LICENTIATE THESIS

Mechanical stabilization of sulfide soils: Influence of soil properties and oxidation on strength development

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Soil Mechanics

LULEÅ UNIVERSITY OF TECHNOLOGY

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September 2026

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PREFACE

The research presented in this licentiate thesis was carried out within the Division of Mining and Geotechnical Engineering under the research subject of Soil Mechanics at Luleå University of Technology, Sweden. This work forms part of my doctoral studies and reflects the efforts, guidance, and support of many individuals and organizations.

I would like to express my sincere gratitude to my main supervisor, Christian Maurice, for his continuous guidance, constructive feedback, and encouragement throughout this research. His expertise and support have been invaluable in shaping both this work and my development as a researcher. I am also deeply grateful to my co-supervisors, Qi Jia, Josef Mácsik and Tan Manh Do, for their expertise, thoughtful discussions, and contributions at various stages of this study.

My thanks also extend to my colleagues, collaborators, laboratory staff, and all project partners (Trafikverket, Ecoloop, Mitta, Umeå DAC, Labmind, Novia) whose cooperation have contributed to the successful completion of this work. The research was funded by the Swedish road administration's program Branschsamverkan i grunden (BIG), Svenska Byggbranschens Utvecklingsfond (SBUF) and the Interreg Aurora program through the project "Best Practices for Sustainable Stabilization and Reuse of Sulfidic Soils with Minimized Environmental Impact" (MinImpact; Project ID: 20361791).

Beyond academia, I acknowledge my gratitude to nature, whose gifts and resources sustain me and make all progress possible.

Finally, I wish to express my deepest gratitude to my family for their support, patience, and encouragement throughout my academic journey.

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September 2026
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ABSTRACT

Sulfide soils are commonly encountered along the coastal regions between Sweden and Finland in post-glacial lowland areas. These silty and clayey soils are characterized by high natural water content, low undrained shear strength, high compressibility and significant organic content. Due to their poor geotechnical properties, sulfide soils are frequently excavated during infrastructure development projects. While sulfide minerals remain stable under waterlogged conditions, once excavated and exposed to atmospheric oxygen, they are subjected to oxidation which generates acidity and creates significant environmental challenges. As a result, excavated sulfide soils are often transported to specially designed landfills where they are either maintained under saturated conditions or treated with chemical buffering agents to minimize oxidation. These management approaches require strict environmental control and long-term maintenance, making sulfide soil disposal technically challenging and expensive. One alternative is the reuse of excavated sulfide soils in construction applications to reduce the transportation costs, landfill demand and environmental impact. However, these soils often do not possess adequate engineering strength for direct reuse and therefore require stabilization to improve their mechanical performance. In addition, as sulfide soils are susceptible to acidification, stabilization must also address the chemical behavior of the soil to ensure long-term performance. Consequently, understanding the interaction between soil chemistry and binder performance is essential for successful stabilization. This thesis investigates the strength development of sulfide soils with a focus on the factors controlling stabilization performance.

The initial part of the work examines the behavior of cement-stabilized sulfide soils under varying sulfur content, organic matter, water content, oxidation state and mixing conditions. Unconfined compressive strength (UCS) testing demonstrated that water content is one of the most critical parameters affecting stabilization efficiency. High sulfur-high organic content soil (HS_HLOI) continuously shows less strength than low sulfur-low organic content soil (LS_LLOI) even at the similar water content. This indicates that sulfur compounds and organic matter interfere with cement hydration and contribute to strength reduction. High water content soils exhibited very low strength development whereas reducing water content significantly improved UCS. For HS_HLOI, UCS increased from 10 kPa at 70% water content to 65 kPa after reducing the water content to 50%, using 10% cement after 7d of curing. In contrast, LS_LLOI achieved strength exceeding 300 kPa and 800 kPa at 60% and 45% water content respectively after 7d of curing. Oxidation

increased the UCS of LS_LLOI under dry mixing conditions but caused only minor changes in HS_HLOI. The results further indicate that dry mixing of cement produced higher strength than wet mixing under laboratory conditions for most cases. SEM-EDS and XRD analysis provide further understanding of hydration products like C-S-H gels, ettringite, and gypsum formation, voids and particle bonding mechanisms.

The second part of the study evaluated the acidification behavior of sulfide soils collected from multiple locations in Sweden using incubation and accelerated cyclic leaching methods. The results showed that acidification behavior depends on the balance between sulfide content and buffering capacity rather than sulfur concentration alone. Soils with low Ca/S ratios exhibited high acidification while soil with high buffering capacity maintained stable pH values during oxidation cycles. The accelerated oven-dry method produced rapid acidification whereas incubation and air-dry methods better represented gradual field oxidation conditions. These findings indicate that oxidation behavior and pH evolution are important factors that reduce overall pH and influence binder performance during stabilization.

Based on the limitations identified in cement stabilization and to reduce the environmental footprints associated with cement use, this thesis introduces alkali-activated binders derived from industrial by-products such as ground granulated blast furnace slag (GGBS) and calcium-based fly ash as potential sustainable alternatives to conventional cement-based binder systems. A preliminary screening experimental program was therefore developed to evaluate the feasibility of cement-free alkali-activated stabilization of sulfide soils. The screening study provides a starting point for future research focused on binder optimization, reaction mechanisms, durability and long-term performance. This thesis shows that successful stabilization of sulfide soils requires an integrated understanding of geotechnical behavior, soil chemistry and binder interactions while highlighting the potential of sustainable alkali-activated binders for future sulfide soil stabilization and its applications.

Keywords: Sulfide soils, Soil stabilization, Cement stabilization, Unconfined compressive strength (UCS), Acidification behavior, Alkali-activated slag

LIST OF APPENDED PUBLICATIONS

PUBLICATION A

Thakur, R. K., Maurice, C., Jia, Q., Do, T., & Macsik, J. (2026). Factors affecting the strength of cement stabilized sulfide soil. In *21st International Conference on Soil Mechanics and Geotechnical Engineering, Vienna 2026*. https://doi.org/10.53243/ICSMGE2026-1127

PUBLICATION B

Thakur, R. K., Mácsik, J., Do, T., Jia, Q., & Maurice, C. (n.d.). Evaluation and validation of complementary methods for assessing acidification potential in sulfide-bearing soils. (Submitted to Scientific Reports-Nature)

PUBLICATION C

Thakur, R. K., Do, T., Macsik, J., Jia, Q., & Maurice, C. (n.d.). Influence of oxidation on mechanical behavior and microstructural characteristics of cement-stabilized sulfide soils. (Manuscript)

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LIST OF ABBREVIATIONS

AAS	Actual acid sulfate soil
ANOVA	Analysis of variance
ASTM	American society for testing and materials
C-A-H	Calcium aluminate hydrate
C-A-S-H	Calcium aluminao silicate hydrate
C-S-H	Calcium silicate hydrate
EDS	Energy dispersive spectroscopy
GGBS	Ground granulated blast furnace slag
HS_HLOI	High sulfur and high loss on ignition (organic matter)
ICDD	International centre for diffraction data
ISO	International organization for standardization
LS_LLOI	Low sulfur and low loss in ignition (organic matter)
N-A-S-H	Sodium aluminao silicate hydrate
PASS	Potential acid sulfate soil
SEM	Scanning electron microscopy
UCS	Unconfined compressive strength
XRD	X-ray diffraction

1 INTRODUCTION

1.1 Background

Large volumes of sulfide soils are excavated every year during the construction of roads, railways, and urban infrastructure in the coastal regions of northern Sweden and Finland. These soils are generally unsuitable for direct use in construction because of their high natural water content (usually higher than their liquid limit), low undrained shear strength (10-30 kPa), high compressibility, and considerable organic matter content (3-10%), which result in poor engineering performance (Åhnberg et al. 2003; Jasim Al-Jabban 2019; Ziagharib 2025). These soils are typically composed of fine-grained sediments containing iron sulfide minerals, predominantly pyrite (FeS_2) (1-6%) together with mono-sulfide (FeS) (0.1-2%), which remain stable under anaerobic and waterlogged conditions, referred as potential acid sulfate soils (PASS) (Sullivan et al. 2009; Nursanti 2025). However, when excavated and exposed to atmospheric oxygen and it may become actual acid sulfate soils (AAS). Sulfide oxidation generates sulfuric acid, resulting in a decrease in soil pH and the mobilization of sulfate and potentially toxic metals such as aluminium. These processes pose significant environmental and engineering challenges during infrastructure development (Dent and Pons 1995; Sullivan et al. 2010; Boman et al. 2023). Due to this, excavated sulfide soils are commonly transported to landfills and managed under controlled conditions to prevent oxidation or treated with alkaline products to neutralise acidity, leading to increased construction costs, transportation requirements, and environmental impacts. Sulfide soil composition may vary considerably between locations, and with depth at the same location. In many areas, sulfide soil is found beneath a layer of sulfate soil, whether acidic or non-acidic, with a transition zone between them (Figure 1). From an engineering perspective, selective excavation and separate management are difficult to achieve, although they may be beneficial from an environmental perspective. Consequently, excavated soil masses often consist of a mixture of soils with different properties.

A suitable alternative to disposal is the stabilization and reuse of excavated sulfide soils in geotechnical applications such as embankments, road foundations, and noise barriers. Chemical stabilization using Portland cement is one of the most widely adopted ground improvement techniques because it improves the engineering properties of soft soils through the formation of cementitious hydration products such as calcium silicate hydrate (C-S-H), calcium aluminate hydrate (C-A-H), and calcium aluminao silicate hydrate (C-A-S-H) gels that bind soil particles together,

reduce pore space, and improve strength and stiffness (Horpibulsuk et al. 2010; Makusa 2013; Wang et al. 2022; Zhou et al. 2024). Unlike other common soft soils, stabilization of sulfide soils is influenced not only by physical properties but also by complex geochemical processes. Several factors may influence the efficiency of cement stabilization. High natural water content increases the effective water to cement ratio, reducing hydration efficiency and requiring higher binder dosages to achieve adequate strength. Organic matter may retard cement hydration by adsorbing calcium ions and delaying the formation of cementitious products responsible for strength development (Clare and Sherwood 1954; Ge et al. 2020). Sulfur-bearing minerals may participate in sulfate reactions during hydration, while oxidation following excavation generates acidity that modifies the chemical environment in which cement hydration occurs (Sherwood 1962; Talluri et al. 2020). Furthermore, stabilization performance may also depend on practical aspects such as binder incorporation method and mixing efficiency, where field conditions often differ considerably from laboratory conditions. Consequently, stabilization performance cannot be predicted solely from binder dosage but rather from the combined influence of soil characteristics, oxidation behaviour, and binder chemistry.

Despite the widespread application of cement stabilization for soft soils, several scientific and engineering challenges remain for sulfide soils. Previous studies have primarily investigated the influence of individual parameters such as binder dosage, curing duration, or water content, whereas comparatively less attention has been given to the combined influence of sulfur content, organic matter, oxidation, acidification, and mixing conditions on stabilization performance (Åhnberg et al. 2003; Rothhämel et al. 2022; Zigharib et al. 2024). In addition, stabilization performance has often been evaluated using mechanical testing alone, while the relationships between soil chemistry, hydration mechanisms, microstructural characteristics, and strength development remain insufficiently understood in the field of sulfide soil stabilization. Reliable methods for evaluating the acidification behaviour of sulfide soils before stabilization are also limited, making it difficult to decide the management strategies and to predict the chemical conditions under which binder hydration occurs.

At the same time, increasing environmental concerns associated with Portland cement production have accelerated the curiosity for sustainable stabilization technologies. Alkali-activated binders produced from industrial by-products such as ground granulated blast furnace slag (GGBS) and fly ash have shown promising performance in stabilizing conventional soft soils (Horpibulsuk et al. 2010; Van Deventer and Jannie S J 2014; Provis 2014, 2018; Davidovits 2020). However, their applicability to sulfide soils remains largely unexplored. Before such binder systems

can be developed, a better understanding of the mechanisms governing conventional cement stabilization is required. This includes identifying the critical factors controlling strength development, understanding how oxidation and acidification influence binder performance. As the composition of excavated soil masses is often uncertain and the soil is rarely uniform under field conditions, it is necessary to identify the relevant controlling factors to determine an efficient binder dosage without underdimensioning the stabilization.

Based on these knowledge gaps, this research was designed to improve the understanding of the coupled geotechnical and geochemical processes governing sulfide soil stabilization. The work first investigates the factors controlling the strength development of cement-stabilized sulfide soils, followed by evaluation of oxidation and acidification processes that influence binder performance. Building upon this understanding, a preliminary screening study of alkali-activated slag was conducted to assess its feasibility as a sustainable alternative to Portland cement. The screening results demonstrated that slag alone provides only limited improvement under the investigated conditions, thereby highlighting the need for further optimization using blended alkali-activated binder systems. These findings establish the scientific foundation for the remaining doctoral research, which will focus on developing sustainable binders for sulfide soil stabilization.

1.2 Problem Statement

Although cement stabilization has been widely applied to improve the engineering properties of soft soils, its application to sulfide soils remains challenging because stabilization is governed by complex geochemical processes (sulfide minerals and organic matter content). High water content, organic matter, sulfur-bearing minerals, oxidation, and acidification collectively influence binder hydration and strength development, making the engineering performance of stabilized sulfide soils difficult to predict. Previous studies have primarily investigated the influence of individual parameters such as binder dosage, curing duration, or water content, whereas comparatively few have systematically examined the combined influence of sulfur content, organic matter, oxidation, acidification, and mixing conditions on stabilization performance in sulfide soils (Åhnberg et al. 2003; Rothhämel et al. 2022; Zigharib et al. 2024). Furthermore, stabilization performance has often been evaluated using mechanical testing alone, while the relationships between oxidation, hydration mechanisms, microstructural characteristics, and strength development remain insufficiently understood, particularly for sulfide soils (Wang et al. 2022; Zhou et al. 2024). Reliable methods for assessing the acidification behaviour of sulfide soils prior to stabilization are also limited, making it difficult to predict the chemical environment in which binder hydration occurs. In addition, although

alkali-activated binders have shown considerable potential for stabilizing common soft soils, their applicability to sulfide soils has received very limited attention, particularly under chemically aggressive and acidic conditions (Horpibulsuk et al. 2010; Van Deventer and Jannie S J 2014; Provis 2014, 2018; Davidovits 2020). Consequently, there is a need for a better understanding of the coupled mechanisms governing sulfide soil stabilization, from the influence of soil properties and oxidation behaviour on cement performance to the development of sustainable alternative binder systems. Addressing these challenges forms the basis of the research presented in this thesis.

1.3 Research aim and objectives

The aim of this research is to improve the understanding of the mechanisms governing stabilization of excavated sulfide soils and to establish the scientific basis for their sustainable reuse in geotechnical engineering applications. To achieve this aim, the research has been divided into complementary stages that together constitute the scientific framework of this licentiate thesis.

Objective 1: To identify the critical parameters governing the strength development of cement-stabilized sulfide soils through laboratory investigation of water content, sulfur content, organic matter, cement dosage, curing duration, and mixing method. (Related publications: Paper A and Paper C)

Objective 2: To assess how oxidation impact the cement hydration and strength development using mechanical testing, SEM, XRD, and statistical analysis. (Related publications: Paper C)

Objective 3: To evaluate methods to assess the acidification behaviour of sulfide and acid sulfate soil. (Related publications: Paper B)

Objective 4: To investigate an alternative to Portland cement as binder for the stabilization of sulfide soil (next step of PhD research)

1.4 Research questions

RQ1. What are the critical parameters and how do they affect the strength of stabilized sulfide soils?

RQ2. How does the acidification potential of sulfide soils influence binder performance in strength development?

RQ3. How can Portland cement be partially or fully replaced in the stabilization of sulfide soils while maintaining engineering performance and reducing environmental impacts?

Table 1: Appended publications with connection to research questions.

Publication	Title	Research questions		
		1	2	3
A	Factors affecting the strength of cement stabilized sulfide soil	✓		
B	Evaluation and validation of complementary methods for assessing acidification potential in sulfide-bearing soils		✓	
C	Influence of oxidation on mechanical behavior and microstructural characteristics of cement-stabilized sulfide soils	✓	✓	

1.5 Research scope and limitations

This licentiate thesis focuses on laboratory investigation of sulfide soils collected from northern Sweden with varying sulfur content, organic matter and natural water content. The research primarily investigates the mechanical and physicochemical mechanisms governing cement stabilization.

The scope includes:

- Characterization of representative sulfide soils,
- Laboratory stabilization using Portland cement,
- Investigation of strength development through unconfined compressive strength testing,
- Evaluation of oxidation effects on stabilization performance,
- Assessment of acidification behaviour using incubation and accelerated laboratory methods,
- Microstructural characterization using SEM and XRD.

The thesis does not include large-scale field validation, long-term durability assessment under varying environmental condition (e.g., freeze-thaw or wet-dry cycles) or alternative binders. These topics constitute the remaining work of the PhD project and will build directly upon the understanding established in this licentiate thesis.

1.6 Author's contributions

The authors are numbered, and their contribution is shown in Table 2.

1 Ramesh Kumar Thakur
2 Christian Maurice
3 Qi Jia
4 Josef Mácsik
5 Tan Manh Do

Table 2: Individual author contribution to the publications

Term	Publication A	Publication B	Publication C
Conceptualization	1, 2	1, 2, 4	1, 2, 5
Methodology	1, 2	1, 2	1, 2
Investigation	1	1	1
Writing – original draft	1	1	1
Writing – review and editing	1, 2	1, 2, 4	1, 2, 5
Supervision	2, 3, 4, 5	2, 3, 4, 5	2, 3, 4, 5
Funding acquisition	2	2	2

2 LITERATURE REVIEW

2.1 Sulfide soils

Sulfide soils are naturally occurring fine-grained sediments containing iron sulfide minerals, predominantly pyrite (FeS_2), which form under waterlogged and oxygen-deficient conditions. Typical percentage of pyrite is 1-6% and mono-sulfide is 0.1-2% (Sullivan et al. 2009; Nursanti 2025). These soils are widely distributed in coastal lowlands throughout the world, including Australia, Southeast Asia, North America, and Northern Europe, where they are commonly referred to as potential acid sulfate soils (PASS) or, according to the recently adopted international terminology, hypersulfidic soils (Dent and Pons 1995; Sullivan et al. 2010; Boman et al. 2023; Edén et al. 2023). In Sweden and Finland, sulfide soils primarily occur in post-glacial marine sediments deposited during the Littorina Sea stage, where sulfate-rich seawater, reactive iron minerals, abundant organic matter, and anaerobic conditions promoted the formation of iron-sulfides through microbial sulfate reduction (Åström and Björklund 1995; Sohlenius and Öborn 2004; Michael et al. 2017). A typical soil profile in northern Sweden and Finland has been given in Figure 1.

From a geotechnical perspective, sulfide soils are generally classified as clayey silts or silty clays with high natural water content (50-150%), low undrained shear strength (10-30 kPa), high compressibility, and significant organic matter content (3-10%). Their natural water content often exceeds the liquid limit, resulting in low bearing capacity and excessive settlements when subjected to engineering loads (Åhnberg et al. 2003; Jasim Al-Jabban 2019; Ziagharib 2025). These unfavourable engineering properties make sulfide soils one of the most problematic soil types encountered during infrastructure development in northern Sweden such as roads and railways, often require excavation of large soil volumes.

Unlike many other soft soils, sulfide soils present both geotechnical and environmental challenges. While they remain chemically stable below the groundwater table, excavation exposes the soil to atmospheric oxygen, initiating sulfide oxidation and acid generation and it may become actual acid sulfate soils (AAS), also referred as sulfuric soils. Consequently, excavated sulfide soils are often managed as environmentally sensitive materials requiring controlled handling, treatment, or disposal to minimize acidification and metal release (Rothhämel et al. 2022; Boman et al. 2023). Current management practices generally involve transportation to engineered landfills designed to maintain saturation in the cover

layer to prevent oxidation, both the transportation and landfall management, substantially increase project costs and environmental impacts.

Figure 1: Typical sulfide soil layers

The increasing volume of excavated sulfide soils generated by infrastructure projects has therefore created a growing need for sustainable management strategies that enable beneficial reuse rather than disposal. Among the available alternatives, cement-stabilization represents one of the most promising approaches because it improves engineering properties while reducing the need for landfill disposal. However, successful stabilization requires a thorough understanding of both the physical and chemical characteristics of sulfide soils, particularly the interactions between sulfide oxidation, soil chemistry, and binder hydration.

2.2 Oxidation and acidification of sulfide soils

Sulfide soils remain chemically stable under natural waterlogged conditions because the absence of oxygen prevents oxidation of sulfide minerals. The stability of these soils is maintained by reducing (anaerobic) environments, where pyrite (FeS_2) and other sulfide minerals persist without generating acidity (Dent and Pons 1995; Sullivan et al. 2010). However, excavation, drainage, lowering of the groundwater table, or temporary stockpiling expose sulfide soils to atmospheric oxygen, initiating a series of oxidation reactions that fundamentally alter their chemical environment.

The oxidation of pyrite is a complex process involving both chemical and microbiological reactions. In the presence of oxygen and water, pyrite is oxidized to produce sulfuric acid and dissolved iron, which lowers the soil pH and may mobilize potentially toxic metals (Dent and Pons 1995; Evangelou and Zhang 1995). Under favourable conditions, iron-oxidizing bacteria such as Thiobacillus ferrooxidans further accelerate oxidation, particularly in strongly acidic environments (Nordstrom 1982). As oxidation progresses, soils that were originally classified as hypersulfidic (potential acid sulfate soils) may transform into sulfuric soils (actual acid sulfate soils) when the soil pH decreases below the threshold (<4) defined by international classification systems (Boman et al. 2023).

The rate and extent of acidification depend on several interacting factors rather than sulfur concentration alone. These include sulfide mineral content, particle size, oxygen availability, groundwater conditions, organic matter, and, importantly, the buffering capacity provided by carbonate minerals such as calcite (Dent and Pons 1995; Fanning et al. 2017). Consequently, soils with similar sulfur contents may exhibit substantially different acidification behaviour depending on their calcium content and overall geochemical composition. Recent studies have shown that the balance between acid-generating sulfides and acid-neutralizing minerals, often expressed by the Ca/S ratio, provides a better indicator of acidification behaviour than sulfur concentration alone (Trafikverket 2023). Some soils having high sulfur content, their acidity is neutralized because of high buffering capacity and neutralizing agents (e.g. shell material)(Boman et al. 2023).

From an engineering perspective, oxidation not only changes the chemical environment but may also influence the physical and mineralogical characteristics of the soil. Sulfide oxidation can modify particle aggregation, mineral composition, and pore-water chemistry, thereby altering the conditions under which cement hydration occurs (Sherwood 1962; Puppala et al. 2004). Acidification reduces soil pH and may retard hydration reactions by decreasing the availability of calcium ions required for the formation of cementitious products such as C-S-H and C-A-S-H gels (Clare and Sherwood 1954; Ge et al. 2020). Consequently, oxidation and acidification may influence both the short-term strength development and the long-term performance of stabilized sulfide soils.

Because oxidation directly affects the physicochemical environment controlling binder reactions, reliable assessment of acidification behaviour is an important prerequisite for sustainable stabilization. Several laboratory methods have therefore been developed to evaluate the acidification potential of sulfide soils, including long-term incubation tests and accelerated leaching procedures. These methods provide

valuable information regarding the rate of acid generation, buffering capacity, and potential changes in soil chemistry before stabilization measures are implemented (Sullivan et al. 2010; Nystrand et al. 2023).

Although the oxidation mechanisms of sulfide soils are relatively well established, comparatively little attention has been given to how and to which extent oxidation modifies binder performance and stabilization mechanisms. Understanding these interactions is essential for predicting the engineering performance of stabilized sulfide soils and forms an important component of the research presented in this thesis.

2.3 Stabilization of sulfide soils

Stabilization through mixing binder is one of the most widely adopted techniques for improving the engineering properties of soft soils. The primary objective of stabilization is to increase strength and stiffness while reducing compressibility, permeability, and long-term settlement, thereby enabling the reuse of otherwise unsuitable soils in civil engineering applications. Among the available stabilization techniques, chemical stabilization using hydraulic binders such as Portland cement and lime has proven particularly effective for fine-grained soils because it modifies both the physical structure and chemical characteristics of the soil (Makusa 2013; Pham et al. 2021; Luo et al. 2024; Zhou et al. 2024).

When Portland cement is mixed with water, hydration reactions occur almost immediately, producing cementitious compounds including calcium silicate hydrate (C-S-H), calcium aluminate hydrate (C-A-H), and calcium aluminosilicate hydrate (C-A-S-H). These hydration products bind adjacent soil particles together, fill pore spaces, and create a denser soil skeleton that substantially improves mechanical properties (Horpibulsuk et al. 2010; Scrivener et al. 2018a; Wang et al. 2022). As hydration continues during curing, additional cementitious products develop, leading to progressive increases in strength and stiffness while reducing the deformability of the stabilized soil.

But stabilization of sulfide soils is considerably more complex because binder performance is governed by interactions between soil mineralogy, geochemistry, and environmental conditions. Several physical and chemical factors influence the efficiency of cement stabilization, including natural water content, binder dosage, curing duration, mixing efficiency, sulfur-bearing minerals, organic matter, and oxidation state (Åhnberg et al. 2003; Al-Jabban et al. 2017; Rothhämel et al. 2022; Ziagharib 2025). These factors influence the hydration process by modifying the availability of water, calcium ions, and reactive surfaces required for cementitious reactions.

Among these parameters, water content is generally considered one of the most influential factors controlling strength development. Adequate moisture is essential for cement hydration; however, excessive water increases the effective water-to-cement ratio, dilutes the binder, and creates additional pore space, resulting in lower strength development (Makusa 2013; Wang et al. 2022; Luo et al. 2024). Previous studies have shown that optimizing water content can significantly improve the performance of cement-stabilized fine-grained soils by promoting more efficient hydration and reducing porosity.

The presence of organic matter introduces additional complexity because organic compounds may adsorb calcium ions released during hydration and prolong the induction period of cement hydration. As a result, soils containing high organic content generally exhibit slower strength development and often require higher binder dosages to achieve comparable engineering performance (Clare and Sherwood 1954; Ge et al. 2020). Similarly, sulfur-bearing minerals influence stabilization through sulfate reactions. Moderate sulfate concentrations may contribute to the formation of ettringite during early hydration, whereas excessive sulfate availability can promote expansive mineral formation and adversely affect long-term durability (Sherwood 1962; Puppala et al. 2004; Talluri et al. 2020).

From an engineering perspective, one important parameter is the mixing method, which controls the degree of contact between soil particles and the binder. Efficient mixing promotes homogeneous binder distribution, uniform hydration, and improved particle bonding, whereas insufficient mixing results in localized cementation and reduced stabilization efficiency. Dry mixing creates local zones of high cement concentration, while wet mixing provides more uniform binder distribution but may increase the water content and cause dilution. Although wet mixing often performs better during in-situ stabilization, dry mixing may be more suitable for high water content sulfide soils, but the optimal method depends on soil type and mixing conditions (Sebesta and Harris 2009; Pakbaz and Farzi 2015; Ziagharib 2025). In practice, stabilization performance therefore depends not only on binder composition but also on the quality of field mixing and construction procedures.

The engineering performance of stabilized soils is commonly evaluated using the unconfined compressive strength (UCS) test, which provides a simple and reliable measure of strength development during curing. However, mechanical testing alone cannot fully explain the mechanisms responsible for strength improvement. Consequently, advanced microstructure analysis such as scanning electron microscopy (SEM), energy-dispersive spectroscopy (EDS), and X-ray diffraction

(XRD) are increasingly used to investigate the formation of hydration products, particle bonding, pore filling, and mineralogical evolution within stabilized soils (Scrivener et al. 2018a; Liu et al. 2023; Zhou et al. 2024).

Cement stabilization has been successfully applied to a wide range of problematic soils, its application to sulfide soils also works well although it depends on the characteristics of the soil, and these soils behave differently depending on their origin history. Previous studies have investigated the influence of individual parameters such as binder dosage or curing duration, whereas few have systematically examined the combined effects of water content, sulfur content, organic matter, oxidation, and binder incorporation on the mechanisms governing strength development. A better understanding of these coupled interactions is therefore essential for improving stabilization strategies and enabling the sustainable reuse of excavated sulfide soils.

2.4 Sustainable binders for sulfide soil stabilization

Portland cement remains the most widely used hydraulic binder for soil stabilization because of its effectiveness, availability, and well-established engineering performance. However, cement production is responsible for approximately 7-8% of global anthropogenic carbon dioxide (CO_2) emissions, primarily due to limestone calcination and the high energy demand of clinker production (Andrew 2018; Scrivener et al. 2018b). Consequently, reducing cement consumption has become an important objective in sustainable stabilization of soil using binders.

One promising approach is the utilization of industrial by-products as alternative binders. Materials such as ground granulated blast furnace slag (GGBS), fly ash, metakaolin, and steel slag contain reactive aluminosilicate phases that can form cementitious products when activated under alkaline conditions. These materials, commonly referred to as alkali-activated binders (AABs) or alkali-activated materials (AAMs), have received increasing attention because they can achieve engineering properties comparable to conventional cement while significantly reducing carbon footprints (Van Deventer and Jannie S J 2014; Provis 2014, 2018; Davidovits 2020). The stabilization mechanisms of alkali-activated binders differ from those of Portland cement. Instead of relying primarily on clinker hydration, aluminosilicate precursors react with alkaline activators, such as sodium hydroxide or sodium silicate, to form three-dimensional binding gels including sodium aluminosilicate hydrate (N-A-S-H) and calcium aluminosilicate hydrate (C-A-S-H). These reaction products improve particle bonding, reduce pore volume, and increase soil strength through mechanisms like those observed in conventional cement stabilization (Horpibulsuk et al. 2010; Provis 2014). Several studies have investigated alkali-activated binders for stabilizing soft clays, dredged sediments, and contaminated soils (Cristelo et al. 2011, 2012a, b;

Zhang et al. 2013; Singhi et al. 2017). In addition to reducing CO_2 emissions, these binders promote the beneficial reuse of industrial by-products that would otherwise require disposal, supporting circular economy principles within the construction sector.

Despite these advantages, the application of alkali-activated binders to sulfide soils remains largely unexplored. Sulfide soils present a chemically aggressive environment characterized by high water content, sulfur-bearing minerals, organic matter, and the potential for acidification following oxidation. These conditions may influence the activation reactions, reaction products, and long-term durability of alkali-activated systems. Due to these reasons, the direct transfer of knowledge obtained from conventional soft soils cannot be assumed for sulfide soils.

The research presented in this thesis establishes the scientific understanding required to address these challenges. By identifying the key parameters controlling cement stabilization and clarifying the influence of oxidation and acidification on binder performance, the present work provides the foundation for the next phase of this doctoral research, which will investigate the feasibility of alkali-activated binders as sustainable alternatives to Portland cement for sulfide soil stabilization.

2.5 Summary of current knowledge

Previous research has demonstrated that soil stabilization using hydraulic binders can significantly improve the engineering properties of soft soils through the formation of cementitious hydration products such as C-S-H, C-A-S-H, C-A-H, and ettringite. The performance of stabilized soils is known to depend on several factors, including binder type and dosage, curing conditions, water content, and soil mineralogy. However, the stabilization of sulfide soils is considerably more complex because it involves coupled geotechnical and geochemical processes. Existing studies have primarily focused on influence of water content, binder dosage, curing time and environment, whereas the individual as well as combined influence of sulfur content, organic matter, oxidation, and acidification on stabilization performance remains insufficiently understood (Åhnberg et al. 2003; Rothhämel et al. 2022; Ziagharib 2025; Thakur et al. 2026; Ziagharib et al. 2026). In addition, the mixing method influences binder distribution, hydration, and particle bonding. Therefore, stabilization performance depends on both binder composition and the quality of field mixing and construction (Sebesta and Harris 2009; Pakbaz and Farzi 2015).

Also, previous investigations have evaluated stabilization performance primarily through mechanical testing usually UCS test. Comparatively few studies related to sulfide soil stabilization have integrated mechanical behaviour with microstructural characterization to explain how oxidation and soil chemistry influence cement

hydration, particle bonding, and strength development. Therefore, the mechanisms governing stabilization of sulfide soils remain only partially explored.

Reliable assessment of acidification behaviour prior to stabilization also remains an important challenge. Although several laboratory methods have been developed to evaluate the acidification potential of sulfide soils, limited attention has been given to how these methods can support stabilization design by predicting the physicochemical environment in which binder hydration occurs. Likewise, increasing environmental concerns associated with Portland cement production have stimulated research into low-carbon binders. However, the application of alkali-activated binders to sulfide soil stabilization has received very limited attention.

The literature reviewed indicates that successful stabilization of sulfide soils requires an integrated understanding of soil properties, mixing method, oxidation, acidification, and binder interactions. Addressing these combined processes is essential for improving the reuse of excavated sulfide soils and for developing sustainable stabilization strategies. The following chapter describes the experimental methodology adopted to investigate these mechanisms.

3 RESEARCH METHODOLOGY

3.1 Research framework

The research framework adopted in this thesis is illustrated in Figure 2. The research was designed to improve the understanding of the mechanisms governing stabilization of sulfide soils and to establish the scientific foundation for their sustainable reuse in geotechnical engineering applications.

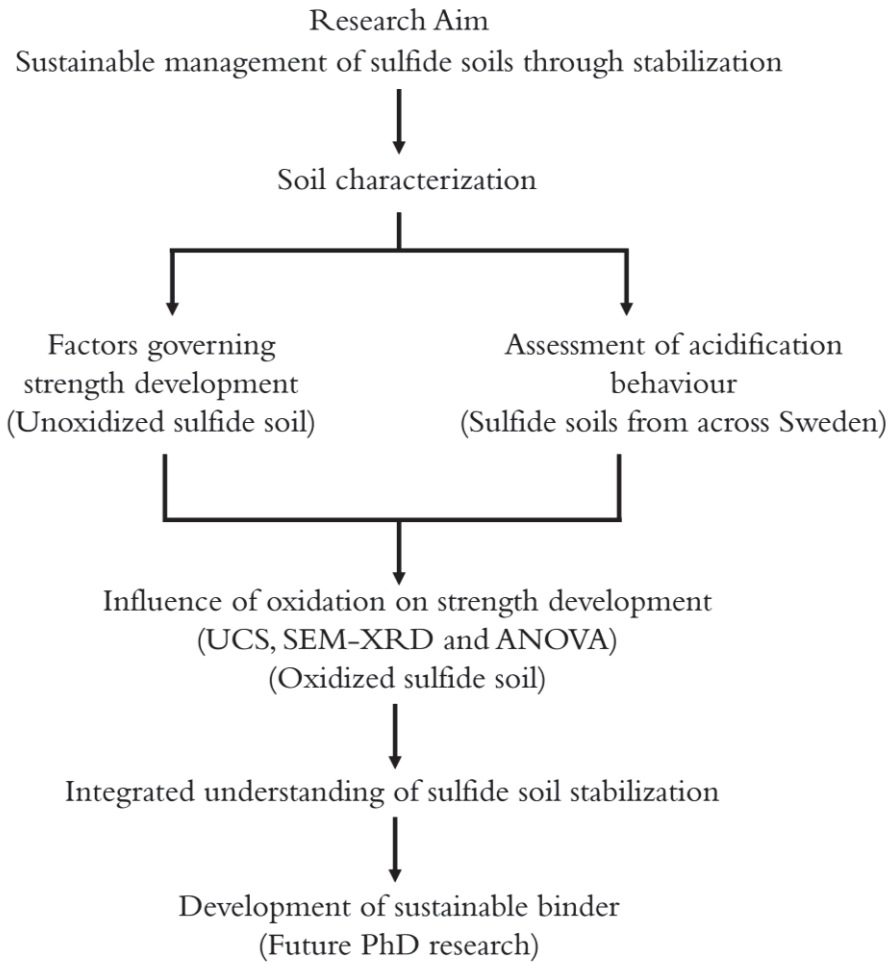

Figure 2: The progression of the research from characterization of sulfide soils to the development of sustainable stabilization strategies

The study began with literature and the characterization of sulfide soils collected from northern Sweden. Based on the identified soil properties, two complementary research directions were pursued. The first focused on identifying the key parameters controlling the strength development of cement-stabilized sulfide soils under unoxidized/oxidized conditions, including the effects of water content, sulfur content, organic matter, binder dosage, curing duration, and mixing method. The second focused on evaluating the acidification behaviour of sulfide soils using different laboratory methods to improve understanding of the environment that influences binder performance.

The knowledge obtained from these investigations was subsequently integrated through a detailed study of oxidized sulfide soils, combining mechanical testing with microstructural characterization using SEM, XRD, and statistical analysis. This integrated approach provides a wider understanding of the coupled geotechnical and geochemical mechanisms governing stabilization performance. The outcomes of the present research establish the basis for the future doctoral work, which will investigate alkali-activated binders as sustainable alternatives to Portland cement for sulfide soil stabilization.

3.2 Materials

The experimental investigations presented in this thesis were conducted using sulfide soils collected from several locations in northern Sweden. The soils were selected to represent the variability commonly encountered during excavation with respect to sulfur content, organic matter, natural water content, and mineralogical composition. Based on their engineering properties and chemical characteristics, two representative soils were selected for the stabilization studies: a high sulfur-high organic content soil (HS_HLOI) and a low sulfur-low organic content soil (LS_LLOI). According to ISO 17892-4, both soils were classified as clayey silt. Detailed characterization of these soils presented in Table 3 given below.

Table 3: Soil properties and chemical composition

Parameter	HS_HLOI		LS_LLOI	
	unoxidized	oxidized	unoxidized	oxidized
Ca, Calcium*	5560		3540	
Fe, Iron*	33700		14100	
S, Sulfur*	18000		4580	
pH at 20°C	5,7	3,1	6,4	3,8
Water content **	98		60	
Liquid limit (LL)**	95		58	
Plastic limit (PL)**	71		38	
Organic content**	9		5	
Sand**	6	10	13	12
Silt**	76	83	73	82
Clay**	18	7	14	6

* mg/kg of dry soil, ** (%). The table appears in a manuscript (Paper C).

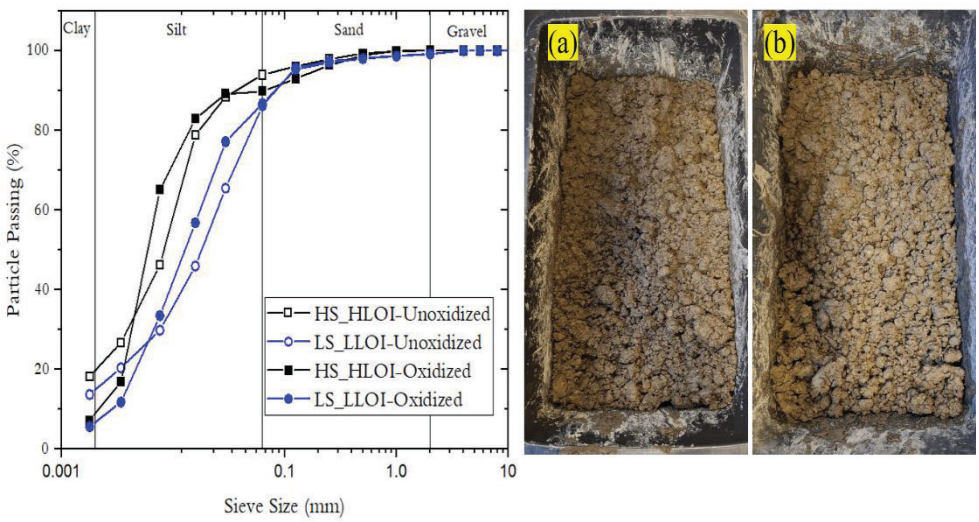

Figure 3: Particle size distribution chart; (a) HS_HLOI soil, (b) LS_LLOI soil

The particle size distribution of the soils before and after oxidation has been given in Figure 3, including the fresh soils samples. This figure appears in a manuscript (Paper C).

For the laboratory stabilization experiments, Portland cement (CEM II/A-LL 42.5 R) manufactured by Heidelberg Materials Cement Sverige AB was used as the primary hydraulic binder. This cement was selected because it is widely applied in ground improvement projects and represents current engineering practice for stabilization of fine-grained soils.

Microstructural investigations were performed on selected stabilized specimens using SEM and XRD to investigate particle bonding, hydration products, and mineralogical changes following stabilization. These analyses provided complementary information for interpreting the observed mechanical behaviour.

The acidification assessment was performed using soil samples collected from nine locations across Sweden, representing a broad range of geochemical conditions along Swedish coastlines. These soils were used to evaluate different laboratory methods for assessing acidification potential in Laboratory. The chemical composition of the soil is given the Table 4.

Table 4: pH and chemical composition of the studied soils

Soil	pH (initial)	pH (oxidized)	Fe/S	Ca/S
Robertsfors	4,0	2,8	3,9	1,3
Uppsala	8,2	5,4	4,7	0,6
Kalmar	6,8	4,1	5,1	0,9
Uddevalla	8,7	5,2	12,3	1,8
Kungsbacka	8,5	7,0	21,3	21,3
Gothenburg	8,3	7,0	3,8	3,1
Umeå	4,4	3,8	2,7	0,6
Skellefteå	8,4	4,0	9,4	1,8
Sunderbyn	7,4	4,0	2,4	0,5

The table appears in a manuscript which is under peer review (Paper B).

The future research will extend the present work by investigating alkali-activated binders based on industrial by-products, including ground granulated blast furnace slag (GGBS), fly ash (Class C), and chemical activators, as sustainable alternatives to Portland cement for sulfide soil stabilization.

Table 5: Materials used in the research

Material	Application	Related study
HS_HLOI & LS_LLOI sulfide soil	Cement stabilization	Paper A & C
Nine sulfide soil from distinct location	Acidification assessment	Paper B
Cement	Hydraulic binder	Paper A & C
SEM & XRD	Microstructure study	Paper C
Merit (GGBS), Class C-Fly ash	Alkali activated binder	Next stage research

3.3 Experimental program

The experimental program was designed to investigate the factors governing the stabilization of sulfide soils and to establish the basis for their sustainable reuse. The research was conducted through three complementary studies, each addressing a specific aspect of sulfide soil management (the overall research aim).

- The first study focused on identifying the key parameters controlling the strength development of cement-stabilized sulfide soils under unoxidized conditions. Laboratory experiments were performed to evaluate the influence of water content, sulfur content, organic matter, cement dosage, curing duration, and binder incorporation method on the UCS of stabilized specimens. This study established the baseline understanding of stabilization behaviour and identified the governing parameters affecting engineering performance.
- The second study investigated the acidification behaviour of sulfide soils collected from different regions of Sweden. Laboratory incubation and accelerated cyclic leaching methods (MRM air-dry and MRM oven-dry) were used to evaluate the acidification potential of the soils. The objective was to improve the understanding of the chemical environment influencing

binder performance and to assess the suitability of different laboratory methods for assessing acidification behaviour.

- The third study examined the influence of oxidation on stabilization performance. Mechanical testing was combined with microstructural characterization using SEM and XRD to investigate hydration mechanisms, mineralogical evolution, and particle bonding in oxidized cement-stabilized sulfide soils. In addition, ANOVA was applied to quantify the significance of the investigated parameters and their interaction effects on strength development.

Together, these investigations provide a broad understanding of the physical and chemical processes governing sulfide soil stabilization. The knowledge gained forms the scientific basis for the next phase of the doctoral research, which will investigate sustainable binder alternatives to Portland cement.

The experimental and analytical methods employed throughout the research program are briefly described in the following section, while detailed procedures are presented in the corresponding appended papers.

3.4 Experimental and analytical methods

The experimental program employed a combination of mechanical, chemical, and microstructural characterization techniques to investigate the stabilization behaviour of sulfide soils. The selection of analytical methods was based on their ability to evaluate both the engineering performance and the physicochemical mechanisms governing stabilization. Detailed descriptions of the experimental procedures are presented in the corresponding appended papers. Therefore, only a brief overview is provided here.

3.4.1 Unconfined compressive strength (UCS)

The engineering performance of stabilized sulfide soils was evaluated using the UCS test. UCS testing is one of the most widely used laboratory methods for assessing the strength development of chemically stabilized fine-grained soils because it provides a direct measure of load-bearing capacity without lateral confinement (Horpibulsuk et al. 2010; ASTM 2024).

The soil was homogenised by mixing for 2 min, and then the cement binder was added in powder or slurry form at the required dosage and mixed again for 5 min in a Hobart dough mixer. Immediately after mixing, the soil was placed in a cylindrical mould (50x100 mm) in five layers, with each layer compacted by tapping the tube 30 times against the working surface to achieve an identical density. The tapping method was adopted from (Al-Jabban et al. 2020). The UCS samples were then

stored in a closed, humid container at room temperature for 7 and 28 days until UCS testing. The UCS tests were conducted at a loading rate of 1 mm/min, and the axial load and deformation were recorded. Failure was defined either by the peak load or at 20% strain, whichever occurred first. A typical flowchart is given in the Figure 4.

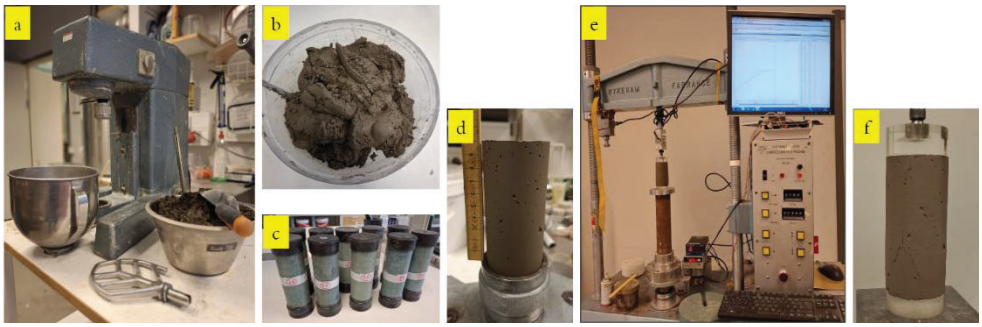

Figure 4: Procedure from UCS sample preparation to the testing (a to f), not in scale

3.4.2 Acidification assessment

The acidification behaviour of sulfide soils was investigated using laboratory incubation and accelerated cyclic leaching (MRM) methods. These methods simulate sulfide oxidation under laboratory conditions and provide information on pH evolution, buffering capacity, and acidification potential. The laboratory results were further compared with a digital classification tool developed for rapid assessment of sulfide soil acidification. These methods provide important information regarding the chemical environment that influences binder hydration and stabilization performance.

The acidification potential was evaluated using three methods: incubation, MRM air-dry, and MRM oven-dry. For all methods, 25 g of soil was mixed with deionized water at a liquid-to-solid (L/S) ratio of 3:1 by mass.

- **Incubation Method:**
  The soil was mixed with deionized water, equilibrated for 30 min, and then filtered. The filtrate was analysed for pH and electrical conductivity (EC), while the retained soil was air-dried at room temperature for one week before the next leaching cycle. This procedure was repeated for 10 weeks wetting-drying cycles.
- **MRM Method:**
  The soil was initially air-dried for 24 h and gently grounded into a fine powder without crushing the soil grains. The soil was then mixed with deionized water, equilibrated for 30 min, and filtered. The filtrate was analysed for pH and EC, while the retained soil was dried for 24 h either at

room temperature (24 ± 3 °C) for the MRM air-dry method or at 105 °C for the MRM oven-dry method. The procedure was repeated for 15–20 cycles, depending on the acidification or neutralisation behaviour of the soil. The experimental workflow for MRM-air dry is shown in Figure 5.

- **Digital Tool Assessment:**
  The acidification potential was also estimated using a digital tool developed by Ecoloop AB, Sweden. The soil was classified based on total S, Ca, Fe, and the measured initial and oxidised pH values. The assessment system was developed using an empirical and data-driven approach that combines geochemical characterisation, experimental oxidation testing, and long-term field observations.

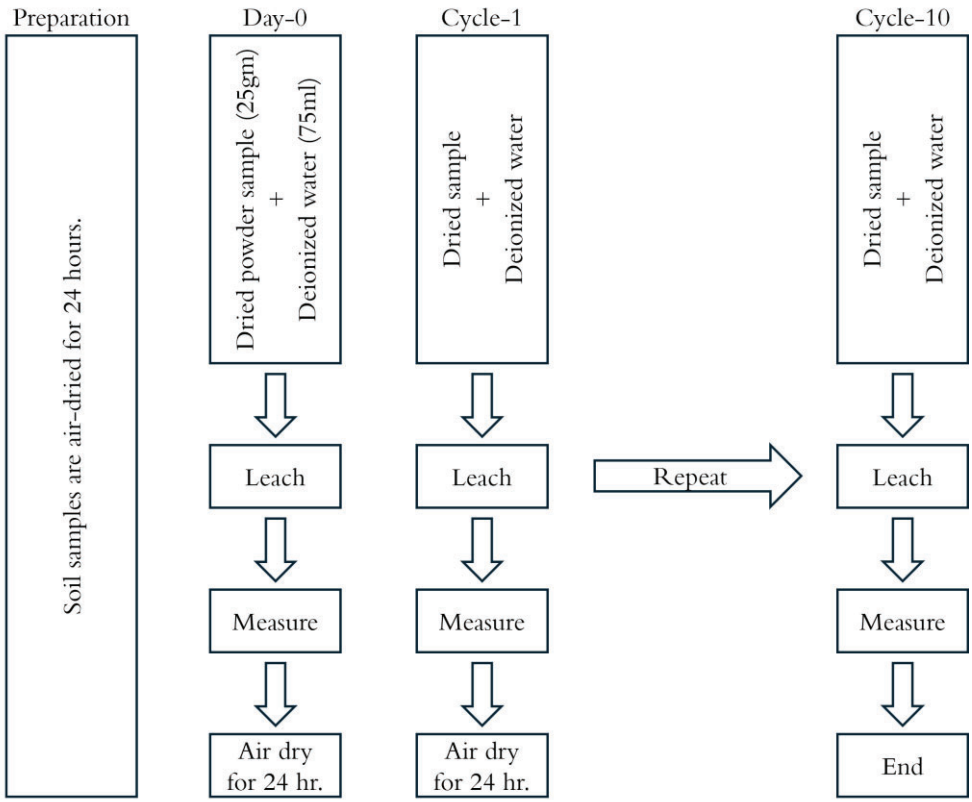

Figure 5: Experimental procedure of the MRM air-dry method showing sample preparation, drying, leaching, and measurement steps

3.4.3 Microstructural analysis (SEM and XRD)

SEM was used to investigate the microstructural evolution of stabilized sulfide soils. SEM imaging provides information on particle arrangement, pore structure, and the

formation of cementitious products, while XRD analysis was performed to identify the crystalline mineral phases present before and after stabilization.

- Representative samples were collected after UCS testing at 28 days. Hydration was stopped by immersing small fragments in isopropanol for approximately 5 h. The samples were then air-dried for 24 h and oven-dried at 40°C for two weeks to remove the remaining isopropanol while preserving the hydration products(Snellings et al. 2018a, b)
- For SEM analysis, the dried samples were fractured to expose fresh internal surfaces and mounted on aluminium stubs using conductive carbon tape. The samples were examined using a Magellan 400 (FEI) scanning electron microscope in secondary electron mode at 20 kV, a beam current of 0.2 nA, and a working distance of 4.5-6 mm. Energy-dispersive X-ray spectroscopy (EDS) was also used on selected samples to determine elemental composition.
- For XRD analysis, the dried samples were gently ground to a particle size below 63 μm and analysed using a PANalytical Empyrean diffractometer with Cu-Kα radiation at 45 kV and 40 mA. Diffraction patterns were collected over a 2θ range of 5-80° for 2 h per sample. Mineral phases were identified using the International Centre for Diffraction Data (ICDD) Powder Diffraction File database.

3.4.4 Statistical analysis

Statistical evaluation of the experimental data was carried out using factorial analysis of variance (ANOVA). This analysis was performed to evaluate the significance of the investigated factors and their interaction effects on UCS development. Statistical significance was assessed at a 95% confidence level, with p-values below 0.05 considered significant (Douglas 2019). Four separate ANOVA models were developed to facilitate the interpretation of the experimental results. The factors investigated and their levels are given in the Table 6 below.

Table 6: Factors and levels used in the experimental program

Experimental factors	Levels included in the study
Soil type	HS_HLOI and LS_LLOI
Oxidation condition at stabilization	Unoxidized and oxidized before stabilization
Cement dosage	5% and 10% by dry weight of soil
Mixing method	Dry and wet mixing of cement
Curing time before UCS testing	7 days and 28 days

The methodology presented in this chapter provides the experimental framework for investigating the stabilization behaviour of sulfide soils. The following chapter summarizes the principal findings of the appended papers and highlights their contributions to the overall research objectives.

4 RESULTS AND DISCUSSIONS

The findings presented in the appended papers are synthesized and discussed in this chapter according to the research questions introduced in 1.4. Rather than describing each study individually, the results are integrated to explain how soil characteristics, oxidation and acidification, and binder influence the engineering performance of stabilized sulfide soils.

4.1 Effect of water content

Figure 6 shows the effect of water content on the UCS of cement-stabilized sulfide soils using dry mixing. Lower water content generally increased the strength of both soils. For HS_HLOI soil, the 7days UCS increased from approximately 10 kPa at 70% water content to 65 kPa at 50%, reaching 70 kPa after 28 days. For LS_LLOI soil, the 7 days UCS reached 360 kPa at 60% water content and 870 kPa at 45%, while the 28 days UCS reached 570 kPa at 60%. These results confirm that water content strongly influences strength development during cement stabilization.

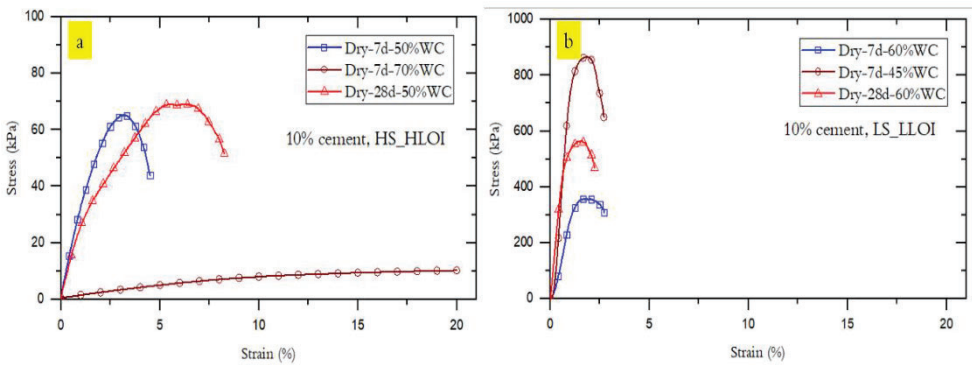

Figure 6: Stress-strain plot for (a) HS_HLOI, (b) LS_LLOI at 10% cement dry mixed – unoxidized soil (Thakur et al. 2026)

High water content reduced stabilization efficiency by increasing the water to cement ratio, diluting the binder, and increasing pore water within the soil. As a result, strength development remained limited even at higher cement dosages. Reducing the water content substantially improved UCS, particularly for the LS_LLOI soil. This agrees with previous studies showing that an appropriate wate to cement ratio improves cement hydration, reduces pore volume, and strengthens particle bonding (Makusa 2013; Wang et al. 2022; Luo et al. 2024). Therefore, controlling water content is essential for effective stabilization of sulfide soils.

4.2 Effects organic matter and sulfur content

Water content is an important factor which can be understood by the explanation and plot given in section 4.1. However, water content alone cannot explain the differences in UCS between HS_HLOI and LS_LLOI. As shown in Figure 7, the oxidized soils stabilized with 10% cement had water contents of 60±2% but showed considerably different strengths. Compared with HS_HLOI, the UCS of LS_LLOI was approximately 300 kPa higher after 7 days and 500 kPa higher after 28 days. This indicates that other soil characteristics like sulfur content, organic matter, and their effects on cement hydration, also strongly influenced strength development.

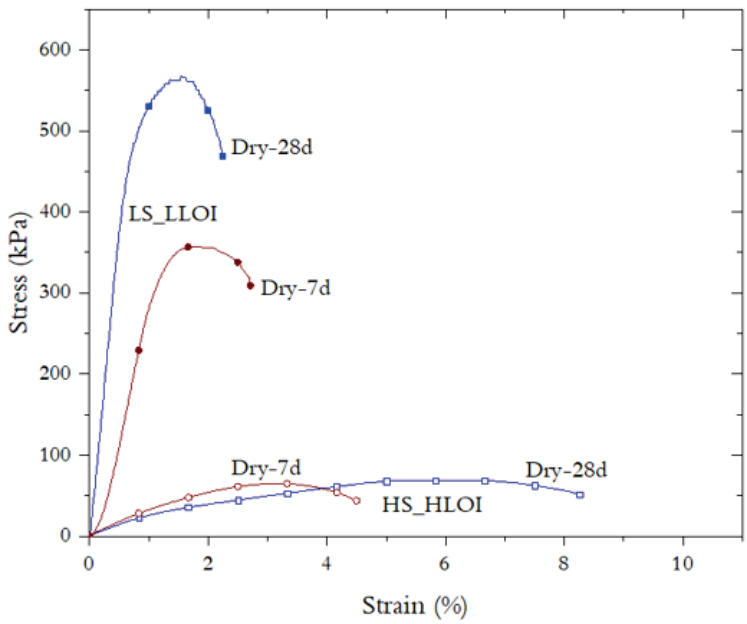

Figure 7: Stress-strain plot for HS_HLOI and LS_LLOI soil at 60% WC – oxidized soil

⋆This figure appears in a manuscript (Paper C).

The HS_HLOI soil consistently developed lower UCS than the LS_LLOI soil, showing that soil chemistry strongly influenced binder performance. The higher organic matter content of HS_HLOI may have delayed cement hydration by adsorbing calcium ions and limiting the formation of strength producing cementitious products. Its higher sulfur content may also have affected cement hydration through interactions between sulfate bearing minerals and hydration products. Although the individual effects of sulfur and organic matter could not be separated in natural conditions, their combined influence reduced stabilization efficiency. Similar findings have been reported for organic rich and sulfate bearing

soils, which often require higher binder dosages to achieve comparable strength (Clare and Sherwood 1954; Puppala et al. 2004; Ge et al. 2020).

4.3 Effect of binder dosage, curing duration and mixing method

As shown in Figure 8, both soils showed limited strength development between 7 and 28 days at 5% cement. Dry mixing generally showed higher UCS than wet mixing, although the difference was small for HS_HLOI. For LS_LLOI with 10% cement, dry mixing increased UCS by approximately 80 kPa after 7 days and 273 kPa after 28 days compared with wet mixing. These laboratory results were obtained in laboratory and uniform mixing conditions, which may be difficult to reproduce in the field. The higher strength obtained by dry mixing may result from direct contact between powdered cement and soil particles and promoting calcium-ion exchange (Makusa 2013; Pakbaz and Farzi 2015). This effect was more evident in LS_LLOI, where the lower water content provided sufficient moisture for hydration without excessive binder dilution. In wet mixing, the added slurry increased the water to cement ratio and may have initiated cement hydration before mixing with

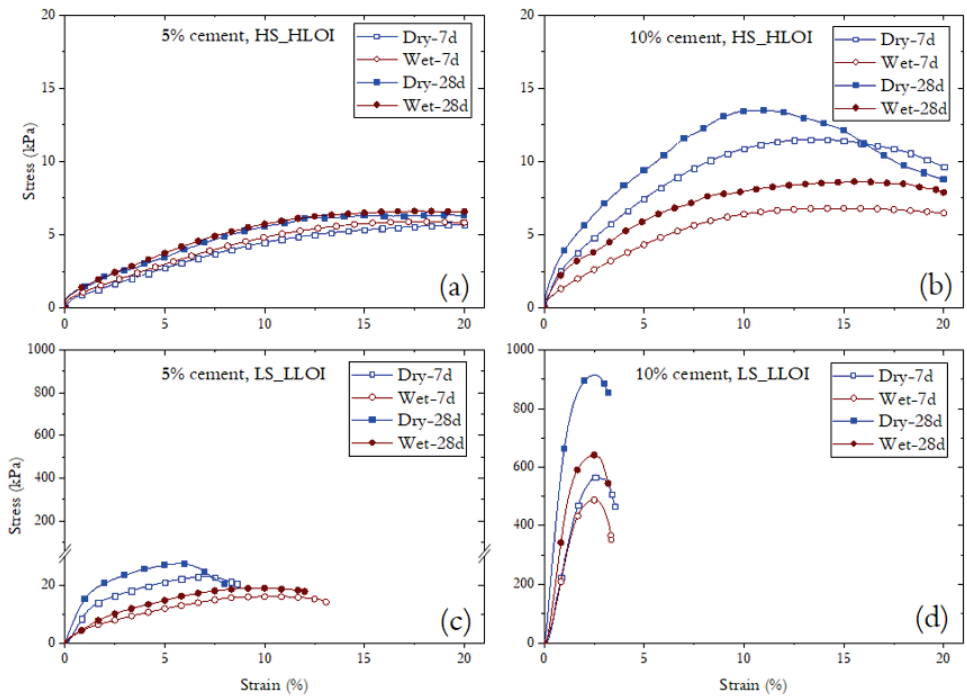

Figure 8: Stress-strain curve (a) and (b) HS_HLOI 5% & 10% cement respectively; (c) and (d) LS_LLOI 5% & 10% cement (Thakur et al. 2026)

the soil, reducing subsequent soil–cement interaction and strength development (Sherwood 1962; Sebesta and Harris 2009). Although making a cement slurry only requires adding 20–25% water by powder mass, it does not significantly affect the overall water content of the matrix. As expected, increasing the cement dosage improved UCS by producing more hydration products and longer curing increased strength through continued cement hydration and matrix densification. However, the strength improvement depended strongly on soil characteristics. The effect of cement dosage was greater for LS_LLOI than for HS_HLOI, indicating that favourable soil conditions are important for efficient binder performance.

4.4 Effect of oxidation

Figure 9 presents stress–strain curves for oxidized and unoxidized HS_HLOI (a, b) and LS_LLOI (c, d) soils stabilized with 5% and 10% cement after 28 days of curing under dry and wet mixing conditions. The bulk densities ranging from 1.5 to 1.6 g/cm^3.

Oxidation affected both UCS and stress–strain behaviour, although the magnitude depended on soil type, cement dosage, and mixing method. For HS_HLOI (Figure 9a and Figure 9b), oxidation slightly increased UCS for dry mixing with 5% cement and for both mixing methods with 10% cement. The improvement was most evident for dry mixing with 10% cement. However, both oxidized and unoxidized samples remained ductile and exhibited gradual strain hardening. LS_LLOI showed a good response to oxidation (Figure 9c and Figure 9d). Under dry mixing, the oxidized samples developed approximately 18 and 300 kPa higher UCS than the unoxidized samples with 5% and 10% cement, respectively. The samples exhibited brittle failure, with a rapid loss of stress after the peak load. The untreated oxidized HS_HLOI and LS_LLOI soils had UCS values of only 4.0 and 4.9 kPa, respectively. These results indicate that oxidation enhanced the strength of the cemented soil skeleton rather than reducing stabilization performance, contrary to the initial hypothesis. The strength improvement may be related to oxidation-induced changes in the physicochemical properties of the soils. Although oxidation reduced the pH from 5.7 to 3.1 in HS_HLOI and from 6.4 to 3.8 in LS_LLOI, the increase in UCS indicates that pH alone did not control stabilization performance. Both soils also changed from clayey silt to sandy silt after oxidation, suggesting some breakdown of clay aggregates and redistribution of fine particles, although the change was small. These changes may have influenced particle packing and soil–binder contact (Sherwood 1962; Puppala et al. 2004; Wang et al. 2022). The oxidized soils also

appeared wetter during mixing than the unoxidized soils despite having similar water contents at the time of sample preparation.

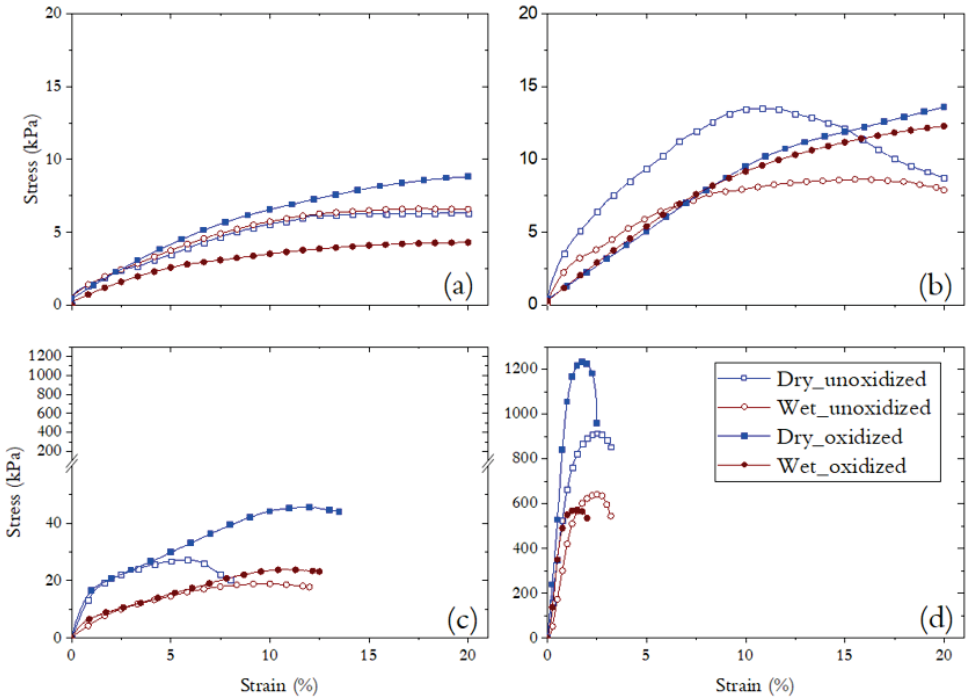

Figure 9: Stress-strain plot (a) HS_HLOI stabilized with 5% cement, (b) HS_HLOI stabilized with 10% cement, (c) LS_LLOI stabilized with 5% cement, and (d) LS_LLOI stabilized with 10% cement

⋆This figure appears in a manuscript (Paper C).

Oxidation increased the UCS of LS_LLOI under dry mixing conditions but caused only minor changes in HS_HLOI. This indicates that oxidation does not always reduce stabilization efficiency through acid generation. Instead, it changes the physicochemical conditions governing cement hydration. The response therefore depends on the combined effects of soil mineralogy, water content, organic matter, and sulfur-bearing minerals rather than on pH alone. These findings differ from the initial hypothesis that oxidation would reduce strength because of increased acidity.

4.5 Microstructural characteristics

The XRD patterns of the untreated oxidized soils (Refer to figure 4 in paper C) indicate that both HS_HLOI and LS_LLOI were predominantly composed of quartz, feldspar, illite, albite and calcite. Pyrite reflections were also identified particularly in HS_HLOI soil. The presence of residual pyrite suggests that although there was noticeable drop in the pH value, oxidation of sulfide minerals was not complete. Similar observations have been reported for partially oxidized soils, where pyrite may persist even after prolonged atmospheric exposure due to limited oxygen diffusion within the soil matrix (Dent and Pons 1995; Evangelou and Zhang 1995). The untreated SEM micrograph (Figure 10a-b and Figure 11a-b) further reveals a loose soil fabric consisting of different mineral particles with limited particle bonding and large pore spaces. The poorly connected structure explains the low UCS measured for untreated soils particularly for HS_HLOI soil.

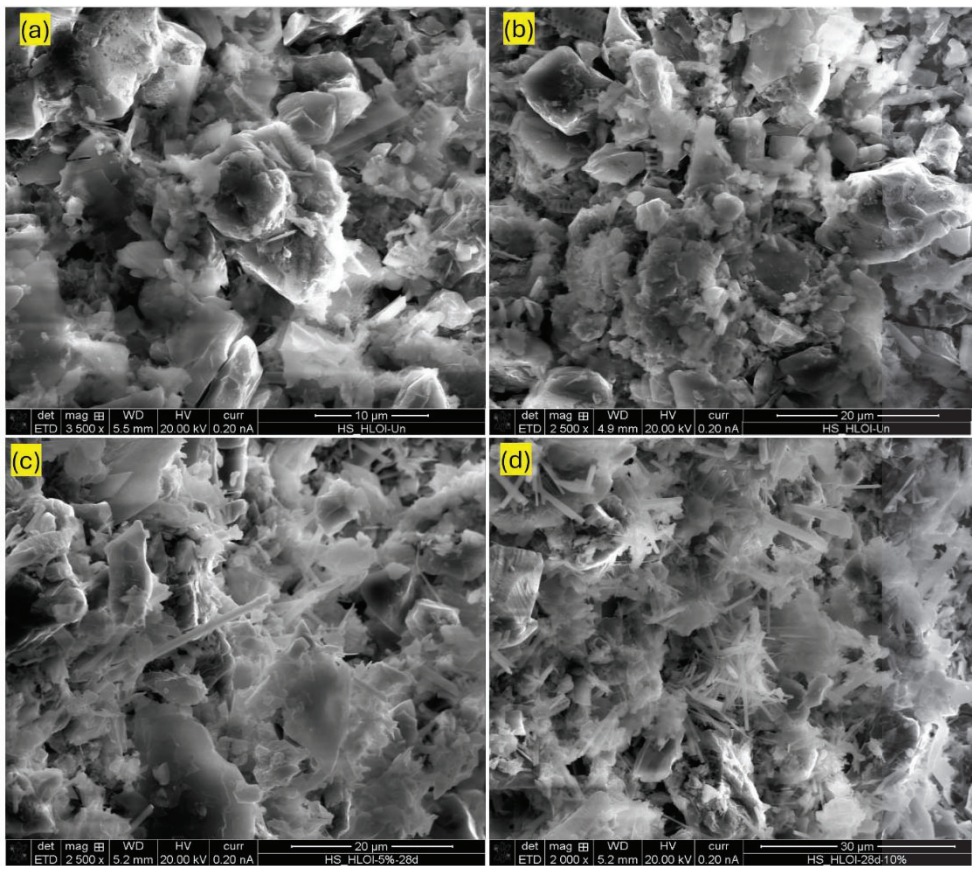

Figure 10: SEM micrographs of HS_HLOI soil: (a) untreated soil, (b) untreated soil at lower magnification, (c) stabilized with 5% cement and (d) stabilized with 10% cement after 28 days

Following cement stabilization, mineralogical changes were observed in both soils. The XRD patterns clearly shows the appearance of hydration products including C-S-H and ettringite together with gypsum. C-S-H gel exists in an amorphous phase, and it was difficult to detect in XRD pattern though it can be seen in the SEM images. The major crystalline minerals such as quartz and feldspar remained unchanged probably because of their relatively low reactivity. Quartz therefore acted as primarily as an inert material whereas the newly formed hydration products were responsible for binding the surrounding particles. The SEM observations are consistent with the XRD results and shown by progressive microstructural densification with increasing in cement dosage. At 5% cement (Figure 10c and Figure 11c), the formation of cementitious matrix was evident around soil particles together with localized needle like ettringite crystals bridging adjacent particles.

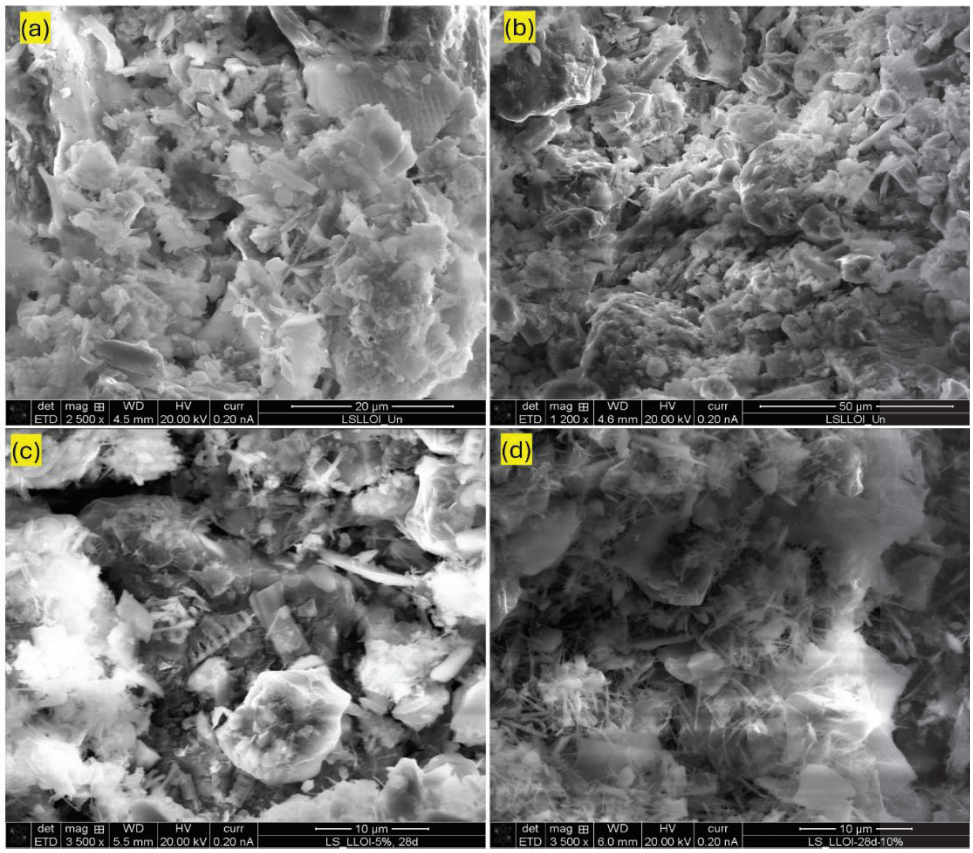

Figure 11: SEM micrographs of LS_LLOI soil: (a) untreated soil, (b) untreated soil at lower magnification, (c) stabilized with 5% cement and (d) stabilized with 10% cement after 28 days

*Figure 10 and Figure 11 appears in a manuscript (Paper C).

Although considerable pore space was still visible, the soil matrix became denser than that of untreated soil corresponding to increase in UCS observed after stabilization. Increasing the dosage to 10% (Figure 10d and Figure 11d) produced even more denser and continuous cemented matrix. Large quantities of C-S-H gel surrounded and interconnected particle bonding. The progressive reduction in pore space and increased continuity of the cementitious matrix explain the increase in compressive strength with increasing cement content, though it was not significant. The influence of cement dosage on microstructural development was more visible in LS_LLOI than in HS_HLOI. The LS_LLOI specimens exhibited a more homogeneous cementitious matrix with extensive gel and ettringite needle formation, filling pore spaces. The HS_HLOI specimens retained larger voids and isolated unreacted particles including pyrite minerals. This observation is consistent with the mechanical behaviour, where LS_LLOI developed higher UCS than HS_HLOI.

A direct microstructural comparison between unoxidized and oxidized soil could not be performed because the soil samples had already undergone oxidation prior to the SEM and XRD investigations. Therefore, microstructural data for the unoxidized sample is not available.

4.6 Statistical significance of oxidation

A factorial ANOVA was performed to quantify the effects of parameters on the UCS of HS_HLOI and LS_LLOI soils. The models showed a strong fit to the experimental data, with R^2>0,99 and non-significant lack of fit (p>0,05).

ANOVA result shows that cement dosage was the most influential factor for both soils (p<0,0001), followed by the mixing method. Oxidation was also statistically significant, but its effect was smaller, indicating that it modified cement performance rather than directly controlling strength development. Several interaction effects were significant, including oxidation-cement dosage, oxidation-mixing method, and cement dosage-mixing method. (For the detailed description, Table 4 and Figure 7 can be referred from Paper C).

4.7 Acidification behaviour

Figure 12 shows the changes in pH and EC during wetting-drying cycles for the representative soils from Robertsfors, Kalmar, and Kungsbacka, while the results for all soils are presented in Paper B. The results show that testing conditions strongly influenced acidification behaviour.

The Robertsfors and Umeå soils had already undergone oxidation before testing, as indicated by their low initial pH values (Table 4). Their pH therefore remained relatively stable during all tests, suggesting limited further acidification. However, the

initial changes in EC indicate the release and leaching of soluble ions and accumulated oxidation products. EC later stabilised as the concentration of leachable ions decreased.

The Kungsbacka soil maintained a high pH because of its low sulfur content and strong buffering capacity associated with its higher calcium content. Its pH remained stable under the MRM air-dry method, whereas oven-drying produced lower values because the elevated temperature accelerated oxidation. The Gothenburg soil showed similar behaviour, with stable pH under incubation and MRM air-dry conditions but faster acidification under oven-drying.

Whereas, the Kalmar, Uppsala, Uddevalla, Skellefteå, and Sunderbyn soils showed weaker buffering, likely because of their lower calcium contents. Under incubation and MRM air-dry conditions, their pH values partly recovered and moved towards similar levels over time. The MRM oven-dry method produced faster acidification and lower final pH values. This confirms that temperature and moisture conditions strongly influence the rate of acidification. Longer testing would be required to determine whether the methods eventually produce similar final pH values.

EC generally decreased during repeated leaching cycles, indicating the gradual removal of soluble ions. The decrease was more pronounced in oven-dried samples, suggesting that accelerated oxidation initially produced more soluble ions that were subsequently leached. Robertsfors and Umeå showed higher initial EC because oxidation products had already accumulated in these soils.

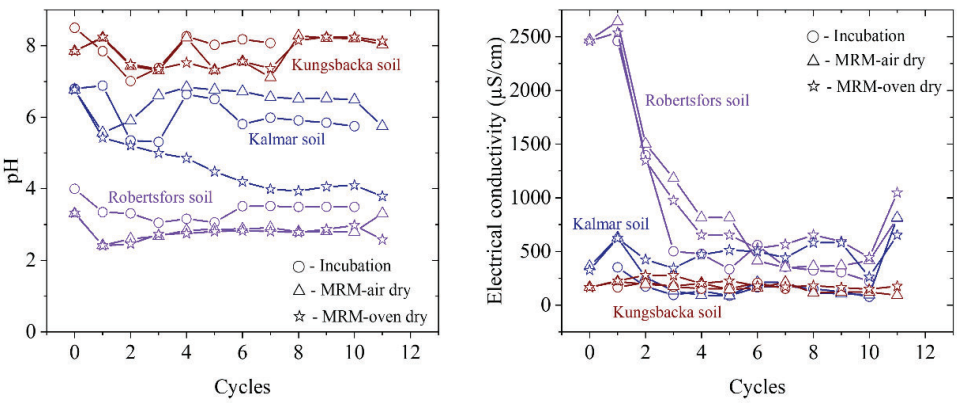

Figure 12: pH and EC vs leaching cycles for Kungsbacka, Kalmar and Robertsfors soil

*This figure appears in a manuscript which is under peer review (Paper B).

4.8 Engineering implications

The management of excavated sulfide soils should begin with material characterization before selecting a stabilization strategy. Existing soil classification systems are very rough with few categories, based on environmental parameters rather than geotechnical (Boman et al. 2023; Trafikverket 2023). Soils within the same classification can respond very differently to cement stabilization. Therefore, using a predefined binder dosage based only on soil classification or experience from another site may result in insufficient treatment or unnecessary binder consumption. The condition of the excavated material should first be assessed to determine whether stabilization is technically and economically suitable.

Water content should be evaluated at an early stage. For soils with very high natural water content (typically water content > 65%), simply increasing the cement dosage may not be efficient because hydration occurs under an unfavourable water to cement ratio for example HS_HLOI soil. If possible, drainage or controlled dewatering, or blending with drier material could be considered before increasing the binder dosage. When wet mixing is used, the water added through the cement slurry should also be included in the assessment, particularly for soils with water contents close to or above their liquid limit. The chemical properties of the soil should be considered together with its physical condition. Characterization should include sulfur content, organic matter, pH, and buffering capacity. However, any of these properties alone may not be enough to determine whether a soil is suitable for stabilization or not. For example, total sulfur content does not indicate how much acidity can be neutralized by the soil itself, nor does it account for the effects of water content and organic matter on binder performance. Soils with similar sulfur contents may therefore require different management strategies because of differences in buffering capacity and other properties.

Excavated material is also unlikely to have a uniform oxidation state. Soil excavated from below the groundwater table may remain largely unoxidized, while material exposed during excavation, transport, or stockpiling may become partially oxidized. These materials can then become mixed during handling. In such cases, management should not be based on the assumption that the entire excavated volume represents either unoxidized sulfide soil or oxidized sulfate soil. Representative sampling should therefore consider excavation depth and exposure conditions, especially when soil from different areas or stockpile layers will be blended before stabilization. The remaining oxidation potential of partially oxidized soil should also be considered. A low pH shows that oxidation and acid generation have occurred, but it does not confirm that all reactive sulfides have been oxidized. Residual sulfide minerals may generate further acidity during storage or stabilization. After three months of

oxidation, some pyrite remained which is visible in SEM, but because detailed sulfur-based chemical analysis was not performed (sulfur forms and concentration), it cannot be mentioned how much oxidation actually occurred. Traditional curing methods in analysing strength development after 7 and 28 days do not take into consideration the fact that sulfide oxidation is a microbiological process. Binder addition affects the microbiological population and their growth. The present work can therefore not predict the soil chemistry in years and decades from now. Current pH should therefore be treated as an indicator of the present chemical condition rather than a direct measure of the remaining acidification potential and future conditions. Additional geochemical analysis may be needed where this distinction is important.

The geographical origin of the soil should guide sampling and site investigation rather than directly determine how the soil is managed. The acidification study showed considerable differences among soils from different locations in Sweden. Acidification depended mainly on the balance between sulfide content and buffering minerals rather than on sulfur concentration or geographical origin alone. Experience from one location should therefore not be applied directly to another without material characterization. Different soil layers within the same project may also require separate assessment.

Once the soil condition has been established, binder dosage and mixing method can be selected according to the required engineering performance. Although binder dosage strongly influences strength, increasing it should not replace proper characterization. For soils with excessive water, high organic matter, and unfavourable chemical conditions, the cement dosage required may become uneconomical. Such soils may require alternative management or should be sent to the landfill disposal, while materials with more favourable properties can be prioritized for reuse.

The choice between dry and wet mixing should also reflect field conditions. Dry mixing produced higher strength in the laboratory, but this does not mean that it will always be preferable in the field. Wet mixing may provide better binder handling and distribution, whereas dry mixing avoids adding more water. The selected method should therefore balance constructability, mixing quality, initial soil water content, and the additional water introduced during mixing.

The results support a screening to management approach. Initial characterization can identify materials that may be suitable for stabilization and reuse and those likely to require more extensive treatment. This should be followed by geochemical and acidification assessments where oxidation is a concern. Stabilization trials can then

determine suitable binder dosages and mixing conditions. For heterogeneous excavated materials, testing should represent the material that will be stabilized.

4.9 Alternative binder – a preliminary investigation

As an initial step toward sustainable stabilization, a preliminary screening programme was conducted to evaluate alkali-activated slag (GGBS) as a potential alternative binder. The screening study investigated the influence of activator to binder ratio, Na_2SiO_3/NaOH ratio, NaOH molarity, and curing time while maintaining a constant slag dosage of 10% by dry soil weight. Portland cement and untreated soil were included as reference materials. The experimental program is presented in Table 7 below.

Table 7: Screening experimental program

Parameters	Levels investigated	Purpose
Binder	10% GGBS	Preliminary precursor evaluation
Activator/Binder	0,3 & 0,5	Effect of activator dosage
Na_2SiO_3/NaOH	1,0, 1,5 & 2,0	Effect of silicate present
NaOH molarity	8M, 10M & 12M	Effect of alkalinity
Curing time	7 & 28 days	Strength development with time
Reference mixes	Untreated soil & 10% cement	Comparison

The preliminary screening study (Table 8) showed that slag without activation did not improve the strength of the investigated sulfide soil, confirming that alkali activation is essential. Varying NaOH molarity between 8 and 12 M produced only minor changes in UCS, whereas increasing the activator to binder ratio resulted in good improvement. Despite activation, the achieved strengths remained considerably lower than those obtained using cement, indicating that slag alone is insufficient. Therefore, further optimization should focus on blended precursor systems rather than increasing alkali concentration.

Table 8: Summary of the screening results

Binder system	Average UCS (kPa), 28d	Interpretation
Untreated soil	9	Reference
Soil + 10% cement	1800	High strength
Soil + 10% slag	10	No improvement
Soil + 10% slag (activated)	18	Slight improvement

5 CONCLUSIONS

The present research investigated the stabilization of sulfide soils with the objective of improving the understanding of the physical and chemical processes governing their engineering behaviour. The research integrated laboratory investigations on strength development, oxidation and acidification, and microstructural characteristics to establish the basis for sustainable stabilization of sulfide soils. Based on the findings presented in this thesis, the following conclusions can be drawn:

- Water content was identified as one of the most influential parameters controlling the strength development of cement-stabilized sulfide soils. High water content reduced stabilization efficiency by increasing the effective water to cement ratio and limiting particle to particle contact during hydration.
- Organic matter and sulfur-bearing minerals reduced stabilization efficiency by modifying the chemical environment governing cement hydration. The combined influence of these parameters resulted in significantly lower strength development for the high sulfur-high organic content (HS_HLOI) soil compared with the low sulfur-low organic content (LS_LLOI) soil.
- Increasing cement dosage and curing duration improved strength development, while dry mixing produced higher UCS than wet mixing under laboratory conditions.
- Oxidation modified the physicochemical environment of sulfide soils and influenced stabilization performance. However, oxidation did not necessarily reduce strength development, indicating that stabilization behaviour is governed by multiple interacting mechanisms rather than pH alone.
- Microstructural characterization showed increasing amount of formation of C-S-H gel and ettringite with increasing cement dosage. SEM observations further revealed matrix densification, improved particle bonding and pore filling which is the reason behind increased UCS.
- Factorial ANOVA identified cement dosage as the main factor controlling UCS, followed by mixing method and curing duration. Oxidation had a smaller direct effect but significant interactions with cement dosage and mixing method, showing that its influence should be evaluated together with other stabilization parameters.
- Acidification behaviour was mainly controlled by sulfide content, buffering capacity, and oxidation conditions. The methods (Incubation, MRM and digital tool) generally agreed for clearly acidic and non-acidic soils but

differed for soils with intermediate properties. The digital tool provided rapid screening, while the MRM oven-dry method accelerated acidification. In contrast, the MRM air-dry and incubation methods allowed slower oxidation and more time for buffering reactions.

To summarize, strength development was strongly influenced by water content, cement dosage and mixing method. Individual effect of sulfur and organic matter content could not be fully separated because these properties varied simultaneously between the investigated soils. Oxidation also influenced stabilization performance, but its effect depended on soil characteristics and interaction with cement dosage and mixing conditions. Oxidation did not necessarily result in reduced strength. The acidification studies further showed that acidification behaviour cannot be predicted from sulfur content alone but depends on the balance between acid generating sulfides, buffering capacity and oxidation conditions. The preliminary alternative binder screening showed that the investigated alkali-activated GGBS system did not provide adequate improvement to replace Portland cement under the tested conditions. Consequently, this question remains open and will be addressed during the remaining doctoral research through further screening and development of suitable low-carbon binder systems.

6 FUTURE RESEARCH

The research presented in this licentiate thesis has improved the understanding of the physical and chemical mechanisms governing the stabilization of sulfide soils using Portland cement. The results showed that stabilization performance is controlled by the interaction between soil characteristics, oxidation, acidification, and binder hydration. While these findings establish a basis for the reuse of excavated sulfide soils, several research challenges remain before sustainable stabilization strategies can be fully implemented. The preliminary alternative-binder screening represents the transition from understanding conventional cement stabilization towards exploring more sustainable binder systems for sulfide soils. The initial screening showed that GGBS alone, under the investigated alkali-activation conditions, did not provide sufficient strength to replace Portland cement. Changes in activator composition produced limited improvements, indicating that further investigation of binder composition and stabilization chemistry is required rather than optimization of the tested system alone.

The next phase of the doctoral research will therefore explore alternative low-carbon binder systems, initially considering combinations of GGBS and fly ash together with suitable activation approaches. The selection and development of subsequent binder systems will be guided by the results of the screening experiments and their compatibility with the specific physicochemical characteristics of sulfide soils. Attention will be given to water content, organic matter, sulfur-related chemistry and acidification, which have been identified in the present research as important factors affecting stabilization. The remaining doctoral research will therefore progress from screening towards the identification and development of low-carbon binder systems. The objective is to reduce dependence on Portland cement while maintaining adequate engineering strength and promoting the beneficial reuse of excavated sulfide soils in geotechnical engineering applications.

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Department of Civil, Environmental and Natural Resources Engineering
Division of Mining and Geotechnical Engineering

ISSN 1402-1757
ISBN: 978-91-8142-089-0 (print)
ISBN: 978-91-8142-090-6 (pdf)

Luleå University of Technology 2026

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