste materials after the valuable components have been extracted from ore during the mining or mineral extraction process. They consist of finely ground rock particles, minerals, and water. Tailings are typically deposited in tailings storage facilities or ponds that designed to contain and manage the waste materials safely. Understanding tailings properties is essential for effective tailings management and addressing environmental considerations.

Tailings, composed of crushed rock, minerals, and water, have varying compositions depending on the processed ore. Tailings typically have a wide range of particle sizes, from fine silt and clay-sized particles to larger sand and gravel-sized particles. As shown in Figure 5-1, particle size distribution was conducted for tailings

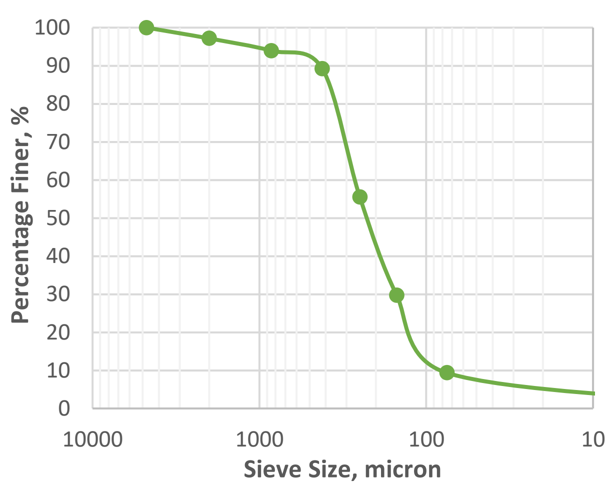


Figure 5-1: Particle Size Distribution Curve of Tailings

materials following the standard ASTM C136. Bulk density of the tailings (1.613 gm/cm^3) was measured by following the ASTM C29 on the oven dry tailings sample. Specific Gravity (2.72) of the tailings samples was determined by following ASTM C128.

5.3.2 Cemented Paste Backfilling

Cemented paste backfill (CPB) offers significant advantages in terms of technology, economics, and environmental impact compared to rock and hydraulic fill. It enables a substantial amount of tailings to be returned underground, resulting in reduced space requirements and lower rehabilitation costs. CPB is a customized mixture of unaltered tailings, including fine particles. It typically contains 75 to 85% solids, a hydraulic binder comprising 3-9% of the dry paste weight, and sufficient water content for easy transportation. The addition of binder in paste tailings is an essential component to increase the strength and stability. CPB acts as a barrier, preventing water seepage and reducing the formation of acid mine drainage by restricting oxygen diffusion. Portland cement is widely used as it sets and hardens through chemical reaction with water. When Portland cement come into contact with water cement hydration occurs. Throughout the hydration process, the primary components of Portland cement react with water, forming hydration products that contribute to the setting and hardening of concrete. Portland cement (PC) is produced by crushing and blending specific quantities of raw materials, such as limestone, clay, and shale. Typically, modern PC mainly consists of clinker plus a small quantity of gypsum (3–7% wt.) which is used to regulate the initial setting time. Clinker is a vital ingredient which represents about 95% wt. of the PC. Typically, PC and its clinker mainly consist of four oxides: lime (CaO), silica (SiO_2), alumina (Al_2O_3) and iron oxide (Fe_2O_3) in addition to the minor oxides (Klieger & Lamond, 1994).

5.3.3 AMD Prediction Approaches

To address the environmental concerns related to mining activities, the development of acid mine drainage (AMD) prediction methods is crucial when excavating or exposing significant bedrock. These methods aim to minimize uncertainty, identify potential risks, and facilitate the selection of effective strategies for extraction and waste handling. By providing insights into the behavior of mining materials and components, the prediction methods also help to identify any potential adverse conditions.

When assessing the potential impacts of AMD and related processes, it is necessary to address several important aspects. Determining the physical and geochemical conditions that facilitate weathering and contaminant transport is necessary. The prediction methods for AMD vary depending on the different phases of mine project development. Typically, chemical, mineralogical, and physical analyses of waste components are performed as part of the initial characterization process.

5.3.4 Static Prediction Methods

Static tests provides initial assessment of acid-generating components (e.g., sulphides) and acid-consuming components (mainly carbonates) in waste materials. In the AMD studies, a static test is used for analytical methods that evaluate the characteristics and quantities of different components within a sample at a specific moment. There are numerous methods for static test analyses available. One of the widely used static tests in AMD studies is the acid base accounting (ABA) method.

Static tests assume complete reactions of sulphides and carbonates without considering kinetics or chemical equilibria. Moreover, static tests do not offer predictions regarding drainage quality. However, they serve as a quick, cost-effective screening method to determine the preliminary acceptability or unacceptability of water quality. To assess or predict reaction rates and the geochemical evolution accurately, a combination of kinetic tests and static tests is necessary.

5.3.5 Kinetic Prediction Methods

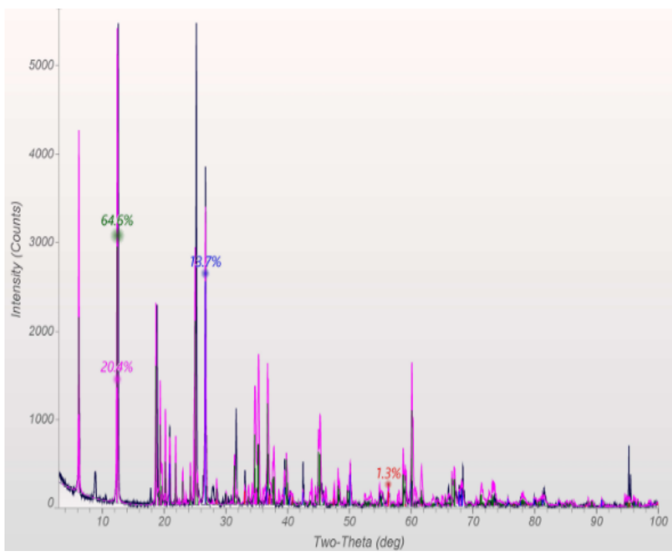
Kinetic tests evaluate the dynamic performance and reactivity of excavated and exposed materials. These tests are usually conducted when static test analysis suggests the potential for AMD generation or when the results are inconclusive. Prediction testing provides a short-term assessment of a phenomenon that occurs over a longer period. Designing a kinetic prediction test poses challenges as it involves either modeling actual field conditions, which may result in a test duration that is too short, or creating accelerated conditions that may not accurately represent real-world scenarios.

Kinetic prediction tests aim to simulate the long-term processes of acid production and consumption, as well as predict the quality of drainage, in laboratory or field settings. Designing a reliable prediction test for AMD is challenging due to the inability to replicate exact field conditions within a feasible timeframe. Various tests of different types can be employed for kinetic testing, each differing in complexity, duration, cost, and the type of data they can provide. One popular kinetic test approach is the utilization of columns to mimic the weathering of rock or tailings in flooded or percolation leach scenarios.

5.4 Experimental Analysis

5.4.1 Elemental Analysis of Tailings

The objective of major element analyses is to identify and measure the total amounts of common mineral forming compounds in a sample. X-ray diffraction (XRD) test was done on the samples from collected tailings materials and the result is shown in the Figure 5-2. XRD is a scientific technique used to analyse the crystallographic structure and composition of materials. XRD involves directing a beam of X-rays onto a sample which results in the scattering of X-rays by the crystal lattice of the material. By measuring the angles and intensities of the diffracted X-rays, information about the atomic spacing and arrangement within the sample can be obtained.



Phase ID (4)	Chemical Formula	PDF-#	Wt% (ESD)	DD% (ESD)	RIR	μ
Quartz	SiO_2	98-000-0369	13.7 (?)	15.7 (?)	4.12	91.2
Clinochlore IIb-4	$Mg_{4.54}Al_{0.97}Fe_{0.46}Mn_{0.03}(Si_{2.85}$	98-000-0165	64.6 (?)	64.1 (?)	0.77	111.9
Pyrite	FeS_2	98-000-0363	1.3 (?)	1.8 (?)	3.00	956.9
Chlorite - IIb	MgFeSiAlOOH	98-000-0159	20.4 (?)	18.3 (?)	1.46	267.2

XRF(Wt%): Fe2O3=11.5%, MnO2=0.3%, SO3=1.8%, SiO2=40.8%, Al2O3=13.9%, MgO=24.0%

Figure 5-2: XRD Results of Tailings Sample

5.4.2 Acid Base Accounting Test

The evaluation of acid potential, neutralization potential, the comparative calculation of net neutralization potential (NNP) and neutralization potential ratio (NPR) is collectively referred as acid-base accounting (ABA). ABA encompasses various methods, but the most straightforward approach involves using sulphide-S to calculate AP, while NP is determined through a single procedure. They are expressed in comparable and consistent unit kg CaCO3/per tonne of rock or tailings materials. The difference between the two values is termed as the net neutralization potential or Net NP. The Table 1 describes the guidelines of interpreting ABA results through the values of NNP and NPR.

$$\text{Net Neutralization Potential (NNP)} = NP - AP \tag{5-1}$$

$$\text{Neutralization Potential Ratio (NPR)} = NP/AP \tag{5-2}$$

Acid Potential Measurement

The acid potential (AP) is determined by analysing the total sulphur content and calculating AP under the assumption that all sulphur is converted to sulphate, resulting in the production of four moles of H+ per mole of oxidized pyrite. Each mole of sulphur generates two moles of acid, which can be neutralized by 1 mole of calcium carbonate. Consequently, the molar ratio of sulphur to calcium carbonate is 1:1. The acid potential (AP) of the sample, expressed in tonnes of calcium carbonate equivalent per 1000 tonnes, can be calculated by multiplying the percentage of sulphur by 31.25.

Neutralization Potential Measurements

All materials containing acid-generating minerals like pyrite have the potential to produce acid, but the occurrence of AMD depends on the availability of neutralizing alkalinity. The measurement of neutralization ability is a crucial aspect of drainage chemistry, and the determination of neutralization potential (NP) through static tests is a significant component of acid-base accounting. To assess NP a recommended procedure is the Sobek et al. (1978) method. In this process, a sample treats with an excess of standardized hydrochloric acid and heated to ensure complete reaction. A fizz test is conducted to verify that an adequate amount of acid has been added to react with all acid-consuming minerals presence. The remaining unreacted acid is then titrated with standardized base to achieve a pH of 7, allowing for the calculation of the calcium carbonate equivalent of the consumed acid. While the Sobek method is the standard procedure, there are several alternative methods available for measuring laboratory NP, some of which are promoted as being more accurate by minimizing discrepancies between laboratory and field results.

Table 5-1: Guidelines for Interpreting the Static Test Results (US EPA, 2003)

Guidelines from Robertson and Broughton (1992)			
Criteria	**Acid Potential (AP)**	**Uncertain Behavior**	**Neutralizing Potential (NP)**
NNP	< -20 tonnes/kilotonne	> -20 to < +20 tonnes/kilotonne	> + 20 tonnes/kilotonne
NPR	< 1	1 to 3	>3
Guideline from Price et al. (1997)			
Sulfide-S	**Paste pH**	**NPR**	**Potential for AMD**
Sulfide-S <0.3%	>5.5	---	None
Sulfide-S >0.3%	<5.5	<1	Likely
		1 - 2	Possibly
		2 - 4	Low
		>4	None

5.4.3 Column Leach Testing

Column leach tests enable the testing of mine wastes to simulate weathering conditions. A column refers to a structure that contains a mass of materials and allows for the qualitative analysis of water drainage through the sample. It consists of a basin with enclosed sides and a bottom equipped with a drain. The water that seeps through the specimen is collected and analysed to assess the potential for AMD. As shown in Figure 3, the column leach testing setup is designed to achieve a weekly wet-dry cycle and leaching cycle. The 6 inch x 12 inch cylindrical plastic mold are used as column. They are made of PVC materials. The cylinders are filled with mixture of cemented paste backfill materials. The mixture ingredients contain mostly tailings, cement and water. The CPB mixture were poured into each cylindrical column up to the height of 6 inch leaving rest of the length for pouring water solution. There are total eight columns from which six columns are filled with CPB mixture and other two column are filled with only tailings without any binder. To simulate the drying environment of natural weather, heat lamps were placed to ensure drying of the

a)
b)

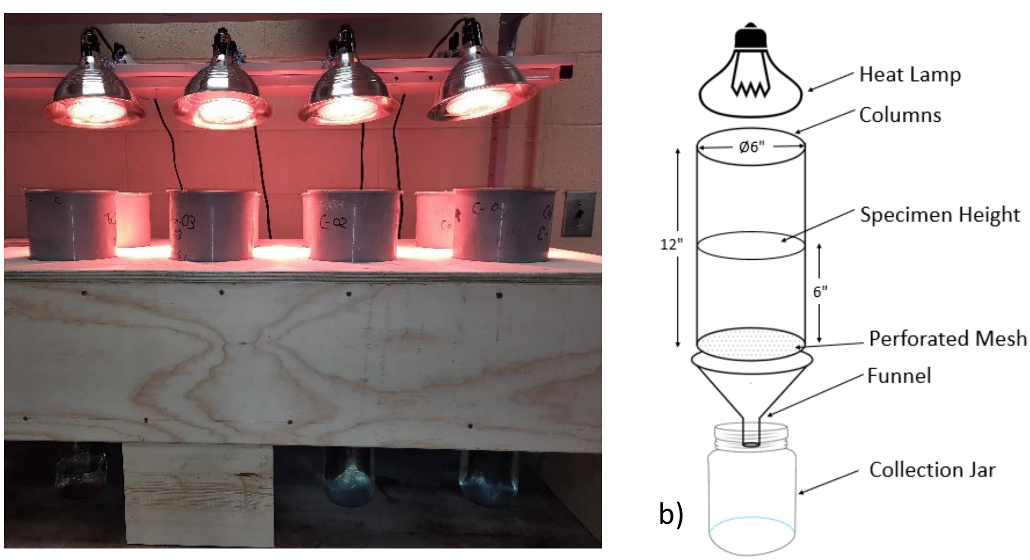


Figure 5-3: Experimental Set-up of Column Leach Test: a) Set-up in the Lab, b) Schematic Drawing

samples between test solutions applications. Throughout the testing duration, the maintained temperature is 21° Celsius. The bottom part of the columns perforated with 1mm size mesh to leach the water. Sample were wetted by applying the deionized water from the top of the surface and leachate were collected in a container through the funnel at the base. Glass wool filter material was placed inside each funnel to screen any solid substances from the leachate water. Every week, around 1 litre of deionized water was poured into the columns to percolate through the cemented tailings samples and the leachates were collected weekly. The internal vibration concept was used as the compaction method to refer the reduction of air content while measuring the AMD potential in CPB mixtures. The test matrix of all the eight column is described in the Table 5-2.

The pH and electrical conductivity (EC) are measured through a portable waterproof instrument ExStik II pH/Conductivity meter. The model of the instrument is Extech EC500 and electrical conductivity is expressed in mS/cm. The EC500 meter features a digital display that shows the pH or EC value, depending on the selected mode. It utilizes a replaceable electrode to measure pH and a built-in conductivity cell for EC measurements. To ensure greater accuracy in measuring EC500 instruments, Toledo EL20 pH meter was used for pH measurements and Thermo-scientific A322 portable meter was used to measure conductivity. This enabled to obtain more comparable and precise results.

Table 5-2: Test Material Components of Column Leach Test

Compaction	Material Components of CPB according to Weight Percentage			
No Vibration (NV)	Column 1 2% Cement 78% Tailings 20% Water	Column 2 4% Cement 76% Tailings 20% Water	Column 3 6% Cement 74% Tailings 20% Water	Column 7 (Controls) Only Wet Tailings Material 4800 gm
With Vibration (WV)	Column 4 2% Cement 78% Tailings 20% Water	Column 5 4% Cement 76% Tailings 20% Water	Column 6 6% Cement 74% Tailings 20% Water	Column 8 (Controls) Only Wet Tailings Material 4800 gm

5.5 Results and Discussion

5.5.1 Interpretation of ABA Results

The positive Acid Production Potential (AP) value of +98.6 kg $CaCO_3$/tonne indicates that the tailings sample has the potential to generate acid when exposed to oxygen and water. This means that there are acid-generating minerals or elements present in the tailings material that could contribute to acid formation. However, the low Neutralization Potential (NP) value of 12.4 kg $CaCO_3$/tonne suggests that the tailings contains limited amount of acid consuming minerals or elements that can neutralize the acid producing capacity. This is further confirmed by the negative Net Neutralization Potential value of -86.1 kg $CaCO_3$/tonne, indicating an overall deficit in acid neutralization. The Neutralization Potential Ratio (NPR) of 0.1 reveals that the material has a very low ability to neutralize the acid it generates. A ratio below 1 suggests a higher risk of acid generation and a limited capacity for neutralization.

Based on these results of Table 5-3, it can be interpreted that the material has a significant potential for acid generation, but a very limited ability to neutralize the acid (low NP and negative Net NP). The low NPR value indicates an imbalance in favour of acid generation, implying a high risk of acid formation and associated environmental concerns of acid mine drainage.

Table 5-3: Acid Base Accounting (ABA) Results of Tailings Sample

Paste pH	Total Sulfur	Sulfate (as S)	Sulfide	Acid Production Potential (AP)	Neutralizing Potential (NP) at pH 8.3	NNP At pH 8.3	NPR
	%	%	%	Kg $CaCO_3$/tonne			
5.9	3.25	0.096	3.15	98.6	12.4	-86.2	0.1

5.5.2 Column Leach Test Results

The percolated leachate water from the column is collected in separate containers each week after applying a solution (deionized water). The results of the column leach test are

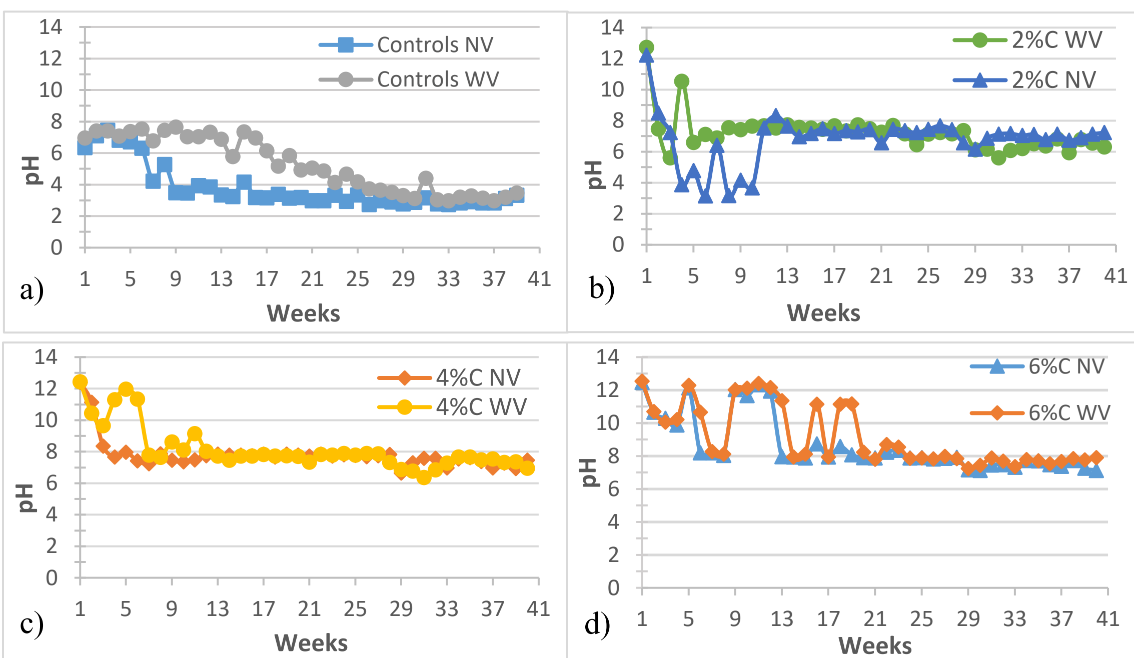


Figure 5-4: Column Leach Test Results: a) Controls (Un-cemented Tailings), b) 2% Cemented Tailings, c) 4% Cemented Tailings, d) 6% Cemented Tailings

presented in the Figure 5-4 following the test matrix described in table 5-2. In the initial weeks, the pH of the leachate water from both tailings-containing columns ranged from 6 to 8. For columns containing 2%, 4%, and 6% cement, the measured pH on the first week was around 10 to 12. This higher pH indicates the presence of initial hydroxide alkalinity and the subsequent formation of cement hydration products. After 40 weeks of measurements, the pH of the leachate water dropped to less than 4 from the tailings contained columns, indicating significant acid generation. In contrast, the leachate water from all the cemented paste columns maintained a pH value around 6 to 8 even after 40 weeks of measurements which was around 10 to 12 during the initial weeks.

The influence of compaction on cemented tailings columns has not been significantly observed until 40 weeks of measurement. Both compacted and un-compacted columns yielded similar pH value ranges during several weeks of measurements. Specifically, for the 2% cemented tailings columns, the un-compacted samples exhibited pH values ranging from 3 to 5 in the first 10 weeks, while the compacted samples showed values ranging from 6 to 8. The lower percentage of cement content in the cemented paste backfilling mixture resulted in acid generation from those columns. However, from the 10th week until the 40th week of measurement, the pH values measured from the leachate water of those 2% cemented columns remained around 6 to 8.

Electrical conductivity indicates water's capacity to conduct electricity, which is determined by the presence of substances capable of carrying electrical currents. As the concentration of conductive substances increases in water, its conductivity rises. Contaminated water typically exhibits higher conductivity compared to uncontaminated water. This is attributed to the presence of dissolved metals, sulfates, and hydrogen ions, all of which are capable of conducting electrical charge. Table 5-4 provides the range of the EC data in leachates released from the column leach test. The initial electrical conductivity (EC) values in the leachates were higher in the cemented columns, primarily due to the presence of cement components. Throughout the 40 weeks of measurements, the average EC value for these columns ranged between 2 to 3 mS/cm. However, throughout the same duration, the average EC value increased in the un-cemented tailings samples indicating their acid generating nature. The average EC values in the leachate water samples from the un-cemented tailings columns were found to be between 4 to 5 mS/cm. This higher EC value suggests the potential generation of acidity in the tailings-containing columns.

Table 5-4: Electrical Conductivity (mS/cm) Measurements Data from Column Leach Test

Columns	**Weeks**	**Max.**	**Min.**	**Avg.**	**Stdv.**
C-01	40	8.51	2.12	3.36	1.18
C-02	40	8.05	2.17	3.38	1.1
C-03	40	6.52	1.35	3.16	1.03
C-04	40	8.22	2.05	3.52	1.28
C-05	40	8.42	1.83	3.14	1.22
C-06	40	9.93	1.1	3.11	1.37
C-07	40	7.53	2.78	4.67	1.05
C-08	40	6.64	3.02	4.85	0.89

5.6 Conclusion

Storing sulphide tailings underground can be advantageous, potentially providing intimate mixing with alkaline binders and low oxygen conditions during operations. However, the assessment of acid mine drainage (AMD) has emerged as a modern research area due to the growing concern regarding potential groundwater pollution caused by underground waste disposal. The results of the acid-base accounting test indicates that the tailing has the high potentiality of acid generation. Then in the laboratory experiment of column leach test, the leached water from the cemented tailings sample consistently exhibited trend of neutral pH values over a period of forty weeks. Until this period of the study, the range of the measured pH values are around 6 to 8 for the cemented tailings columns. In contrast, the leachate water obtained from the tailings columns showed acidic pH values for the same time duration of measurement. The leachate water from those columns showing the pH values around 3 to 4 indicating acidic nature. This nature of acid generation from the column leach test of un-cemented tailings confirms the results of acid-base accounting. Addition of cement provides extra neutralization potential to the cemented columns which leads to the higher pH values comparing to the un-cemented columns.

Hence, the utilization of cemented paste backfill (CPB) is widely acknowledged as advantageous in mitigating the overall environmental consequences linked to mining activities. CPB helps to minimize the amount of tailings that need to be disposed of on the surface, thus reducing surface impacts by minimizing the required space. Moreover, CPB reduces the presence of free water, leading to a decrease in leachate production. Additionally, the inclusion of cement in CPB offers extra capacity for neutralization and decreases the effective porosity. When tailings are mixed with cement and water to create a paste, it can effectively bind and immobilize sulfide minerals that are typically responsible for acid mine drainage. This prevents the exposure of sulfides to oxygen and water, which are the key triggers for acid generation. By encapsulating these materials, cemented paste backfill significantly reduces the risk of acid mine drainage formation, making it an effective approach for environmental protection in mining operations.

The challenge in validating laboratory predictions with field verifications lies in the multitude of factors that can impact the results. These factors include changing groundwater flow and quality, the effects of new backfill in neighbouring stopes and ventilation patterns. To overcome these challenges in a real mine setting, it may be necessary to proceed with more controlled conditions and long-term observation of trends in mine water quality.

Chapter 6: Conclusion and Recommendation

6.1 Conclusion

This thesis focuses on investigating the optimization of cemented tailings backfill. The research covers several aspects including the study of strength characteristics, measurement of elastic properties using ultrasonic methods, determination of yield stress, and assessment of acid mine drainage potential. The results and observation from those studies are described in the following.

The UCS testing in the Instron frame provides a good stress-strain curve for low-strength backfill samples. The uniaxial compressive strength results show a range of approximately 0.5 MPa for 4% cement samples and 1 MPa for 6% cement samples. Ultrasonic wave velocity measurements show that both P-wave and S-wave velocities range between 1.13 to 1.71 km/s and 0.63 to 0.93 km/s, respectively. The 6% cement samples consistently exhibit higher velocities and elastic properties compared to the 4% cement samples. While slump height is commonly used to assess consistency, it can be unreliable due to variations in yield stress and density. Yield stress is a preferred indicator of consistency, as high or low values can impact the material flow and strength.

An appropriate particle size distribution is crucial for optimizing the strength of cemented paste backfill (CPB) and reducing cement costs. Well-graded materials decrease porosity and increase particle contact, leading to cost savings by reducing the need for excessive cement. A broader particle size distribution facilitates early strength development in CPB. Factors like water/cement ratio, moisture content, binder composition, particle gradation, and curing conditions affect the CPB strength. A combined investigation approach is necessary for feasible mixture development.

Acid-base accounting tests show high acid generating potential in the tailings, while column leach tests reveal acidic pH values in un-cemented tailings leachate within first few weeks. In the laboratory experiment of column leach test, the leached water from the cemented tailings sample consistently exhibited trend of neutral pH values over a period of forty weeks. Until to this date of the study, the range of the measured pH values are around 6 to 8 for the cemented tailings columns.

6.2 Recommendation

- Mixing diverse range of coarser particles from crushed waste rock with finer tailings materials can result in a well-graded particle size distribution. This practice improves packing density, provides structural reinforcement and stability of the mixture. Furthermore, a well-graded distribution reduces permeability and fluid movement through the material.
- While measuring the ultrasonic properties in the porous soft cemented tailings samples, effective acoustic coupling is crucial for obtaining high-quality data. It is recommended to use an ample amount of couplant. Whenever feasible, applying pressure to the specimen helps eliminate any trapped air between the platen and the specimen.
- It is advisable to verify the velocities by using a reference system whenever feasible. This will assist in accurately selecting S-waves as it has been noted that the system can generate a convolved signal.

- To estimate the rheological behavior of paste, one of the common methods can be implied using a rheometer to directly measure parameters like shear stress, shear rate, and viscosity. Along with slump test aspects of self-consolidating behaviour, flow table test can be also analyzed to understand flow behavior of cemented paste tailings. Other emerging methods include L-pipe tests, inclined pipe tests, and loop pipe tests, can implement in measuring consistent paste transportation analysis. These methods provide quantitative data on the rheological behavior of the paste.
- Proper sampling should be done for conducting acid mine drainage study. Other static and kinetic methods can also be employed to have comparative results and analysis. Good judgement of acid drainage potential should include combined studies of all physical, chemical, mineralogical analysis.
- Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) is an efficient analytical technique that can be used to determine the concentrations of various metal elements in a sample. It is commonly employed for trace analysis of metal elements in environmental samples for acid mine drainage prediction. ICP-OES is highly sensitive and capable of detecting a wide range of metal elements at trace levels. It is an essential tool for predicting acid mine drainage by analyzing the composition of the drainage water, identifying potential environmental contaminants, and monitoring changes in metal concentrations over time.

References

Abo-Qudais, S.A. 2005. Effect of concrete mixing parameters on propagation of ultrasonic waves. *Construction & Building Materials*, 19(4): 257–263. doi:10.1016/j.conbuildmat.2004.07.022.

Annor, A.B. 1999. A Study of the Characteristics and Behavior of Composite Backfill Material, in Department of Mining and Metallugical Engineering, McGill University: Montreal.

Aref, K. Hassani, F. P. and Churcher, D. A. 1989. A study on liquefaction potential of paste backfill, in Proceedings: Fourth International Symposium on Mining with Backfill Innovations in Mining Backfill Technology, Montreal, Canada, 405-414.

ASTM Annual Book of 2003, Volume 4.02. Manual of Aggregate and Concrete Testing. ASTM International., PA, USA

ASTM C128 – Standard Test Method for Relative Density (Specific Gravity) and Absorption of Fine Aggregate, 2015, ASTM International, PA, USA.

ASTM C136. 2014. Sieve analysis of fine and coarse aggregates. ASTM International, PA, USA.

ASTM C143. 2020. Slump of hydraulic cement concrete. ASTM International, PA, USA.

ASTM C29 - Standard Test Methods for Bulk Density and Voids in Aggregate, 2017, ASTM International, PA, USA.

ASTM C39. 2021 - Compressive strength of cylindrical concrete specimens. ASTM International, PA, USA.

ASTM C702. 2011. Reducing samples of aggregates to testing size. ASTM International, PA, USA.

ASTM D2216 - Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass, 2019, ASTM International, PA, USA

ASTM D2845 – Laboratory determination of pulse velocities and ultrasonic elastic constant of rock, 2008, ASTM International, PA, USA

ASTM D6913. 2017. Particle size distribution (Gradation) of soils using sieve analysis. ASTM International, PA, USA.

Barnes HA, Hutton JF, Walters K (1992) An introduction to rheology. China Petroleum Press, Beijing, pp 1–14

Belem T, Benzaazoua M (2008) Design and application of underground mine paste backfll technology. Geotech Geol Eng 26:147–174

Belem T, El Aatar O, Bussière B, Benzaazoua M, Fall M, Yilmaz E (2006) Characterization of self-weight consolidated paste backfll. In: Proceedings of 9th international seminar on paste and thickened tailings—paste'06, Limerick, Ireland. 3–7 April 2006, p 333–345

Belem, T., Benzaazoua, M., Bussiere, B., Dagenais, A.M., 2002. Effects of settlement and drainage on strength development within paste backfill. In: Proceedings of the 8th Tailings and Mine Waste. Vail, Colorado, USA.

Benzaazoua, M., Bussière, B., Demers, I., Aubertin, M., Fried, É., & Blier, A. (2008). Integrated mine tailings management by combining environmental desulphurization and cemented paste backfill: Application to mine Doyon, Quebec, Canada. Minerals Engineering, 21(4), 330–340. http://doi.org/10.1016/j.mineng.2007.11.012

Benzaazoua, M., Marion, P., Picquet, I., and Bussière, B. (2004c): The use of pastefill as a solidification and stabilization process for the control of acid mine drainage. Minerals Engineering, 17 (2), pp. 233 – 243.

Benzaazoua, M.; Belem, T.; Yilmaz, E. 2010, Novel lab tool for paste backfill. Canadian Mining Journal 27.

Bertrand, V.J. (1998): A Study of Pyrite Reactivity and the Chemical Stability of Cemented Paste Backfill. Master of Applied Science Thesis, Department of Mining and Mineral Process Engineering, University of British Columbia, December 1998.

Bissonnette, B. 1995. Paste fill plant operation at the Louvicourt Mine, Paste Backfill Seminar, Hotel Confortel Val d'Or, Quebec, CANMET Division Report MRL 95 – 140.

Bloss, M. L. and Greenwood, A. G. 1998. Cemented rock fill research at Mount Isa Mines Limited 1992-1997. In: Minefil 198, proceedings of the sixth international symposium on mining with backfill, 14-16 April, in Brisbane. M. Bloss, ed. Brisbane: Australasian IMM, pp. 207-215.

Boldt, C. M. K. Atkins, L. A. and Jones, F. M. 1993. The backfilling research being conducted by the U.S. Bureau of Mines, Minefill 93, Johannesburg, pp. 389 - 395.

Brady, B., Brown, E.T. Springer. (2006). Rock Mechanics for underground mining: third edition, ISBN: 1-4020-2116-X

British Columbia AMD Task Force, (1989). Draft Acid Rock Drainage Technical Guide. Vol. 1. Crown Publications, Victoria, B.C.

Chen, L. J. and Annor, A. 1995. A study on the properties of gold mine tailings fills, Presented at 97th Annual General Meeting of CIM Rock Mechanics and Strata Control Session, Halifax, N.S., Canada,

Chen, Q.S., Zhang, Q.L., Qi, C.C., Fourie, A., Xiao, C.C., (2018). Recycling phosphogypsum and construction demolition waste for cemented paste backfill and its environmental impact. J. Cleaner Prod. 186, 418–429.

Chotard, T., Gimet-Breart, N., Smith, A., Fargeot, D., Bonnet, J.P., and Gault, C. 2001. Application of ultrasonic testing to describe the hydration of calcium aluminate cement at the early age. *Cement and Concrete Research, 31(3*): 405–412. doi:10.1016/S0008-8846(00)00446-4.

Clark, I. H. 1988. The properties of hydraulically placed backfills, in Proceedings: Backfill in South Africa Mines, Johannesburg, SAIMM, 15-33.

Clayton, S., Grice, T., & Boger, D. V. (2003). Analysis of the slump test for on-site yield stress measurement of mineral suspensions. *International Journal of Mineral Processing*, *70*(1–4), 3–21. https://doi.org/10.1016/s0301-7516(02)00148-5

Craig, R. F. 2004. Soil mechanics, Seventh edition, Van Nostrand Reinhold.

Ercikdi B, Baki H, *İ*zki M (2013) Effect of desliming of sulphide-rich mill tailings on the longterm strength of cemented paste backfll. J Environ Manage 115:5–13

Ercikdi, B. Cihangir, F. Kesimal, A. and Deveci, H. “Practical Importance of Tailings for Cemented Paste Backfill” (2017). In Paste Tailings Management, edited by Yilmaz, E. Fall, M. Springer International Publishing, Switzerland.

Espley, G. H. Beattie, H. I. and Pasieka A. R. 1970. Cemented hydraulic backfill within the Falconbridge group of companies, CIM Bulletin, 1002-1010.

Fall M, Belem T, Samb S, Benzaazoua M (2007) Experimental characterization of the stress-strain behaviour of cemented paste backfll in compression. J Mater Sci 42(11):3914–3992

Fall M, Benzaazoua M, Ouellet S (2004) Effect of tailings of paste backfll properties. In: International symposium Mine Fill 2004, Beijing, 19–21

Fall M, Benzaazoua M, Ouellet S (2005) Experimental characterization of the influence of tailings fneness and density on the quality of cemented paste backfll. Miner Eng 18(1):41–44

Fall M, Benzaazoua M, Saa EG (2008) Mix proportioning of underground cemented tailings backfll. Tunn Undergr Space Technol 28(1):80–90

Fourie, A.B., Helinski, M., Fahey, M., 2006. Filling the gap - A geomechanics perspective. Australian Centre for Geomechanics Newsletter, Vol. 26, No. 5, pp. 1-4.

Franks DM, Boger DV, Côte CM et al (2011) Sustainable development principles for the disposal of mining and mineral processing wastes. Res Policy 36(2):114–122

Galaa A.M., Thompson B.D., Grabinsky M.W., and Bawden W.F. (2011). Characterizing stiffness development in hydrating mine backfill using ultrasonic wave measurements. *Canadian Geotechnical Journal*. 48(8): 1174-1187. https://doi.org/10.1139/t11-026

Grabinsky, M.; Bawden, W.F.; Simon, D.; Thompson, B., 2008, In situ properties of cemented paste backfill in an Alimak Stope. *61st Canadian Geotechnical Conference*, Edmonton, AB, Canada.

Grice T (1998) Underground mining with backfll. In: The second annual summit on mine tailings disposal systems, Brisbane, Australia, p 5–15

Hassani F, Archibald J (1998) Mine backfill. In: Canadian Institute of Mine, Metallurgy and Petroleum, Published on CD-ROM Proceedings, Canada, 263p

Hedley, D G F, 1995. Final report on the stiff backfill project for M.R.D., Mining Research Directorate, Canadian Rock burst Research Program, Sudbury, Ontario.

Hibbeler, R.C., 1997. Mechanics of Materials, 3rd ed. Prentice-Hall, Upper Saddle River, NJ, pp. 530–536.

Holtz D. R., Kovacs W. D. 1981. An Introduction to Geotechnical Engineering, ISBN 0-13-484394-0, Prentice Hall, New Jersey, USA.

Huynh L, Beattie DA, Fornasiero D, Ralston J (2006) Effect of polyphosphate and naphthalene sulfonate formaldehyde condensate on the rheological properties of dewatered tailings and cemented paste backfll. Miner Eng 19:28–36

James, M., Jolette, D., Aubertin, M., & Bussière, B. (2003). An Experimental Set-up to Investigate Tailings Liquefaction and Control Measures. In International Symposium on Major Challenges in Tailings Dams (ICOLD) (Vol. 4711, pp. 153–164). Montreal, QC, Canada.

Kesimal, A., Yilmaz, E., Ercikdi, B., Alp, I., & Deveci, H. (2005). Effect of properties of tailings and binder on the short-and long term strength and stability of cemented paste backfill. Materials Letters, 59(28), 3703–3709. http://doi.org/10.1016/j.matlet.2005.06.042

Kistinger, S. (1997): Reclamation Strategy at the Ronneburg Uranium Mining Site Before Flooding the Mine. In: Proceedings of the Fourth International Conference on Acid Rock Drainage, Vancouver, BC, Canada, May 31 to June 6, 1997. Volume III, pp. 1335 – 1344.

Klieger, P., & Lamond, J. F. (1994). Significance of Tests and Properties of Concrete and Concrete-making Materials (illustrate). ASTM International.

Landriault D (1995) Paste backfll mix design for Canadian underground hard rock mining. In: Proceedings of the 97th annual general meeting of the CIM rock mechanics and strata control session, Nova Scotia, Canada, p 652–663

Levens, R.L., Marcy, A.D. and Boldt, C.M.K. (1996): Environmental Impacts of Cemented Mine Waste Backfill. U.S. Department of the Interior, Bureau of Mines, Report of Investigations RI 9599.

Liu, G., Li, L., Yang, X., & Guo, L. (2016). Stability analyses of vertically exposed cemented backfill: A revisit to Mitchell's physical model tests. In International Journal of Mining Science and Technology (Vol. 26, Issue 6, pp. 1135–1144). Elsevier BV. https://doi.org/10.1016/j.ijmst.2016.09.024

Lu, J., Alakangas, L., Jia, Y., & Gotthardsson, J. (2013). Evaluation of the application of dry covers over carbonate-rich sulphide tailings. Journal of Hazardous Materials, 244–245, 180–94. http://doi.org/10.1016/j.jhazmat.2012.11.030

MEND (1991): Acid Rock Drainage Prediction Manual, Report 1.16.1b, March, Vancouver, BC

MEND (1997): Prediction of Metal Leaching and Acid Rock Drainage at Minesites in British Columbia

Reports, Report 1.20.1, April, Vancouver, BC

MEND (2006): Paste Backfill Geochemistry – Environmental Effects of Leaching and Weathering, Report 10.2, April, Vancouver, BC.

Michael, D. (2008) Ultrasonic wave measurement through cement paste backfill. Master's Thesis, University of Toronto.

Milne, D. (1997). Underground design and deformation based on surface geometry (Doctoral Dissertation, University of British Columbia).

Neville, A. M. 1987. Properties of concrete, Longman Scientific and Technical-Longman, Singapore.

Ouellet, J. Bidwell, T. J. and Servant, S. 1998. Physical and mechanical characterization of paste backfill laboratory and in-situ testing. In: Mine fill 98, proceedings of the sixth international symposium on mining with backfill, Brisbane Australia, 249-253.

Ouellet, J., Bussière, B., Mbonimpa, M., Benzaazoua, M., and Aubertin, M. (2006): Reactivity and mineralogical evolution of an underground mine sulphidic cemented paste backfill. Minerals Engineering, Volume 19, Issue 5, pp. 407 – 419.

Ouellet, S., Bussiere, B., Benzaazoua, M., Aubertin, M., Fall, M., & Belem, T. (2003). Sulphide Reactivity within cemented paste backfill: oxygen consumption test results. In the 56th Annual Canadian Geotechnical Conference and 4th joint IAH-CNC/CGS Conference (pp. 176–183). Winnipeg, Manitoba, Canada.

Pashias, N., Boger, D.V., Summers, J., Glenister, D.J., 1996. A fifty cent rheometer for yield stress measurement. Journal of Rheology 40 (6), 1179–1189.

Paterson, A.J.C. (2004) High density slurry and paste tailings, transport systems. International Platinum Conference 'Platinum Adding Value', The South African Institute of Mining and Metallurgy.

Potvin, Y. (1988). Empirical open stope design in Canada (Doctoral dissertation, University of British Columbia).

Qi. C, Fourie, A. (2019). Cemented paste backfill for mineral tailings management: Review and future perspectives. Minerals Engineering, 144, 106025. https:// doi.org/10.1016/j.mineng.2019.106025

Quan, W. Someehneshsin, J. Abugharara, A. Zhang, Y. and Butt, S. 2021. Effects of low binder proportions and internal vibration on early age behaviour of cured cemented tailings backfill for mining by drilling applications. 55th US Rock Mechanics / Geomechanics Symposium, ARMA 21-1753, Houston, Texas, USA.

Ross-Watt, D. A. J. 1989. Backfilling on the base metal mines of the Gold Field Group, in Proceedings: Fourth International Symposium, Innovations in Mining with Backfill, Montreal, Canada, Publication, A.A. Balkema, pp. 351-360.

Roux LK, Bawden WF, Grabinsky MW (2004) Liquefaction analysis of early age cemented paste backfll. In: 8th international symposia on mining with backfll, Beijing, China, p 233–241

Ruan ZE, Li CP, Shi C (2016) Numerical simulation of flocculation and settling behavior of whole tailings particles in deep-cone thickener. J Cent South Univ 23(3):740–749

Schowalter, W.R., Christensen, G., 1998. Toward a rationalization of the slump test for fresh concrete: comparisons of calculations and experiments. Journal of Rheology 42 (4), 865–870

Servant, S., 2001. Determination of the mechanical parameters of mining backfills made of cement residues. M.Sc. Thesis, McGill University, Montreal, Quebec, Canada.

Shacker, D. (2019). Research into the interpretation of deformation measured by extensometers (Doctoral Dissertation, University of Saskatchewan).

Simon D (2005) Microscale analysis of cemented paste backfll. Ph.D. Thesis. Graduate Department of Civil

Engineering, University of Toronto, 208p

Sobek, A. A., Schuller, W. A., Freeman, J. R., and Smith, R. M., 1978, Field and Laboratory Methods Applicable to Overburdens and Minesoils: US Environmental Protection Agency, EPA-600/2-78-054

Someehneshin, J. Quan W. Abugharara, A. & Butt, S. (2020). Assessment of Freestanding Vertical Face for the Backfill Using the Run of the Mine Tailings and Portland Cement. 54th US Rock Mechanics / Geomechanics Symposium ARMA, 20(A), 1882nd ser.

Someehneshin, J. Quan, W. Abugharara, A. & Butt, S. (2020). Backfill analysis and parametric evaluation of the cement binder on cured strength and curing time. GeoCalgary, Alberta.

Taylor, H.F.W. (1997): Cement Chemistry, Thomas Telford editors, 459 pages.

Taylor, P. C., Kosmatka, S. H., & Voigt, G. F. (2006). *Integrated materials and construction practices for concrete pavement: A state-of-the-practice manual*. Washington, DC.

Thomas, E. G. NanteI, J. H. and by Notley, K.R. Fill technology in underground metalliferous mines. Published by International Academic Services, Queen's University, 1979

U.S. Environmental Protection Agency (U.S. EPA), 2003, EPA and Hardrock Mining: A Source Book for Industry in the Northwest and Alaska, Appendix C: Characterization of Ore, Waste Rock, and Tailings, Washington, D.C.

US EPA, (2003). "Understanding Earth through Seismology." Retrieved from: https://opentextbc.ca/geology/chapter/9-1-understanding-earth-through-seismology/

Vick, S. 1990, "Planning, design, and analysis of tailings dams, BiTech", *Publishers, Vancouver*.

World Tailings Failure Database. https://worldminetailingsfailures.org/

Wu, A. (2022). "Rheology of Paste in Metal Mines", *Springer Metallurgical Industry Press*, China. ISBN 978-981-16-9243-7, doi 10.1007/978-981-16-9243-7

Yilmaz E, Benzaazoua M, Belem T, Bussiere B (2009) Effect of curing under pressure on compressive strength development of cemented paste backfll. Miner Eng 22(9–10):772–785

Yilmaz E, Benzaazoua M, Bussière B, Pouliot S (2014) Influence of disposal configurations on hydrogeological behaviour of sulphidic paste tailings: a field experimental study. Int J Miner Process 131:12–25

Yilmaz, E. (2010). Investigating the consolidation behavior, hydro-mechanical and microstructural properties of cemented paste backfills using the versatile CUAPS apparatus. University du Quebec en Abitibi-Temiscamingue (UQAT), Canada.

Yilmaz, E. Fall, M. (2017) "Paste Tailings Management", Springer Nature, ISBN 978-3-319-39682-8, doi 10.1007/978-3-319-39682-8, Canada.

Yilmaz, E., Belem, T., Bussiere, B., Mbonimpa, M., Benzaazoua, M., (2010), Evaluation of the one-dimensional consolidation behaviour of early age cemented paste backfills. Canadian Geotechnical Journal.

Yilmaz, E., El Aatar, Belem, T., Benzaazoua, M., Bussiere, B., (2006). Effect of consolidation on performance of cemented paste backfill. The 21st Underground Mine Support Conference, Quebec, Canada

Zhao L (2015) Study on rheological behavior of the slurry backfill material. Dissertation, Shandong University of Technology

Zhao Y., Taheri A., Karakus M., Deng A. Guo L., (2021), The Effect of Curing Under Applied Stress on the Mechanical Performance of Cement Paste Backfill (CPB), Journal of Minerals, 11, 1107, MDPI