Sustainable Incorporation of Plaster of Paris Waste to Check the Effect of Freezing and Thawing on Soils of Different Regions/Environments

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I Dedicate this Dissertation

To

My Beloved Parents, Honorable Supervisor and friend who gave me a lot of Support and Encouragement

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I would like to begin by expressing my gratitude to the Almighty Allah for His blessings and guidancethroughout my academic journey.

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Sincerely,

Engr. Muhammad Yaseen Butt

Abstract

In several earlier investigations into soil stabilization, the effects of calcium-based compounds on both coarse- and fine-grained soils were analyzed and explored. However, research has yet to be carried out on how soils changed with calcium-based products or Plaster of Paris waste (POPW) react to freeze-thaw cycles. This study examined the effects of POPW addition on the strength and F-T behavior of three soils (A, B, and C) with varied plasticity's. These tests aimed to identify how the addition of POPW affected these properties under F-T cycles. To monitor the strength performance, unconfined compressive strength tests were carried out. To get further insight into the durability of the treated samples, the mass losses that occurred after being subjected to F-T cycles were measured. The samples that had been treated and those that had been left untreated were compared after being compacted and cured for 28 days at the optimal moisture content. Following the curing process, the samples were subjected to compression testing in the F-T chamber at 1, 3, 5, 7, and 11 cycles. POPW content in the treated samples varied from 3% in soil A to 5% in soil B to 1% in soil C, with each value reported as a percentage of the total dry soil weight. POPW treatment increased the compressive strength and the F-T durability of the samples. During the curing process, the samples treated with POPW were increasingly stronger, and the mass loss that occurred when the samples were subjected to F-T cycles was far less severe in the treated samples than in the control samples. According to the results of the F-T tests, the samples that started with the greatest strength ratings ended up losing the least strength over time. Using POPW in place of industrial waste in soil stabilization attempts was discovered to be beneficial financially.

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List of Abbreviations

F-T:	Freeze Thaw
POPW:	Plaster of Paris Waste
UCS:	Unconfined Compressive Strength
SEM:	Scanning Electron Microscopy
ASTM:	American Society of testing Materials
PI:	Plasticity Index
MDD:	Maximum Dry Density
OMC:	Optimum Moisture Content
USCS:	Unified Soil Classification System

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Chapter 1

Introduction

1.1 Background

Soil is a fundamental part of civil engineering, as it is the material which supports the superstructures, such as buildings, roads, and bridges. As the population grows, so does the demand for suitable land for construction (Holtz, Kovacs, and Sheahan 1981). Unfortunately, urbanization has led to a decrease in this land, causing a need for the use of problematic soils for construction purposes. Clayey soils, for example, are prone to volumetric changes when exposed to water, resulting in differential settling, cracking of foundations, loss of strength, slope failures, and breaking up of sewer lines. Studies have shown that the damages caused by these problematic soils can cost up to twice as much as those caused by natural hazards (L. Li et al. 2015).

Soil quality improvement is an important part of geotechnical engineering and an effective way to recycle soils. Stabilization is a frequently employed technique for improving the quality of these soils. The process involves a complex series of steps and utilizes a variety of techniques (Kalhor et al. 2019). Different materials, such as calcium-based materials, can be used to stabilize clayey soils and enhance their physical and mechanical properties. Other techniques and practices, like grouting and compaction, also be used to improves soil quality. The effectiveness of soil stabilization can be influenced by various factors. These include soil type, the type of admixture or stabilizer that is used, the amount of admixture or stabilizer that is applied, and the environment in which the soil is being stabilized. In some cases, it may be necessary to use a combination of techniques in order to achieve the desired results (L. Li et al. 2015). Soil quality improvement is not only beneficial from a technical perspective, but it is also beneficial from an ecological and financial viewpoint. Reusing in-situ soils for construction projects can save money and reduce the amount of waste that is sent to landfills. It can also reduce the need for new construction materials, which can have negative environmental impacts (Larson and Pierce 1994).

Calcium-based materials, such as calcium hydroxide and lime, can improve soil structure by hardening the connections between soil particles. When these materials are combined with clay, between them the cationic exchange occurs, and the clay particles and calcium ions, which results in flocculation. The timeframe of this process exhibits considerable variation, ranging from a few months to several years. The duration is impacted by various elements, including the hydration and chemical decomposition processes of the aluminates and silicates which found in the clay (NLA 2004). The existing literature has extensively examined the effects of (F-T) freeze and thaw cycles on the clay which is treated with calcium-based substances. However, there is a lack of focus on the materials durability. The behavior of clay materials during freeze and thaw cycles is influenced by various factors, including the type and mineralogy of clay mineral, the saturation level of a clay, and the amplitude and the time of the (F-T) freeze and thaw cycles (Svensson and Hansen 2010).

Numerous investigations have been undertaken to examine the effects like mechanically and physically of freeze-thaw cycles on soil. The application of lime treatment is a frequently utilized approach to alleviate the results and impact of F-T cycles. The aforementioned treatment has been documented which tells the improvement in the mechanical properties of the soil (Nguyen et al. 2019). Furthermore, comprehensive research has provided evidence of the effectiveness of fly ash in reducing the detrimental impacts of frost on soil (Andavan and Pagadala 2020). The unconfined compression strength (UCS) of expansive soil which was treated with cement exhibits an increase when freeze-thaw cycles applied to it(Lu et al. 2020). The lime stabilized kaolinite clay samples that shown greater levels of UCS were observed to be the most resilient samples during F-T testing, as they displayed a lower degree of strength deterioration (Monitoring 2014). The strength of soil contains cement lime exhibited a drop in response to an increase in F-T cycles (He, Wang, and Gu 2021). The shear strength and stiffness was decreases of Illite clay when it was exposed to the F-T cycles (Steiner, Vardon, and Broere 2018). The cohesion decreases and uniaxial compressive strength also decreases of soil belonging to Qinghai-Tibet Plateau when freeze and thaw applied on it (Mt et al. 2015). There was no effect on aggregate stability of northern soils by rate of freezing. On the disruption of aggregate of soils, the effect of freezing is less as compare to effect of rain drop impact energy (Mostaghimi et al. 1988).

The intent and the aim of this research and study is to investigate how soils located in snowy areas respond to F-T cycles when it comes to their strength characteristics. To mitigate the issues of settlement, volume change, mass loss and strength loss that have been experienced by Pakistan, these soils are stabilized using Plaster of Paris waste material (POPW), which is a calcium-based material and then check the variation of strength of these soils using F-T cycles.

1.2 Problem Statement

Soil engineering properties, such as permeability, strength and compressibility, are often detrimentally affect or by the F-T cycle in regions where seasonal freezing and thawing occurs. This cycle has an impact on a variety of engineering applications, such as roads, railroads, pipelines, and buildings, and can render them unsafe or ineffective.

Extensive studies have been conducted on utilizing industrial and waste materials for treating soils subjected to F-T cycles i.e. lime (Abdulrahman Aldaood, Bouasker, and Al-Mukhtar 2014), silica fume (Kalkan 2009), nano silica (Kalhor et al. 2019), coal ash (Shibi and Kamei 2014), cement (Lu et al. 2020), lead (Zhongping et al. 2021), nano clay (Khazaleh, Karumanchi, and Bellum 2023), polypropylene fiber (Khazaleh, Karumanchi, and Bellum 2023) etc. Previous additives used for the treatment of soil under F-T cycles have several problems. Firstly, they are often expensive and not readily available, which limits their practicality for widespread use (Lu et al. 2020). Secondly, some of these additives are environmentally harmful and can cause pollution if not handled correctly (Kalkan 2009). Thirdly, some of these additives have limited effectiveness and do not provide long-term solutions. Finally, the use of these additives may not be sustainable in the long run, as their availability may be limited due to the depletion of natural resources required to produce them (Aryal and Kolay 2020).

The problems highlight in the literature need for research into sustainable and cost-effective solutions for incorporating waste materials into soils to mitigate the adverse and poor effects of freezing and thawing on soil properties. Calcium-based materials are the most effective for treating soil under F-T cycles, and the research aims to investigate the use of a calcium-based waste material, specifically the waste material from Plaster of Paris (POPW), for stabilizing soils in snow-amid regions. The use of such waste material is seen as economically viable and eco-friendly, as it does not release harmful gases during its manufacturing process and only releases water in the form of heat. This approach offers a potential solution to the problem of using expensive and environmentally harmful additives for soil stabilization under F-T cycles. This research aims to evaluate and check the positive and negative effects of this approach in terms of improving soil properties and providing long-term stabilization.

1.3 Aims and Objectives of the Study

This study aimed is to investigate the sustainable use of POPW to mitigate the effects of freezing and thawing on soils in various regions/environments. The study will explore the potential of waste materials as a viable solution for sustainable soil stabilization.

The objectives of this study are as follows:

- To investigate the mechanical behavior of subsequent soils under F-T cycles.
- To analyze the impact of POPW on the index and mechanical characteristics of various soils under F-T cycles.
- To scrutinize the alterations in the microstructure of various soils treated with POPW under F-T cycles via scanning electron microscopy (SEM) tests.

1.4 Scope of work

- To investigate the behavior of snow amid soils from the Ayubia, Skardu and Kashmir, Pakistan for better management of snow related challenges and infrastructure planning.
- To determine the physical characteristics of the soils, including their Atterberg limits and soil classification, to understand the basic properties of soil and its behavior.
- To analyze the microstructure of soil using scanning electron microscopy (SEM) testing.
- Following this, waste material (POPW) will be incorporated into the soils at optimal ratios to investigate their potential for sustainable soil stabilization. This will offer economical and eco-friendly material for construction, mitigating the impact on environment.
- To check the behavior of freeze and thaw, treated samples would be placed in refrigerator for F-T cycles ensuring long term stability of infrastructures.
- After that, UCS test would be performed again to check the strength of soil providing insights into stabilization techniques.

1.5 Research Layout

- Chapter 1: Introduction
- Chapter 2: Literature Review
- Chapter 3: Methodology
- Chapter 4: Results and Discussions

- Chapter 5: Conclusions and Recommendations

Chapter 2

Literature Review

2.1 Introduction

This chapter provides a thorough analysis of the literature that is relevant to the main objectives discussed in Chapter 1 of this study. This paper offers a thorough examination of Clayey soils, encompassing a detailed analysis of Clay mineralogy. Furthermore, the text provides an overview of the freezing and thawing phenomenon of soil, along with an analysis of the different factors that impact this process on soil. Furthermore, it illuminates the challenges related with freezing and thawing on soil in Pakistan and globally. Furthermore, it explains Previous research on waste material incorporation for soil stabilization under freezing and thawing conditions. Furthermore, it describes the gap in literature review related with treatment of soil under freeze and thaw process with waste materials and at last, the summary of this chapter is explained.

2.2 Clayey Soils

Clay is an assemblage of tiny and submicroscopic particles produced as a byproduct of the weathering and breakdown of rock materials by chemical processes (Velde 2013). Clay is predominantly made up of fine-grained components, a naturally occurring material. It is typically soft when it has the necessary amount of water but will become more rigid after drying it (Guggenheim et al. 1995). Clay is a term that connects to the study of particle size and minerology. Clay particles may display various characteristics, including a net negative charge, plasticity, and a size less than 0.002 millimeters in diameter (Firoozi and Baghini 2016). Because of their extremely minute dimensions, clay minerals are not affected by the gravitational forces that act on larger objects; rather, the electrostatic forces that result from the charged surfaces of clay particles are the ones that have the most influence (Velde 2013).

2.3 Clay Minerology

Clay particles are almost entirely made up of minerals that are collectively referred to as clay minerals. Clay minerals that give clay become more brittle when they dry up (Guggenheim et al. 1995). The structure of clay is the arrangement of the various particles that come together to make a clay crystal. Ions make molecules by bonding to create molecules, which then connect with other molecules to form a structure similar to a sheet. After that, these sheets are stacked one over the other to create layers. Clay minerals are made up of silicon tetrahedrons and aluminum octahedrons, which are the two essential structural components that make them up (Firoozi, Firoozi, and Baghini 2016). In the case of the tetrahedral unit, known as the silicon tetrahedron, a silicon ion is surrounded by four oxygen ions. On the other hand, in the octahedral unit, known as the aluminum octahedron, aluminum, magnesium, iron, or other ions are surrounded by six oxygen or hydroxyl ions. Figures 2.1 and 2.2 present a diagrammatic representation of the fundamental units of the tetrahedron and the octahedron.

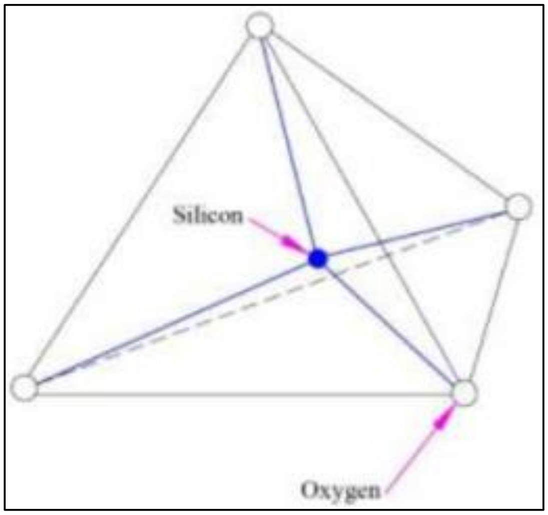


Figure 2.1 Unit of Tetrahedral mineral

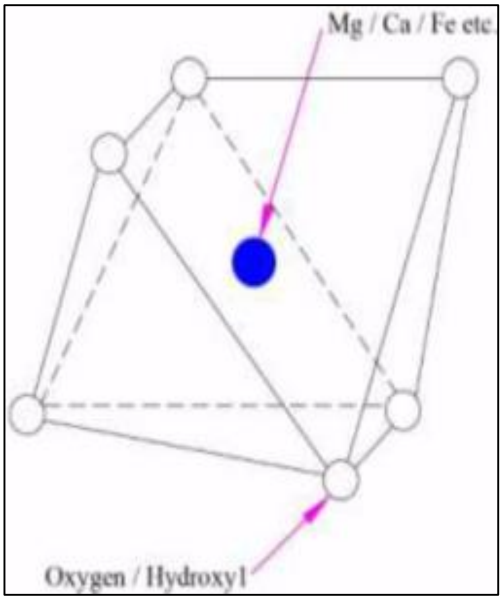


Figure 2.2 Unit of Octahedral Mineral

Clay minerals are composed of fundamental structural components that, upon interconnection, give rise to silica tetrahedral and aluminum octahedral sheets. The sheets are interconnected in two distinct manners, resulting in the formation of a layered structure which referred as a single 1:1-layer structure and a layer of 2:1- structure (Al Ani, T., & Sarapaa 2008). The structure of the 1:1-layer silicate is distinguished by the substitution of a hydroxyl ion from the octahedral sheet with the apical oxygen of the tetrahedral sheet. The objective of this procedure is to generate the 1:1 layered arrangement of clay minerals, such as kaolinite.

The formation of the 2:1-layer structure occurs by the linkage of an octahedral sheet with two tetrahedral sheets. This linkage leads to the substitution of hydroxyl groups in the octahedral sheet with apical oxygen ions originating from the tetrahedral sheet. The occurrence of a clay mineral possessing a 2:1-layer structure, such as Illite, takes place. In clay the depiction arrangement of the octahedral and tetrahedral sheets minerals can be observed in Figures 2.3 and 2.4. The provided figures depict the structural composition of the 1:1-layer and 2:1-layer arrangements.

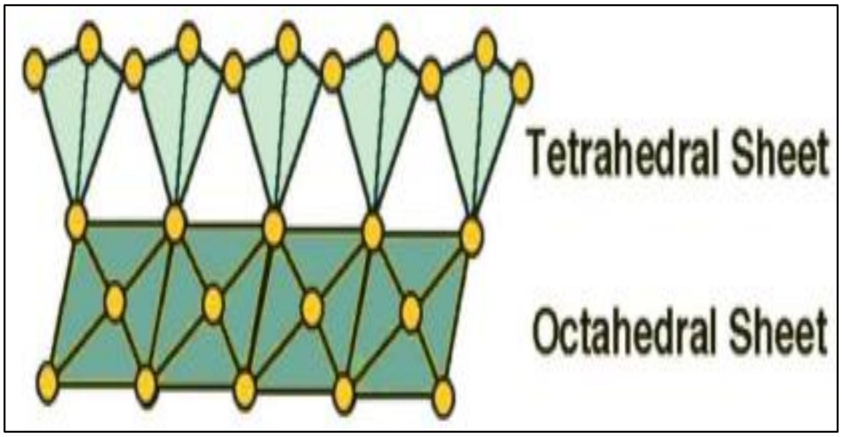


Figure 2.3 Structure of 1:1- layer of clay mineral (Kaolinite)

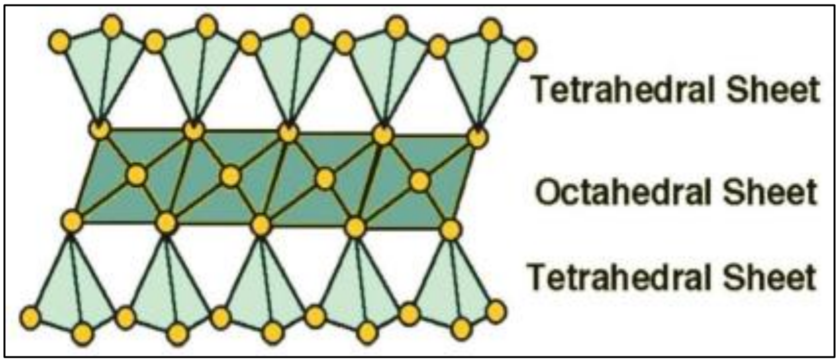


Figure 2.4 Structure of 2:1- layer of clay mineral (Illite)

Clay minerals can take on a variety of distinct structures because diverse combinations of silica tetrahedron and aluminum octahedron sheets, bonding, the presence of metallic ions, and isomorphous substitution can lead to their formation. The formation of clay mineral deposits can occur either as a result of the weathering of parent minerals, which results in the formation of clay-rich residual soils such as kaolinite, or as a result of the hydrothermal alterations of host rocks, such as the formation of Cornish china clay (Al Ani, T., & Sarapaa 2008). Kaolinite, montmorillonite, and Illite are the three most frequent types of clay minerals, and geotechnical engineering particularly emphasizes their properties.

2.4 Introduction to Freezing and Thawing

Soil freezing and thawing is a common phenomenon that occurs in various regions and environments around the world (Larsbo et al. 2019). It is due to the fluctuation of temperature, which leads to the water molecules' expansion and contraction in the soil. As water molecules freeze, they expand, which later forces soil particles to pressure on the surrounding and expand

Similarly, when the ice melts, it contracts, and the pressure is released. This cycle of expansion and contraction can cause significant changes the properties of the soil physical and mechanical, affecting its overall performances like stability and strength, (Hoang et al. 2023). Therefore it is important to understanding the basic behavior of soils under freezing and thawing conditions, because wide range of industries including geotechnical engineering, agriculture, and construction effects by it (Wu et al. 2020). The freezing and thawing process on soil is shown in figure 2.5.

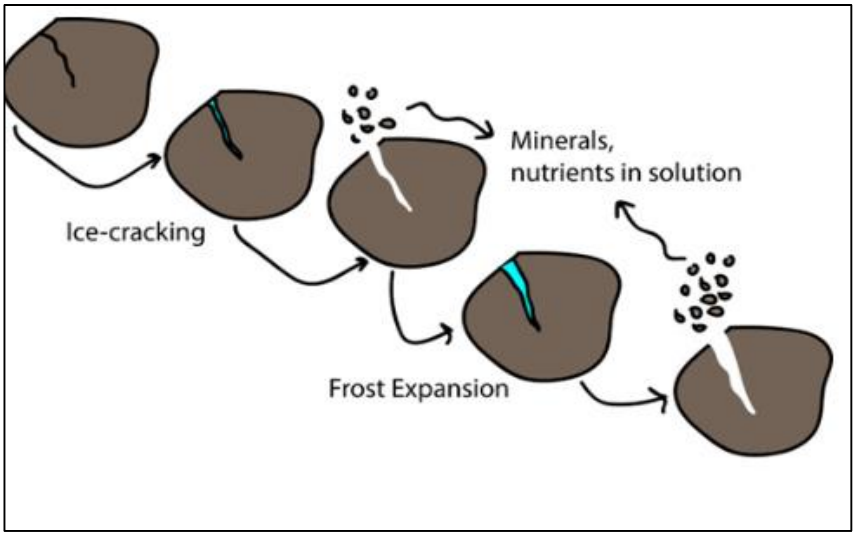


Figure 2.5 Freezing and Thawing Process on Soil

2.5 Factors Affecting the Freezing and Thawing of Soil

Several factors can influence the extent and severity of freezing and thawing of soil, which includes its temperature, soil composition, its moisture content, and the presence of salts or other impurities (During n.d.).

2.5.1 Temperature

Temperature which have a crucial role to determining whether the soil will freeze or thaw, with most soils freezing at temperatures below 0°C (32°F) and thawing at temperatures above the 0°C. However, the rate of freezing and thawing can vary depending on the temperature gradient, which is the difference in soils depth and its temperature between the soil surface (Oztas and Fayetorbay 2003). Given below are effects of temperature on soil freezing and thawing:

1. **Soil freezing:** As temperature decreases, the soil slowly starts to freeze because the moisture in the soil also stated freezing, and the soil becomes harder and less permeable. The depth of

soil freezing depends on the temperature, duration of low temperatures, and moisture content of the soil. Generally, the colder the temperature, the deeper the soil will freeze (Koopmans and Miller 1966).

2. **Frost heave:** When water freezes inside soil, it expands and can cause the soil to heave upward. Frost heave can be especially problematic in areas with clay soils, as these soils tend to hold water and are more susceptible to expansion (Teng et al. 2020).
3. **Soil thawing:** As temperatures rise above freezing, the frozen soil begins to thaw. Rate of thawing is depending on several factors, including the temperature, the duration of the thawing period, and the moisture content of the soil. Thawing can result the soil becoming more permeable and allowing water to infiltrate more easily (Blume-Werry et al. 2019).
4. **Soil erosion:** Rapid thawing of the soil can cause erosion, particularly if the soil is saturated with water. This can be especially problematic in areas with steep slopes or where there is no vegetation cover (Zhang et al. 2021).

2.5.2 Soil Composition

Soil composition is also affect by freezing and thawing process, as different types of soil have different properties that can impact the rate and extent of expansion and contraction (Wang et al. 2020). Given below are effects of soil composition on soil freezing and thawing:

1. **Mineral content:** The mineral content of soil affects its ability to store and transfer heat, which can affect its freezing and thawing properties. For example, sandy soils tend to freeze and thaw more quickly than clay soils, which are more resistant to temperature changes (Zhai et al. 2021).
2. **Organic matter:** Amount of organic material in the soil can affect its ability to hold moisture and its overall structure. Soils with high organic matter content tend to have better drainage and can resist frost heave, while soils with low organic matter content are more susceptible to erosion and frost damage (Huang et al. 2021).
3. **Soil structure:** The structure of the soil, including its texture, porosity, and compaction, can affect the freezing and thawing (F-T) of soil. Soils with a porous structure allow water to drain more easily, which can reduce the risk of frost heave. Compacted soils, on the other hand, can prevent water from draining, leading to ice formation and increased risk of damage (Ding et al. 2019).

2.5.3 Moisture Content

Moisture content is also a critical factor in determining the extent of freezing and thawing of soil. When soils are saturated with water, they tend to expand more during freezing and contract more during thawing, leading to significant changes the properties like mechanical and physical. However, when soil is dry, they tend to be more resistant to freezing and thawing, as there is less water available to expand and contract (Wei et al. 2019).

2.6 Effect of Freezing and Thawing on Soil Properties

The freezing and thawing of soil can have significant effects on its physical and mechanical properties, including its strength, stiffness, permeability, and compressibility (Qu et al. 2019).

2.6.1 Strength and Stiffness

One of the most common freezing and thawing effects on soil is the reduction in its strength and stiffness, which can lead to significant deformation and damage. As water molecules freeze and expand, they can exert pressure on the surrounding particles, leads to cracks and ice lenses formation. When ice melts, the pressure is released, causing the soil to shift and settle (Liu, Qin, and Lan 2020).

2.6.2 Permeability

Another common freezing and thawing effect on soil is the increase in its permeability. As water molecules freeze and expand, they can create pore spaces within the soil, allowing water to infiltrate more easily. This can lead to increased waterlogging, erosion, and soil instability (Korshunov et al. 2021).

2.6.3 Compressibility

Freezing and thawing can affect the compressibility of soil, with frozen soils typically exhibiting higher compressibility than thawed soils. When soils freeze, the volume of water increases in the soil, which later causes pore water pressure to increase. This lead to an increase in the compressibility of the soil. This can lead to settlement and deformation of structures built on frozen soils, as the soil can continue to compress over time (Fan, Yang, and Yang 2019).

2.6.4 Soil Type

The freezing and thawing effect on soils can also depend soil type its environmental conditions. For example, high clay content soils may experience greater reductions in strength due to freezing and thawing than soils with low clay content. Similarly, the rate at which soils freeze and thaw can also affect their behavior. Soils that freeze slowly and thaw slowly may experience less damage than soils that freeze and thaw quickly (Ren and Vanapalli 2020).

2.7 Strategies for Mitigating the Effects of Freezing and Thawing on Soil

Since soil is the most effective load-bearing material, it is vital to develop civil infrastructure. As a result of the progression of human development and population growth, there has been a rise in the desire for more efficient land use that can improve living conditions and facilitate travel. Because of this, the construction will need the use of land that has geotechnical characteristics that are undesirable. Soils frequently need better shear strength, low subgrade strength, freezing and thawing, high swelling potential and compressibility, and low permeability. All of these issues can be exacerbated by freezing and thawing. These issues could result in the failure in soil, which would later cause a great damage to the superstructures. It is necessary to improve the ground before using land with geotechnical problems that could be more favorable. Changing soil parameters to improve the soil's performance in engineering applications is known as soil stabilization (Lim et al. 2014). Densification, dewatering, chemical additives, and freezing or heating the soil are all viable methods for improving the quality of the soil (Wiszniewski, Skutnik, and Cabalar 2016).

Most of the approaches for modifying the soil rely on the soil's mechanical, chemical, or biological stability. The primary goal of the many different soil stabilization approaches is to improve and better results of the characteristics of the soil (Van Impe 1989). One of the oldest ways that is still used today is soil mechanical stabilization, which is used to stabilize the soil. The methods of mechanical stabilization alter the physical characteristics of the soil. Compaction, drainage, dynamic compaction, preloading, and other methods, among others, can all contribute to achieving this goal. Because these procedures require the use of heavy machinery and a significant amount of human resources, we cannot recommend them as cost-effective solutions for ground development. The enhancement of soil qualities can be accomplished by applying biological approaches by employing microorganisms, bio-enzymes, and biopolymers.

Various chemical additives are combined with the soil to change its mechanical properties in chemical stabilization. These chemical additives have a direct and physicochemical interaction with the soil particles. The vast majority of these reactions are either cementitious or pozzolanic, and this distinction is determined by the additive being applied. Incorporating chemicals, additives, and waste products into the soil as part of the stabilization process is considered chemical stabilization. Materials based on calcium provide several major advantages over other traditional methods of stabilization, including the fact that they are more effective, need fewer resources to produce, and pose a lower risk to the environment. There are several strategies that can be utilized to mitigate the adverse and bad effects of the freezing and thawing of the soil, including the incorporation of waste materials into the soil matrix.

2.7.1 Treatment with Lime

A Two different types of clayed soil of lime-stabilized (high plasticity and low plasticity) were tested for how freezing and thawing affected their permeability and strength (Yldz and Soğanc 2012).

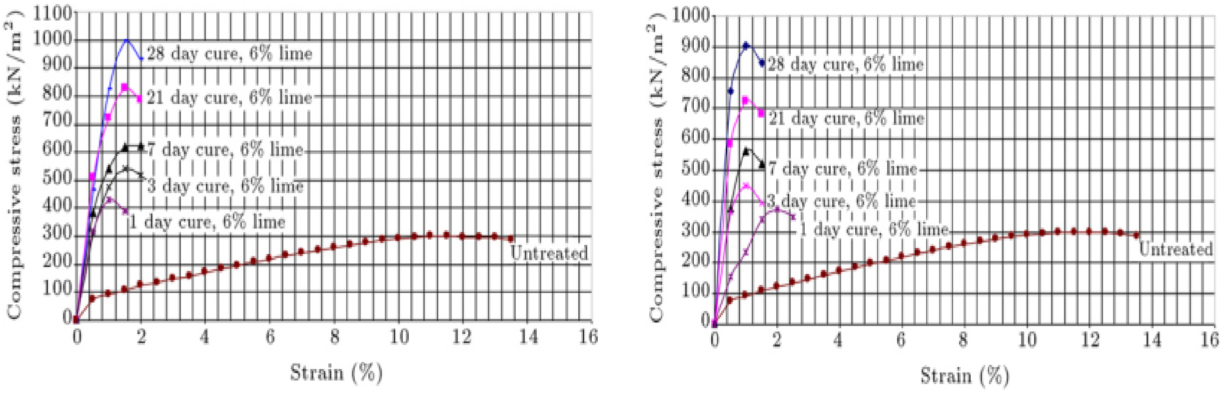


Figure 2.6 Compressive Stress Strain relationship for low plastic clays (without and with F-T cycles)

The strength results of soil were all over the place. When allowed to cure for 28 days, stabilized high-plasticity clay has a strength of roughly 15 times greater than stabilized low-plasticity clay. By the time the freeze and thaw cycles were over, strength of both types of stabilized clay had decreased by between 10 and 15 percent. Figure 2.6 and Figure 2.7 shows the connections between compressive stress and strain for low and high plastic clays with and without F-T cycles, respectively.

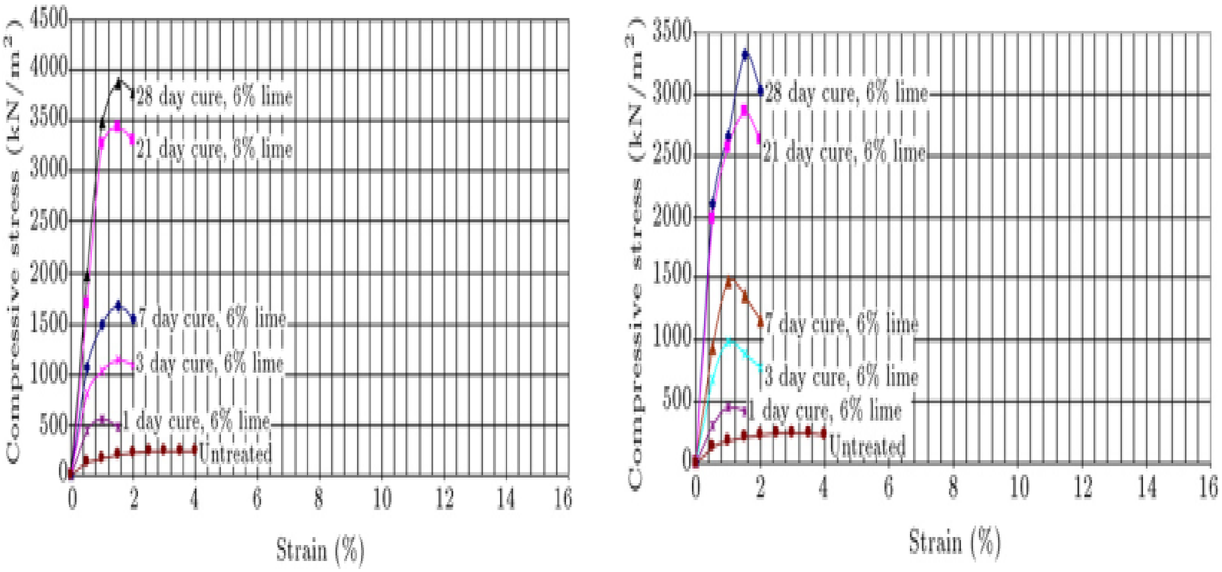


Figure 2.7 Compressive Stress Strain relationship for high plastic clays (without and with F-T cycles)

2.7.2 Treatment with Cement

Expansive clay subjected to F-T cycles its deformation and strength behaviors investigated by (Lu et al. 2020). The evaluation of the experiments that were carried out shows that incorporating cement into expansive soil lessens the soil's sensitivity and lesser the moisture presence and that the hydration response that is elicited by the cement successfully mitigates the unfavorable effects of swelling and shrinking that is induced by the repeated occurrence of freeze-thaw cycles. When cement is mixed into expansive soil, it leads to a significant increase in unconfined compressive strength as well the resilient modulus of the soil. On the other hand, the strain that causes failure does not rise in a proportional manner. However, the influence of cement will be lessened because of the cycles of freezing and thawing. Figure 2.8 and Figure 2.9, respectively, exhibit the effect of F-T cycling on the resilient modulus of expansive soil as well as the strain failure caused by the soil.

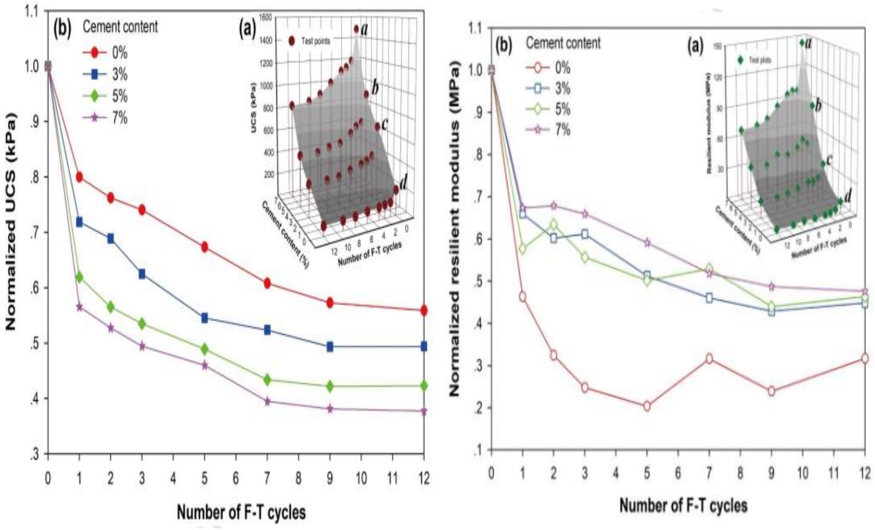


Figure 2.8 Effect of cement on UCS and Resilient Modulus of expansive soil under F-T cycles

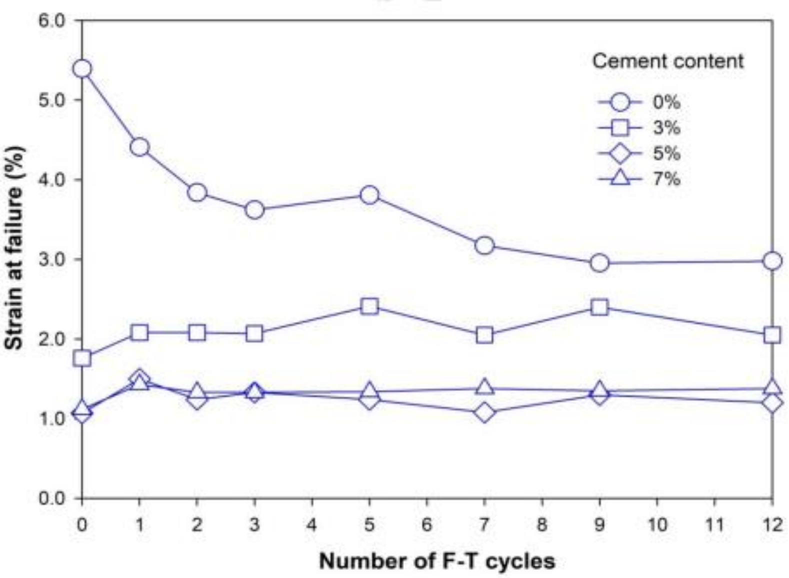


Figure 2.9 Effect of cement on strain failure of expansive soil under F-T cycles

2.7.3 Treatment with Cement and Lime

The stabilization of soil contains hexavalent chromium by using cement and lime is done by (He, Wang, and Gu 2021). Soil strength decreases by increasing in the number of F-T cycles. Later, trend will be reversed by adding cement and lime as a binder in it. The strength variation of stabilized soil shown in Figure 2.10 subjected to F-T cycles.

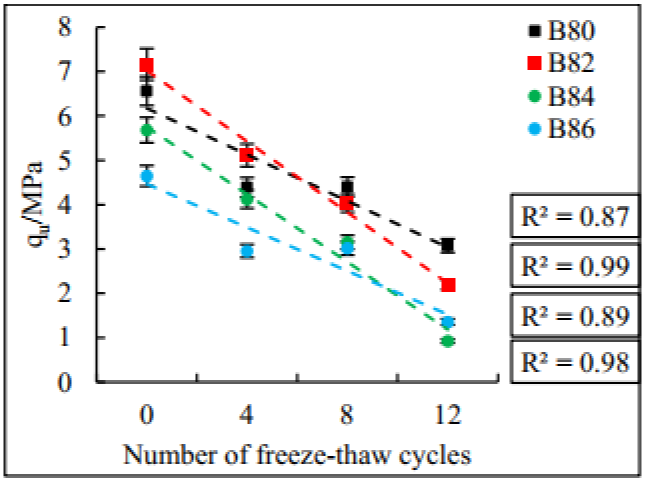


Figure 2.10 Strength variation of stabilized soil subjected to F-T cycles

2.7.4 Treatment with Nano Silica

Freezing and thawing effect on fine grained soil stabilized by nano silica is investigated by (Kalhor et al. 2019). Soil Subjected to nine freeze-thaw cycles, both untreated and treated soil containing 2% nano silica had a drop in strength of roughly 64% and 42%, respectively, as determined by the research. In addition, the ductility of stabilized soil specimens improves as increase infreeze-thaw cycles. Freezing and thawing effect on nano silica stabilized soil samples is shown in figure 2.11.

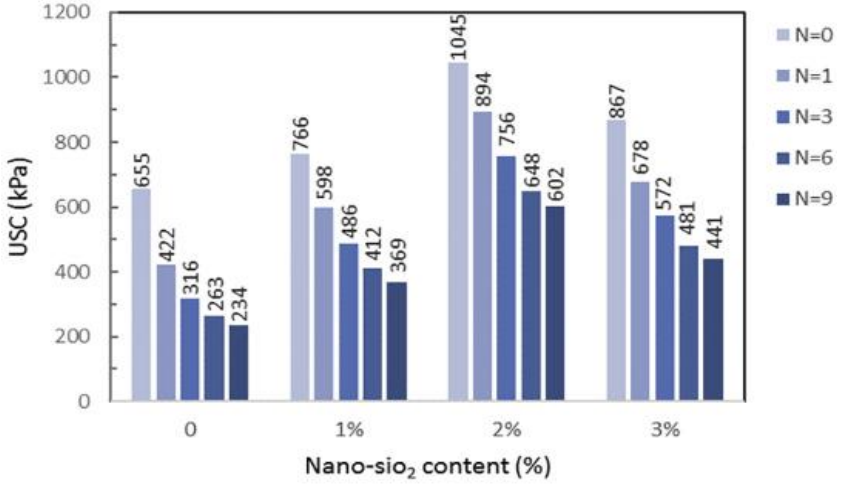


Figure 2.11 Effect of F-T cycles on strength of nano silica stabilized samples

2.7.5 Treatment with Cement and Polypropylene Fiber

The stabilization of Kaolin clay with polypropylene fiber and cement for long-term durability under F-T cycles is studied by (Aryal and Kolay 2020). Kaolin soil which was stabilized which contains 10% cement, 5% cement and contains + 0.5% fiber, and the soil which contains 10% cement and additional 0.5% fiber met the durability requirements set forth by the Portland Cement Association. The percentage soil loss during F-T tests with different combinations figure 2.12 illustrate the results.

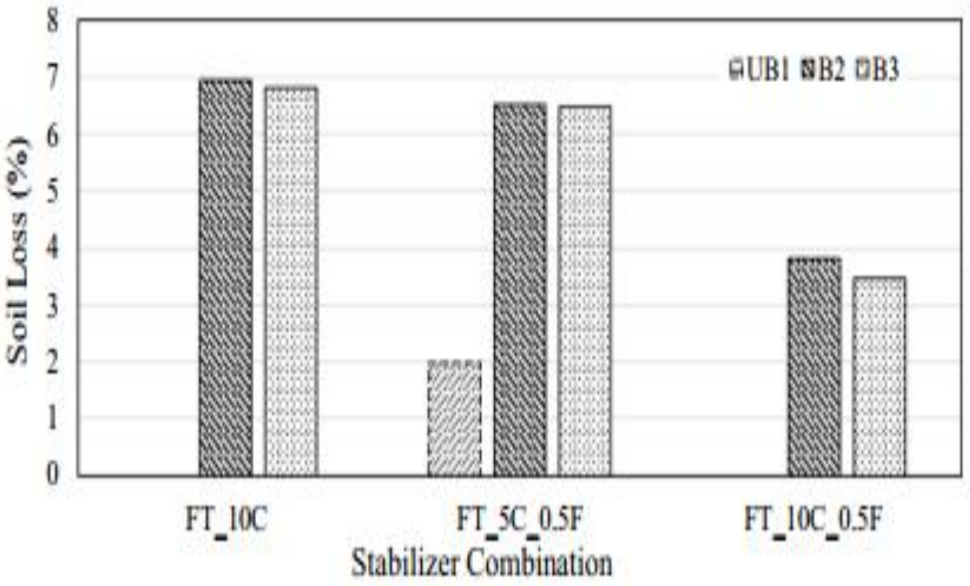


Figure 2.12 Percentage soil loss during F-T tests with different combinations

2.7.6 Treatment with Silica Fume

The Silica fume's effects fine-grained soils geotechnical qualities of that have been through freeze-thaw cycles is investigated in (Kalkan 2009). Fine-grained soils and the soil with silica fume combinations compacted to moisture to get maximum compaction later subject of extensive laboratory investigations. The results demonstrate that stabilized silica fume soil samples are substantially more resistant to the of freezing and thawing than natural soil samples are. The silica fume reduces the degradation of unconfined compressive strength and permeability caused by repeated freezing and thawing. Figure 2.13 shows the effect of silica fume on UCS after F-T cycles.

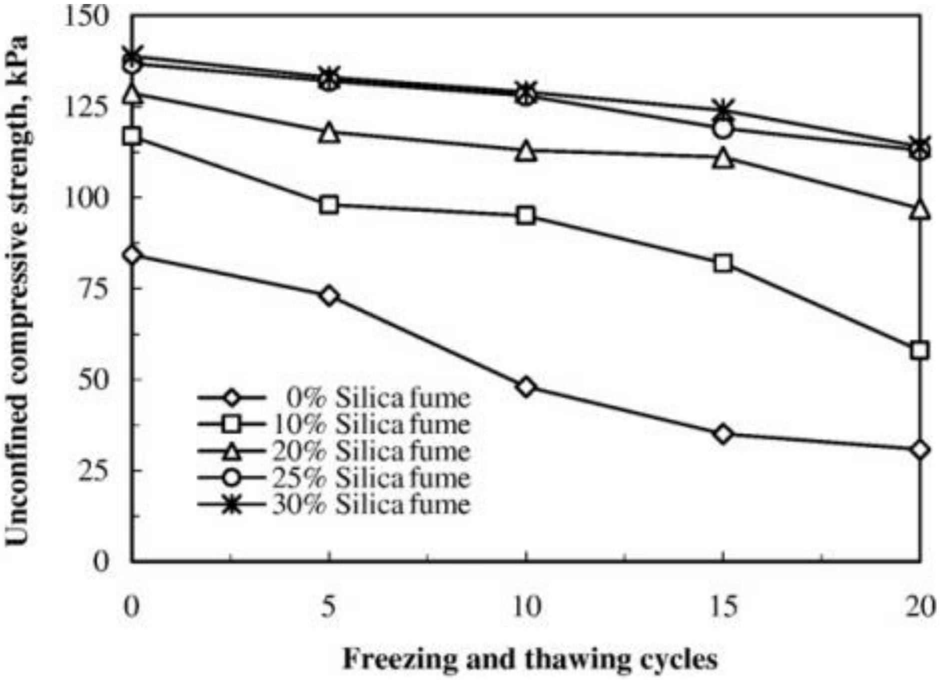


Figure 2.13 Effect of silica fume on UCS after F-T cycles

2.8 Research Gap Present in Literature

Previous studies have shown the importance of considering as a cost-effective, environmentally friendly, and potent stabilizer that lessens the impact of F-T and increases soil strength. The best substance for treating soils exposed to F-T cycles is calcium-based (Turkoz et al. 2015). This research aims at improving soils with calcium-based waste. As a calcium-based substance, Plaster of Paris (POPW) waste can be used to treat soils that have been exposed to (F-T) cycles. The POPW is both economically and environmentally friendly. It only produces harmless gases out of water during the manufacturing cycle (Savaş et al. 2018).

Chapter 3

Methodology

3.1 General

The fundamental goal of this study is to study the effectiveness and suitability of Plaster of Paris waste (POPW) as a soil stabilizing agent. This study utilized three distinct varieties of clayey soils, namely Soil A, Soil B, and Soil C. Samples of Soil A, Soil B, and Soil C were collected from Neelum Valley, Ayubia, and Sakardu, respectively, in Pakistan. The primary rationale behind selecting soils for this investigation is their challenging characteristics resulting from repeated freezing and thawing cycles. The laboratory tests were performed following the standards set by the American Society for Testing Materials (ASTM). This section will elaborate on the utilized materials and conducted tests.

3.2 Materials

3.2.1 Soil

The research used three different soils that were collected from three locations in Pakistan: Neelum Valley, Ayubia and Skardu. The visual representation of Soil A, Soil B, and Soil C is shown in figure 3.1, Figure 3.2, and Figure 3.3, respectively.

Figure 3.1 Soil A (Location: Neelum Valley)

Figure 3.2 Soil B (Location: Ayubia)

The reason for choosing these locations is that the structures in these areas are prone to problems due to temperature variations. The soil consistency from each location may vary, and it is necessary to investigate the effects of stabilizing each soil type with POPW for different freeze-thaw cycles. By conducting this research, we can determine if the stabilization method is effective in mitigating the problems caused by temperature variations in the soil at these locations.

Figure 3.3 Soil C (Location: Skardu)

3.2.2 Additives

The research used an additive called Plaster of Paris waste (POPW). Plaster of Paris is a calcium-based material that is commonly used for various applications, such as construction and art. During the manufacturing process of Plaster of Paris, a waste material is produced. In this research, we utilized POPW as an additive for the treatment of soils under freeze-thaw cycles. POPW is a fine white powder as shown in figure 3.4 that is collected from Khewra district. One of the beneficial properties of Plaster of Paris is that it does not generally shrink or crack when it dries, which makes it suitable for use in soil stabilization (E. A. FitzPatrick 1975).

Figure 3.4 Plaster of Paris Waste (POPW)

3.3 Soil Characterization

3.3.1 Grain Size Analysis and Hydrometer Test

To find out the gradation of soil between particle sizes of 75mm and 75µm (retained on No. 200 sieve), a grain size analysis will be performed following the ASTM standard D6913-17 (Astm D6913-04R2009 2004). The sieves used for this analysis will include No.4, No.10, No.40, No.60, No.100, No.140, and No.200. The sieving process will involve both-way motion of sieve vertical and lateral, and the mass of each fraction will be determined after shaking the specimen. It is crucial to match the initial mass of the quantity sieve to the sum of masses retain on all sievesThis test requires a significant amount of time to perform, and all sieves must be clean and dry to obtain accurate results. Proper pulverization of the soil sample is necessary to ensure that the weight retained and passed through the sieves is determined accurately.

The hydrometer test was performed followed the ASTM standard D7928 (ASTM International 2017) for grain size distribution determination of fine-grained soils that possess a particle size smaller than 0.075mm, and to identify whether the soil contains more than 10% of particles that pass through the No. 200 sieve. In order to analyze soil samples that exhibit a range of particle sizes spanning from sand to silt or clay, a combination of sieving and sedimentation techniques are employed.

3.3.2 Atterberg Limits

For the calculation of Atterberg limits, which includes Liquid limit and Plastic limit, mineral water will be used as the wetting agent. The liquid and plastic limit tests will be performed following the ASTM standard D4318-17 (ASTM D4318, ASTM D 4318-10, and D4318-05 2005). As per the standard, the soil fraction passing through the U.S. sieve No.40 will be utilized for performing the liquid and plastic limit tests. In the liquid limit test, the moisture content at which a groove cut in the wet specimen closes will be determined. The standard grooving instrument will be used for this purpose. The assembly of Atterberg limits test is shown in figure 3.5.

Figure 3.5 Atterberg Limits Test Assembly

In the plastic limit test, the moisture content at which a wet sample disintegrates when it is rolled by hand, turning it into threads with a diameter of 3mm, will be determined. For the liquid limit test, the test will be conducted from drier to wetter soil conditions and will be performed at three different trials with varying moisture contents. The soil sample used in the liquid limit test will be of a consistency that requires a number of blows between 15 and 35 to close the groove created in the sample. The plastic limit test will be performed by clean hands on a non-porous surface.

3.3.3 Specific Gravity Test

The specific gravity test will be performed following the ASTM Standard D854-14 (G/Tsadik, Berhane, and Worku 2020). Approximately 30-40g of soil, which has been oven-dried, will be used for each test. The procedure requires complete removal of entrapped air before performing the test. The weighing balance will be checked for accuracy before conducting the test. It is essential to ensure that the soil sample used for the test is completely oven-dried. The apparatus of specific gravity is shown in figure 3.6.

Figure 3.6 Specific gravity test in Progress

3.3.4 Standard Proctor Test

The laboratory compaction tests for this study will be carried out following the ASTM Standard D698-07 (ASTM D698-7 2007). The purpose of the test is to get the value of optimum moisture content and dry density of the soil. The specimen will be compacted in a container with a volume of 944cm^3 (1/30ft^3), using a mold with a diameter of 101.6mm (4in.). The specimen will be compacted in three layers of equal thickness using a hammer, with each layer subjected to 25 blows. The mass of the hammer used in the test will be 2.5kg (6.5lbs), dropped from a height of 30.5mm (12in.). The compaction test assembly is shown in figure 3.7.

Figure 3.7 Compaction Test Assembly

3.3.5 Unconfined Compressive Strength Test

The unconfined compression test (UCS) will be conducted following ASTM standard D2166-13 to get the compressive strength of the soil samples (ASTM 2013). The test mold will have a diameter of 7cm and height of 14cm to maintain a standard ratio of 1:2. The soil samples will be prepared at 95% of their maximum dry density. The test will be conducted using an axial strain rate of 1mm/min, which is the rate at which the sample is compressed. The UCS test is a common way to measure the strength of soils and the load bearing capacity of soil. The assembly of UCS test machine is shown in figure 3.8. The tests will be performed at Geotechnical engineering laboratory of national university of science and technology (NUST), Islamabad.

Figure 3.8 Assembly of UCS Test

3.3.6 Freeze Thaw Test

Following the completion of the 28 days of curing period completed, F-T cycles were applied on both stabilized and control samples as per ASTM D560/560M (ASTM 2015). After being cured, the specimens were frozen repeatedly at 0, 1, 3, 5, 7, and 11 cycles at standard temperature. An application of freezing was performed on the samples for 24 hours at 23^{O}C. We placed them on an air conditioner set to 21^{O}C in a humid environment to defrost the samples for 23 hours. This process of F-T was carried out multiple times. As soon as the F-T cycles were completed, all specimens were retested using unconfined compression. The assembly at which samples were placed for freezing and thawing is shown in figure 3.9. The freeze thaw cycles are performed at ASAB in industrials biotechnology lab, NUST, Islamabad.

Figure 3.9 Assembly of Freeze Thaw Test

3.3.7 Mass Loss

Mass loss of each soil sample was determined after freezing and thawing cycles, a total of 72 samples were prepared from three different soils. After each F-T cycle, the samples were weighed using a 0.1 g resolution electronic scale. This allowed for the determination of mass loss variation across samples.

3.3.8 Scanning Electron Microscopy Test

The scanning electron microscopy (SEM) test will be conducted to investigate the microstructure of soil using ASTM E986 guidelines (ASTM E986-04 2017). The test requires a solid sample that can fit into the microscope chamber, with a maximum vertical dimension of 40mm and a maximum horizontal dimension of 10cm. The purpose of the test is to analyze the soil sample's surface features at high magnification, which provides information on the sample's morphology and texture. SEM is a powerful tool that can help researchers gain insights into the physical and chemical properties of the soil. These tests will be performed at materials lab, School of chemical and material engineering (SCME), NUST, Islamabad.

3.3.9 X-Ray Diffraction Test

The X Ray diffraction test will be performed in accordance with ASTM D5357 (ASTM D5357 2019). This test will be performed to check the elemental composition of soil. The best sample for this test is homogeneous and single phase. Detection limit for mixed material is approximately 2% of the sample. Material should be in powder form. These tests will be performed at materials lab, SCME, NUST, Islamabad.

Chapter 4

Results and Discussions

4.1 General

Within this chapter, the findings and analysis of the different properties of soils were observed and discussed in both treated and untreated soil subjected to freeze-thaw cycles. The subsequent test findings provide a detailed description of the behavior of treated soil in compared to natural soil.

4.2 Results and Discussion

4.2.1 Geotechnical Properties of natural soil samples

The soils used in this study are of three types taken from different regions of Pakistan with different plasticity. While Soil-A from Neelum Valley had high plasticity, Soil-B from Ayubia had medium plasticity, and Soil-C from Skardu had low plasticity. The range of the Plasticity Index is from 8 to 25. They are all fine-grained soils ideal for construction projects. The geotechnical properties of soil samples used is given in Table 1. According to unified soil classification system, soil A, soil B, and soil C, all belongs to CL. The particle size distribution of all the three soils is shown in figure 4.1.

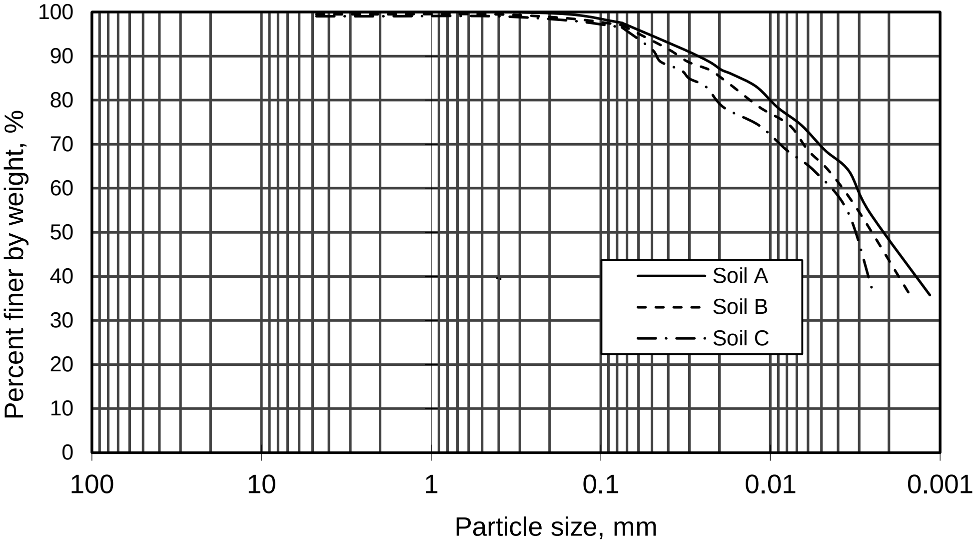


Figure 4.1 Grain Size Distribution Curves

Table 1 Geotechnical Properties of Soil Samples used

Properties	Units	Soil A	Soil B	Soil C
Location	-	Neelum Valley	Ayubia	Skardu
Color	-	Light Brown	Dark Brown	Grey
Grain Size:				
Gravel	%	0	0	0
Sand	%	6	5	4
Silt	%	38	44	47
Clay	%	56	51	49
Maximum Dry unit weight	g/cm^3	1.81	1.90	1.75
Optimum Moisture Content	%	18.31	15.02	17.80
Specific Gravity	-	2.67	2.68	2.63
Atterberg Limits:				
Liquid Limit	%	45.04	38.21	26.83
Plastic Limit	%	20.46	21.12	18.58
Plasticity Index	-	24.58	17.09	8.25
Classification	-	CL	CL	CL

4.2.2 Chemical Composition of POPW

POPW was used as the manufactured additive material used in this study. It was supplied from the district of Khewra, Pakistan. It is a whitish powder. POPW is a dust obtained while heating gypsum powder and transform it to plaster of Paris the waste that remains in the kiln is a waste material which later dumbed into landfill and have no utilization. Chemical composition of POPW are given in Table 2. The specific gravity of POPW was 2.32.

Table 2 Chemical Composition of POPW

Chemical Substances	POPW
CaO	38.6%
SiO_2	1.4%
Al_2O_3	0.2%
Fe_2O_3	NIL

MgO	0.9%
SO_3	48.9%
CO_3	6.03%
TiO_2	0.02%

Plaster of Paris is an inexpensive, non-corrosive, non-combustible, and eco-friendly substance. This waste material is chosen for this investigation due to its unique features and ready availability. The factories do not make use of this material and it is disposed of in landfill as waste material. This issue is alarming that’s why this waste material is used in this study.

4.2.3 Effect of POPW on compaction parameters

Maximum dry density (MDD) and optimal moisture content (OMC) are affected by adding various amounts of POPW, as shown in Figures 4.2 and 4.3. Soil A had an OMC of 18.31–20.56%, Soil B of 15.02–18.3%, and Soil C of 17.8–22.97%, and their corresponding MDDs varied from 1.81–1.73 g/cm^3, 1.90–1.81 g/cm^3, and 1.79–1.68g/cm^3. By observing the compaction results, it is concluded that the optimum values of Soil A, Soil B, and Soil C are 3%, 5%, and 1%, respectively. The results show that by including POPW, the OMC is increased while the MDD is decreased for all soils.

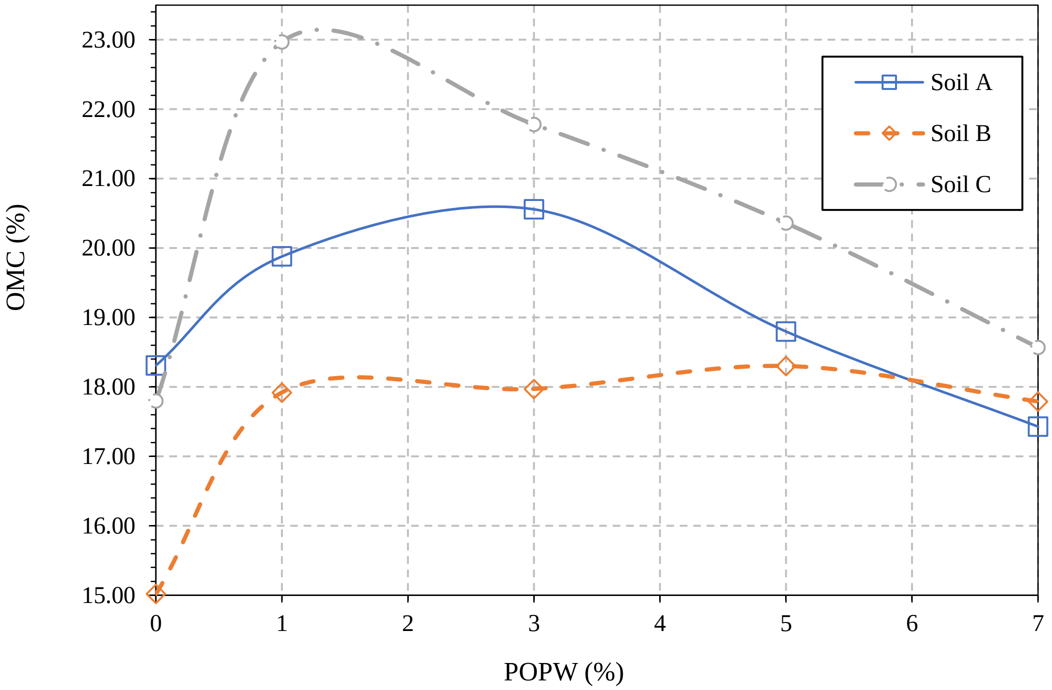


Figure 4.2 Variation of OMC for various POPW contents of soil A, soil B, and soil C

POPW's addition to stabilized samples enhances their OMC by increasing the particles' total surface area. As a result, OMC of the stabilized samples were greater. Because of the lower specific gravity of POPW compared to the specific gravities of soils tested, the MDD steadily decreased in the stabilized samples as the OMC increased (Yarba, Kalkan, and Akbulut 2007). These findings are in line with those that have been found in the research literature on the effects of adding lime, cement, or calcium-based compounds to clay soil (Nguyen et al. 2019).

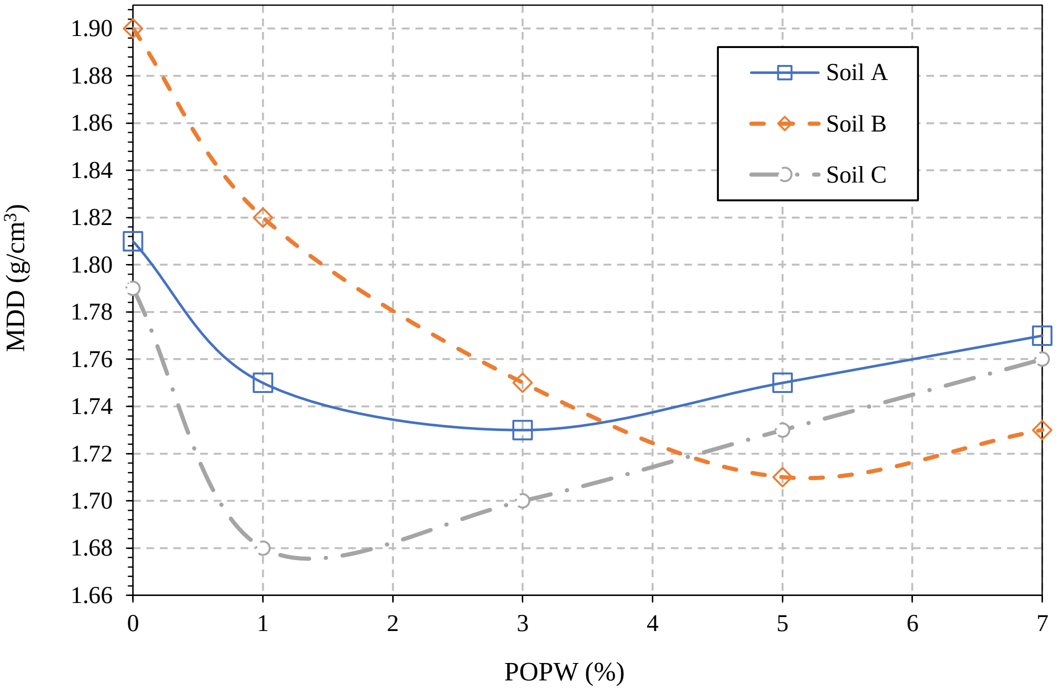


Figure 4.3 Variation of MDD for various POPW contents of soil A, soil B, and soil C

4.2.4 Effect of POPW on Plasticity

Figure 4.4 illustrates how the plasticity index (PI) changes with optimal concentrations for soil A, B and C after 28 curing period. Increasing the curing durations of the samples and adding POPW led to a drop in the PI of the samples. PI decreased from 24.58% to 8.28% for soil A, 17.09% to 5.28% for soil B, and 8.25% to 2.35% for soil C, respectively. Clayey soils benefit from adding POPW because it causes flocculation, lowering the soil's liquid limit and the PI (Goodarzi and Akbari 2014). The substitution of non-plastic POPW particles for plastic clay particles reduces the plasticity properties of the soil specimen (Goodarzi and Akbari 2014). In addition, incorporating POPW into the soil with a high proportion of clay particles results in aggregates forming, reducing the PI (Journal, Vol, and Al-soudany 2018).

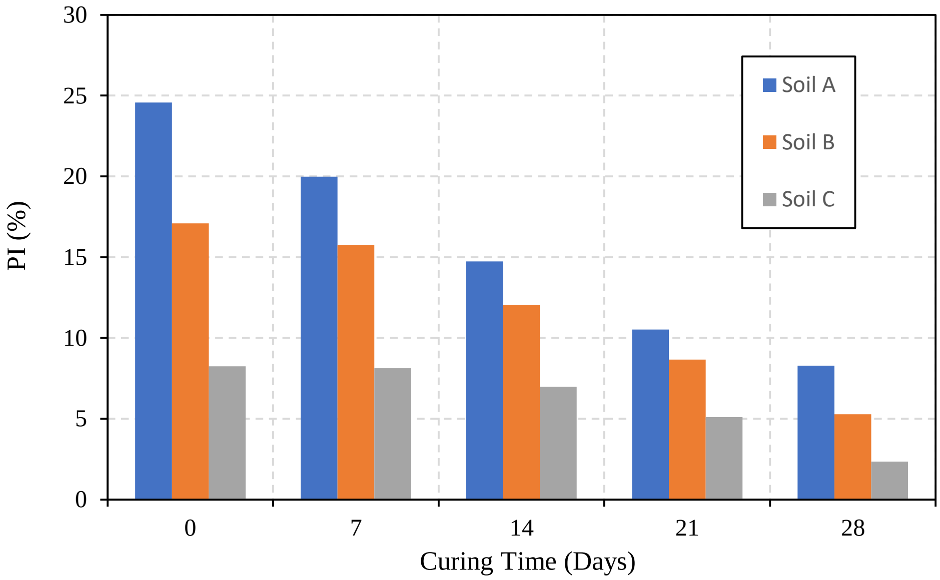


Figure 4.4 Effect of POPW and curing time on PI

4.2.5 Effect of POPW on Specific gravity

Figure 4.5 illustrates how the presence of POPW affects the specific gravity of soil samples.

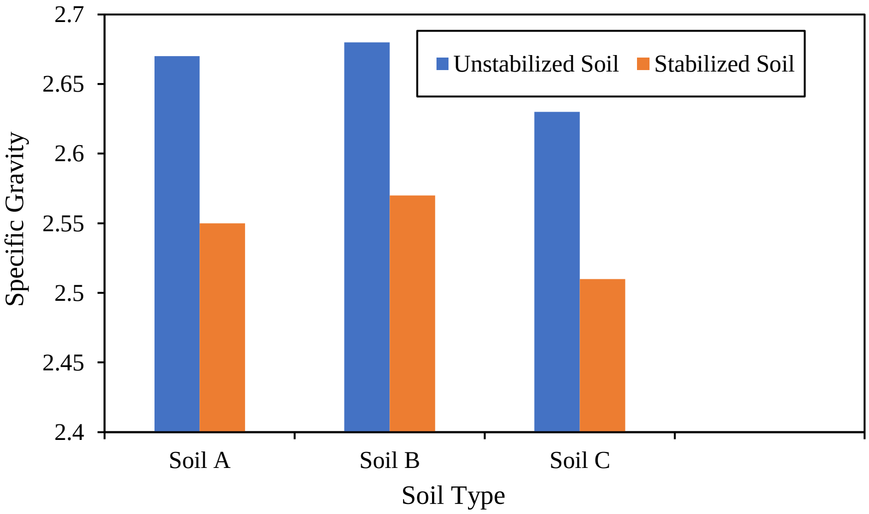


Figure 4.5 Effect of POPW on Specific Gravity

After adding the optimal quantity of POPW content to the soil samples (3% for soil A, 5% for soil B, and 1% for soil C). It is found that the treated soils show less specific gravity than untreated soils. This is because POPW has a lower specific gravity than the soil particles. A reduction in specific gravity indicates an increase in the number of voids, which impacts the qualities and strength of the soil (W. Li et al. 2020).

4.2.6 Effect of POPW on compressive strength

Figure 4.6 and 4.7 illustrates the untreated soils and impact of POPW on the compressive strength of soil A, B, and C at varying curing durations. The addition of POPW increases the compressive strength values of soil A, B, and C. The strength of both untreated and treated samples was evaluated after being subjected to curing periods of 0, 1, 7, 14, and 28 days to determine the impact of curing duration on their strength. Soil A exhibits a smaller particle size than Soil B and Soil C, rendering it a more appropriate material for POPW. The enhanced strength properties of soil samples stabilized with POPW have been attributed to a confluence of internal friction factors, the pozzolanic activity of soil particles, and a chemical reaction between soil particles and POPW particles. All samples exhibited a steady increase in compressive strength for up to 28 days. The observed increase in compressive strengths over time in stabilized samples can be attributed to the chemical reactions between soil particles and POPW particles during POPW hydration. After 28 days of curing, Soil A, Soil B, and Soil C led to 653%, 410%, and 356%, increase in UCS by adding optimum amounts of POPW for all soils, respectively.

The short-term ion exchange reaction, which causes soil particles to flocculate, and the long-term pozzolanic reaction, which results in cementitious materials, are both responsible for improving strength values. The increase in strength enables the soil to support heavier loads while lowering the possibility of structural deformation (A. Aldaood, Bouasker, and Al-Mukhtar 2014b). The UCS value is employed as a primary control check to assess the effectiveness of soil additives in several soil stabilization techniques. Determining strength is one of the most important design factors for construction. Additionally, cohesive soils' bearing capacity is assessed using their undrained shear strength, which is half their UCS value (A. Aldaood, Bouasker, and Al-Mukhtar 2014a).

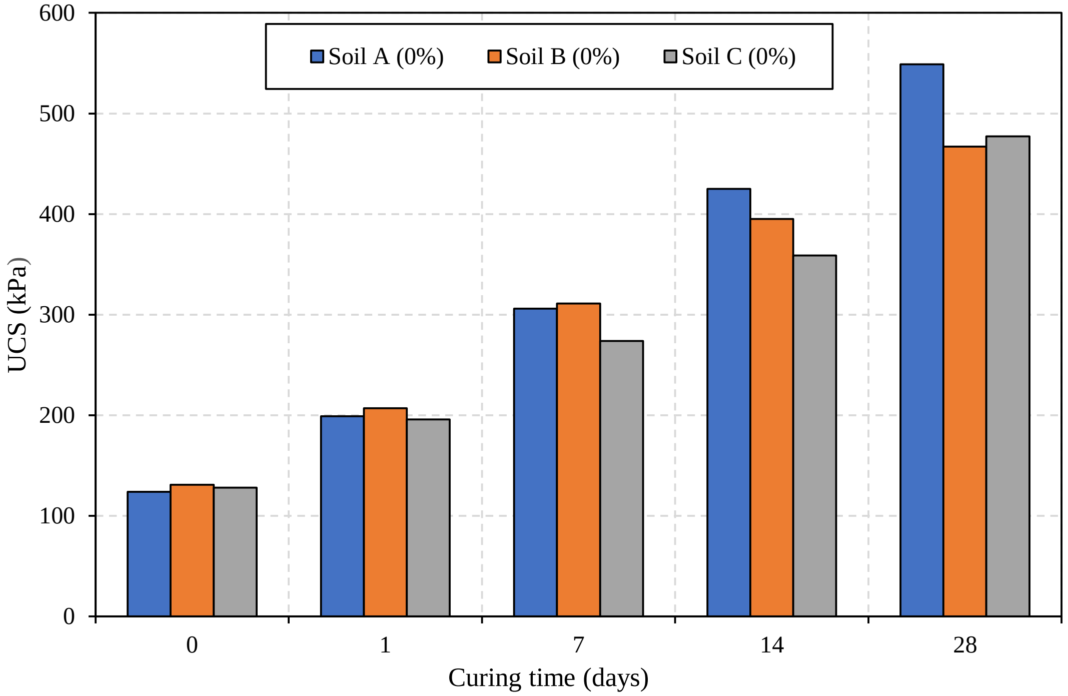


Figure 4.6 Variation of UCS values for Natural Soil A, Soil B, and Soil C with different curing times

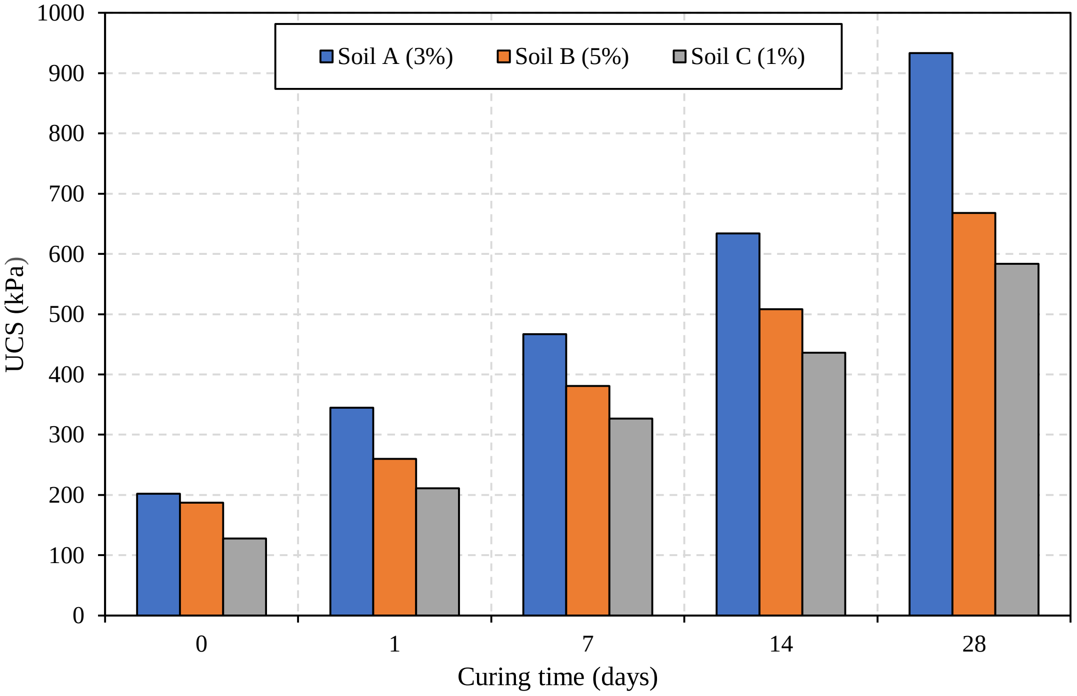


Figure 4.7 Variation of Optimum UCS values for Soil A, Soil B, and Soil C with different curing times

4.2.7 Effect of F-T on compressive strength

Compressive strength was determined by subjecting samples through a number of freezing and thawing cycles. Test results are depicted in Figures 4.8 and 4.9. As the frequency of freezing and thawing cycles rises, a modest drop in compressive strength. The soil and additive mixture types determined the extent to which freezing and thawing cycles affected compressive strength. When the 11th cycles of freezing and thawing completed, the soil A showed the most noticeable change compared to soils B and C. The degree to which freezing and thawing affects the deterioration of different materials varies (Hori and Morihiro 1998).

The results of the experiments demonstrate that the additive mixtures had a substantial impact on the freezing-thawing capabilities of the soil. The strength parameter of both unsterilized and stabilized soil samples were observed to change as the number of freezing and thawing cycles increased. However, the stability of stabilized samples was enhanced by the additive mixtures when compared to unsterilized samples subjected to the same freezing and thawing cycles. Stabilized samples were subjected to 11 freezing-thawing cycles, and the degree of deterioration was measured as a percentage loss in compressive strength after 28 days of curing. Yet, the additive mixtures mitigate the effects of freezing and thawing on strength behaviors.

Soil samples stabilized with various chemical combinations were more resistant to the effects of freezing and thawing than those without stabilization. Alterations in soil behavior caused by freezing and thawing are driven primarily by shifts in soil structure. Compressive strength declines in unstable soil samples because of structural changes brought on by particle rearrangement and crack initiation. (Viklander and Eigenbrod 2000). The process of freezing and thawing generates expansion and contraction. In addition to damaging the micro pores of the stabilized samples, this expansion also induced a localized increase in tensile strength. Fractures formed on a microscopic scale as the number of F-T cycles increased. As the number of F-T cycles grew, these micro-fractures created a bond causes the stiffness in the stabilized samples, causing a decrease in their compressive strengths (Hori and Morihiro 1998).

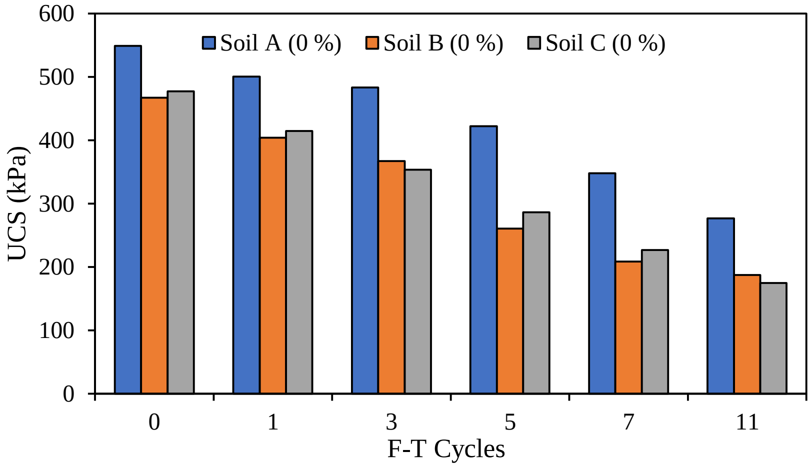


Figure 4.2 Effect of F-T cycles on UCS values of Natural Soil A, Natural Soil B, and Natural Soil C at 28 days

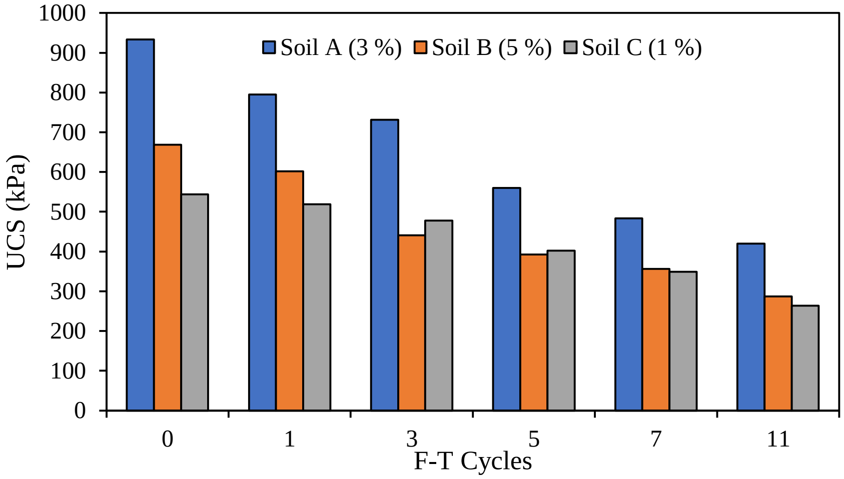


Figure 4.3 Effect of F-T cycles on Optimum values of UCS of Soil A, Soil B, and Soil C at 28 days

4.2.8 Effect of F-T on mass loss

Clay soil's strength has been negatively impacted by F-T action. The F-T cycle is a multi-physical process in which pore water moves toward lower temperatures while subjected to uniform pressure fields. As previously mentioned, water loss is unavoidable even when the samples are covered in plastic wrap to limit exposure to the atmosphere during F-T cycles (Abdulrahman Aldaood, Bouasker, and Al-Mukhtar 2014). Due to water evaporation caused by F-T activity, the soil is prone to fracture and lose some of its mass. Weighing the specimens before and after exposure to F-T cycles allowed researchers to assess the impact of treatment (POPW) on their durability. The difference between the two weights demonstrated mass loss caused by F-T conditions. The outcomes are displayed in Figures 4.10, 4.11, and 4.12 for soil A, soil B, and soil C.

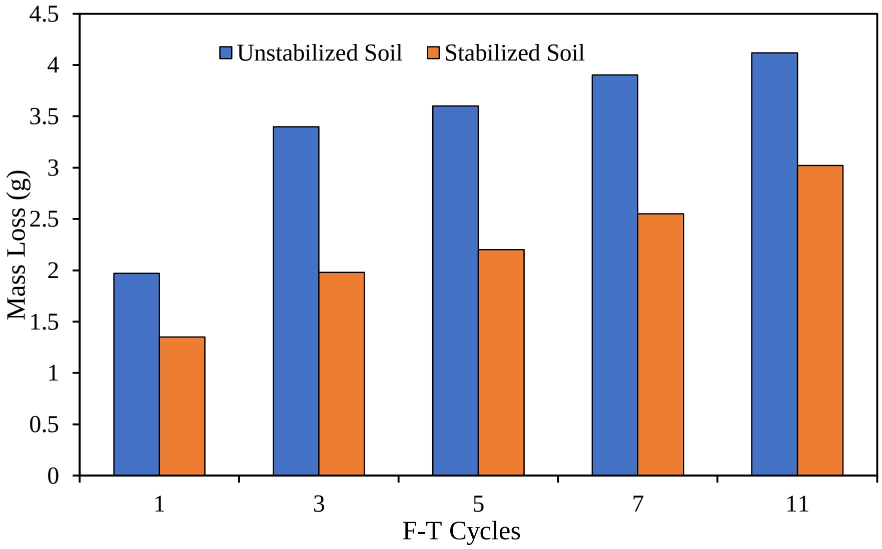


Figure 4.4 Variation of mass loss of Soil A with varying F-T cycles

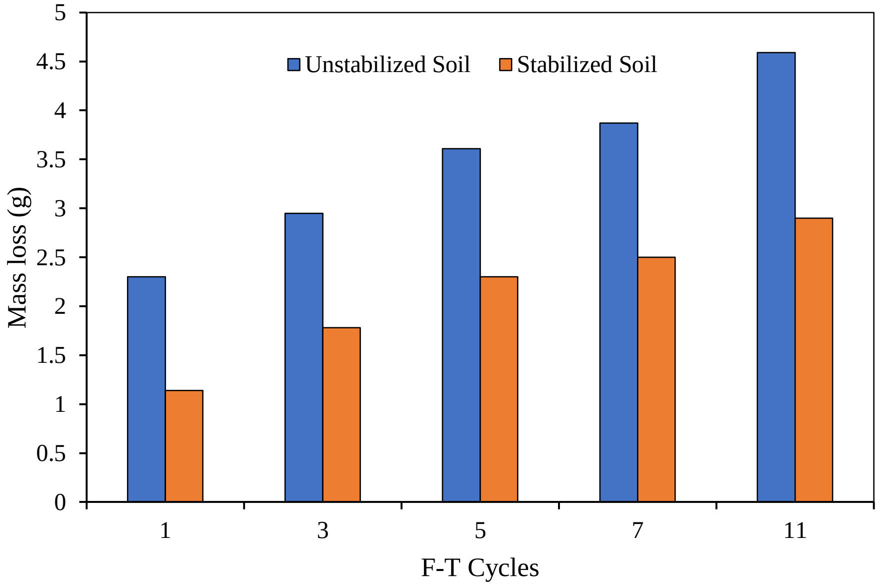


Figure 4.5 Variation of mass loss of Soil B with varying F-T cycles

It is clear from the results that mass loss increased as the frequency of F-T cycles increased. POPW was added to the soil, which reduced mass loss. The interaction between additive and water reduced mass loss in stabilized specimens and created a more substantial structure that constrained water outflow. Also, this might be because the hydration products of calcium-based material cover the surface of the samples, delaying water evaporation and sublimation of ice (Boz and Sezer 2018). However, when the number of F-T cycles increased, the coated protective layer gradually broke down, significantly speeding up the rate of water loss. The mass decrease for each specimen was less than 10%. It was demonstrated in the literature that mass losses of between 10 and 15 percent had little to no impact on the strength of soil near specimen surfaces (Seyfried, Wilcox, and Cooley K.R 1990; Zaimoglu 2010).

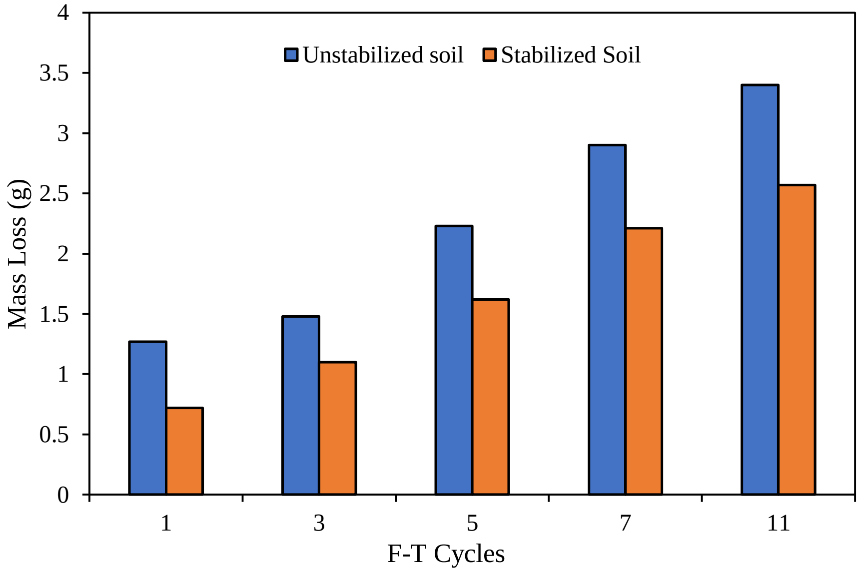


Figure 4.6 Variation of mass loss of Soil C with varying F-T cycles

4.2.9 Effect of POPW on Microstructure of soil subjected to F-T cycles

The addition of POPW affects the microstructure of soil under F-T cycles. The presence of POPW has an impact on the microstructure of soil through processes such as ion exchange reactions, flocculation/aggregation, and the creation of cementitious products via a prolonged pozzolanic reaction. As mentioned earlier, the liberation of calcium ions leads to the formation of soil particle clusters. The analysis of changes in microstructure or the formation of an aggregation/flocculated structure is conducted using the scanning electron microscopy (SEM) technique. Nevertheless, the verification of cementitious product formation is conducted through X-ray diffraction (XRD) analysis.

SEM techniques analyzed the alteration in the microstructure of soil. The microstructures of untreated soil samples, untreated soil samples under 11 F-T cycles, samples with the optimum amount of POPW content after the curing of samples for 28 days, and samples with the optimum amount of POPW under 11 F-T cycles after the period of 28 days curing were compared using SEM techniques (Figures 4.13, 4.14 and 4.15). The image makes it very clearly that untreated soil samples consist of scattered structures. Pores and cracks are found in the untreated samples. On the other hand, adding POPW alters the soil microstructure from deflocculated to flocculated.

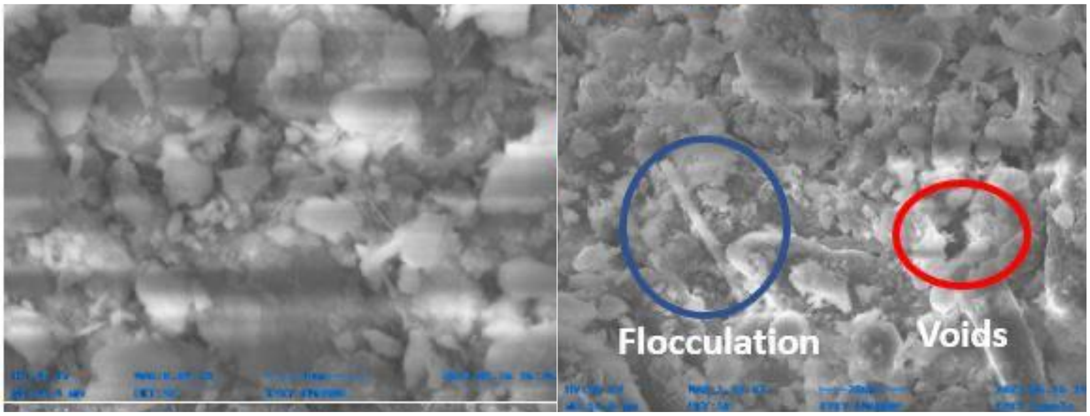


Figure 4.7 SEM analysis of soil A (a) Untreated Sample (b) Treated sample after curing time of 28 days under 11 F-T cycles

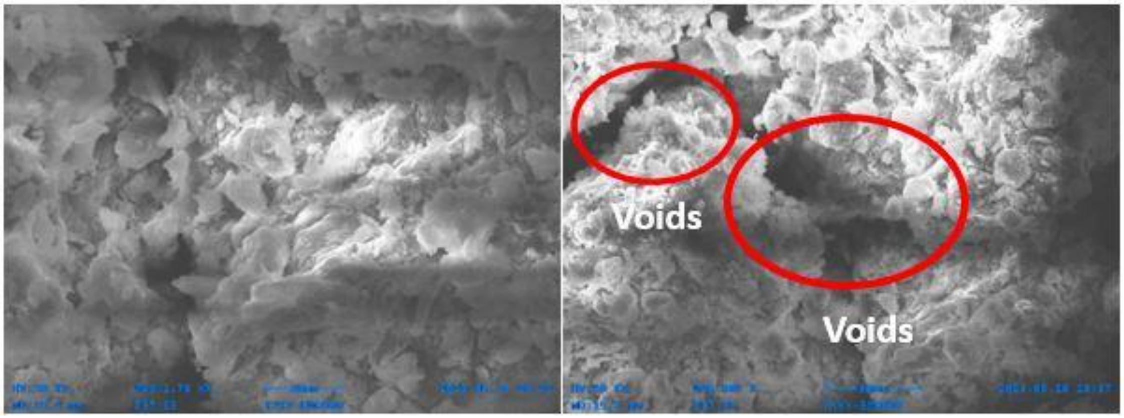


Figure 4.8 SEM analysis of soil B (a) Untreated Sample (b) Untreated Sample under 11 F-T cycles

The bond forming between the particles of soil and POPW is facilitated by the affinity of clay minerals to the POPW surface. This results in an increase of frictional forces and, subsequently, an enhancement of the adhesive properties between the soil and POPW. This increase the strength of treated soil cured for 28 days. The calcium cations were liberated when POPW and soil were mixed, and the clay grains coagulated (Boardman, Glendinning, and Rogers 2001; Castro-Fresno et al. 2011).The act of freezing causes the water in the pores expanded, leading to cracks and fissures in the matrix. However, these cracks are more in untreated samples under F-T cycles than in treated samples under F-T cycles due to the adhesive property of POPW in it.

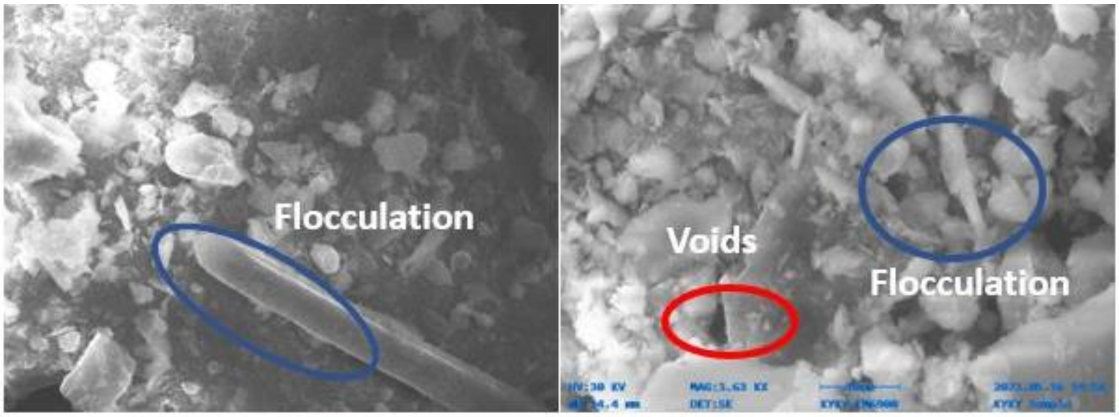
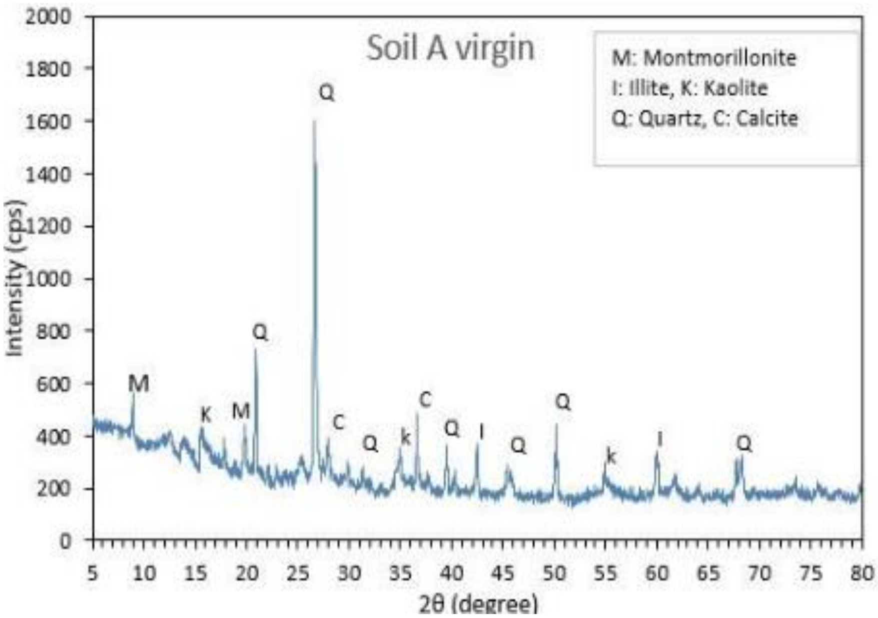


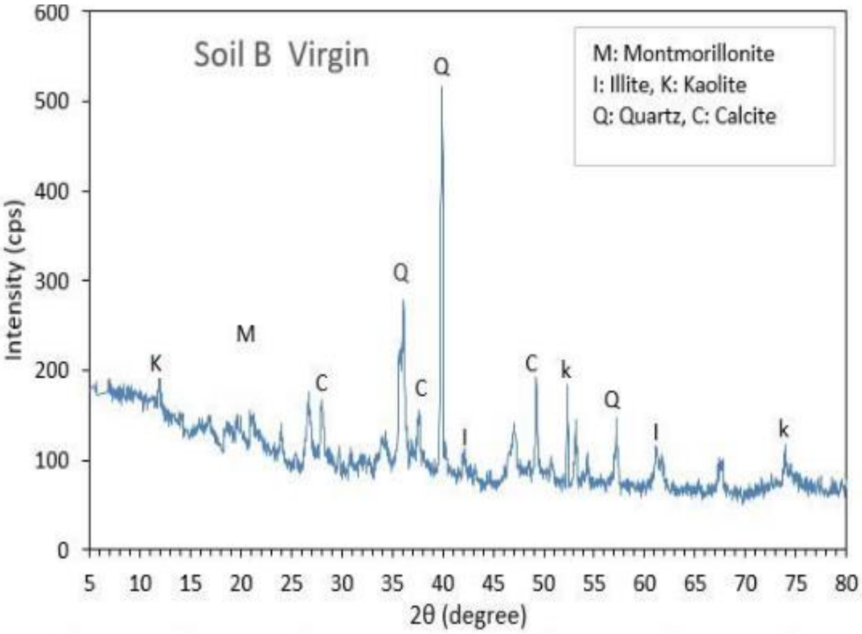
Figure 4.9 SEM analysis of soil C (a) Treated sample after curing time of 28 days (b) Treated sample after curing time of 28 days under 11 F-T cycles

Based on the X-ray diffraction (XRD) analysis conducted on untreated soil samples A, B, and C, as depicted in Figures 4.16a, 4.17a, and 4.18a, the primary minerals identified include montmorillonite, Illite, kaolinite, quartz, and calcite. In Figure 4.16b, 4.17b, and 4.18b, it can be observed that the introduction of optimal POPW to the clay samples following 11 freeze-thaw cycles led to the development of cementitious substances, specifically calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH), as indicated by X-ray diffraction (XRD) analysis.



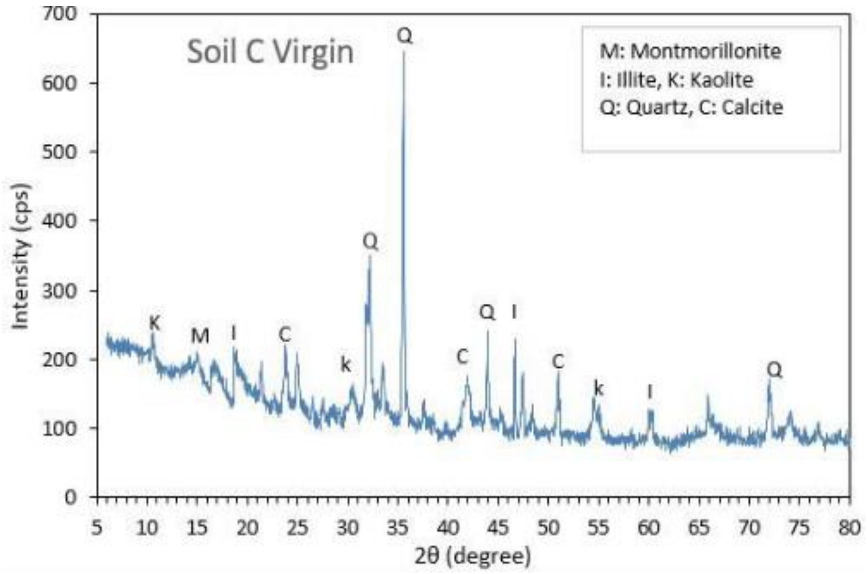
(a)

Figure 4.16 XRD Analysis of (a) Natural soil A



(a)

Figure 4.17 XRD Analysis of (a) Natural soil B



(a)

Figure 4.18 XRD Analysis of (a) Natural soil C

Chapter 5

Conclusions

The current research utilized F-T cycles for soil remediation using POPW derived from plaster of Paris, a calcium-based chemical. Changes in the strength properties and Microstructure of fine-grained soil were evaluated as a function of freeze-thaw cycles and their influence on the addition of calcium-based additives. To achieve this, we conducted a battery of unconfined compression tests, as well as XRD and scanning electron microscopy analyses on raw and processed samples. The most important findings of this investigation are as follows:

1. POPW is a cost-effective and favorable to the environmental and soil enhancement material. When used to remediate clayey soil, this dramatically increases the strength compared to other additives. The optimum additive percentages for Soil A, Soil B, and Soil C treatment are 3%, 5%, and 1%, respectively. Strength enhancement is an important benefit as the strength of soil is a critical factor in many construction and engineering projects. Improving the strength of the soil can help to prevent soil instability, settlement, and other issues that can impact the long-term stability and safety of a structure.
2. The testing results revealed that adding additive materials reduced the maximum dry density while increasing the optimal moisture content for Soil A and Soil C. The decrease in MDD suggests that the soil became less compacted and more porous, which could potentially impact its strength and stability and increase in OMC suggests that the soil could be more easily compacted at higher moisture levels. However, in the case of Soil B, the trend was reversed. Adding additive materials increased the maximum dry density, which could potentially improve the strength and stability of the soil. However, the optimal moisture content decreased, which suggests that the soil may be more difficult to compact at lower moisture levels.
3. The mass loss increased with the cycles of F-T increases. On the other hand, the mass loss was decreased by the addition of POPW. According to the quantity of POPW content and the number of cycles, Soil A, Soil B, and Soil C, respectively, each generated a more significant mass loss and effective percentage at 3%, 5%, and 1% POPW content. The loss of soil mass throughout the cycles of freeze-thaw can have a sustainable impact on properties and stability of soil. Freeze-thaw cycles can cause soil to expand and contract, leading to cracking and

fragmentation, which can result in significant mass loss. This can have negative impacts on the long-term stability and performance of soil and structures built on the soil. The addition of POPW can help to mitigate these negative impacts by improving the strength and stability of the soil and reducing the mass loss during freeze-thaw cycles.

4. Freeze-thaw (F-T) cycles lowered the strength of all specimens. The first cycle drastically reduced the strength for specimens stabilized on a calcium-based material. POPW improved resistance to freeze-thaw action by increasing strength and effectiveness. POPW can increase strength and effectiveness, which can help to mitigate the negative impact of freeze-thaw cycles on soil. This is likely due to the unique properties of POPW, which can help to stabilize the soil and reduce the mass loss during freeze-thaw cycles.
5. The soil samples of all three soils changed from deflocculated to flocculated state with the addition of POPW in it as observed by SEM techniques and cementitious material products were formed as can be seen and observed in XRD analysis.
6. By comparing the results of Soil A, Soil B, and Soil C, it is recommended that strength of all soils have been improved by adding POPW in them. It is also recommended that the addition of POPW has the potential to enhance the strength and stability of the weaker soils, making them more resilient to the effects of freezing and thawing. This approach can help improve the overall performance and durability of the soils, ensuring their suitability for construction and minimizing potential issues related to soil instability. However, it is important to carefully evaluate the optimal dosage and mixing techniques for incorporating POPW to achieve the desired results without compromising the soil's other properties.

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