`Stabilization of silty clay through fungal-induced calcite precipitation

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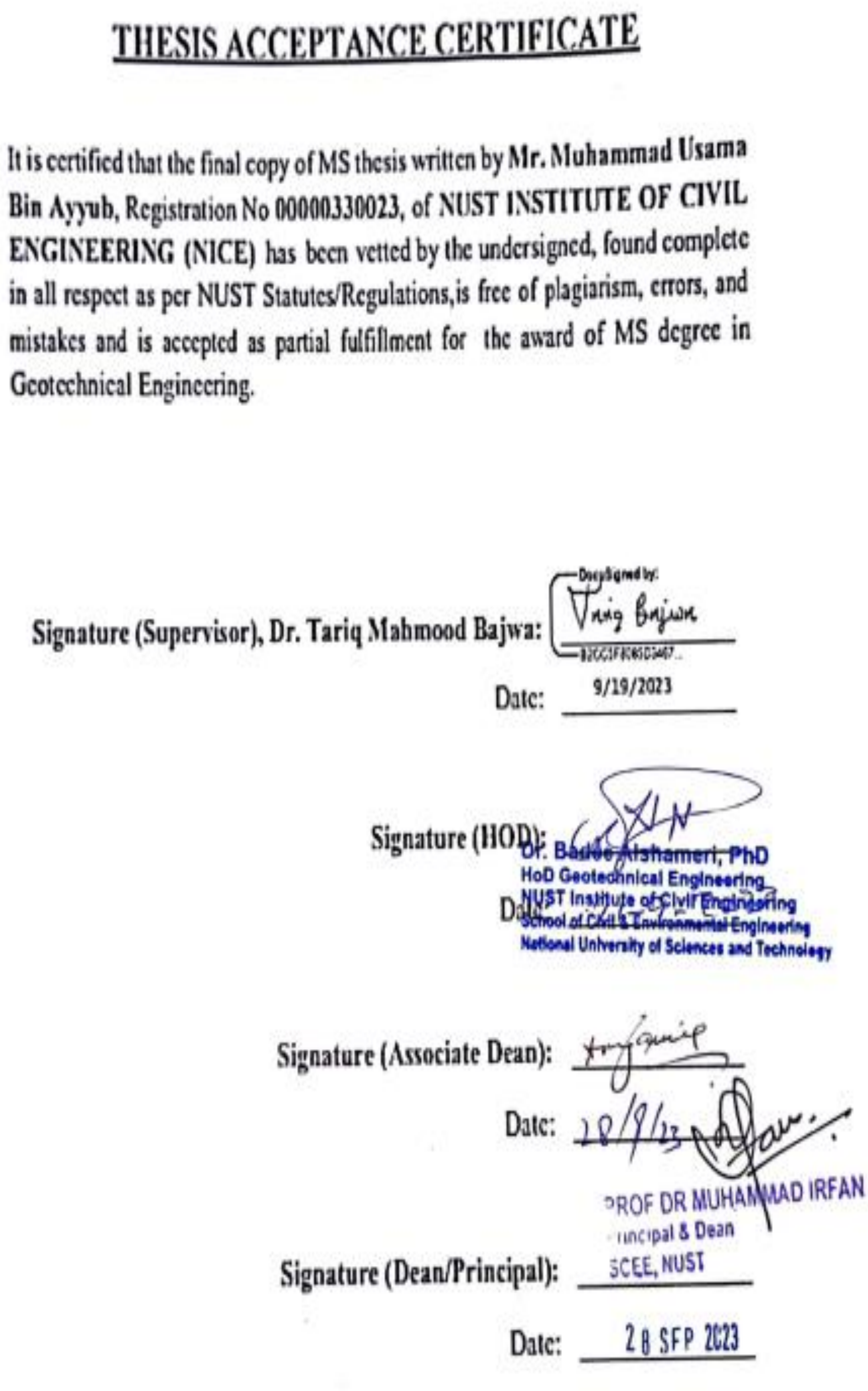

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DEDICATED TO

My late father, mother and aunts, whole family, teachers (Dr. Tariq Bajwa, Dr. Faraz Bhatti, Dr. Muhammad Arshad), and friends (Abbas, Furqan).

This is the result of all your support and encouragement.

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Abstract

Research studies show that fungal-based microbial-induced calcite precipitation (MICP) extensively enhances the strength behaviour of concrete materials. However, fungal-based MICP's effectiveness in silty clay has not been investigated yet. This study examines fungal-based MICP's influences in stabilisation of silty clay during wetting and drying cycles. The *Fusarium oxysporum* fungal inoculum, in combination with a calcium chloride cementitious solution, was used to stabilise the soil. The laboratory tests, including Atterberg limits, unconfined compressive strength (UCS), specific gravity, X-ray diffraction (XRD), scanning electron microscopy (SEM), etc., were carried out to attain the study objectives. The test results show that the soil specimens treated with 0.25 M cementitious solution in combination with fungal inoculum provide peak strength. The soil strength reduces from 2549.20 to 1108 kPa giving 130.07% decrease between 1st and 9th wetting and drying cycles, Comparatively, the strength of untreated soil changes from 1215.40 to 429.70 kPa, showing a reduction of 182.85% between 1st and 7th cycle. The untreated samples of soil show less stability than the treated soil and collapsed after the 7th cycle. The study findings conclude that the fungal-based MICP technique can effectively strengthen the clayey soil due to changes in the structure of treated soil.

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Chapter 1

Introduction

1.1 General

Soils with weak engineering properties pose significant challenges in constructing and maintaining civil engineering infrastructures. These soils exhibit poor load-bearing capacity, high compressibility, and low shear strength, making them prone to settlement, instability, and failure. Understanding the causes, impacts, and potential mitigation strategies associated with weak soils is crucial to improve their performance properties for sustainable civil engineering structures. This research work explores the reasons behind weak soil engineering properties, their effects on structures, and effective approaches to address these challenges.

Soils with weak engineering properties are prone to settlement and subsidence, leading to uneven or excessive structural deformations. This can result in cracks, tilting, or even structural failure in buildings, roads, and other infrastructure. Weak soils often exhibit low shear strength, making them susceptible to slope failures. Slope instability can lead to landslides or dam collapses, endangering nearby structures and transportation networks. Weak soils can pose significant challenges during the construction of foundations. Insufficient load-bearing capacity and excessive settlement can result in foundation failure, compromising the stability of the entire structure. Soils with weak engineering properties often have poor drainage characteristics. This can lead to water accumulation, increasing the pore pressure within the soil. Excessive pore pressure can reduce soil strength and trigger instability.

Recently, there has been growing interest in utilizing environmentally friendly techniques such as, “Microbially Induced Calcium Carbonate Precipitation (MICP)” for soil stabilization to improve the performance properties of weak soils. This research work explores the concept of MICP, its mechanism, advantages, and potential applications in soil stabilization. Mechanism of MICP Microbially Induced Calcium Carbonate Precipitation involves using specific microorganisms, typically bacteria, to promote the formation of calcium carbonate (CaCO3) within the soil matrix. The process begins with injecting a solution containing the bacterial culture and a calcium source into the target soil. The bacteria then produce an enzyme called urease, which hydrolysis urea, releasing carbonate ions and raising the pH of the surrounding environment. The elevated pH, in the attendance of calcium ions from the injected solution, triggers the precipitation of calcite, effectively binding soil particles with each other and improving the overall strength and cohesion of the soil.

MICP offers a sustainable alternative to traditional soil stabilization techniques that rely on chemical additives. The process utilizes naturally occurring bacteria and environmentally benign materials such as urea and calcium. MICP can be a cost-effective solution compared to conventional methods, as the bacterial culture and injection materials are relatively inexpensive. The calcium carbonate formed through MICP provides long-term stability to the soil, improving its resistance to erosion, settlement, and deformation. MICP can be helpful in a great range of soil types, including cohesive and granular soils, making it a versatile soil stabilization method. MICP can stabilize soils in situ without excavation, making it suitable for retrofitting and preserving existing infrastructure.

MICP is a biomineralization process in which microorganisms facilitate the precipitation of calcium carbonate minerals from soluble calcium and carbonate ions in the environment. *Fusarium oxysporum*, a common filamentous fungus, has gained attention for its potential role in MICP due to its ability to produce organic acids that promote calcium carbonate formation. This article delves into the process of MICP mediated by *Fusarium oxysporum*, its mechanisms, applications, and environmental significance.

Fusarium oxysporum secretes organic acids, such as citric, oxalic, and gluconic acids, into the surrounding environment. These acids act as chelators, binding to calcium ions and releasing them into the solution. As the organic acids released by the fungus chelate calcium ions, carbonate ions in the solution combine with the calcium ions to form calcium carbonate crystals. This precipitation process occurs in the vicinity of the fungal mycelium. The fungal mycelium provides a substrate for calcium carbonate crystals to adhere to, facilitating the formation of biofilms. These biofilms further enhance precipitation by providing a structured matrix for mineral accumulation.

1.2 Need for research

The soil obtained from Top City Islamabad gives a very low bearing capacity (~135 kPa). This soil is considered unsuitable to sustain high pressure under the loads. So, this study uses fungal-based MICP treatment to examine the mechanical behaviour of this soil for wetting and drying cycles, for an environment friendly sustainable infrastructure development, unlike to traditional methods of soil stabilisation.

1.3 Objectives

The objectives of this study are defined as follows.

- To investigate the mechanical behaviour of fungal-based MICP treated silty clay for wet-dry cycles.

1.4 Chapters breakdown

The outlines of the chapters of this thesis are as follows.

1. Chapter 1 highlights the introduction, need, and objectives of the study.

2. Chapter 2 integrates the literature relating to the study.

3. Chapter 3 reports the methods employed and materials used to attain the set objectives of the study.

4. The results of the study are reported in Chapter 4

5. Chapter 5 highlights the conclusions and recommendations based on the study' test results.

Chapter 2

Literature Review

2.1 General

The weathering of rocks, either by chemical or mechanical means result in the formation of fines - called soil. The weathering process occurs due to chemical changes, wind or by running water. A soil is also composed of organic matter which is formed through the decomposition of the dead bodies of animals, plants and humans (Nortcliff et al., 2006). Soil is one of the basic components of any engineering project and it is essential to study and test the properties of soil before beginning the construction project. Many infrastructures have failed due to soil foundation failure. It is very important to study the properties of the soil such as, bearing capacity, compressional strength, settlement factors, chemical composition, hydraulic conductivity, porosity, minerology and reactions with other chemical substances (Yakun Zhang, 2021).

2.2 Types of soils

The soil is usually classified in five types which are sandy soil, clay soil, silt soil, and peat. This classification is based on the particle gradation and the percentage of the organic matter present in the soil. Sandy soils are non-cohesive or have negligible cohesion between the particles, not moisture retentive, highly porous and have larger soil particles as compared to the clayey soils. The cohesion can be the result of the presence of the clay particles. Clay soils are highly cohesive, lesser in size than the sandy soil particles, water retentive and denser than the sandy soils. The particles of the silt soils are smaller than clay soils, are highly water retentive and have a high cohesive strength between the particles. The soils which have more than 20 percent of organic matter in them are classified as peat soil (Brinkgreve et al., 2005).

2.3 Problems associated with silty clays in geotechnical engineering.

Silty clays, while possessing certain advantageous properties, can also present a range of challenges in geotechnical engineering. These challenges stem from their unique characteristics, which combine aspects of both clay and silt soils. Understanding and addressing these issues is essential to ensure the success and safety of construction and engineering projects. In this article, we explore some of the prominent problems associated with silty clays and discuss potential mitigation strategies (McCabe et al., 2006).

2.3.1 Compaction and settlement

Silty clays can be susceptible to significant settlement when subjected to loads. Their compressibility and tendency to undergo consolidation can result in long-term settlement of structures. This settling can lead to uneven foundation support, causing structural distress and potential damage. Proper compaction techniques during construction and careful consideration of settlement characteristics are crucial to mitigate this problem (McCabe et al., 2006).

2.3.2 Slope stability

One of the most pressing issues with silty clays is their role in slope instability. When saturated, they can experience a reduction in shear strength, leading to landslides or slope failures. The plastic and cohesive nature of these soils exacerbates the problem. To address this issue, comprehensive slope stability analysis, appropriate drainage measures, and reinforcement techniques are necessary (Ma et al., 2022).

2.3.3 Water retention and drainage

Silty clays, despite having better permeability compared to clay soils, can still retain water for extended periods. In construction, inadequate drainage can result in delayed project timelines, compromised stability, and costly repairs. Installing proper drainage systems and utilizing geosynthetic materials can help manage water-related issues (Ma et al., 2022).

2.3.4 Construction delays

Construction involving silty clays can be susceptible to weather-related delays. These soils are highly sensitive to moisture content changes, and construction during wet conditions can lead to difficulties in excavation, compaction, and forming stable foundations. Project planning that considers seasonal variations and incorporates appropriate construction techniques can help minimize these delays (Tang et al., 2023).

2.3.5 Expansive behaviour

Silty clays can exhibit expansive behaviour with changes in moisture content. Swelling due to water absorption and shrinking during drying can lead to ground movement, which can damage structures and infrastructure. This behaviour is particularly concerning in regions with significant rainfall fluctuations. Adequate moisture control and the use of soil stabilizers can help mitigate this issue (Tang et al., 2023).

2.3.6 Erosion and sedimentation

Due to their fine particle size and cohesive nature, silty clays are prone to erosion by water runoff. This can result in sedimentation in nearby water bodies, affecting water quality and aquatic ecosystems. Implementing erosion control measures, such as vegetative cover and erosion-control blankets, is essential to prevent these environmental issues.

2.3.7 Foundation design challenges

Designing foundations on silty clays requires careful consideration of their properties. Their plasticity and compressibility can lead to differential settlement, affecting the stability of structures. Engineers must conduct thorough site investigations, consider suitable foundation types, and incorporate proper design techniques to address potential challenges (Sun et al., 2021).

In conclusion, while silty clays possess certain beneficial properties in geotechnical engineering, they come with a set of challenges that demand careful attention and strategic solutions. Adequate site investigations, comprehensive geotechnical analyses, and appropriate engineering strategies are essential to mitigate the problems associated with silty clays. By addressing these challenges, engineers can ensure the safety, stability, and longevity of construction and engineering projects in areas where silty clays are prevalent (Sun et al., 2021).

2.4 Soil improvement techniques

Soil improvement techniques have been introduced in the last century. Chemical and mechanical soil stabilisation methods are considered as the basic types of soil improvement techniques. Some of the techniques becoming common are soil-cement wall (Bou et al., 2018) and deep mixing method. These methods are considered very effective, but they have a major drawback of contaminating the groundwater table because of the pollution potential of the chemical solutions (Fan et al., 2018). Hence great care should be taken while considering the application of soil-cement. In mechanical soil stabilisation, the poor soil is mixed with a different graded soil to change its gradation. Using this technique, better compaction of the soil can be achieved (Anjan Patel, 2019). The drawback of this method is the availability of the required graded soil as well as excessive testing.

2.4.1 Vibroflotation

Vibro-floatation, an immensely effective technique employed for the enhancement of cohesionless or less cohesive soils, plays a pivotal role in geotechnical engineering. This method involves the simultaneous saturation and vibration of the soil using a specialized device known as a vibroflot, which, in turn, significantly increases the soil's density.

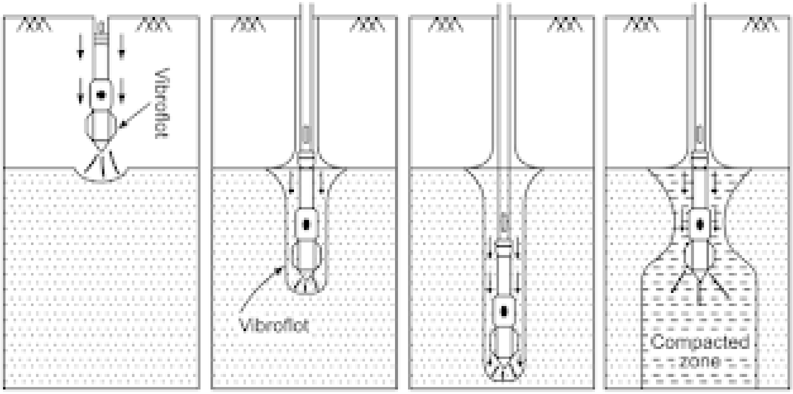


Figure 2.1: Process of vibroflotation

The fundamental principle behind vibroflotation lies in its ability to promote soil particle settlement in such a way that voids are adequately filled. The vibratory action induces finer particles to descend into the voids, effectively occupying the hollow spaces and thereby enhancing the overall density of the soil fill. Moreover, the compaction of coarse-grained soil particles is notably facilitated through this technique, compared to their fine-grained counterparts (E. Brown, 1977).

However, despite its numerous advantages, vibroflotation is not without its drawbacks. One of the main challenges is the complexity involved in performing the requisite calculations and testing. Additionally, this method is primarily suitable for less cohesive soils, limiting its applicability in certain scenarios. Furthermore, the convenience of employing the vibroflot, the associated costs, and the time required for the entire process are some of the factors that necessitate careful consideration before opting for this technique.

2.4.2 Grouting

Grouting, a highly effective method in geotechnical engineering, involves injecting a substance into poor soil layers to fill voids and enhance cementitious properties. This technique has proven invaluable in addressing challenges related to open-cut excavations, foundations, and tunnels, offering practical solutions for mitigating associated problems.

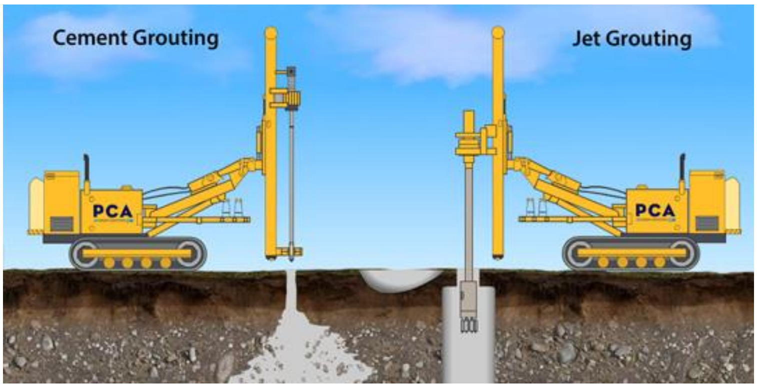


Figure 2.2: Pictorial representation of cement grouting and jet grouting

By introducing grouting, the permeability of the soil is substantially reduced, leading to a notable increase in its bearing capacity. The conventional approach to grouting typically entails the insertion of cement, lime, or a combination of both into the targeted soil layer. On occasion, fine sand or fine-fissured rocks are employed as grouting agents. However, contemporary engineering practices have evolved to embrace non-conventional methods, incorporating various chemicals such as colloidal silica, sodium silicate, micro fine cement, polymers, and resins for grouting purposes. These innovative techniques have expanded the possibilities and efficacy of soil improvement endeavours.

Nevertheless, it is essential to acknowledge that grouting is not without its challenges. One prominent drawback lies in the potential contamination of the groundwater table, which demands meticulous attention and environmental safeguards to mitigate any adverse effects. Additionally, the cost associated with grouting projects can be a significant consideration, prompting engineers to carefully weigh its benefits against financial constraints. (Spagnoli et. al, 2020)

2.4.3 Cement stabilisation

Cement stabilization is a widely employed soil improvement technique wherein an optimal percentage of cement is incorporated into the soil. This addition of cement initiates a significant reaction with water, known as hydration, which plays a crucial role in strengthening the soil. The strength of the soil is greatly influenced by the bonding that occurs due to the hydration process, where cement particles react with water to form crystals. These crystals interconnect and contribute to the overall increase in the compressive strength of the soil. Furthermore, the induced crystals also lead to an increase in the unit weight of the soil, contributing to its enhanced stability and load-bearing capacity.

Over the years, cement stabilization has been extensively utilized and proven effective in various construction applications. However, despite its advantages, modern times have witnessed a shift away from its widespread preference due to certain environmental risk factors associated with its use, as well as the relatively high cost of implementation. The environmental concerns primarily stem from the potential for cement stabilization to impact the surrounding ecosystem, such as leaching of harmful substances into the groundwater or soil and disrupting the natural balance of the area. As a result, engineers and environmentalists have become more cautious and considerate about the potential ecological consequences when opting for this technique. Moreover, the cost implications of cement stabilization have also become a significant consideration, especially in large-scale construction projects. As construction practices evolve, alternative and more eco-friendly stabilization methods have emerged, seeking to strike a balance between effective soil improvement and sustainability. (EuroSoilStab, 2002)

2.4.4 Lime stabilization

Lime stabilization stands out as a widely used and cost-effective method of additive stabilization, making it a popular choice among various soil improvement techniques. This process involves the careful addition of lime to the soil in varying percentages, ensuring it reaches its optimum level for effective results. Lime's remarkable ability to enhance the soil's cementation properties through cation exchange is the key mechanism behind its success in stabilizing soils.

Figure 2.3: Truck spreading lime for stabilisation of soil

The introduction of lime into the soil initiates a transformative process, wherein the cations in the lime interact with the soil particles, leading to improved bonding and increased strength. This cementation effect plays a crucial role in stabilizing the soil, making it more resilient and capable of withstanding various environmental stresses.

A series of experimentation studies have shed light on the positive impact of lime stabilization. Remarkably, even with a mere 2 percent addition of lime, significant changes were observed in the plastic limit of several soils, marking a notable increase of up to 40%. Such findings underscore the potency of lime stabilization as a versatile and potent technique in geotechnical engineering. One of the remarkable aspects of lime stabilization is its versatility, as it can be effectively employed with a diverse range of soil types, each presenting its unique challenges and characteristics. Moreover, lime stabilization has proven to be compatible with various construction applications, including road subgrade improvement, foundation stabilization, and the reinforcement of slopes. While lime stabilization offers several advantages, it is essential to recognize that its success largely depends on factors such as soil composition, environmental conditions, and the level of expertise in executing the stabilization process. Engineers and geotechnical specialists are continuously refining and optimizing the lime stabilization technique to ensure its consistent and reliable application across various projects. (Sherwood, 1993)

2.4.5 Chemical stabilization

One of the finest methods for enhancing the engineering qualities of poor soil is chemical stabilisation. One of the most prevalent compounds for stabilising deficient soils is calcium chloride. When calcium chloride is applied to soil, it functions as a soil flocculent, aiding in the process of compaction. For stabilising purposes, sodium silicate has also been used. The availability of the chemicals and their mixing with in-situ soil are the disadvantages of chemical stabilisation. (Rogers et. al, 1993)

2.4.6 Fly ash stabilisation

Fly ash stabilization has emerged as a highly sought-after technique in contemporary geotechnical engineering, owing to the abundant availability of fly ash, a by-product of coal-fired power plants. This method has gained popularity due to its quick action and economic cost, making it a preferred choice for enhancing the engineering properties of soils. Numerous studies have demonstrated the efficacy of fly ash in improving soil properties, particularly in terms of its binding capabilities. When fly ash is added to the soil, a chemical reaction occurs, leading to increased cohesion and stability. Although the results are promising, it is essential to note that they may not be on par with the outcomes achieved through lime and cement stabilization, which remain the gold standard in certain scenarios.

However, like any soil improvement technique, fly ash stabilization comes with its limitations and potential challenges. One significant concern arises from the production of sulphuric matters when fly ash reacts with moisture or water. This can result in soil expansiveness, leading to a loss of strength and compromising the stability of the stabilized soil. Engineers and researchers are diligently working to address these issues and find ways to mitigate the potential negative effects. Another noteworthy challenge associated with fly ash stabilization is the phenomenon of slaking. Slaking occurs when the stabilized soil comes into contact with water, leading to the disintegration of the soil particles and subsequent loss of strength. This poses a potential risk, especially in regions with varying moisture conditions or during periods of heavy rainfall.

Figure 2.4: Fly ash to be used in stabilisation

Despite these challenges, ongoing research and development efforts aim to optimize fly ash stabilization techniques and overcome its limitations. By understanding the mechanisms behind soil expansiveness and slaking, engineers can devise strategies to counteract these effects and enhance the overall performance of fly ash stabilization. Moreover, advancements in geotechnical testing and the incorporation of additives to mitigate potential issues are being explored to further improve the effectiveness of fly ash stabilization. By leveraging the benefits of this environmentally friendly and widely available material, engineers can harness its potential to create stable and sustainable foundations for various construction projects. (Maclaren et. al, 2003)

2.4.7 Geotextiles stabilisation

Geotextiles, an essential component in modern geotechnical engineering, are fabricated from synthetic materials such as polyester, polyvinyl chloride, polyethylene, nylons, and other resilient compounds. These versatile materials come in three primary forms: grid, woven, and non-woven, each offering distinct advantages depending on the specific application (Tiwari et al., 2021). One of the standout features of geotextiles is their impressive compressive strength, which plays a pivotal role in stabilizing poor soils and enhancing overall stability. When embedded in such soils, geotextiles effectively contribute to an increase in compressive strength, bolstering the structural integrity and longevity of the construction (Tiwari et al., 2021).

Particularly in the context of unpaved roads, soft soils often present a challenge that can be effectively addressed through geotextile stabilization. Studies from the past have consistently demonstrated that the load-bearing capacity and strength of base course and subgrade materials witness notable improvements when non-biodegradable materials are employed, such as geotextiles, fibres, geo-composites, and geogrids. These materials provide the necessary reinforcement and support to withstand heavy traffic loads, prevent rutting, and mitigate settlement issues, offering an effective solution for creating durable and reliable roadways (Tiwari et al., 2021).

Figure 2.5: Geotextile implementation on road construction

However, it is essential to acknowledge that geotextile stabilization does come with certain drawbacks that warrant consideration. One of the primary concerns is the relatively high cost associated with these materials, which can impact the overall project budget. Moreover, large-scale field testing may be necessary to ensure the optimal performance and suitability of geotextile stabilization in a specific environment. (EuroSoilStab, 2002). Despite these challenges, engineers and researchers continue to explore innovative approaches and refine geotextile stabilization techniques. Ongoing advancements in material technology and construction practices seek to address cost concerns and streamline testing protocols, ultimately making geotextile stabilization a more feasible and efficient solution (EuroSoilStab, 2002)

2.4.8 Other stabilisation techniques

Numerous innovative soil stabilization techniques have been introduced, expanding the array of options available to geotechnical engineers. One such method involves the addition of bitumen to the soil, resulting in enhanced water resistance and increased cohesive forces between soil particles. As a consequence, the soil's overall strength experiences a noticeable improvement. Thermal stabilization represents another fascinating approach, wherein the temperature of the soil is manipulated through cooling or heating. When the soil is subjected to low temperatures, the moisture within its pores freezes, forming ice crystals. This transformation contributes to a substantial increase in the soil's strength. On the contrary, heating the soil to higher temperatures leads to a reduction in moisture content. Consequently, the electric repulsion forces between the soil particles decrease, promoting an additional rise in the soil's strength (Filimonov et al., 2013).

Electrical stabilization is yet another intriguing technique that has been explored in various studies. By applying direct current to two ends of a sample of soil, the water within the soil's pores migrates towards the cathode of the current circuit. This movement is driven by the presence of cations in the water, facilitating a process known as electro-osmosis. This particular method has proven effective for draining cohesive soils, thereby enhancing their engineering properties (EuroSoilStab, 2002). While these innovative stabilization methods offer promising results, they are not without their considerations. One significant factor limiting the common use of electrical stabilization is the cost associated with its implementation. Engineers must carefully assess the benefits and weigh them against the financial implications when considering this approach for soil improvement projects (Filimonov et al., 2013).

Overall, the ever-expanding repertoire of soil stabilization techniques presents exciting possibilities for enhancing soil properties and optimizing construction projects. As research and development continue to advance, geotechnical engineers are equipped with a diverse toolkit, allowing them to tailor solutions to specific soil conditions and project requirements. By striking a balance between effectiveness, feasibility, and cost, engineers can harness the potential of these novel stabilization techniques, fostering sustainable and resilient infrastructure development (EuroSoilStab, 2002).

2.4.9 Biopolymers

Biopolymers, natural polymers derived from living organisms and cells, have recently garnered significant attention from researchers in the geo-environmental engineering domain. A wealth of studies has showcased the diverse applications of biopolymers, ranging from erosion reduction in soils to enhancing soil strength and hydraulic conductivity. These remarkable properties have piqued the interest of scientists seeking sustainable and eco-friendly soil stabilization solutions (Lear and Lewis, 2012). The bio-soil stabilization technique, in particular, has emerged as a promising avenue, offering a multitude of positive outcomes. Notably, it exhibits self-proliferation, enhancing the mechanical properties of the soil and demonstrating resistance to biodegradation. Moreover, its low environmental impact is a key advantage that aligns with the principles of eco-conscious engineering (Pham et al., 2013).

Two primary mechanisms underpin bio-stabilization. Firstly, biopolymers contribute to the precipitation of minerals within the soil pores, bolstering the soil structure. Secondly, they facilitate the production of a biofilm that envelops the surface of soil particles, thereby enhancing particle contact and further improving soil cohesion (Lear and Lewis, 2012). To maximize the efficacy of biopolymers, biogenic excrement has emerged as a preferred method over cultivating microbes directly in the soil. This approach overcomes various drawbacks associated with traditional biological techniques, such as the need for nutrient and food injection for microbes, extended growth periods, excrement precipitation, and challenges in clayey soil applications (Chang et al., 2012).

By harnessing naturally occurring and edible biopolymers, the environmental impact is significantly reduced, making them an eco-friendly and sustainable choice. Among the various polysaccharide groups tested for soil treatment, cellulose stands out as highly potent due to its gelation characteristics, leading to the production of stable and thick reinforcement (Adibkia et al., 2007). On the other hand, curdlan, with its clogging potential, has demonstrated promise in large-scale soil stabilization through grouting (Ivanov and Chu, 2008). Additionally, the presence of beta-glucan in soil has been linked to notable improvements in the mechanical properties of the soil matrix (Chang et al., 2015).

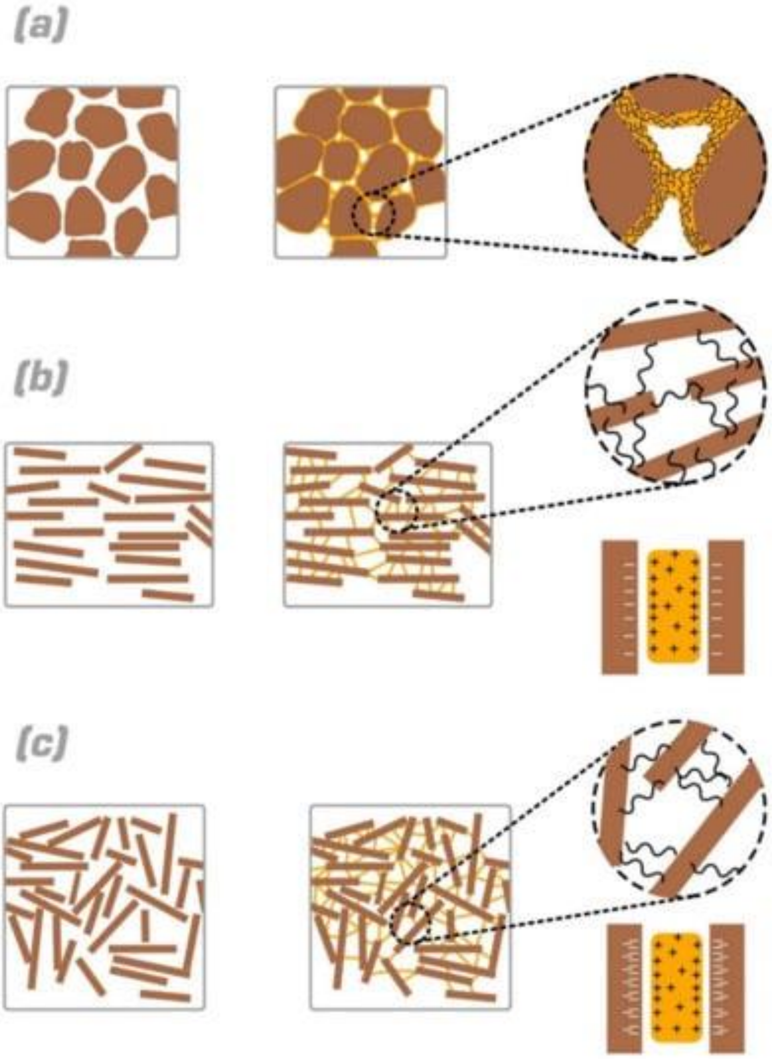


Figure 2.6: Biopolymers interacting with different types of clays.

As the exploration of biopolymers for soil stabilization continues, it opens up a realm of possibilities for sustainable and environmentally friendly engineering practices. By leveraging the unique properties of biopolymers and optimizing their applications, researchers and engineers can pave the way for more resilient and ecologically sensitive infrastructure development. As advancements in biopolymer technology progress, the potential for cost-effective and eco-conscious soil stabilization solutions will only continue to grow (Adibkia et al., 2007).

2.5 Microbial induced calcite precipitation

Enzyme induced carbonate precipitation (EICP) method and microbe induced calcite precipitation (MICP) method are developed which are considered environmentally friendly methods (StocksFisher et al., 1999; DeJong et al., 2006, 2010; Yasuhara et al., 2012; Hamdan and Kavazanjian, 2016). In these methods, bacteria are added to the soil which can induce calcite precipitation and increase the cementitious properties of the soil. The calcite precipitation relies upon the hydrolysis of urea in which enzyme urease act as catalyst (Khodadadi et al., 2017). The field application of these methods is still under research process (Van Paassen, 2011; Gomez et al., 2015). Another environmentally friendly method microbially induced desaturation and precipitation (MIDP) is also proposed (Rebata-Landa and Santamarina, 2012; He et al., 2013; He and Chu, 2014).

Fungus has been also proposed for the MICP. Many fungi are well known for the production of a reasonable amount of carbon dioxide (CO2) during their growth. The proteins and CO2 released from the fungus *Fusarium oxysporum* were reacted with the aqueous Ca2+ ions which resulted in the production of calcium carbonate (CaCO3) crystals of different morphology which were truly biogenic. In addition, the hypha of the fungi also contributes to the increase of the strength of soils. Rhizopus oligosporus has been used to increase the shear strength of the loose sand. Inoculum of Rhizopus Oligosporus were mixed in the loose sand and the compressive strength was examined for different curing periods. Through scan electron microscope (SEM), mycelium and hypha binding the particles of the loose sand were seen. Below are some of applications of MICP. MICP can be utilized for enhancing the load-bearing capacity and stability of foundation soils. By injecting the MICP solution into the weak soil beneath a structure, the soil's strength and stiffness can be significantly improved, reducing settlement and increasing the structural integrity of the foundation. Weak soils on slopes are susceptible to landslides and erosion. MICP can be utilized to stabilize these slopes by improving the cohesion and shear-strength of the soil, also reduces the risk of failure and enhancing slope stability.

MICP can help mitigate soil erosion by strengthening the soil matrix and binding soil particles together. This is particularly beneficial in areas prone to erosion, such as riverbanks, coastal regions, and construction sites. Weak subgrade soils can pose challenges in pavement and road construction. MICP can be employed to improve the strength and stability of these soils, providing a solid foundation for the pavement layers and reducing the need for excessive excavation or costly soil replacement.

2.6 Wetting and drying cycles

Wetting and drying cycles are fundamental phenomena in geotechnical and civil engineering that profoundly influence the behaviour and performance of soils, materials, and structures.

Engineers and researchers must consider these cycles when designing, analyzing, and maintaining various projects to ensure the safety, stability, and durability of infrastructure. By comprehending the intricate relationships between moisture content, soil mechanics, and engineering structures, professionals can make informed decisions that contribute to the overall success and sustainability of geotechnical and civil engineering endeavours (Rajaram er al., 1999).

Wetting and drying cycles, also known as wet-dry cycles or wetting-drying cycles, play a pivotal role in geotechnical and civil engineering practices. These cycles involve the alternation between periods of moisture accumulation (wetting) and moisture depletion (drying) in soils and materials. The dynamic interplay between these cycles significantly influences the behaviour and properties of materials used in construction and geotechnical applications. This article explores the importance of wetting and drying cycles, their effects on soil mechanics, and their relevance to various aspects of geotechnical and civil engineering (Groffman et al., 1988).

2.6.1 Soil suction and strength

Wetting and drying cycles induce changes in soil suction, which is the ability of soil to retain water against the force of gravity. During wetting, soil suction decreases as water fills pore spaces, reducing the strength of soil and increasing its compressibility. Conversely, during drying, soil suction increases, enhancing soil strength and stiffness. Understanding these variations is crucial in designing stable foundations, retaining walls, and other structures (Groffman et al., 1988).

2.6.2 Volume changes and settlement

Wetting and drying cycles cause volume changes in soil due to the fluctuating water content. Swelling occurs during wetting as clay particles absorb water and expand, leading to potential heave and structural damage. On the other hand, drying induces shrinkage and settling as water is lost from the soil, impacting the stability and long-term performance of engineered structures (Diel et al., 2019).

2.6.3 Soil erosion and slope stability

In geotechnical and civil engineering, maintaining slope stability is paramount. Wetting and drying cycles affect slope stability by influencing the erosion and consolidation of soil particles. Prolonged wetting can lead to increased pore water pressure, reducing the soil's effective stress and potentially triggering landslides. Careful consideration of these cycles is crucial when designing and managing slopes, embankments, and cuttings (Groffman et al., 1988).

2.6.4 Pavement design and performance

Wetting and drying cycles also impact pavement design and performance. Repeated cycles can lead to pavement cracking and deformation due to the expansion and contraction of underlying soils. Proper consideration of moisture variations and their effects on subgrade soils is essential in designing durable and resilient pavements (Rajaram er al., 1999; Groffman et al., 1988).

2.6.5 Soil-Structure interaction

In civil engineering projects, structures interact with underlying soil. Wetting and drying cycles can induce differential settlements, potentially compromising the structural integrity of buildings and infrastructure. Predicting and mitigating these effects through proper foundation design and construction techniques is vital to ensuring the long-term stability of structures.

2.6.6 Durability of construction materials

Wetting and drying cycles can accelerate the deterioration of construction materials like concrete, masonry, and metal. These cycles contribute to freeze-thaw damage, corrosion, and degradation of materials over time. Engineers must account for these effects when selecting materials and designing structures to ensure longevity and minimize maintenance costs (Diel et al., 2019).

2.6.7 Environmental considerations

Wetting and drying cycles also impact the behaviour of engineered systems in response to environmental changes. Understanding how these cycles interact with climate fluctuations, such as rainfall patterns and temperature variations, is crucial for developing resilient infrastructure that can adapt to changing conditions (Rajaram er al., 1999).

2.7 Soil properties

2.7.1 Soil gradation

Gradation of soil refers to the arrangement and distribution of particles of different sizes within a sample of soil. This characteristic is essential in understanding the behaviour and engineering properties of soils, as it directly influences factors like permeability, compaction, and shear strength. Soil particles are classified into different size fractions, typically gravel, sand, silt, and clay, based on their diameters. The gradation of soil is often depicted using a gradation curve, which is a graphical representation of the percentage of soil particles retained on each sieve size in a logarithmic scale. This curve provides insights into the soil's texture and composition (Nagraj et al., 2016).

A well-graded soil, also known as a well-graded aggregate, contains a balanced distribution of particle sizes, from coarse to fine. This kind of gradation offers improved compaction and drainage properties due to the interlocking nature of the particles, resulting in higher stability. On the other hand, a poorly graded soil has an uneven distribution of particle sizes and can lead to voids, causing reduced compaction efficiency and weaker mechanical properties. The concept of gradation is crucial in civil engineering and construction. For instance, in road construction, well-graded soils are preferred as they offer better load-bearing capacity and drainage, which contribute to the durability of the road. In the field of geotechnical engineering, the gradation of soil influences the design of foundations, embankments, and retaining walls (Jun-gao et al., 2015).

2.7.2 Atterberg limits

Important concepts in soil mechanics that describe the behaviour of soils in terms of their moisture content and plasticity include liquid limit, plastic limit, and plasticity index. These characteristics are crucial for determining the engineering behaviour of soils and are required for many geotechnical and construction applications.

2.7.2.1 Liquid limit (LL)

The moisture level at which a soil begins to change from a plastic, semi-solid state to a liquid state is known as the liquid limit of the soil. It represents the level of moisture at which the consistency and behaviour of the soil change. The Casagrande's method, which involves repeatedly grooving a sample of soil and adding water until the two sides of the groove just touch when subjected to 25 blows in a typical liquid limit device, is used to determine the liquid limit. The soil's liquid limit is determined by the moisture content at this time.

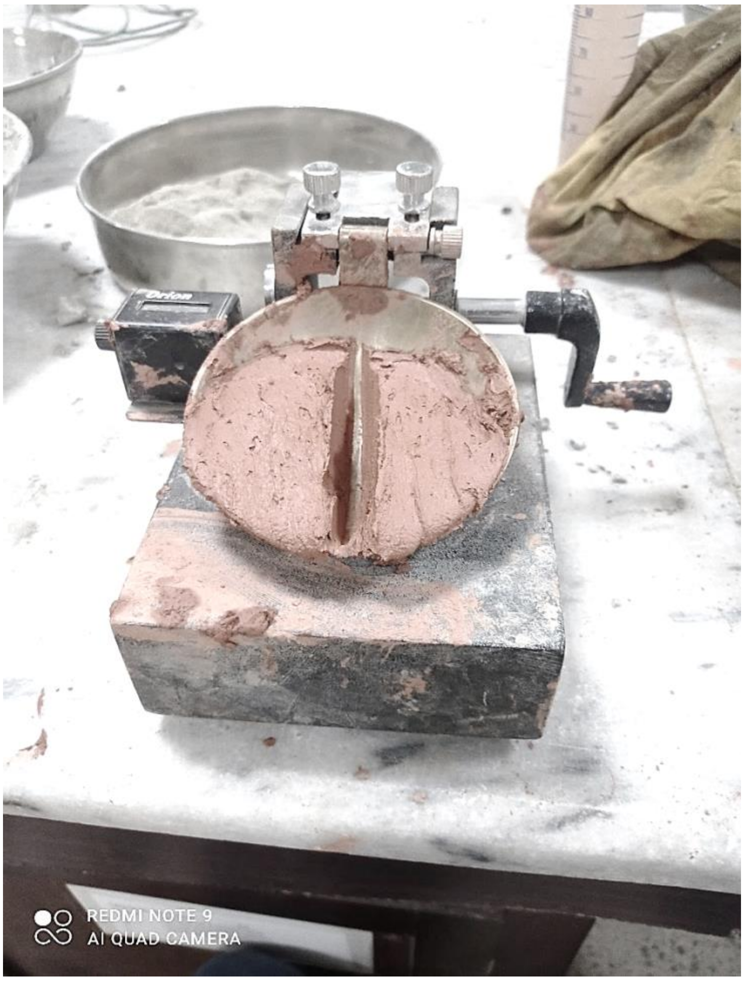


Figure 2.7 : Casagrande's Apparatus used for liquid limit

2.7.2.2 Plastic limit (PL)

The lowest moisture content at which a soil can still be rolled into a thread of 3 mm diameter without crumbling is known as the plastic limit of the soil. It denotes the separation of the soil's plastic and semi-solid states. By forming a sample of soil into threads and gradually lowering the moisture content until the threads begin to break, the plastic limit is ascertained. The soil's plastic limit is determined by the moisture content at this time.

2.7.2.3 Plasticity index (PI)

The plasticity index of a soil is a numerical measure of its plasticity and is calculated as the difference between the liquid limit and the plastic limit. To find the plasticity index, we subtract liquid limit from the plastic limit.

2.7.3 Specific gravity

Figure 2.8: Pycnometer on a hot plate for conducting specific gravity test

Specific gravity, also known as relative density, is the ratio of mass of soil particles of the given volume to the mass of water of an equal volume at a specified temperature.

2.7.3.1 Pycnometer method

To determine specific gravity of any soil in a lab setting, a test known as the pycnometer method or bottle method is commonly employed. The sample is firstly sieved to remove any coarse particles or debris. A clean and dry pycnometer, which is a small container with a known volume and a tight-fitting lid, is weighed. Distilled water or deionized water is inserted into the pycnometer, and its weight is recorded. The pycnometer is then filled with water and weighed again to determine the mass of the water-filled pycnometer. A specific volume of the dried sample of soil is placed in the pycnometer. The lid is secured tightly to prevent any soil particles from escaping. The pycnometer is then filled with water, and any trapped air bubbles are removed by gently tapping the container. The pycnometer is weighed again to determine the mass of the pycnometer, soil, and water combined.

The specific gravity of the soil can be calculated using the following formula:

Specific Gravity = (Mass of Soil + Pycnometer + Water) / (Mass of Pycnometer + Water) - (Mass of Pycnometer)

The specific gravity values obtained from the test provide valuable information about the soil's composition. Generally, the specific gravity of soil particles ranges between 2.60 to 2.75. If the specific gravity is lower, it indicates the presence of organic materials or lightweight particles. If it is higher, the soil may contain heavy minerals or dense particles. The specific gravity of soil is used in various geotechnical analyses and calculations, including the determination of the void ratio, porosity, and the degree of saturation of soil. Additionally, it aids in classifying soil types, assessing their relative densities, and estimating their shear strength.

2.7.4 Optimum moisture content (OMC) and maximum dry density (MDD)

The optimum moisture content (OMC) of soil is a critical parameter in geotechnical engineering that refers to the moisture content at which a soil exhibits its maximum density during compaction. It represents the ideal balance between moisture and compaction effort, resulting in the highest possible dry density of the soil. Achieving the OMC is essential for constructing stable and durable structures. Understanding the OMC is vital for designing and constructing foundations, embankments, and other earthworks. Engineers use this knowledge to optimize compaction methods and achieve the desired soil characteristics for various projects. By attaining the OMC, construction professionals ensure the long-term stability and performance of structures by creating a solid foundation that can withstand imposed loads and environmental stresses (Gurtug et al., 2004).

Determining the OMC involves conducting a Proctor compaction test, where samples of soil are compacted using a standardized compaction effort and varying contents of moisture. The DD of compacted soil is measured for each moisture content level. The moisture content at which the maximum dry density is obtained is the OMC. The significance of OMC lies in its influence on the engineering property/properties of the soil. Below the OMC, insufficient moisture leads to inadequate compaction and reduced soil density, resulting in weakened load-bearing capacity. Conversely, excessive moisture above the OMC can lead to reduced soil cohesion, increased pore water pressure, and decreased strength.

Maximum dry density (MDD) is a fundamental property in geotechnical engineering that refers to the highest achievable density of a soil when compacted under specific conditions. It is a key factor in determining the optimal compaction effort for construction projects, as it provides insights into the soil's ability to resist deformation and support structures (Connelly et al., 2008).

The significance of MDD lies in its application to achieve the desired soil compaction during construction. Engineers use MDD values to select appropriate compaction methods, machinery, and moisture levels to ensure that the soil reaches its maximum density. Proper compaction ensures that structures are built on a stable foundation, reducing settlement and improving overall structural integrity (Gurtug et al., 2004).

2.7.5 Unconfined compressive strength (UCS)

Unconfined compressive strength (UCS) is a geotechnical property depleted to assess the shear strength of a sample of soil in its natural state, without the need for specialized confining pressure. This property is determined through a laboratory test in which a cylindrical sample of soil is subjected to axial loading until failure occurs. UCS is a mechanical property in geotechnical engineering that measures the capacity of a soil to withstand axial loading without any lateral confinement. It plays a crucial role in assessing the stability and load-bearing capacity of soil structures, foundations, and earthworks. The UCS test is a widely used laboratory procedure to determine this strength parameter (Bodour et al., 2022).

The UCS test holds significance in various aspects in the field geotechnical engineering. It helps engineers understand the soil's bearing capacity, aiding in the design of stable and secure foundations for structures. It is particularly important in assessing the suitability of soil for shallow foundations. UCS values contribute to evaluating the stability of slopes, embankments, and retaining walls. This information is essential for mitigating risks associated with soil failure and landslides. Engineers use UCS data to predict the behaviour of soil during tunnelling and excavation, ensuring safety and stability in underground construction projects. UCS values help classify and assess the quality of construction materials, such as rock and cohesive soils, for various engineering applications (Sunitsakul et al., 2012).

2.7.6 Fourier transform infrared

FTIR is used to assess the quality of construction materials like clay, cement, and asphalt. It helps determine the presence of additives, contaminants, and the level of curing in construction materials. FTIR aids in identifying pollutants and contaminants in soils, making it valuable for environmental monitoring and remediation efforts. FTIR can track changes in soil composition due to weathering, chemical reactions, or other environmental factors, aiding in long-term stability assessments. While FTIR is a powerful technique, its interpretation requires expertise and reference data for accurate analysis. Advanced data processing and comparison with established spectral libraries are often necessary to deduce meaningful information about soil properties.

In geotechnical applications, FTIR is employed to study various aspects of soils. FTIR helps identify mineralogical components in soils by detecting characteristic absorption peaks associated with specific minerals. This aids in understanding the composition and origin of soil materials. FTIR is used to analyze organic compounds present in soils, such as humic and fulvic acids. This information is crucial for assessing soil fertility, contamination, and degradation processes. The functional groups identified by FTIR provide valuable information for soil classification based on composition. Different soils exhibit distinct spectral patterns, allowing for accurate classification and differentiation (Mujah et al., 2017).

This non-destructive method provides valuable insights into the composition and structure of soil, aiding in environmental, agricultural, and geological studies. During an FTIR test of soil, a finely powdered sample is prepared and placed in the spectrometer. The instrument emits an infrared beam that interacts with the soil's molecules, causing them to vibrate at characteristic frequencies. By measuring the energy absorbed by the sample at different frequencies, a unique spectrum is generated. This spectrum acts as a fingerprint, revealing the presence of various organic and inorganic compounds, such as minerals, organic matter, and contaminants. FTIR analysis offers several advantages, including rapid results, minimal sample preparation, and the ability to detect even trace amounts of substances. Researchers and environmentalists utilize FTIR to monitor soil quality, assess pollution levels, and identify specific functional groups present in organic matter. Furthermore, the technique's non-destructive nature enables repetitive measurements on the same sample, facilitating longitudinal studies (Kalkan, 2020).

In summary, Fourier Transform Infrared (FTIR) spectroscopy is an essential tool in geotechnical engineering for characterizing soil properties and composition. It helps identify minerals, organic compounds, and functional groups present in samples of soil, facilitating soil classification, quality assessment, and environmental analysis. This technique enhances the understanding of soil behaviour and influences decision-making in various geotechnical and environmental projects (Kalkan, 2020).

2.7.7 X-Ray diffraction

X-ray Diffraction (XRD) is a vital tool in geotechnical engineering for determining the mineralogical composition and crystal structure of samples of soil. It assists in identifying minerals, quantifying their abundance, and predicting soil behaviour, influencing decision-making in areas ranging from foundation design to construction material selection. XRD plays a crucial role in understanding soil properties, behaviour, and geological history, making it an indispensable tool in geotechnical analysis. XRD helps identify minerals present in samples of soil by matching the observed diffraction pattern with reference patterns of known minerals. This aids in determining the mineralogical composition and the potential reactivity of soil components. XRD can quantify the relative abundances of different minerals within a sample of soil, offering insights into the geological history and processes that influenced soil formation. In an XRD test of soil, finely ground samples are exposed to X-rays, resulting in the scattering of X-ray photons by the crystal lattice of the minerals within the soil. By measuring the angles and intensities of the diffracted X-rays, a unique diffraction pattern is generated. This pattern acts as a distinctive fingerprint, allowing researchers to determine the types and relative abundances of minerals present in the soil (Tang et al., 2020).

XRD analysis offers ability to analyze both crystalline and semi-crystalline materials. It is mainly used in geology, environmental science, and archaeology to unknot the geological history of soil, assess soil stability, and identify mineralogical changes due to natural or anthropogenic influences. Researchers can also infer soil properties such as particle size, mineral weathering, and soil maturity through XRD results. Additionally, this technique aids in predicting soil behaviour, fertility, and potential for nutrient release. XRD is particularly useful for analyzing clay minerals, providing information about their type (e.g., kaolinite, montmorillonite) and their impact on soil properties such as plasticity, swelling, and shrinkage. The mineralogical information obtained through XRD can offer insights into the behaviour of soils under different conditions (Zhao et al., 2014).

For example, certain minerals may contribute to soil expansion or contraction upon wetting and drying. XRD can be used to assess the mineralogical composition of construction materials like cement and concrete, aiding in quality control and ensuring proper material performance. XRD helps geotechnical engineers understand the geological history of a site by identifying the types of minerals present. This information is valuable for assessing the site's suitability for various engineering applications. XRD's ability to provide detailed mineralogical information about samples of soil enhances the understanding of soil behaviour and properties. However, the technique requires expertise in both data collection and interpretation. Comparing XRD spectra to established databases and conducting thorough analyses are essential to accurately interpret results (Qabany et al., 2014).

2.7.8 Scanning electron microscopy

Scanning electron microscopy (SEM) is an advanced imaging technique that plays a critical role in geotechnical engineering by providing high-resolution images of samples of soil at the microscale. SEM allows engineers and researchers to visualize the surface morphology, mineral composition, and particle interactions within soils, offering valuable insights into their behaviour and properties. SEM is a powerful technique of imaging that offers detailed insights into the microstructure and surface morphology of samples of soil. This method utilizes electron beams to examine the soil's surface at high magnifications, providing valuable information about its particle distribution, texture, and mineralogical composition. In an SEM test of soil, a minute part of the sample is coated with a thin layer of conductive material and placed in the microscope's vacuum chamber (Wang et al., 2022).

A focused electron beam scans the sample's surface, causing various interactions such as secondary electron emission. These interactions generate signals that are transformed into high-resolution images, revealing the topographical features of the soil's particles and aggregates. SEM analysis provides essential information about soil structure, including particle shape, size, and arrangement. Researchers can identify mineral types, study soil aggregation, and observe the effects of weathering and degradation on soil particles (Liu et al., 2019).

The technique's ability to visualize microorganisms and their interactions within the soil matrix is also invaluable in microbiological studies. Furthermore, SEM's versatility allows for the examination of various soil types, from mineral-rich to organic-rich soils. It aids in understanding soil erosion, compaction, and the interactions between soil and plant roots. This information contributes to improved soil management practices, agricultural productivity, and environmental conservation.

SEM is used to study soil porosity and pore network connectivity, helping to understand fluid flow, drainage behaviour, and storage capacity. SEM allows visualization of interactions between soil particles, such as particle-to-particle contact, cementation, and soil structure development. SEM is used to analyze soil failure mechanisms, helping to understand the causes of soil instability and deformation. While SEM provides valuable information, it requires specialized equipment, sample preparation, and interpretation skills. Sample preparation often involves coating samples with a conductive layer to prevent electron charging and enhance imaging quality. Additionally, image interpretation requires expertise to distinguish mineral phases and other features accurately. In conclusion, SEM is a powerful tool in geotechnical engineering for visualizing and analyzing samples of soil at the microscale. It enhances the understanding of soil behaviour, mineral composition, particle interactions, and pore structure. By revealing intricate details of soil properties, SEM contributes to the development of more accurate geotechnical analyses and engineering solutions (Liu et al., 2019; Wang et al., 2022).

Chapter 3

Materials and Methodology

3.1. Materials

3.1.1 Fungus cultivation of *Fusarium oxysporum* on Agar plates

Fusarium oxysporum is a filamentous fungus commonly used in research and industrial applications. Cultivating *F. oxysporum* on agar plates is a fundamental technique that allows researchers to study its morphology, growth characteristics, and interactions with other microorganisms. This guide provides step-by-step instructions for growing *F. oxysporum* on agar plates.

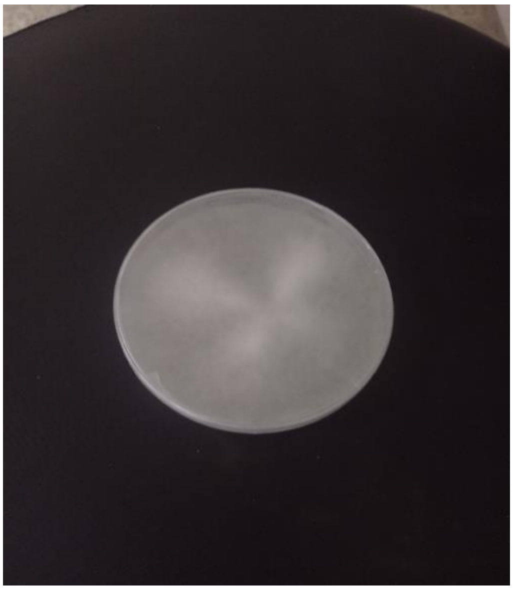


Figure 3.1: *Fusarium oxysporum* grown in a Petri dish

The materials, devices and other specifications in these tests include Fusarium *oxysporum* spore suspension or culture, agar plates (Potato Dextrose Agar or similar), inoculation loop or needle, incubator or warm, dark area (25-28°C), sterile distilled water, laminar flow hood or sterile workspace, alcohol or disinfectant for sterilization, and Petri dish. Potato Dextrose Agar (PDA) was sterilized for 15 minutes in autoclave. Sterilized agar was poured into sterile Petri dishes and allowed to solidify. A *Fusarium oxysporum* spore culture was obtained from ASAB laboratory, NUST. The spore concentration was adjusted using sterile distilled water to achieve the desired inoculum density. An inoculation loop or needle was flame sterilized until it turned red-hot and then it was allowed to cool. The *F. oxysporum* spore suspension was gently spread evenly over the surface of the agar plate. To prevent contamination, the preparation of the fungal inoculum was being done under sterile conditions. The Petri dish was sealed using parafilm which is used as a sealing material in ASAB laboratory.

The sealed plates were placed in an incubator or a warm, dark area with a temperature of 25-28°C. The fungus was allowed to grow undisturbed for several days to weeks, depending on the visual results. The growth of *Fusarium oxysporum* on the agar plates was being regularly observed. Any signs of contamination were monitored and contaminated plates were discarded. The growth of fungus was kept monitored after 5 days so that a proper grown plate of the fungus can be extracted for using. From the Figure 3.1, we can see that the fungus has grown on the agar plate after seven days. We can see the grown Mycelium on the plate which is a sign of the proper growth of the fungus. Once the fungus was grown sufficiently, a portion of the mycelium to a new agar plate was carefully transferred for subculturing and further experimentation. Proper aseptic technique was maintained to prevent contamination during subculturing.

Figure 3.2: *Fusarium oxysporum* inoculum prepared in laboratory

3.1.2 Preparation of 0.25 M calcium chloride solution

A 0.25 M (molar) solution of calcium chloride ($CaCl_2$) is commonly used in various scientific and laboratory applications. This solution was prepared by accurately measuring the mass of calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) and dissolving it in a calculated volume of distilled water. The detailed methodology outlining the step-by-step procedure for preparing a 0.25 M calcium chloride solution is as follows.

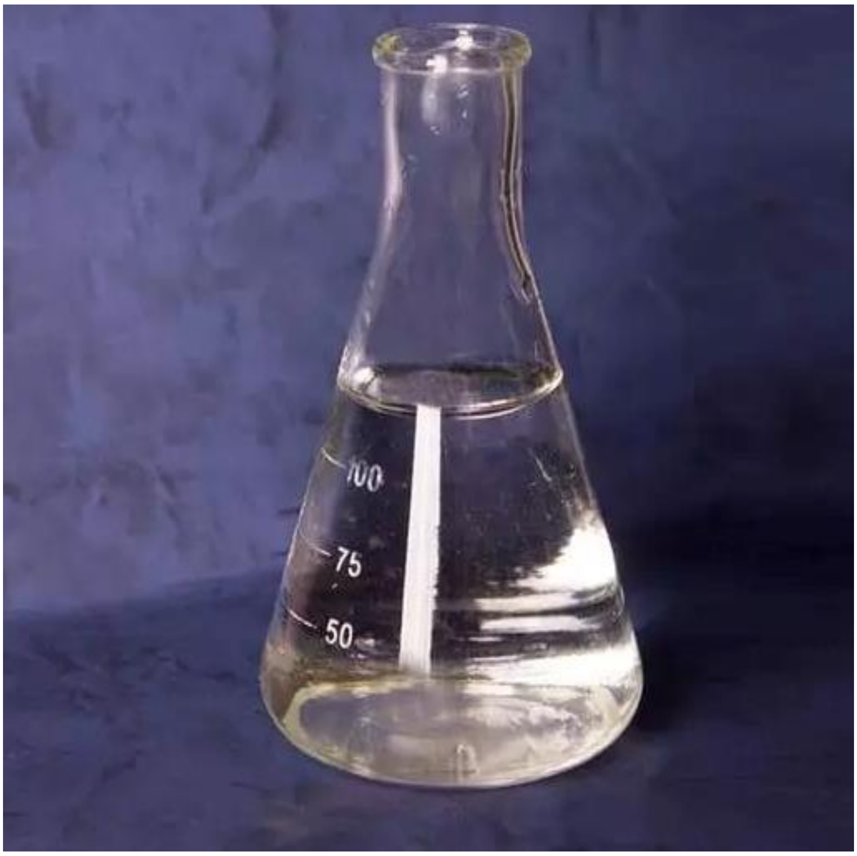


Figure 3.3: 0.25 M solution of calcium chloride

The materials and devices involve in these tests include calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$, analytical balance, distilled water, graduated cylinder or volumetric flask, stirring rod or magnetic stirrer, weighing boat or weighing paper, container or bottle for solution storage, and safety goggles and lab coat. The solution was prepared in a well-ventilated area under a fume hood, as calcium chloride can release fumes. The molar mass of calcium chloride ($CaCl_2$) and calcium chloride dihydrate ($CaCl_2 \cdot 2H_2O$) was determined by adding the atomic masses of each constituent element (Ca, Cl, H, and O). The molar mass of $CaCl_2 \cdot 2H_2O$ is approximately 147.02 g/mol. The mass of calcium chloride dihydrate was calculated which was needed to prepare 0.25 moles.

The mass molar equation (mass, g = moles × molar mass) was used for this purpose. The analytical balance was set to zero using an empty weighing boat and paper. The calculated mass of calcium chloride dihydrate was carefully added to the weighing boat. Touching the substance directly was avoided. The weighed calcium chloride dihydrate was added into a clean and dry container. A small volume of distilled water was added to the container and stirred gently using a stirring rod or magnetic stirrer to facilitate dissolution.

More distilled water was added to the container while stirring until all the calcium chloride dihydrate was dissolved. Adding distilled water was continued and stirred until the solution reached the desired volume. A graduated cylinder or volumetric flask was used to accurately measure the volume. The solution was mixed carefully to ensure homogeneity. The pH of the solution was checked using a pH meter.

Calcium chloride solutions are usually slightly acidic. The prepared calcium chloride solution was transferred to a suitable container or bottle. The container was labelled with the concentration (0.25 M), date of preparation, and other relevant information. Waste materials, such as weighing paper, were disposed in accordance with laboratory waste disposal guidelines. The equipment used, including glassware and stirring rod were cleaned and sanitized. The preparation of a 0.25 M calcium chloride solution involves careful measurement, calculation, and dissolution techniques to ensure accurate and reliable results. Following this detailed methodology while adhering to safety precautions will yield a properly prepared solution suitable for various scientific and laboratory purposes.

3.2 Methods

3.2.1 Basic engineering properties of soil

To classify the soil according to the unified soil classification system (USCS), grain size analysis using the hydrometer method (ASTM D422) and sieve analysis (ASTM D6913) were performed. Plasticity index was determined by Casagrande method (ASTM D4318) to classify the soil as sandy, clayey, or silty with relevance of soil gradation. The specific gravity of the soil solids was evaluated using the pycnometer method (ASTM D854). Standard Proctor compaction test was performed to assess the maximum dry density and optimum moisture content (ASTM D698).

3.2.2 Standard Proctor test

Figure 3.4: Apparatus for Standard proctor test in NICE Geotech lab

MDD is determined through a Proctor compaction test, where a sample of soil is compacted using a standardized compaction effort, typically with a specific amount of compaction energy applied. The sample is compacted at various moisture contents, and the dry density is measured for each level of compaction. The percentage of moisture at which the extreme dry density is obtained is the optimum moisture content (OMC), which corresponds to the most effective moisture content for compaction.

The standard compaction tests were performed to develop the moisture content – density relationships. The soil was passed through sieve # 4, placed in tray and mixed with water at different percentages. The mixture was mixed uniformly with gloved hands. After thorough mixing, the specimen was transferred into the standard proctor mold in three layers and was blowed 25 times at each layer with the rammer. After the compaction the upper part of the mold was removed, and the mass of compacted soil and mold was found by a digital balance. This procedure was repeated for different percentages of moisture. After this the compaction curve was obtained and then estimated OMC and MDD.

3.2.3 Unconfined compression strength

Figure 3.5: UCS testing machine used

The sample of soil is subjected to axial loading at a constant rate of deformation that is a strain rate of 2 mm/s. The loading is applied gradually until the sample fails or undergoes significant deformation. During this process, the axial load and deformation are carefully monitored. The maximum axial load endured by the sample of soil at failure, along with the corresponding deformation, is recorded. This provides the UCS value. The UCS sample is prepared by oven drying the soil and passing it through sieve no. 16 to obtain the field conditions of the soil. This soil is then mixed with the water at OMC and placed in a UCS mold of height to diameter of 1:2. This soil was compacted, and the untreated samples were prepared.

For MICP treated samples, the soil was oven dried and passed through sieve no. 16 to attain the field conditions of the soil. This soil was mixed at half of the OMC of fungal inoculum and half of the OMC of the cementation solution. After mixing, same procedure was done as for untreated samples of soil. These samples were then tested in strain controlled UCS machine as shown in Figure 3.5.

3.2.4 Fourier Transform Infrared

FTIR spectroscopy comprises of exposing a sample of soil to the infrared (IR) radiation and measures the absorption or transmission of the radiation at different wavelengths. This generates a unique spectral pattern, often referred to as an FTIR spectrum, which represents the chemical bonds and functional groups within the sample of soil. The untreated samples of soil were oven dried and passed through sieve no. 16, whereas fungal based MICP treated samples of soil were scratched from the surface of the treated UCS samples and passed from sieve number 16. These samples were then placed in Elfen tubes and tested with FTIR machine at USPCASE, National University of Sciences and Technology (NUST), Islamabad Pakistan.

3.2.5 X-Ray diffraction

XRD involves exposing a sample of soil to X-rays and measuring the diffraction pattern of the X-rays as they interact with the crystal lattice of minerals present in the soil. This diffraction pattern produces a unique XRD spectrum that provides information about the arrangement of atoms in the soil's minerals. The untreated samples of soil were oven dried and passed through sieve no. 16, whereas fungal based MICP treated samples of soil were scratched from the surface of the treated UCS samples and passed from sieve number 16. These samples were then placed in Elfen tubes and tested with XRD machine at USPCASE, National University of Sciences and Technology (NUST), Islamabad Pakistan.

Figure 3.6: XRD machine used in the analysis.

3.2.6 Scanning Electron Microscopy

SEM involves bombarding the surface of a sample with a focused beam of electrons. The interaction between the electrons and the sample's surface produces signals that are then used to create detailed images of the sample's topography and composition. SEM enables the examination of samples of soil at magnifications ranging from low to very high, allowing researchers to study fine details that might not be observable with other techniques. SEM combined with energy-dispersive X-ray spectroscopy (EDS) can identify and map the elemental composition of minerals present in the soil. The untreated samples of soil were oven dried and passed through sieve no. 16, whereas fungal based MICP treated samples of soil were scratched from the surface of the treated UCS samples and passed from sieve number 16. These samples were then placed in Elfen tubes and tested with SEM machine at Islamic University, Islamabad Pakistan.

3.3 Samples curing

The samples were cured by two methods, which are open air drying and closed curing. Closed curing is done by wrapping the soil mixed with fungus and cementation solution with the plastic paper so that no moisture and air can enter or leave from the sample premises. The samples were kept at room temperature about 25 ^{0}C so that the Fungal based MICP can be processed. For air drying, the UCS samples were kept in lab at room temperature and the moisture was allowed to leave the sample premises.

3.4 Wetting and drying cycles

UCS samples are prepared and wrapped in cotton bandage. Deionized water is added to the soil containers gradually to avoid disturbance to the soil structure. The water is added until the soil reaches a predetermined moisture content. The containers are then sealed airtight to prevent moisture loss. The sealed containers are placed on a stable surface to prevent movement during the wetting phase. After the wetting phase, the containers are opened, and excess surface water is removed using blotting paper. The containers are then placed in a controlled environment, such as an oven or desiccator, set to a specific temperature. Air circulation is maintained to facilitate moisture evaporation. The samples of soil are periodically weighed to monitor moisture loss and ensure a gradual drying process. The wetting and drying cycle is repeated for a predetermined number of cycles to simulate the actual conditions. After each cycle, the samples of soil are visually inspected for any signs of cracking, structural changes, or other alterations. Figures 3.8 – 3.11 shows process visuals to highlight steps involved in the wetting-drying cycles.

Figure 3.8: Samples placed in water for wetting cycle

Figure 3.9: Samples taken out from container after full saturation.

Figure 3.10: Samples unwrapped after full saturation during wetting phase

Figure 3.11: Samples put in oven for the drying phase

Chapter 4

Calculations and Results

4.1 Gradation

From the graph, the blue line shows the gradation curve of the untreated samples of soil. When this soil is treated with the fungus based MICP, we can see that the curve has changed from blue to red. We can note that the gradation curve of fungus based MICP treated sample of soil has moved to right as compared to the gradation curve of the untreated samples of soil. From this comparison we can conclude that the particle size of the fungus based MICP treated sample of soil has increased as compared to the untreated samples of soil. This is because of the bonding of the small soil particles with the calcite particles and hyphae of the fungus. It can be said that fungus based MICP impacts the soil structure and makes bonds and thus increases the particle size.

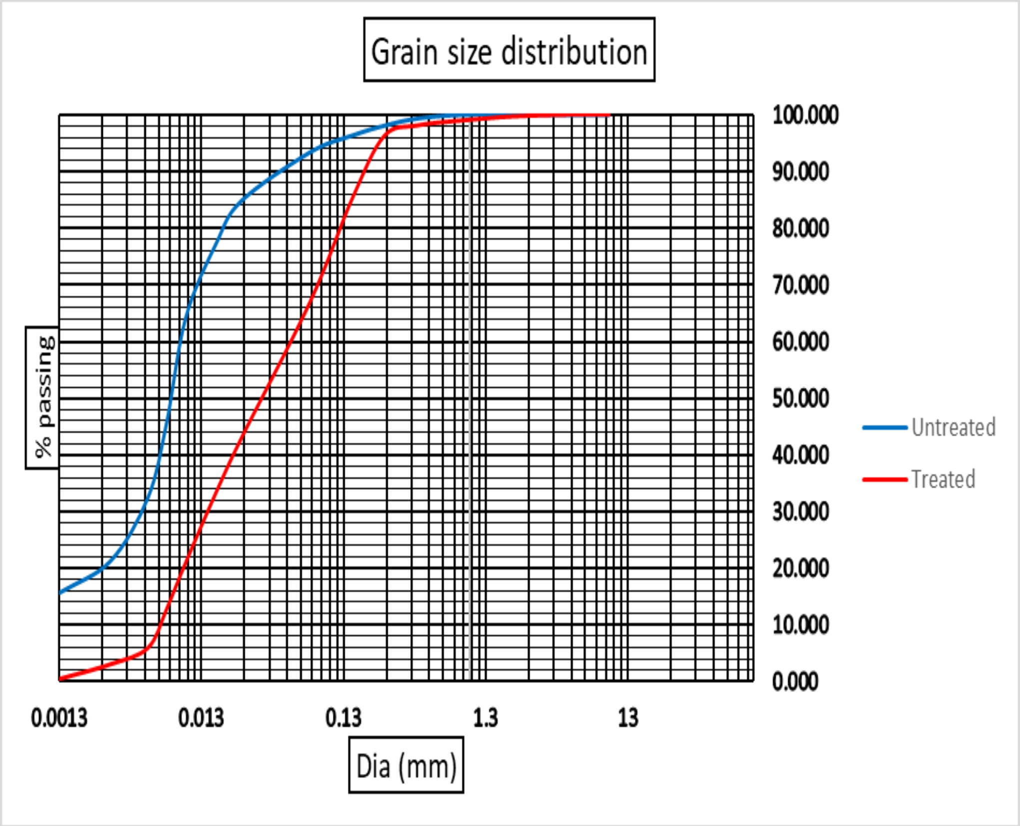


Figure 4.1: Graph showing the comparison between gradation curve of untreated and MICP treated sample of soil.

4.2 Liquid limit, plastic limit, and plasticity index

Graph in Figure 4.2 shows the liquid limit comparison between untreated samples of soil and fungus based MICP treated sample of soil. The red line shows the linearity of the untreated samples of soil obtained from No. of blows and moisture content from Casagrande's apparatus while the blue line shows the linearity of the fungus based MICP treated sample of soil obtained from No. of blows and moisture content from Casagrande's apparatus. It can be seen that the liquid limit of fungus based MICP treated sample of soil has decreased as compared to the liquid limit of the untreated samples of soil. The fungus based MICP treated sample of soil has a liquid limit of 18.91% while the liquid limit of untreated samples of soil is about 20.07%. It can be concluded that fungus based MICP treatment decreases the liquid limit of a soil. As per plastic limit, the plastic limit decreases from 15.11 to 14.22 after the fungus based MICP treatment. The soil shows insignificant differences in plasticity index between the two soils.

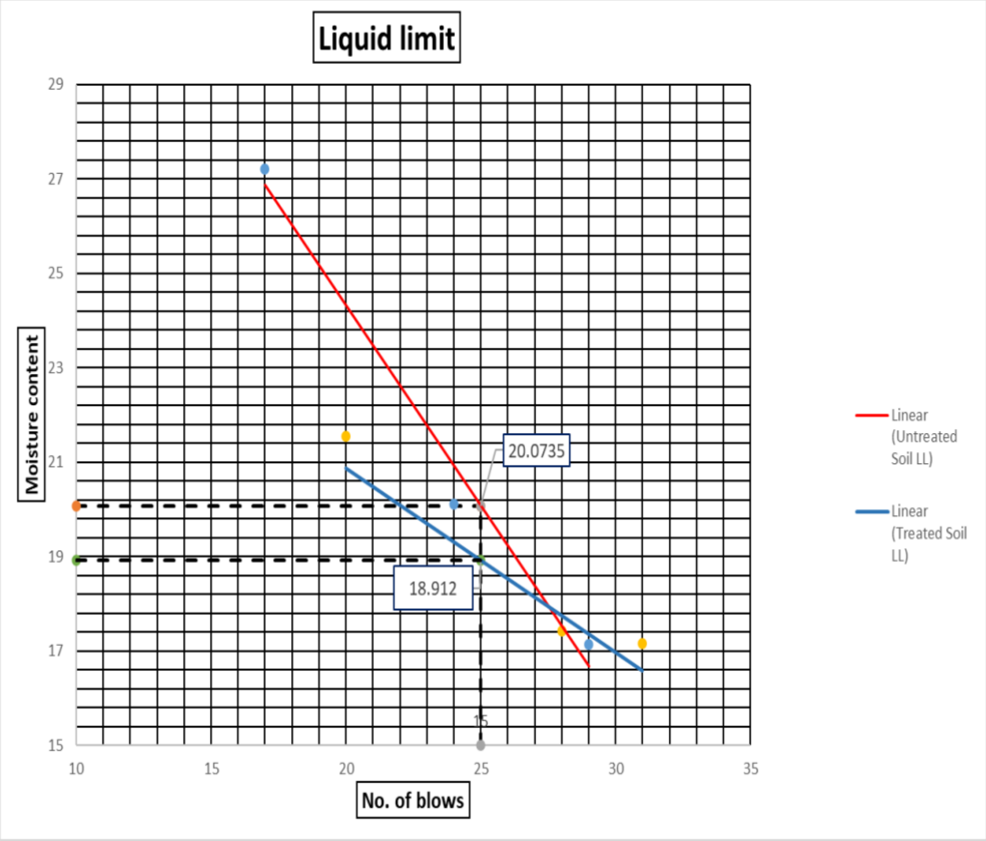


Figure 4.2: Comparison of the liquid limits

4.3 Maximum dry density (MDD) and optimum moisture content (OMC)

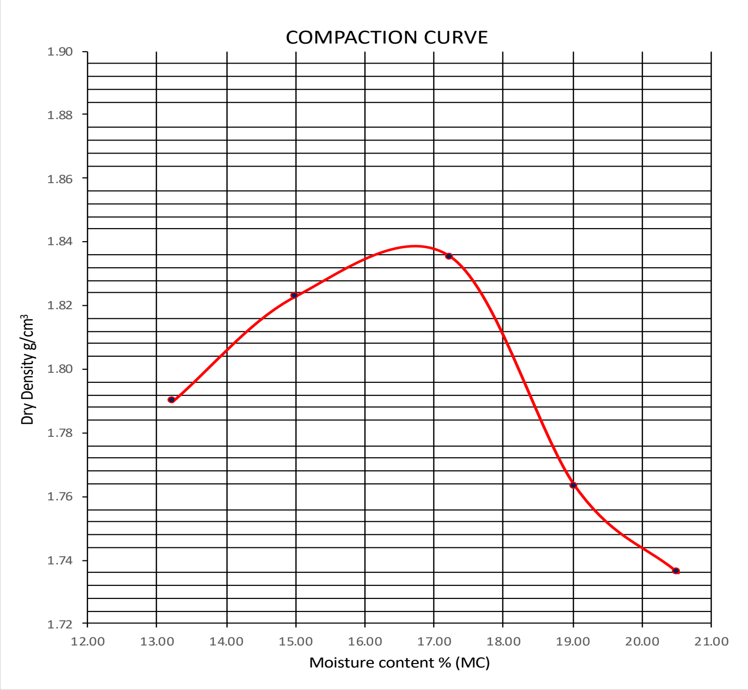


Figure 4.3: Compaction curve of the untreated soil

The graph in Figure 4.3 shows the compaction curve of untreated samples of soil of the undertaken soil. We can see that the water content (w) increases from 13 % up to 16.7% . After w = 16.7%, the curve is declining. So, the peak value of w = 16.7%. This was the optimum moisture content (OMC) of untreated soil. Relatively, the maximum dry density (MDD) of untreated soil is 1.83 g/cm^3.

4.4 Specific gravity

The specific gravity of untreated soil is found to be 2.69.

4.5 Unconfined compression strength

UCS is a critical parameter for evaluating the stability and load-bearing capacity of soils in various engineering applications. For the UCS testing of our samples of soil, we have undertaken two types of curing methods, number 1 is the air drying of the samples and number 2 is closed curing of the samples with the total isolation.

4.5.1 Air dried samples

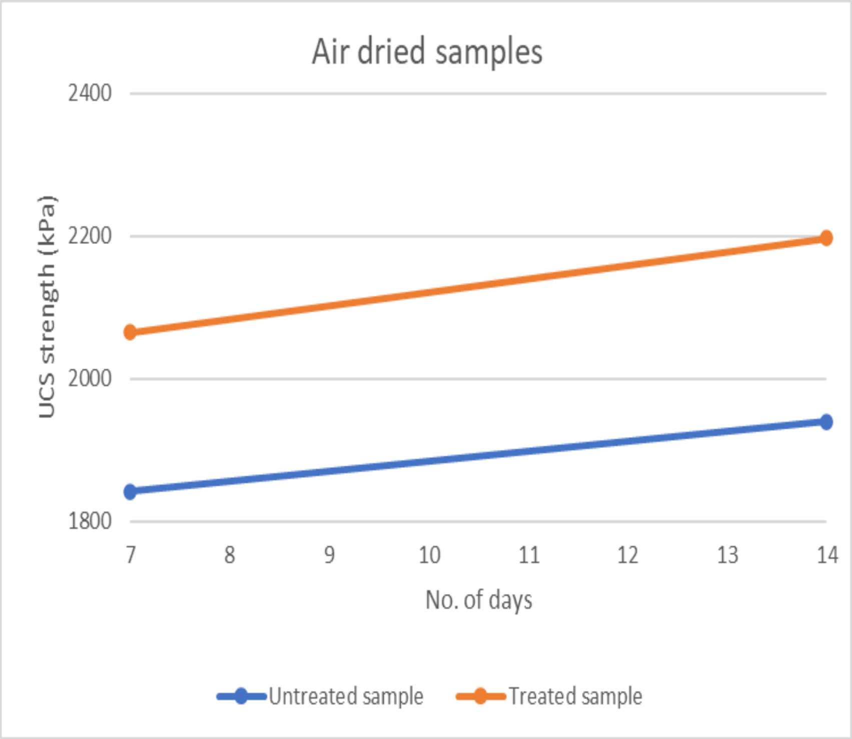


Figure 4.4: Graph showing UCS of air dried samples (untreated and MICP treated)

From the graph shown in the Figure 4.4, we can see the enhancement in the strength of the fungal based MICP treated soil. At 7 days, the strength of the sample of untreated soil is 1841.2 kPa while the strength of the fungus based MICP treated samples of soil is 2064.4. We can clearly notice the enhancement in the strength of the fungus based MICP treated samples of soil as compared to untreated samples of soils.

After the 14 days of air drying, the UCS of the fungus based MICP treated sample of soil is 2196.6 kPa while the unconfined compression strength of the untreated samples of soil is 1939.6 kPa. This clearly elaborates the increase in the unconfined compression strength of the fungus based MICP treated soil as compared to the untreated samples of soil. So, it can be concluded that fungus based MICP treatment can be effective in air drying as compared to the untreated samples of soils. So, this shows the effectiveness of the technique used for the treatment of soil.

4.5.2 Isolated cured samples (closed curing)

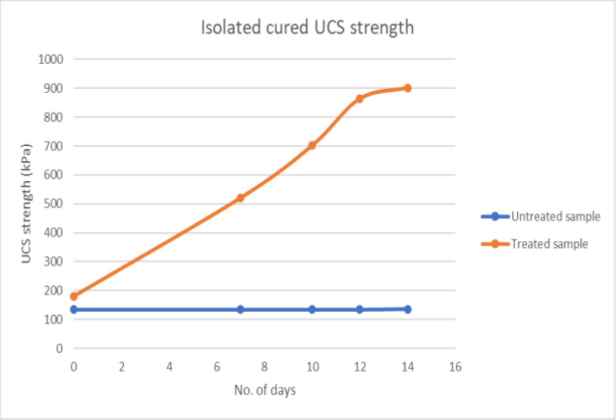


Figure 4.5: Graph showing UCSs for close cured samples (untreated and MICP treated)

From the graph in the Figure 4.5, we can see the contrast between the UCSs of untreated samples of soil and fungal based MICP treated sample of soils which are closely cured. For this purpose, samples were wrapped in plastic food paper. From the graph, we can see that the strength of untreated samples of soils is very less, that is 134.1 kPa when the sample is made and tested freshly. We can see that the fungal based MICP treated sample of soil is showing a UCS of 180.8 kPa, initially. The UCS of the fungal based MICP treated sample of soils is increasing after the different days of testing. The strength of fungal based MICP treated sample of soils have shown a strength of 520.6 kPa after 7 days while there is no increase in the UCS of the untreated samples of soils. After 10 days, the strength of the fungal based MICP treated sample of soils has increased up to 701.4 kPa while there is no change in the UCS of the untreated samples of soils. After 12 days, the strength of the fungal based MICP treated sample of soils has increased up to 863.4 kPa while there is no change in the UCS of the untreated samples of soils. After 14 days, the strength of the fungal based MICP treated sample of soils has increased up to 900.8 kPa while the UCS of the untreated samples of soil has just increased by 1.7 kPa, that is, it showed a strength of 135.8 kPa after 14 days. We can see that fungal based MICP treated sample of soils are showing a significant increase in the UCS at closed curing as compared to untreated samples of soils. So, it can be concluded that fungal based MICP treatment impacts positively on the UCS of the soil in closed curing.

4.6 Wetting and drying cycles

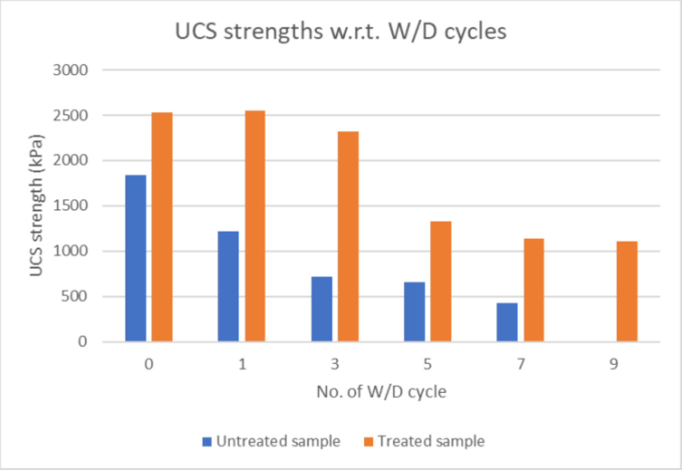


Figure 4.6: UCS results of wetting and drying cycles (untreated and MICP treated)

Graph in the Figure 4.6 shows the UCS test results carried out with wetting and drying cycles. The samples were cured closely and then air dried. At 0th cycle, we can see that the untreated sample of soil is showing a UCS of 1841.2 kPa, while the fungal based MICP treated sample of soils is showing a UCS of 2526.2 kPa. First the samples were wrapped in the cotton bandage with a thread across the body. Then these samples were immersed in water so that they can be completely saturated. This process has taken about 24 hours. After 24 hours, these samples were taken out from the water and the cotton bandage is removed from the outer surface. Then these samples were kept on 42 degrees Celsius for 24 hours so that the moisture is removed, and the samples are dried. So, first wetting-drying cycle has been completed.

So, after the first wetting and drying cycle, we can see that the UCS of the untreated samples of soil has decreased from 1841.2 kPa to 1215.4 kPa. While the UCS of the fungal based MICP treated sample of soil has increased from 2526.2 kPa to 2549.2 kPa. This is because of the phenomenon that the calcite which is precipitated in the sample of soil comes to the surface and hardens it. This phenomenon makes a hard shell like case across the surface of the sample of soil. This hard shell is the main reason which increases the UCS in the fungal based MICP treated sample of soils. The hard case acts like a strength component for the samples.

After the third wetting and drying cycle, we can see that the UCS of the untreated samples of soil has decreased from 1215.4 kPa to 718.5 kPa. While the UCS of the fungal based MICP treated sample of soil has decreased from 2549.2 kPa to 2320.9 kPa. This is because the calcite from the hard shell vanishes from the fungal based MICP treated sample of soil. As the calcite is the main factor that is contributing to the strength, because of the vanishing of the calcite from the fungal based MICP treated sample of soils, so the UCS of the treated sample of soil has decreased. But as compared to untreated samples of soils, the fungal based MICP treated sample of soils are showing greater UCS. So, from this cycle it can be said that fungal based MICP samples of soil are showing sustainability and somewhat resistance to the wetting and drying samples.

After the fifth wetting and drying cycle, we can see that the UCS of the untreated samples of soil has decreased from 718.5 kPa to 656.9 kPa. While the UCS of the fungal based MICP treated sample of soil has decreased from 2320.9 kPa to 1333.6 kPa. This is similar to 3rd cycle. After the seventh wetting and drying cycle, we can see that the UCS of the untreated samples of soil has decreased from 656.9 kPa to 429.7 kPa. While the UCS of the fungal based MICP treated sample of soil has decreased from 1333.6 kPa to 1136.5 kPa. This is similar to 3rd and 5th cycles.

After the ninth cycle, the untreated samples of soils are not showing any UCS. This is because the samples could not retain their shape after the eighth wetting and drying cycle. While after the ninth wetting and drying cycle, the samples which are treated by fungal based MICP are still showing strength. The strength of the fungal based MICP treated sample of soils has decreased from 1136.5 kPa to 1108 kPa from seventh to the ninth wetting and drying sample. This is similar to 3rd, 5th and 7th cycles. From the UCS tests after the applications of wetting and drying cycles, it can be concluded that fungal based MICP treated soil is showing sustainability and resistance to the wetting and drying cycles as contrasted to the untreated samples of soils. It is concluded that fungal based MICP treatment is an acceptable and sustainable method for the treatment of soil with less strengths. From the UCS results upon wetting and drying cycles, we can see that the samples of soil from the fungal based MICP treated soil is showing a great potential for the sustainability and resistance to the wetting and drying cycles. While the untreated samples of soils could not even retain their shape after the eighth wetting and drying cycle.

4.6.1 Void ratio

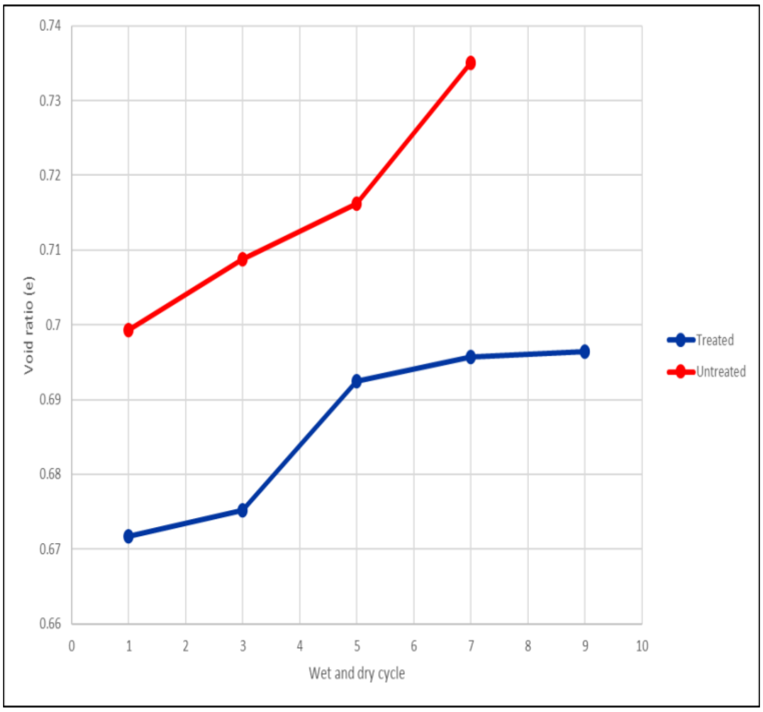


Figure 4.7: Void ratio comparison of untreated and MICP treated sample of soil in context with wetting and drying cycle.

From the graph in the figure 4.7, we can see that the trends of the void ratio for both untreated samples of soils and fungal based MICP treated sample of soil is increasing with respect to the number of wetting and drying cycles. This is because in the untreated samples of soils, the smaller soil particles run out from the samples of soil which create voids in the samples. While in the fungal based MICP treated sample of soil, the void ratio curve is a bit horizontal as compared to the untreated samples of soils void ratio.

Also, we can see that after the seventh cycle, the void ratio of the untreated samples of soils is not shown. This is because during the wetting and drying cycle, the untreated samples of soils could not retain shape after the seventh cycle. So, we cannot find the void ratio of a sample that is not in a feasible state. Furthermore, we can see that the trend of void ratio of fungal based MICP treated sample of soils is bit horizontal. This means that the voids are increasing the fungal based MICP treated sample of soils but is not as much increasing as the void ratio of untreated samples of soils is increasing. So, it can be concluded that fungal based MICP treatment can impact the void ratio of the samples of soil also during the wetting and drying cycles. This is because the voids of the fungal based MICP treated sample of soils get filled with the precipitated calcite as well as with the hyphae of the fungus.

4.6.2 Moisture content percentage

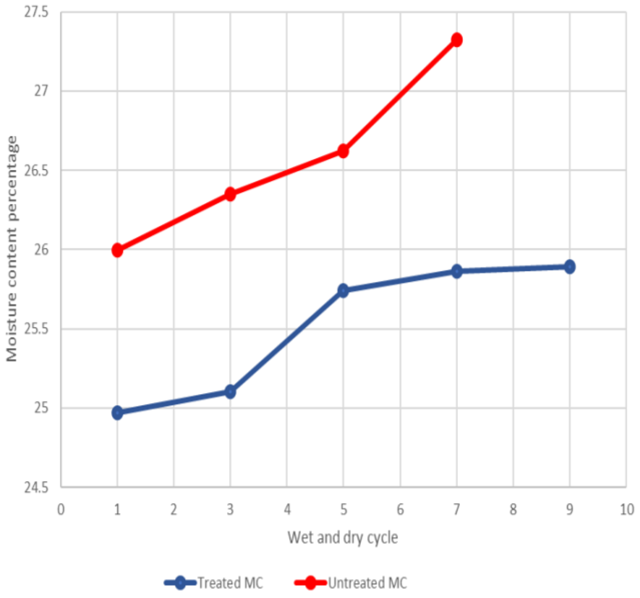


Figure 4.8: A comparison of moisture content percentages during wetting and drying cycles

From the graph in the figure 4.8, we can see that the trends of the moisture content percentage for both untreated samples of soils and fungal based MICP treated sample of soil is increasing with respect to the number of wetting and drying cycles. This is because in the untreated samples of soils, the smaller soil particles run out from the samples of soil which create voids in the samples. These voids create space for the retention of the moisture within the sample of soil. While in the fungal based MICP treated sample of soil, the moisture content percentage curve is a bit horizontal as compared to the untreated samples of soils moisture content percentage.

Also, we can see that after the seventh cycle, the moisture content percentage of the untreated samples of soils is not shown. This is because during the wetting and drying cycle, the untreated samples of soils could not retain shape after the seventh cycle. So, we cannot find the moisture content percentage of a sample that is not in a feasible state. Furthermore, we can see that the trend of moisture content percentage in fungal based MICP treated sample of soils is bit horizontal.

This means that the voids are increasing the fungal based MICP treated sample of soils but is not as much increasing as the void ratio of untreated samples of soils is increasing. This impacts the moisture content percentage in the samples. So, we can conclude that fungal based MICP treatment can impact the percentage of moisture content of the samples also during the wetting and drying cycles. This is because the voids of the fungal based MICP treated sample of soils get filled with the precipitated calcite as well as with the hyphae of the fungus which allow less moisture to be absorbed as compared to the untreated samples of soils.

4.6.3 Mass loss percentage

In the graph shown in Figure 4.9, we can see a comparison between the mass loss percentage of untreated samples of soils and fungal based MICP treated sample of soils concerning the number of wetting and drying cycles. We can see that in the untreated samples of soils, with the increasing number of wetting and drying cycle, the mass loss is increasing rapidly as the curve is very steep.

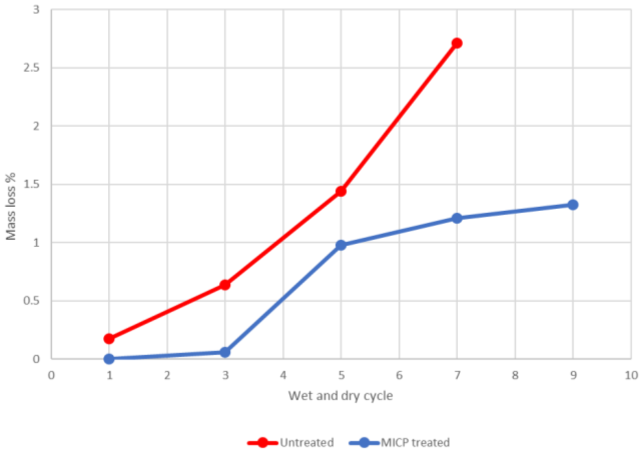


Figure 4.9: A comparison of percentages of mass loss during wetting and drying cycles

Also, we can see that after the seventh cycle, the mass loss percentage of the untreated samples of soils is not shown. This is because during the wetting and drying cycle, the untreated samples of soils could not retain shape after the seventh cycle. So, we cannot find the mass loss percentage of a sample that is not in a feasible state. While noticing the fungal based MICP treated sample of soils, we can see that there is also a percentage of mass loss present. But this mass loss is nothing near the mass loss percentage of the untreated samples of soils. The mass loss in untreated samples of soils is because of the disappearing of small soil particles from the samples because of the wetting and drying cycles. While in the fungal based MICP treated sample of soils, the mass loss is because of the runoff of calcite particles, and the hyphae of the fungus keeps the soil particles from running of the samples. So, it can be concluded that fungal based MICP treatment impacts the mass loss percentage of soil during wetting and drying cycles.

4.7 Fourier transform infrared

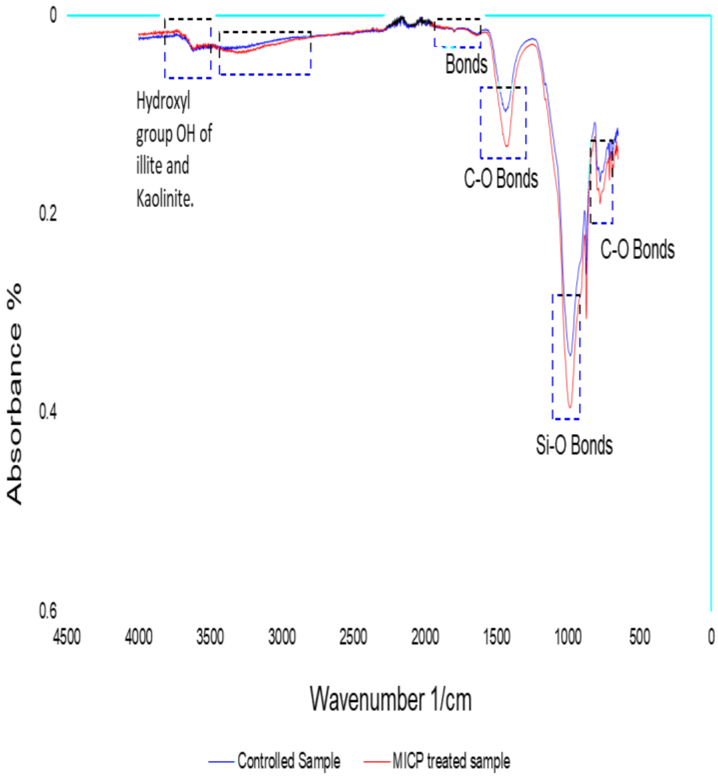


Figure 4.10: A comparison of FTIR of MICP treated and untreated samples of soil

From the FTIR graph shown in Figure 4.10, we can see the comparison of FTIR values of untreated and fungal based MICP treated sample of soils. We can see that there is not much difference in the hydroxyl group (OH^-) group of the clayey minerals (iolite, kaolinite, etc.). This means that fungal based MICP treatment does not impacts the minerology of clayey minerals present in soil. We can also notice that the CH stretch is showing just a little bit difference in the fungal based MICP treated sample of soils as compared to the untreated samples of soils. This is because of a little bit increase in the organic component of the soil because of the addition and growth of the fungus in the sample of soil. This increase in the organic component of the soil because of fungal based MICP treatment is negligible.

It is to be noticed that both untreated and fungal based MICP treated sample of soils were tested in a dry state. So, there is no difference in the HOH bond segment of the curves of both untreated and fungal based MICP treated sample of soils. In the Si-O bond segment of the curves, we can see that there is an increase in the Si-O bonding in the fungal based MICP treated sample of soils as compared to the untreated samples of soils. It can be said that there is a phenomenon happening during the fungal based MICP treatment which causes increase in the Si-O bonds of the soil. This is good aspect of the study as the Si-O bonding also contributes to the strength of the soil. At the C-O segments of the curves of the graph of the FTIR results, we can see that there is an increase in the C-O bonds in the fungal based MICP treated sample of soils as compared to the untreated samples of soils. This is because of the precipitation of calcite in the fungal based MICP treated sample of soils, the C-O bonds increase as compared to the untreated samples of soils because there is less carbonate bonds. So, this proves that calcite has been precipitated in the fungal based MICP treated sample of soils.

4.8 X-Ray diffraction

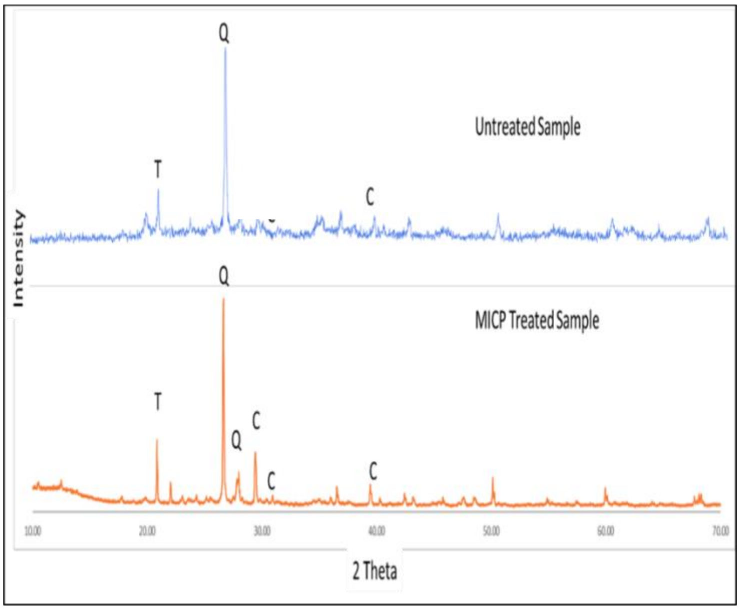
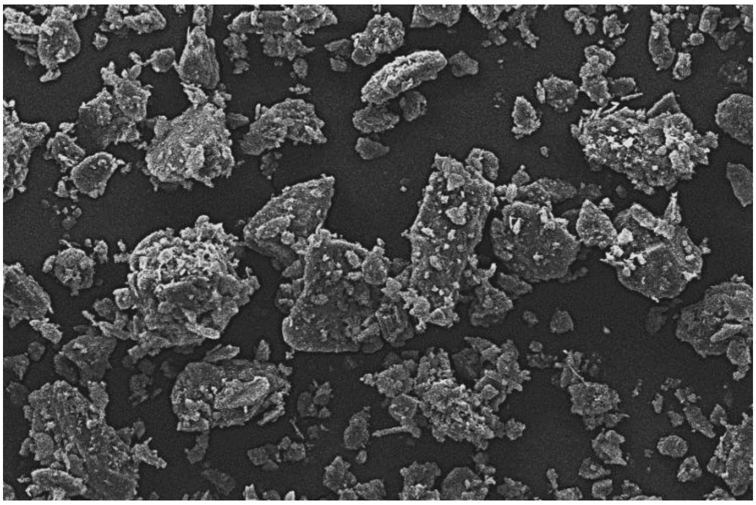
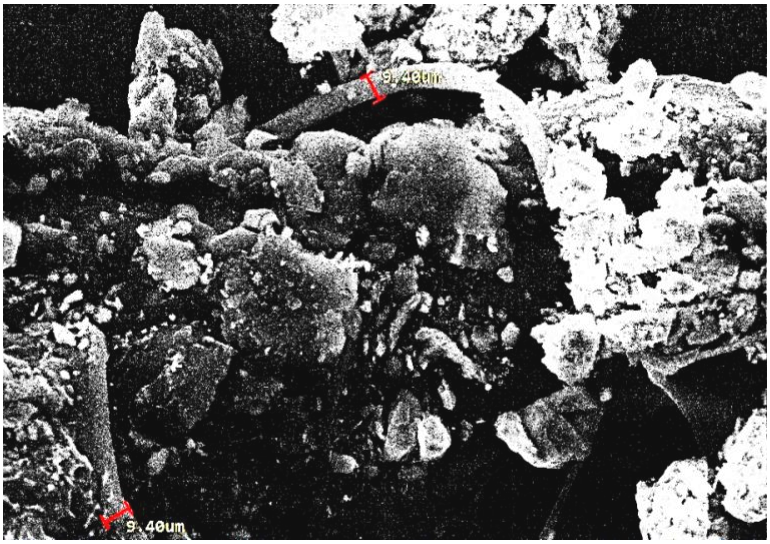


Figure 4.11: A comparison of XRD of untreated and MICP treated soils samples

In the graph shown in figure 4.11, it is a comparison of XRD results of untreated and fungal based MICP treated sample of soils. The blue line (upper portion of the graph) is showing the XRD results of the untreated samples of soil while the reddish (lower portion of the graph) is showing the XRD results of the fungal based MICP treated sample of soils. We can see that the peaks of the calcite (denoted by C in the graph) in the fungal based MICP treated sample of soils are higher as compared to the peaks of calcite of the untreated samples of soils. This proves the precipitation of calcite in the fungal based MICP treatment of soil. There is also a slight increase in the peak of quartz (denoted by Q in the graph) of the fungal based MICP treated sample of soils as compared to the peak of quartz if the untreated samples of soil. This shows that there is a little bit enhancement in the quartz component of the soil which is also beneficial for the strength of the soil. So, it can be concluded that XRD results of this research shows that calcite has been precipitated through the improvement of soil with fungal based MICP treatment method.

4.9 Scanning electron microscopy





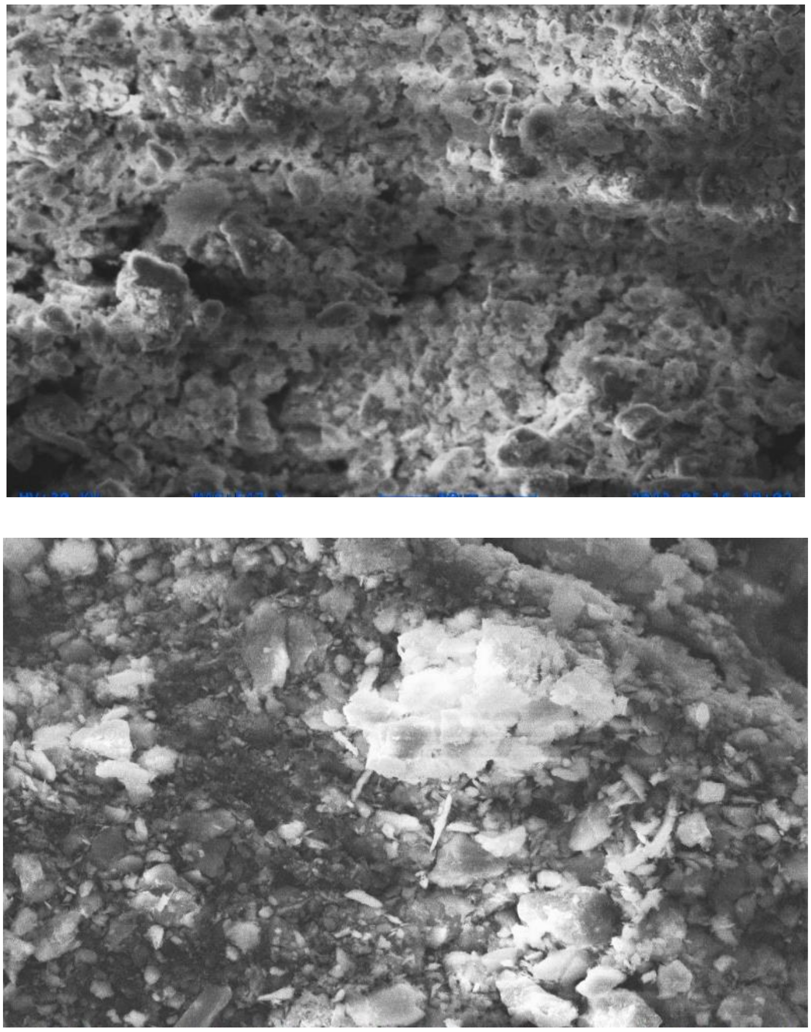


Figure 4.12: From top to bottom (a) SEM of untreated sample of soil; (b) SEM of MICP treated sample of soil; (c) SEM of bonding in MICP treated sample of soil; (d) SEM of MICP treated sample of soil after wetting and drying cycles

In the Figure 4.12 (a), SEM result from the untreated samples of soil is presented. We can see that the soil particles are dispersed and have no bonding between them. This is the main reason of the weak UCS of the untreated soil which needs improvement and treatment. There is no cohesion between the soil particles as can be analysed from the figure. In the Figure 4.12 (b) we can see that the soil particles have been attached together. The voids have become much lesser in the fungal based MICP treated sample of soil as compared to the untreated samples of soils. This shows that fungal based MICP treatment attaches the soil particles together which enhances the UCS of the soil.

In the Figure 4.12 (c), the SEM results are showing the impact of wetting and drying samples on the fungal based MICP treated sample of soil. In this SEM result, we can see that the soil particles are much closer as well as calcite and fungus can be seen in the figure. In the Figure

4.12 (d), the SEM results are showing the impacts of 9th wetting and drying cycles on the fungal based MICP treated sample of soil. We can see that the fungus has been shredded into smaller pieces while the calcite has been washed out from the sample. This proves the strength changing in accordance with the wetting and drying cycles on the fungal based MICP treated sample of soils.

Chapter 5

Conclusions and Recommendations

5.1 Conclusions

- The employment of fungal-based microbially induced calcium carbonate precipitation (MICP) presents a highly ecologically sound approach characterized by its minimal environmental impact, cost-effectiveness, and remarkable efficiency.
- *Fusarium oxysporum* fungus can be used in the calcite precipitation within the soil in the presence of cementation solution.
- The ground water is not impacted with the process of treatment of soil with fungal based MICP.
- Within the realm of soil treatment, fungal-based MICP emerges as a promising solution, particularly in addressing the enhancement of unconfined compressive strength in Silty clay. By harnessing the potential of fungal-based MICP, it becomes possible to significantly augment the structural integrity of such soil compositions.
- An integral facet of fungal-based MICP lies in its ability to induce transformative alterations within the micro-architecture of soil. Through the implementation of this methodology, the cohesive forces binding soil particles are substantially fortified, leading to an overall improvement in the cohesion of the soil matrix.
- The samples of soil treated with fungal based MICP have shown promising results in the increase of UCS.
- The samples of soil treated with fungal based MICP have shown sustainability against wetting and drying cycles in the context of mass lost at each wetting and drying cycle.
- Fungal based MICP treated samples of soil have shown a decrease in the void ratio as compared to the untreated samples of soil.
- The void ratio of fungal based MICP treated samples of soil is increasing very little as compared to the void ratio of untreated samples of soil with respect to wetting and drying cycles.

- Fungal based MICP treated samples of soil have shown great durability as compared to the untreated samples of soil with respect to wetting and drying cycles as untreated samples of soil did not retain their shape after 7th cycle.
- The robustness of fungal-based MICP is amply illustrated through its exceptional outcomes in various analytical techniques, including SEM, XRD, and FTIR. These empirical findings collectively validate the efficacy and appropriateness of the fungal-based MICP method in effecting substantial improvements within treated samples of soil.

5.2 Recommendations

- Apply cementation solution of different salts and molarities.
- Check other properties of soils e.g., permeability, consolidation, etc.

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