

Factors affecting the strength of cement stabilized sulfide soil

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ABSTRACT: Sulfide soils (also called potential acid sulfate soil) typically characterized as clayey silt, usually exhibit very low undrained shear strength with natural water content exceeding their liquid limit. To make these soils suitable for various infrastructure projects, their strength needs to be enhanced. An experimental program was conducted to investigate the implications of several variables on the unconfined compressive strength of cement stabilized sulfide soil. The variables investigated are organic content, water content and sulfur content of the soil. In addition, the impact of cement's dry and wet blending conditions is being explored. Several sulfide soils with varying amounts of sulfur, water, and organic matter contents were collected from northern Sweden. Among those, two soil types were chosen based on water content, organic content and sulfur concentration, namely high sulfur high loss on ignition (HS_HLOI) and low sulfur low loss on ignition (LS_LLOI). The soils are blended with 5% and 10% cement and an unconfined compression test conducted to identify how aforementioned variables influence the strength of stabilized mixtures. The stress-strain behavior of HS_HLOI soils is ductile while brittle behavior is observed in LS_LLOI soils. Dry mixing of cement consistently produces higher strength than wet mixing, especially in LS_LLOI soils due to better cement-soil contact and hydration. The individual effect of sulfur content and organic content on strength remains unclear. However, higher organic content in HS_HLOI soils slows early strength gain, whereas LS_LLOI soils with less organic matter allow more efficient cementation. A similar set of tests is going on for oxidized soil to investigate the effect of oxidation on the strength having the hypothesis that oxidation might change the pH of the soil and the grain size which ultimately affect the strength.

KEYWORDS: Clayey silt, sulfide soil, cement stabilization, unconfined compressive strength, organic content.

1 INTRODUCTION

Sulfide soils, which are characterized as clayey silt, usually exhibit low undrained shear strength and natural water content exceeds their liquid limit. These soils remain stable as long as they are below the groundwater table and not exposed to air, in the environment they formed. They are classified as potential acid sulfate soils (PASS) because they tend to get acidic after being oxidized when exposed to air and lack sufficient alkalinity. Once oxidized, they are referred to as actual acid sulfate soils (ASS) described by (Ziagarib, 2025). From a geotechnical perspective, the poor characteristics of sulfide soil render them unsuitable for supporting structural foundations, leading to settlement issues and instability in construction projects. The fine particle size distribution, typically consisting of 70-80% silt content, combined with high organic matter content (5-15%), further complicates their use in geotechnical applications (Al-Jabban, 2019; Ziagarib, 2025). The management of excavated sulfide soils has become increasingly problematic as coastal development in Northern Sweden intensifies, generating substantial quantities of material that must be treated as hazardous waste. Current disposal practices require expensive landfill operations with specialized environmental controls to prevent oxidation and acid generation, making sulfide soil management both environmentally and economically challenging.

Soil stabilization is a technique used to enhance the engineering properties of soil through mechanical or chemical means, depending on the requirements. Key properties of soil that are targeted to improve are increasing strength, reducing compressibility, permeability, and settlement for the specific geotechnical application. This process turns problematic soils into dense and stable materials which can be used in various infrastructure projects including roads, embankments, noise barriers etc. The selection of appropriate stabilization methods depends on various factors including soil type, intended

application, environmental conditions, and economic considerations. For sulfide soils, chemical stabilization offers the additional benefit of potentially neutralizing acidification processes through the alkaline nature of cementitious binders (Rothhämel et al., 2022). Most common binders for soil stabilization include cement, lime, slag, and fly ash and numerous studies have explored the effectiveness of these additives, along with various industrial residues, in stabilizing sulfide soils. The stabilization process is governed by cement hydration reactions that produce calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H) gels, which bind soil particles together and fill void spaces (Makusa, 2013; Zhou et al., 2024). These reactions begin immediately upon mixing cement with water, creating a progressive strengthening process that continues over extended curing periods (Wang et al., 2022; Luo et al., 2024). Stabilization with cement reduces the volume change and improves strength but such treatment is unsuitable for soils with a high plasticity index by increasing the difficulty with mixing. Soil treated with lime loses cohesion between the soil grains and lime because of wetting and drying cycles, thereby increasing the volume of the soil and makes them limited to areas which are not subjected to freezing and thawing (Firoozi et al., 2017). The dosage of cement that can be added to the soil is approximately 5% in sandy soils and 15% in well graded soils which are determined experimentally by compressive strength test and this quantity must be increased to compensate for the less effectiveness of field mixing compared to laboratory mixing conditions (Archibong et al., 2020). The formation of cementitious bonds significantly improves unconfined compressive strength, with increases of 5-10 times the original soil strength commonly reported (Zhou et al., 2024). However, cement stabilization of sulfide soils presents unique challenges due to the complex chemical environment created by sulfur compounds, organic matter, and high water content (Ziagarib, 2025). The presence of sulfides can

interfere with normal cement hydration processes, potentially leading to delayed strength development or reduced long term durability (Khadka et al., 2020).

The effectiveness of cement stabilization in sulfide soils is influenced by multiple interdependent factors that must be carefully considered. The primary factors affecting cement soil stabilization include soil type, quality of cement used and its dosage, water quantity, and sufficient mixing efficiency (Al-Jabban et al., 2017; Åhnberg et al., 2003). Understanding these factors is critical for optimizing stabilization outcomes and ensuring predictable performance in field applications. The basic properties of soil such as particle size distribution, plasticity index and chemical composition significantly impact stabilization. The presence of clay minerals affects cement hydration through ion exchange processes, while organic matter can interfere with cement setting through chelation mechanisms (Clare et al., 1954; Ge et al., 2020). Additionally, the low initial pH of soil creates acidic conditions that may retard cement hydration and require higher binder dosages for neutralization (Ziagarib, 2025; Rothhämel et al., 2022).

Water content is one of the most critical parameters influencing cement stabilization effectiveness in sulfide soils (Pham et al., 2021; Wang et al., 2022). The relationship between water content and strength development follows a bell-shaped curve, where optimal water content balances adequate cement hydration with minimal dilution effects. Excessive water content dilutes the cement concentration, reduces effective contact between cement and soil particles, and increases porosity, ultimately leading to reduced strength (Luo et al., 2024). Research demonstrates that sulfide soils exhibit distinct optimal water content ranges depending on their composition and organic matter content (Ziagarib et al., 2024). High-sulfur, high-organic soils typically require water contents of 50-55% for optimal strength development, while low-sulfur, low-organic soils achieve maximum performance at 40-45% water content (Ziagarib, 2025). Variations from these optimal ranges result in significant reductions due to either incomplete hydration or excessive dilution (Luo et al., 2024). These studies indicate that proper controls on the water content can improve strength development by 2-3 times than uncontrolled conditions which emphasizes the importance of water content in cement-soil stabilization.

The presence of organic matter in soil significantly influences the effectiveness of cement stabilization based on molecular weight and concentration (Li et al., 2018). Organic matters act as cement retarders by adsorbing calcium ions formed during hydration, thereby prolonging the induction period and delaying strength development (Clare et al., 1954; Ge et al., 2020). The presence of organic matter in sulfide soils (typically 5-15% loss on ignition) creates complex chemical environments that require careful consideration in stabilization design (Ziagarib, 2025) and these are predominant in case of high organic content soils.

In cement stabilization of sulfide soils, the presence of sulfur content also has an important impact with effects varying depending on concentration and chemical form (Sherwood, 1962). Sulfur compounds, primarily in the form of pyrite and other metal sulfides, can undergo oxidation during mixing and curing processes, potentially generating sulfuric acid that interferes with cement hydration. However, moderate sulfate concentrations can also be beneficial in strength development through the formation of primary ettringite and monosulfate hydrates that fill pores and densify the cement-soil matrix but optimal sulfate content varies with soil type and cement dosage (Talluri et al., 2020; Seco et al., 2022). Soils with high sulfur content should be stabilized carefully to prevent the formation

of secondary ettringite, which can significantly reduce the strength of the soil-cement matrix.

The method of cement incorporation significantly influences stabilization effectiveness, with dry and wet mixing approaches offering distinct advantages and limitations. Dry mixing involves the direct application of cement powder to soil which relies on in-situ moisture for hydration activation. This method creates localized zones of high cement concentration that can enhance strength development through concentrated particle to particle contact. Wet mixing uses a pre-mixed cement slurry, ensuring more even cement distribution but sometimes causing dilution. It typically results in 15-40% higher unconfined compressive strength than dry mixing because of better dispersion and hydration (Ericsson et al., 2005; Sebesta et al., 2009; Pakbaz et al., 2015). The research mentioned above was for stabilization in situ which might not be the same in case of laboratory mixing. However, the best mixing method depends on soil type and conditions. While wet mixing often outperforms dry mixing for cement-soil stabilization, dry mixing may be preferable in high water content sulfide soils to avoid excess moisture which exceeds the optimum water content (Ziagarib, 2025).

Although extensive research on cement stabilization of various soil types are available, significant knowledge gaps exist regarding the specific effects of mixing methods on sulfide soil stabilization performance (Ziagarib et al., 2024). Current literature lacks comprehensive understanding of how dry and wet cement mixing interacts with the varied chemical and physical characteristics of sulfide soils, particularly in relation to different organic matter, sulfur content, and water content (Ziagarib et al., 2023). The combined effect of sulfur compound, organic matter and cement hydration is very complex and still poorly understood. The primary objective of this research is to advance the geotechnical performance of cement stabilized sulfide soils by identifying the key factors influencing strength development. The study focuses on evaluating the effects of sulfur and organic matter contents on the effectiveness of cement stabilization under both dry and wet mixing condition of cement.

2 MATERIALS AND METHODS

2.1 *Materials*

Several sulfide soil samples with varying sulfur content, water content, and organic matter concentrations were collected from multiple locations across northern Sweden. The soil samples were systematically categorized into distinct groups based on their organic content, water content, and sulfur concentration parameters. Two representative groups were selected for detailed investigation: high sulfur, high loss on ignition (HS_HLOI) soil and low sulfur, low loss on ignition (LS_LLOI) soil. These soils were classified as clayey silt according to ISO: 17892-4 standard for particle size distribution analysis. The particle size distribution curves are displayed in the Figure 1 given below. The gravel content in both soil samples was negligible and these coarse particles were systematically removed during the sieving process to ensure a homogeneous soil mixture for subsequent sample preparation and testing phases. This homogenization procedure is critical for maintaining consistency in geotechnical and geochemical analyses of sulfide soils.

Table 1 below presents comprehensive basic soil properties, including quantitative measurements of sulfur, calcium, and iron content for both soil categories. The chemical characterization of the soil samples was conducted by ALS Scandinavia, located in Luleå, Sweden, utilizing standardized analytical procedures. The chemical analysis emphasized

precise determination of sulfur content, given its critical role in sulfide soil behavior, while also quantifying calcium and iron concentrations due to their significant influence on soil oxidation processes and mineral precipitation reactions. The sulfide soil exhibited a low pH due to partial oxidation during storage, although full oxidation had not yet taken place.

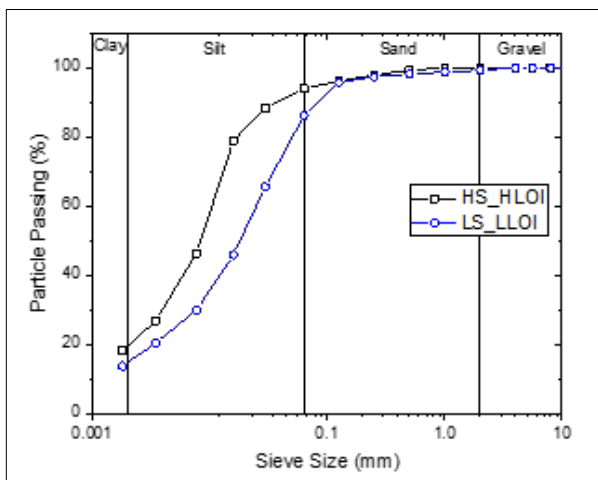


Figure 1. Particle size distribution graph

Table 1. Characterization of soil and presence of other elements

| Parameter | Unit | HS_HLOI | LS_LLOI |
|------------------------|-------------------|---------|---------|
| Ca, Calcium | mg/kg of dry soil | 5560 | 3540 |
| Fe, Iron | mg/kg of dry soil | 33700 | 14100 |
| S, Sulfur | mg/kg of dry soil | 18000 | 4580 |
| pH at 20°C | | 3.1 | 3.8 |
| Water content at 105°C | % | 98 | 60 |
| Organic content | % | 9 | 5 |
| Sand | % | 6 | 13 |
| Silt | % | 76 | 73 |
| Clay | % | 18 | 14 |

Bygg cement used as a hydraulic binder for enhancing geotechnical properties of soils through chemical stabilization processes. This Portland limestone cement, classified as CEM II/A-LL 42.5 R according to EN 197-1 standards, is manufactured by Heidelberg Materials Cement Sverige AB in Sweden. The cement composition comprises 80–94% clinker as the primary hydraulic component, 6–20% low organic carbon limestone that enhances workability and durability and calcium sulfate added as a setting regulator, along with 0-5% minor additional constituents.

2.2 Method

Following the collection of soil and binder, initial characterization was performed as detailed in the previous section. The procedures for mixing, sample preparation, and testing are divided into three sections as follows,

2.2.1 Binder treatment:

Prior to cement addition, coarse particles were removed from the excavated sulfide soil to ensure a homogeneous mixture. Any residual gravel fragments (an artifact of excavation) were screened out during this preprocessing step by sieving. The cement binder (5% and 10% by dry soil weight) was then introduced into the soil and blended using laboratory mixing apparatus (see Figure 2). Binder quantities were calculated

based on the dry mass of soil. Two mixing methods were implemented; (1) Wet mixing, in which cement was delivered as a slurry and (2) Dry mixing, in which powdered cement was incorporated directly into the soil matrix and blended for 10 minutes.

2.2.2 Sample preparation and curing:

Immediately following homogenous blending of the soil with 5% and 10% cement binder by dry weight, unconfined compressive strength (UCS) specimens were prepared using “tapping method” to ensure consistent density and structural integrity adapted from (Al-Jabban et al., 2020). A standard cylindrical mould (5 cm diameter, 10 cm height) was filled in five successive layers and each layer received a controlled 30 taps against a polished marble surface, promoting uniform particle rearrangement and achieving a target dry density of 1.50-1.65 g/cm³ across all specimens. Upon completion of the final lift, both the top and bottom of the mould were sealed with rubber caps to eliminate moisture exchange with the environment. Specimens were then vertically positioned in a sealed container containing a shallow depth of water submerging the lower 2-3 cm of each mould to maintain constant humidity and prevent desiccation. This curing regime was maintained at ambient laboratory conditions for two specified durations, 7 days and 28 days, to capture both early-age and long-term strength development. At each curing interval, moulds were carefully dismantled and the UCS test was conducted in accordance with standardized loading rates, thereby quantifying the progressive gain in compressive strength imparted by the cement stabilization process.



Figure 2. Mixing equipment and sampling tube

2.2.3 Sample testing:

At the prescribed curing intervals, specimens were retrieved from closed containers, extracted from the moulds, and prepared for unconfined compressive strength (UCS) testing. Each UCS test was conducted under a constant axial strain rate of 1 mm/min, during which axial load and axial deformation were continuously recorded. Failure was defined by whichever occurred first, the peak stress or a 20% axial strain threshold. In the case of HS_HLOI specimens, enhanced post-peak cohesion occasionally produced additional load increases beyond the initial peak, making the 20% strain limit the controlling failure criteria. Conversely, LS_LLOI specimens consistently exhibited a clear peak load followed by a loss in strength. The recorded data were processed and analyzed as described in the subsequent section.

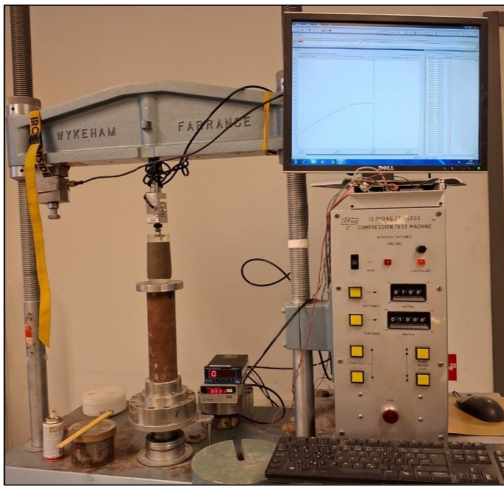


Figure 3. UCS testing machine

3 RESULTS AND DISCUSSION

A series of unconfined compressive strength (UCS) tests showed a clear difference in the stress-strain behavior which is directly related to their composition. HS_HLOI soils showed ductile failure, meaning they could still carry load after reaching peak stress. In contrast, LS_LLOI soils showed a brittle failure which means they reached higher peak strengths but then lost strength quickly after the peak with little deformation afterward.

3.1 Dry and wet mixing of cement:

Referring to the Figure 4, for HS_HLOI soil, the UCS at 5% cement content revealed minimal variation between the sample tested at 7 and 28 days, irrespective of whether cement was incorporated through dry or wet mixing methods. At the increased binder dosage of 10% cement, dry mixing consistently yielded UCS values approximately 5 kPa higher than wet mixing at both 7-day and 28-day curing intervals which was not significant. On other hand, LS_LLOI soils exhibited a similar pattern at 5% cement content, with limited strength development between 7 and 28 days. However, dry mixing produced superior UCS values compared to wet mixing, exceeding by 6 kPa at 7 days and 10 kPa at 28 days. This differential became substantially more pronounced at 10% cement content, where dry mixing achieved UCS values surpassing wet mixing specimens by 80 kPa at 7 days and 273 kPa at 28 days.

These results are from laboratory tests where cement and soil were mixed more uniformly and efficiently compared to field mixing. Achieving the same level of uniformity in the field is challenging due to limitations in mixing equipment and site conditions. The better performance of dry mixing can be attributed to several fundamental cement hydration mechanisms and cement-soil interaction dynamics (Makusa, 2013; Pakbaz et al., 2015).

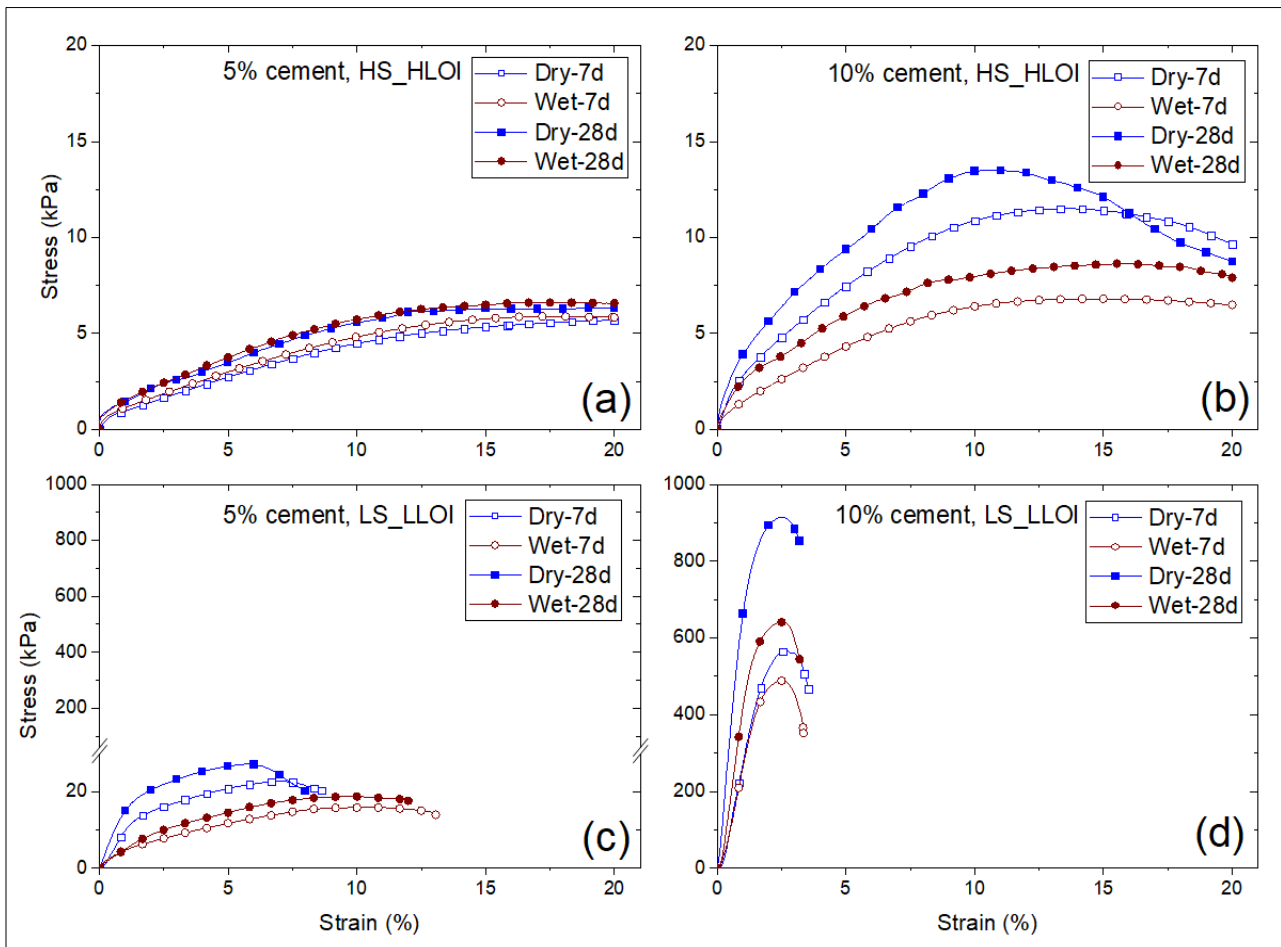


Figure 4. Stress-strain curve (a) & (b) HS_HLOI 5% & 10% cement respectively; (c) & (d) LS_LLOI 5% & 10% cement

In dry mixing, powdered cement particles establish direct contact with soil particles, creating localized zones of high cement concentration that facilitate more efficient calcium ion exchange processes (Reiterman et al., 2022). This concentrated interaction is particularly effective in soils with lower natural water content, in this case LS_LLOI, where the 60% water content provides sufficient moisture for hydration without excessive dilution effects compared to HS_HLOI having 98% water content (Ziagharib, 2025). Though wet mixing provides more uniform cement dispersion throughout the soil matrix, it introduces several limitations that become more pronounced in high water content sulfide soils. The preparation of cement slurry prior to soil incorporation results in initial hydration of cement particles, potentially reducing the reactive surface area available for subsequent soil-cement interactions (Sebesta et al., 2009). This pre-hydration effect is particularly detrimental when dealing with soils containing sulfur compounds that can interfere with normal cement setting processes. The dilution effect inherent in wet mixing becomes critical in sulfide soil stabilization. When cement is dispersed as a slurry, the effective water-cement ratio increases and research indicates that lower water-cement ratios typically result in higher strength, which can be the reason behind the reduced performance observed in wet mixed samples. (Sherwood, 1962; Neto et al., 2021).

3.2 Organic matter and sulfur concentrations:

The sulfur content in both soils (18000 mg/kg in HS_HLOI and 4580 mg/kg in LS_LLOI) creates complex chemical environments that differentially affect dry and wet mixing approaches (Li et al., 2015; Puppala et al., 2004). Sulfate ions can react with cement hydration products to form ettringite and monosulfate compounds, which can either enhance or degrade performance depending on concentration and timing (Li et al., 2015; Li et al., 2025). In dry mixing scenarios, the localized high cement concentrations can more effectively neutralize acidic conditions (pH 3.1-3.8) typical of sulfate soils through rapid alkalinity development (Eko et al., 2001; Neto et al., 2021). This pH buffering capacity is crucial for maintaining optimal cement hydration kinetics in the presence of organic acids that typically retard cement setting (Clare et al., 1954; Ju et al., 2022; Young et al., 1976). The LOI (9% for HS_HLOI and 5% for LS_LLOI) reflects varying organic matter concentrations that significantly influence cement stabilization mechanisms through calcium ion chelation (Hoogsteen et al., 2015; Ge et al., 2020; Shao et al., 2023).

3.3 Water content:

Figure 5 presents the stress-strain curve of cement stabilized sulfide soil (dry mixing of cement) tested after 7 days and 28 days of curing under varying water contents. For HS_HLOI soils, UCS peaked at approximately 10 kPa and 65 kPa for 7-day specimens with 70% and 50% water content, respectively. After 28 days, maximum strength reached 70 kPa at water content of 50%. However, LS_LLOI soils achieved substantially higher strengths in 7 days, peak UCS values of 360 kPa and 870 kPa occurred at 60% and 45% water content, respectively. By 28 days, strength peaked at 570 kPa with 60% water content.

This supplementary test was conducted to evaluate the effect of varying water content on strength development. For HS_HLOI soil, specimens tested at water content of 98% as shown in Figure 4 did not exceed 15 kPa in UCS strength, even with 10% cement and 28 days of curing. However, when the water content was reduced to 50%, the UCS significantly increased, reaching 65 kPa at 7 days of curing with 10% cement which shows the important effect of water content in soil stabilization using cement.

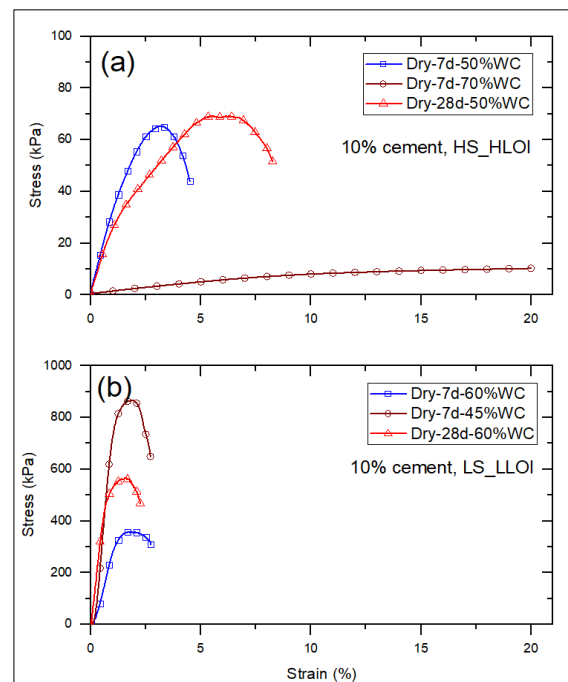


Figure 5. Stress-strain curve (a) HS_HLOI & (b) LS_LLOI

4 CONCLUSIONS

The testing of cement-stabilized sulfide soils prepared in the laboratory has revealed some interesting insights into how the organic matter, sulfur content and water content of the soils behaves under different conditions.

Stress-strain relation: HS_HLOI soil tends to fail in a more gradual and ductile manner, i.e. it can still carry some load even after reaching the peak strength while LS_LLOI soil fails in a sudden and brittle manner, i.e. it reaches higher peak strength but then lose strength rapidly afterward.

Dry and wet mixing of cement: The UCS test results consistently show that dry mixing works better than wet mixing for both soil types. The difference becomes more obvious with increased cement dosage and time of curing. For HS_HLOI soils, dry mixing gives about 5 kPa higher strength than wet mixing when using 10% cement. But a significant difference was observed with LS_LLOI soils, for which dry mixing samples strength was 80 kPa higher after 7 days and 273 kPa higher after 28 days. When cement powder comes into direct contact with soil particles, it creates small pockets of high cement concentration. This helps the calcium ions move around more efficiently with the right amount of water for the cement to work without getting too diluted which can be the reason why dry mixing gives better results in laboratory conditions. The studies on dry and wet mixing of cement conducted in the field have generally found wet mixing of cement to be more effective than dry mixing. However, in the present laboratory based investigation, dry mixing demonstrated superior strength improvement compared to wet mixing. These contrasting results highlight the need for further research to clearly determine the most effective mixing method for stabilizing sulfide soils.

The role of organic matter and sulfur content: The amount of organic matter in these soils makes a big difference. HS_HLOI soils have more organic content (9% LOI compared to 5% in LS_LLOI), which can slow down early strength development by interfering with the cement-soil chemical reaction. However, in LS_LLOI soil having less organic matter, allows the cement to work more efficiently from the start towards strength development comparatively. At this point it is

difficult to make any conclusion about the individual effect of organic content or sulfur concentrations on the strength of cement stabilized sulfide soil.

Future research will focus on microstructural analysis (SEM and XRD) to provide detailed insights into the hydration mechanisms occurring within these samples.

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