Experimental investigations of hydro-mechanical behavior of problematic soils

By

Muhammad Waleed

NUST-2018-MS-Geotech-00000277553

A thesis submitted in partial fulfillment of the requirements for the degree of

Master of Science in Geotechnical Engineering

NUST Institute of Civil Engineering (NICE)
School of Civil and Environmental Engineering (SCEE)
National University of Sciences & Technology (NUST)
Sector H-12, Islamabad, Pakistan.
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(Thesis Supervisor)

NUST Institute of Civil Engineering (NICE)

THIS THESIS IS

DEDICATED

TO

MY BELOVED PARENTS

(For their endless love, support, and encouragement)

ACKNOWLEDGEMENT

All praise to Allah, the Almighty on whom ultimately, we depend upon for sustenance and guidance.

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List of Symbols/Abbreviations

ASTM	American Society for testing materials
CEC	Cation exchange capacity
CBR	California bearing ratio
CKD	Cement kiln dust
CH	High plastic clay
CCLs	Compacted clay liners
GCL	Geosynthetic clay liners
L.L	Liquid limit
ML	Low plastic clay
MDD	Maximum dry density
OMC	Optimum moisture content
PVC	Polyvinyl chloride
P.I	Plasticity index
UCS	Unconfined compressive strength
USCS	Unified soil classification system

Table of Contents

List of Figures

List of Tables

ABSTRACT

Foundation soils of all civil infrastructure projects in the rain amid regions are most commonly subjected to wetting and drying cycles throughout the year due to intermittent rainfalls, which may consequently alter the physical properties of these soils. In some situations, the foundations lose significant strength due to these seasonal climatic variations, which ultimately lead to structure failure, resulting in substantial human and financial losses. Various research studies are available in the literature, reporting different performance properties of treated and untreated soils under different conditions for wetting and drying cycles. Still, the scope of this work needs to be explored, specifically focusing on behavioral changes of the problematic soils. So, the novelty of the research work involves; executing the hydro-mechanical behavior of terrazyme treated problematic soils for various wetting-drying cycles. Laboratory testing approaches, such as unconfined compression, hydraulic conductivity, and compaction tests, etc., were followed to attain the set objectives. The test results showed that the compressive strength decreased, and hydraulic conductivity increased for a gradual increase in wetting and drying cycles, for both treated and untreated soils. The compressive strength of natural soil reduced up to 45%, 34%, and 40% during wetting and drying cycles for Nandipur, Kallar Kahar, and Lodhran soils, respectively, and similarly, 37%, 20%, and 35% decrease in the compressive strength was noted for treated Nandipur, Kallar Kahar, and Lodhran soils. Resultantly, the treated soils provided more strength than untreated soils for wetting and drying cycles. The hydraulic conductivity of treated Nandipur, Kallar Kahar, and Lodhran soils was noticed 15%, 8%, and 10% less than untreated soils, respectively.

Chapter 1

1 INTRODUCTION

1.1 Background

Soil types play an essential role as foundation materials in civil engineering projects. Roads, bridges, buildings, and dams, etc., ultimately transfer their load to the foundation soils. The physical and chemical properties of clayey soils in foundations influence the functionality of overlaying structures, significantly. The soil particles with an effective diameter of 2 µm or less define the clayey soils. Clayey soils undergo a considerable volumetric change, i.e., swells and shrinks with addition and removal of water respectively, which results in settlement/dilation, leading to cracks in the structure, and severe cases, the foundation fails in bearing capacity. The clayey soil is governed by its chemical composition, depending upon its cation exchange capacity (CEC), surface area, and particle thickness, etc. Expansive soils are clayey materials with high plasticity and swell upon wetting and shrinks upon drying. These soils get wetted due to; rainwater, leakage from water supply schemes and/or sewer pipes, and a rise in the groundwater table. These wetting and drying cycles produce cracks within the soil matrix, and ultimately the structure fails due to differential settlement.

Similarly, collapsible soils undergo volume changes upon wetting, loading, or both. These soils contain silt, clay, and salt contents, and when get saturated, a chemical reaction occurs, due to which they settle down, and the foundation fails. The water permeates in the soil matrix, which loosens the bond between colloid particles and its strength reduces. Expansive clays have caused considerable damages in different types of structures, e.g., airports, highways, railways, buildings, etc., worldwide (S. B. Ikizler, 2014); alone in the USA, it caused 2,225 million dollars per year (Jones Jr, 1973). Research is abundantly available in the literature showing the use of different additives, such as cement, lime, enzymes, industrial waste, fly ash, bagasse ash, and rice husk to improve the performance properties of problematic soils (Cuisinier, 2020; Ye, 2018; Saride, 2013). It is paramount for geotechnical engineers to find a stabilization technique that will economically improve the soil characteristics.

One of the most affordable and reliable solutions is to reinforce the soil with bio-enzymes. Bio-enzymes are natural, nonpoisonous, non-combustible, non-hazardous liquid enzymes agitated from vegetable extracts (Patel, 2018). Bio-enzymes are organic and liquid suspensions, used to stabilize the soil and aggregate in roads and structures (Lacuoture, 1995). Terrazyme improves the quality of soil, reducing the plasticity index, and optimum moisture content, which alternately improves its engineering properties such as durability, California bearing ratio (CBR), strength, and hydraulic conductivity.

Terrazyme is a by-product of sugar cane juice, and Pakistan annually produces 64.77 million tons of sugarcane (Pakistan Economic Survey 2019 - 2020), showing great potential for the production of this bio enzyme. Furthermore, Pakistan falls in the intermittent rain amid regions on the globe, and the soil foundations undergo wetting and drying cycles throughout the year, due to which the soil loses its potential strength. Particularly, the soils with higher swelling and shrinkage potential show significant variations in their performance properties during successive wetting-drying cycles, and under severe circumstances, seasonal variations may lead to foundation failure in such soils, resulting in substantial human and financial losses.

So, in this research study, the authors examine the hydro-mechanical behavior of natural and terrazyme treated problematic soils for wetting and drying cycles. Three soils with different liquid limits are selected in the study, collected from different zones of Pakistan. Hydraulic conductivity and unconfined compressive strength tests were performed in the laboratory to examine the hydro-mechanical behavior of these soils. Specimens were facilitated with special arrangements in the laboratory to simulate the proper conditions for wetting and drying cycles to minimize the chances of sample disturbance. The test results showed that the treated soils showed more strength than natural soils, and as expected, the strength gradually decreased with an increase in the number of W-D cycles. The hydraulic conductivity of both treated and untreated soils gradually increased for an increase in the number of cycles, and comparatively, the treated soil showed less hydraulic conductivity than untreated soil.

1.2 Reason justification

Pakistan falls in the rain amid regions due to which rainfall occurs throughout the year. As a result of rainfall, the soil is subjected to wetting-drying cycles in most regions, which consequently influences the hydro-mechanical behavior of soil due to changes in its water content and dry unit weight, and in some situations, these seasonal variations lead to foundation failure, subsequently resulting in significant human and financial losses. Terrazyme is a liquid extract of organic matter (vegetables) that alters the soil's engineering properties reducing the voids and minimizing the water absorption of the problematic soil. The country has a great potential for this bio-enzyme due to the higher production of sugar cane, annually. The novelty of this research work involves evaluating the hydro-mechanical behavior of terrazyme treated problematic soils for different wetting and drying cycles. The study is useful in the context of Pakistan as no such study has been reported in the literature so far as per country perspectives.

1.3 Research objectives

The object of this research is as:

"To investigate the hydro-mechanical behavior of terrazyme treated problematic soils for different wetting-drying cycles".

1.4 Thesis content

The breakdown of this study is as:

- Chapter 1 reports a precise summary of the research study.
- Chapter 2 reports a literature review in the context of previous studies, proceeding the work further.
- Chapter 3 formulates the materials and methods to attain the set objectives of the research study
- Chapter 4 presents discussions on the findings of the research study.
- Chapter 5 presents conclusions and a few key recommendations, concluded from the research study.

Chapter 2

2 LITERATURE REVIEW

2.1 General

Several important factors such as soil mineralogy, quality, and quantity of admixture, compacted effort affect the characteristics of problematic soils, in addition to admixtures and curing. Swelling soils are one of the important types of problematic soils, which are well known for their significant potential to undergo volume changes with changes in the moisture content. The swelling soils are liable to cause some serious damages to infrastructures around the globe due to their heave-up potential. The increase in wetting or moisture content will cause these soils to swell which subsequently causes heaving or lifting of the structures. Similarly, these soils shrink upon drying and due to this the structures settle and cause enormous damage to the super-structure, which ultimately results in cracking and which eventually in severe cases fails the structure (Gillott, 1986).

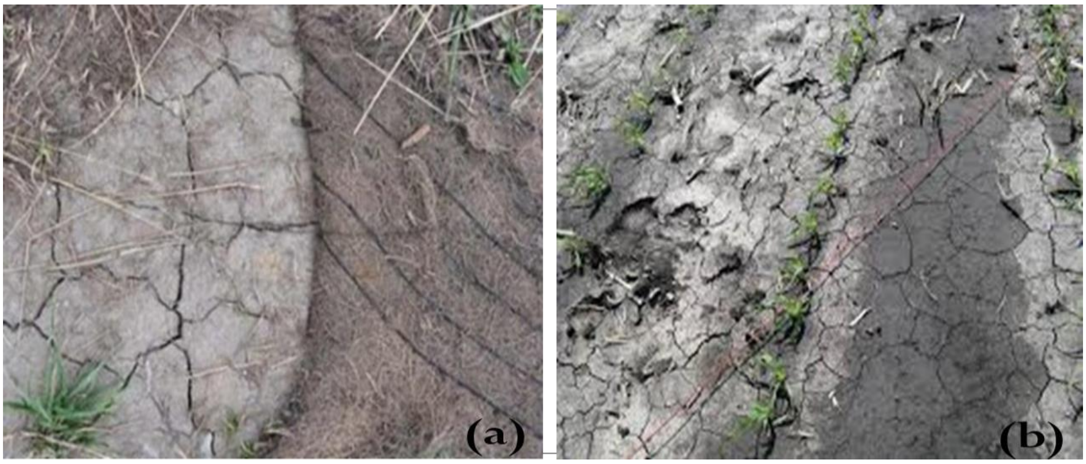

Figure 2.1: Propagation of cracks due to wetting-drying cycles

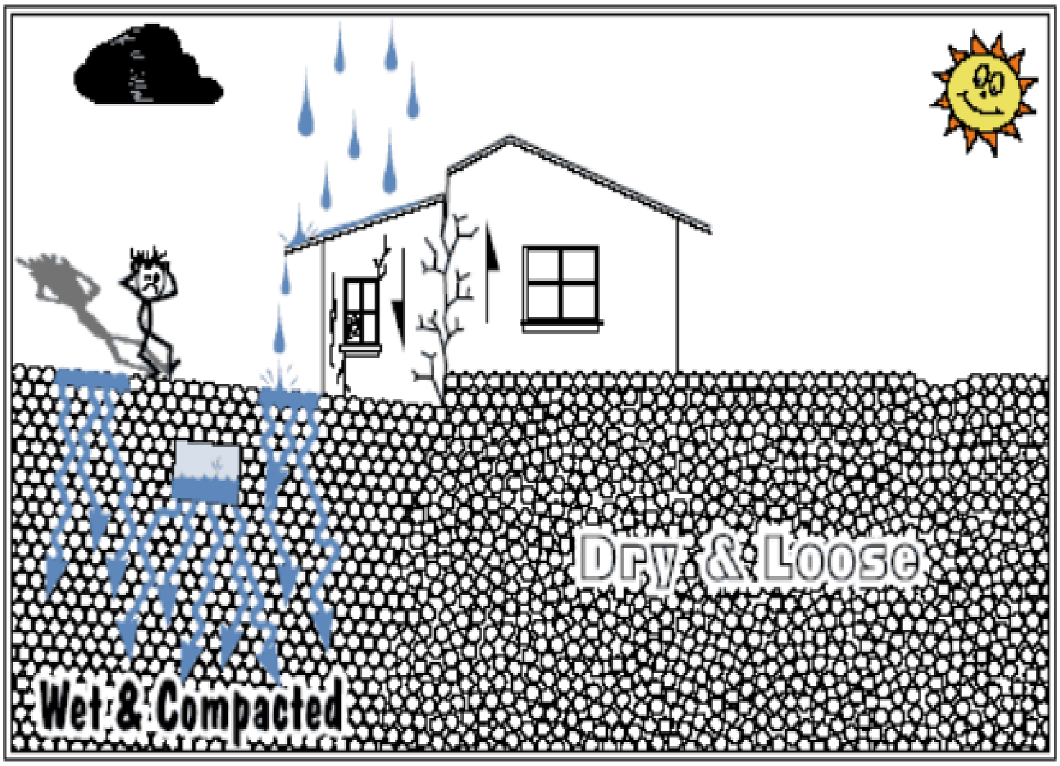

Figure 2.2: House constructed on collapsible soil without any early mitigation

2.2 Properties of problematic soils

Problematic soils, in the context of this research, are categorized into two sub-classes i.e., expansive soils and collapsible soils. A brief overview of both of these types of soils is provided in this section.

2.2.1 Expansive soils

Expansive soils are clayey materials with high plasticity and swell upon wetting and shrinks upon drying. These soils get wetted due to; rainwater, leakage from water supply schemes and/or sewer pipes, and a rise in the groundwater table. An increase in temperature and lowering of the groundwater table decrease in water content. This drying and wetting in these soils produce cracks at a different places (Figure 2.3), which alternately fails the structure due to differential settlement. The clay minerals are characterized by weak Van Der Waal's forces between the adjacent unit cells of colloids. These soils show a very high cation exchange capacity (CEC). Table 2.1 shows the classification of these soils based on liquid limits and Table 2.2 shows the classification of these soils based on swelling potential.

Table 2.1: Clay classification-based on L.L

High Plastic Clays	LL>50
Medium Plastic Clays	30<LL>50
Low Plastic Clays	LL<30

Table 2.2: Soil classification based on swelling potential

SOIL TYPE	SWELL POTENTIAL
Very High	>25
High	5-25
Medium	1.5-5

The mineralogy of expansive soil is mainly composed of montmorillonite, illite, and kaolinite, with dominancy of montmorillonite, and different mineral sheets are stacked in a combination of 1:1 or 2:1, which is the proportion of tetrahedral sheets to octahedral sheets. For the 2:1 combination, octahedral sheets are a sandwich between two tetrahedral sheets 2:1. Due to the higher adsorption potential of montmorillonite, the expansive soils show a great tendency for water absorption.

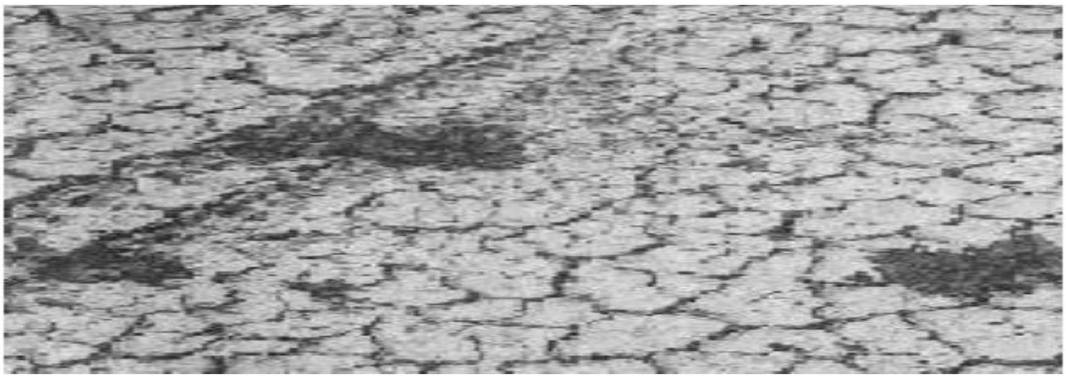

Figure 2.3: Expansive soil showing cracks

2.2.2 Collapsible soils

Collapsible soils undergo volume changes upon wetting, loading, or both. These soils are relatively considered good for foundation structures and contain silt, clay, and salt content, and when get saturated, a chemical reaction occurs, due to which they settle down, and the foundation fails.

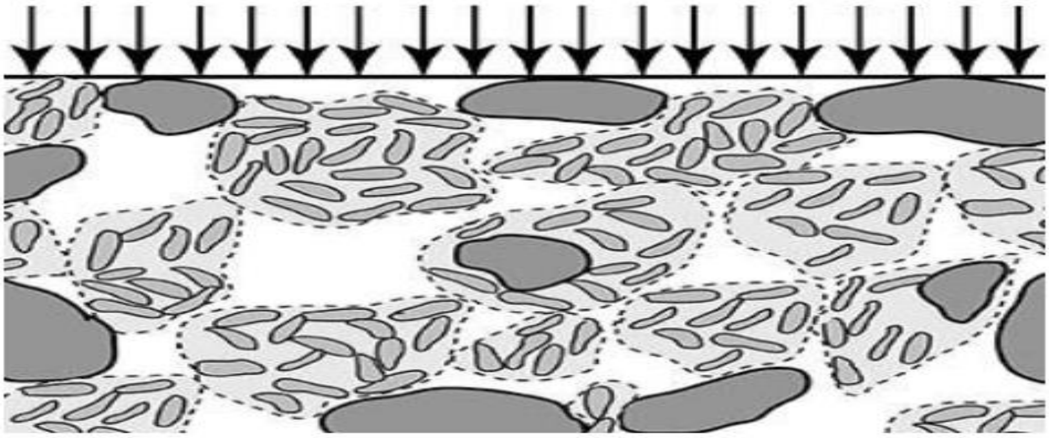

Figure 2.4: Structure of collapsible soil

The change in the weight and the size of the soil occurs when the saturation degree gets more than 50%. These soils contain silt content which acts as a binding material. The water permeates in the soil matrix, which loosens the bond between colloid particles, and it loses its strength. These soils are generally in a dry state with low density and a high percentage of voids. Upon saturation, these soils show a decrease in volume with an increase in dry density. Previous studies show that different types of sediment deposits such as colluvial soil, silt, fine sand, and alluvial soil are subjected to collapse due to changes in the moisture content.

2.3 Terrazyme

Terrazyme also called a bio-liquid enzyme is an organic enzyme, extracted from vegetables and fruits. It is found in liquid form and soluble in water due to its organic nature. The color of terrazyme is dark brownish molasses smell and has no other significant harmful effects (Gupta, 2017). The enzyme is a biological catalyst, made up of proteins. Bio-enzymes are chemicals (organic and liquid), used to stabilize soil and aggregate in roads and structures (Lacuoture, 1995). The fundamental structure of the enzyme is an amino acid, and one or more amino acids combine via a peptide bond to form a protein or polypeptide chain. An amino acid consists of three components attached to the central C-H bond, i.e., i-) an amine group, ii-) R factor, and iii-) carboxylic group. The two ends of amino acids are charged, positively (amine group) and negatively (carboxyl group) with an imbalance proportion which qualifies an amino acid to form a peptide bond with other amino acids to form a protein structure.

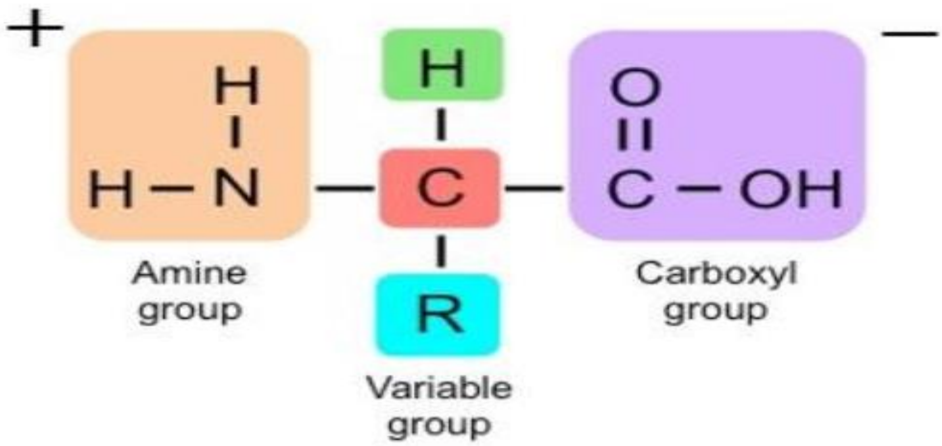

Figure 2.5: Fundamental amino acid structure

Terrazyme improves the quality of soil, reducing the plasticity index, and optimum moisture content, which alternately improves its mechanical properties such as durability, California bearing ratio (CBR), strength, and hydraulic conductivity. Terrazyme repels the clay particles, which alternately provides a protective layer of coating around the clay particles (Yusoff, 2017).

Figure 2.6: Terrazyme sample

2.3.1 Action mechanism of terrazyme

In a clay water mixture, clay particles are surrounded by positively charged ions, creating a film of water around the clay particle, which remains attached or adsorbed on the clay surface. The swelling of clay particles increases the size of a double layer which can be reduced with the cation exchange process. For example, implementation of fermentation processes (in which particles such as glucose are broken down anaerobically) leads to the production of specific micro-organisms resulting in stabilizing the enzyme in large quantities. These soil-stabilizing enzymes catalyze the reactions between the colloid particles and the organic cations, which alternately accelerate the cat-ionic exchange without a part of the end product (Agarwal & Kaur, 2014). Terrazyme replaces adsorbed water with organic cations, thus neutralizing the negative charge on a clay particle. The organic cations reduce the thickness of the electrical double layer, which relatively compact the soils more. Terrazyme promotes the development of cementitious compounds using the following general reaction.

$$H_2O + \text{Clay} \xrightarrow{\text{terrazyme}} \text{Calcium Silicate Hydrates}$$

The parameters such as microorganisms, humus in clay, and colloidal particles generally control the enzyme behavior. Enzymes adsorbed on a soil particle through hydrogen bonding, ionic interaction, and Van der Waal's forces. The enzymes attached to soil particles encapsulate them due to electrostatic attraction, removing the double layer of water, which prevents it from further water adsorption, known as structural deformation of the enzyme. This phenomenon is greatly associated with the intramolecular forces of the enzyme (Zoungrana, 1997). Enzymes react with soil as a base or an acid, altering the electrolytic balance of the soil, which alternately increases the number of cations, available for the cation exchange process with soil, and the soil particles agglomerate (Scholen, 1995).

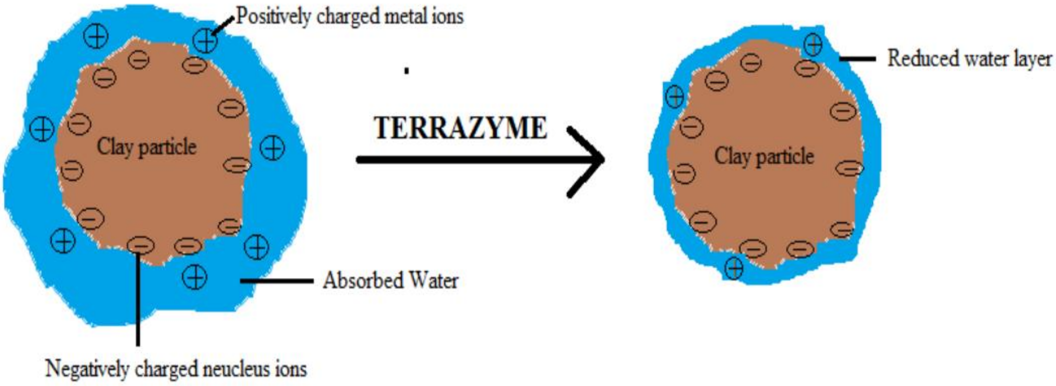

Figure 2.7: Mechanism of terrazyme

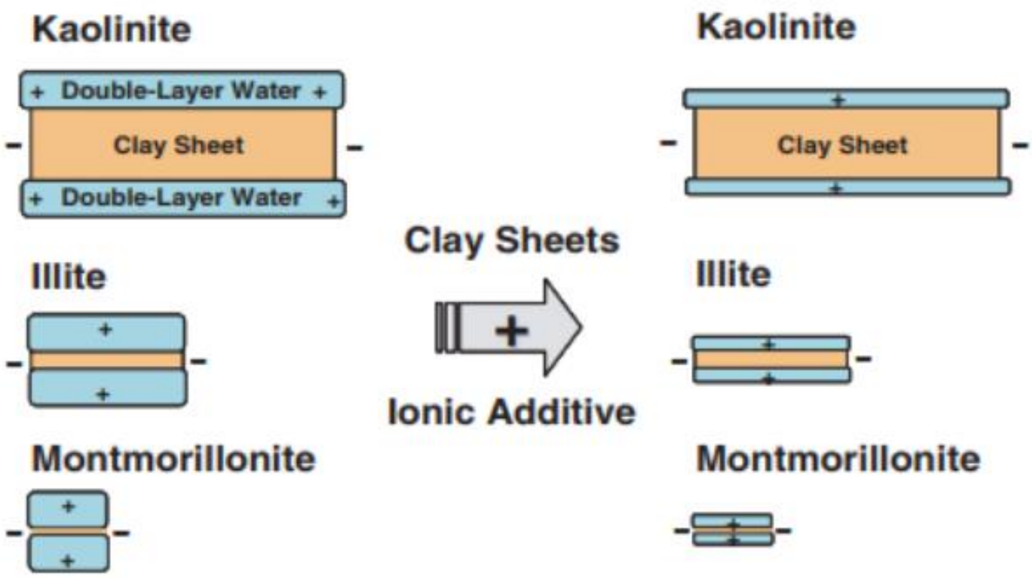

Figure 2.8: Process of clay flocculation due to cation exchange

The soil moisture varies with time due to changes in weather or groundwater conditions. The loss in moisture can severely alter the enzyme's physical structure, which deactivates the enzyme-soil adsorption process. The productivity of enzymes is greatly associated with the number of existing ions in the soil. The ions are already adsorbed on the clay particle, creating an electric barrier and hence reduce the electrostatic attraction between enzyme and clay particles. The dissolved ions may also disrupt the enzyme structure, causing an entire change in its function.

2.4 Unconfined compressive strength

The unconfined compression test is generally performed to estimate the unconfined compressive strength of the saturated cohesive soil. (Wani, 2020) performed UCS tests to understand the behaviour of bio-cemented weak soils. The specimens were prepared at 85% of dry unit weight and samples were sheared at a strain rate of 1.2 mm/min. The study reported that the UCS increased with an increase in treatment for different cycles. This increase was due to the calcite precipitate which held the soil particles together, filling the voids of the soil matrix. (Jjuuko, 2011) conducted UCS tests on natural and dry sand reinforced clayey soils at optimum moisture content. The strain rate of 1.27 mm/min was used in these tests. The study concluded that the UCS decreased up to 40% with the addition of 20% sand in the clay, and this decrease was due to looseness in bonding between clay particles due to the addition of sand particles. (Saride, 2013) studied the influences of 7, 28, and 56 days curing on unconfined compressive strength of natural and treated organic clay soil samples. The additives, i.e., cement and lime were used to reinforce the soils. The addition of lime and cement reduced the plasticity index but showed fewer effects on the UCS of soil. The changes in the behavior of treated soil were associated with the formation of inorganic calcium humic acid due to the reaction between lime and organic matter.

2.5 Hydraulic conductivity

Hydraulic conductivity defines the ability of a porous medium to transmit water within the soil skeleton. (Cuisinier, 2020) studied the hydraulic conductivity of ML treated with cement and quick lime. The study reported that the hydraulic conductivity increased with an increase in the wetting and drying cycles (Francisca, 2010) studied the hydraulic conductivity of bentonite treated silt treated performing falling head test method. The test data showed that k decreased with time and the porosity of the soil particles also reduced with the addition of bentonite. (Phani Kumar, 2004) studied the hydraulic conductivity of the expansive soil treated with fly ash. The specimens were tested at OMC and MDD. The test results showed that the addition of fly ash resulted in a decrease in hydraulic conductivity. This decrease in k was due to an increase in dry unit weight and fly ash. (Benson, 1995) studied the hydraulic conductivity of 13 different clayey soils samples for various compaction efforts, conducting falling head method. The study reported that the hydraulic conductivity decreased for an increase in the compaction effort.

2.6 Past studies for wetting and drying cycles

(Cuisinier et al., 2020) studied the hydraulic conductivity and UCS of lime and cement treated silty clay for different wetting and drying cycles. The UCS tests were performed at a strain rate of 1.04 mm/min. It was noted that the soil strength reduced up to 50% after wetting-drying cycles. However, an increase in strength up to 30% was noted after 90 days curing period. Furthermore, the k gradually increased for an increase in W-D cycles. As expected, the strength of treated samples was more than natural soil, tested under similar conditions, showing an increase from 145 kPa to 340 kPa.

(Maafi Nabil et al., 2019) examined the unconfined compressive strength, plasticity index, and cation exchange capacity of lime treated soil for different wetting and drying cycles, and the test data showed that UCS increased, whereas PI and CEC decreased with an increase in the lime level, and the soil treated with the concentration of lime above 4% provided favorable results for different wetting and drying conditions.

(Zhi Hu et al., 2019) employed electrical resistivity method to examine the mechanical behavior of soil, considering different numbers and cyclic amplitudes for wetting and drying cycles and reported that the strength of the compacted specimens was reduced with an increase in the number and cyclic amplitude for wetting-drying cycles and insignificant variations in strength was noted after 3-4 wetting-drying cycles.

(Wan et al., 2018) tested the hydraulic conductivity of clayey soils for various liquid limits, and different wetting & drying cycles. The prepared samples were saturated, and oven-dried at 50°C, respectively. The study reported that the hydraulic conductivity gradually increased with an increase in the wetting-drying cycles. However, for untreated soils, the k decreased with an increase in the liquid limit.

(Hao Ye et al., 2018) investigated the unconfined compression strength and Atterberg limits of expansive soil for drying-wetting cycles, treated with iron tailing sands and calcium carbide slag, and concluded that the liquid and plastic limits decreased for a gradual increase in the wetting and drying cycles.

(Tang, C. H et al., 2016) examined the mechanical behavior of saturated and unsaturated soil specimens for three drying and wetting cycles and concluded that the wetting drying cycles degraded the soil's mechanical behavior, and the initial water content of the soil most commonly controlled the changes in the performance of the soil samples.

(De-Yin Wang et al., 2016) examined the effects of wetting–drying cycles on soil strength profile of silty clay in micro-penetrometer tests, and concluded that with increasing W–D cycles, the strength tended to decrease, and the penetration curves changed from typical mono-peak pattern to multi-peak pattern after the third W–D cycle.

(Bao-tian Wang et al., 2015) examined the unconfined compressive strength and swelling potential of modifier OTAC-KCI treated swelling soil for different wetting and drying cycles and reported that the admixture not only enabled to reduce the swelling potential but also it increased the unconfined compressive strength.

(Venika Saini et al., 2015) examined the index properties and subgrade strength of the roads of terrazyme treated soil, and the test results showed that the modifier provided significant changes on the mechanical behavior of the treated soils.

(Apichit Kampala et al., 2014) studied the durability of the calcium carbide residue (CCR) and fly ash (FA) stabilizing silty clay for different wetting and drying cycles to guess its performance on pavement applications. The strength analysis showed that the durability was directly related to the unsoaked strength, prior to the wetting and drying cycles and consequently, relationships of strength for various drying and wetting cycles were proposed based on the test data.

Chapter 3

3 MATERIALS AND METHODOLOGY

3.1 General

This chapter presents the materials and methods used in the study to examine the hydro-mechanical behaviour of different soils for various wetting and drying cycles. All the tests were conducted according to ASTM standards.

3.2 Materials

3.2.1 Soil

Three different soils with various consistencies were used in this research, which was collected from Bale wala Nandipur Gujranwala, Buchal Kalan Kallar Kahar, Chakwal, and Lodhran Pakistan.

3.2.2 Terrazyme

Terrazyme used in this research was obtained from Nature Plus Inc USA. Terrazyme retailer was not available in Pakistan, so it was imported from Nature Plus Inc. USA.

Figure 3.1: Terrazyme bottle

3.3 Soil characterization.

3.3.1 Grain size distribution

The mechanical analysis of soils was carried out by performing the sieve analysis and hydrometer tests. Sieve analysis was conducted according to ASTM D422-00 standard, and hydrometer test was conducted by following the guidelines as per ASTM D422-63 standard. A dispersing agent, sodium hexa-meta phosphate was used in the hydrometer test. Figure 3.2 shows a pictorial view of the sieve analysis and hydrometer analysis performed in the laboratory.

Figure 3.2: Scheme of sieve analysis and hydrometer analysis in the laboratory

3.3.2 Atterberg’s limits

Atterberg’s limit tests were performed following the guidelines as per ASTM D423-66, ASTM D424-59, and ASTM D698-70 standard. In these tests, oven-dried samples passing through the #40 sieve were used. Figure 3.3 shows the liquid limit test performed in the laboratory.

Figure 3.3: Liquid limit test performed in the laboratory

Figure 3.4 shows a pictorial picture of the plastic limit test, performed in the laboratory. The plasticity index (P.I.) is an important property defining the swelling behaviour of various soils. The difference between liquid limit (L.L.) and plastic limit (P.L.) is PI, and which is presented in Equation 3-1.

$$\mathrm{P.I.} = \mathrm{L.L.} - \mathrm{P.L} \qquad \text{Equation 3-1}$$

Figure 3.4: Appearance of thread after plastic limit test

For shrinkage limit tests, 40 gm of oven-dried soil sample passing through the #40 sieve was used. The soil sample was prepared at its liquid limit. The shrinkage dish was slightly coated with petroleum jelly to prevent the sticking of the soil particles. The sample was spread in a standard dish in three layers. For each layer, the dish was taped from the base until the soil layer gets smooth and free from air bubbles. The specimen was then air-dried for 6 hours and then placed in an oven at 105 to 110° C for 12 hours. The oven-dried sample was replaced with the same mass of mercury in the dish. The oven-dried specimen and the mass of mercury were then weighed to measure the shrinkage limit. Equation 3-2 is used to measure the shrinkage limit, and Figure 3.5 shows the setup in the laboratory for the shrinkage limit test.

$$S.L = \frac{(Vi - Vf)\rho w}{ws} x100 \quad \text{Equation 3-2}$$

Figure 3.5: Shrinkage limit arrangement in the laboratory

3.3.3 Specific gravity

The specific gravity test of the soil was performed as per specifications in the ASTM D854-54 standard. For this test, 50 grams of oven-dried soil sample passing through the #40 sieve was used. Firstly, the volumetric flask was weighted, and 50 gm of the soil was thoroughly mixed with a small amount of water through shaking.

The admixture was then placed on a hot plate for 15 minutes to remove air voids. The volumetric flask was kept shaking during the heating process. After 15 minutes, the flask was removed from the hot plate and placed on the wooden table for 30 minutes, and the remaining part of the flask was filled with water up to the mark as mentioned in the standard and weighed. The weight of both the volumetric flask and the water-filled volumetric flask was measured separately. Figure 3.6 shows a pictorial view of the specific gravity test performed in the laboratory.

Figure 3.6: Specific gravity test in the laboratory

3.3.4 Moisture-density relationship

The standard Proctor test was carried out as per ASTM D698-12 standard to figure out the relationship between optimum moisture content and maximum dry density of soils. The moisture content was increased by an increment of 3% in these tests. The water was added to the soil and mixed thoroughly with a hand and a spatula. After then, the prepared samples were transferred to the compaction mold. The specimens were compacted in three equal layers with 25 blows of hammer for each layer. It was observed that when the moisture content increased beyond a certain limit, the clay adhered with the hammer and the mold during hammering. A knife with a flat and sharp edge was used to clean the adhered clay from the hammer and the mold. Figure 3.7 shows a pictorial view of the standard Proctor test performed in the laboratory.

Figure 3.7: Standard Proctor test performed in the laboratory

3.3.5 Unconfined compressive strength (UCS)

The UCS tests were performed as per ASTM D2166 standard to examine the compressive strength of the soil. The mold with 7cm diameter and 14cm height was used to perform the tests and to maintain the standard ratio of 1:2 as per the criteria described in the standard. The samples were prepared at 95% of the maximum dry density of soil as in the standard Proctor test, following the same procedure as discussed in the preceding section (compaction curve). After preparation, the samples were passed through different wetting and drying cycles. The wetting and drying cycles were completed as per the procedure discussed in Section 3.6. The samples were then transformed to a UCS device, and the load was applied until the specimens failed. Figure 3.8 shows pictorial views of a few samples after failure. In these tests, an axial strain rate of 1 mm/min was used as per the criteria mentioned in (Arabani, 2020). Equation 3-3 was then used to determine the undrained shear strength of the soil.

$$\text{Shear Strength} = \frac{q_u}{2} \qquad \text{Equation 3-3}$$

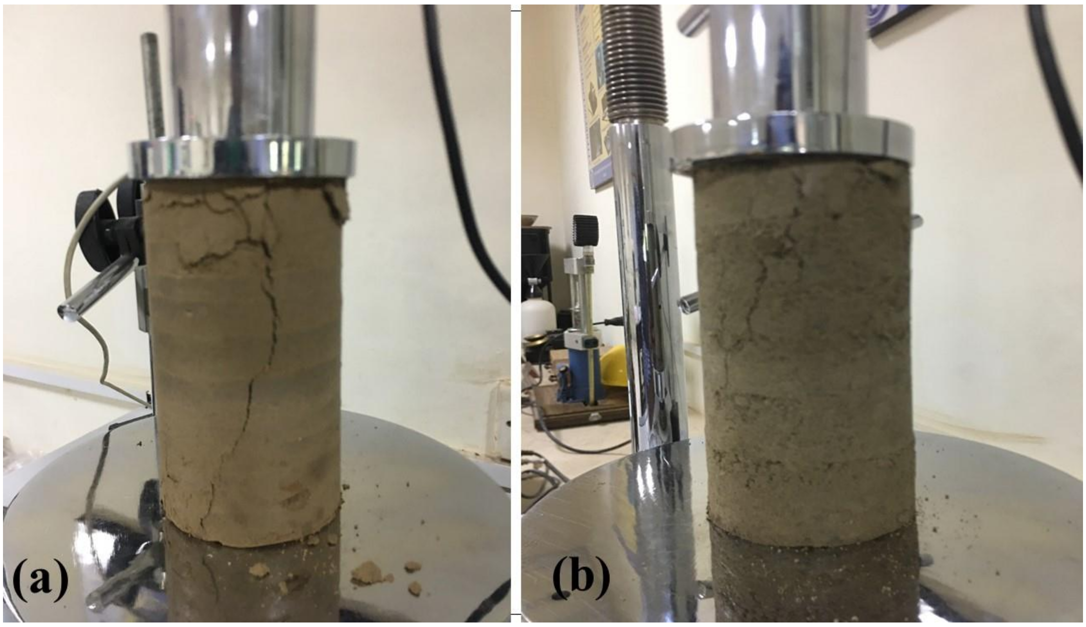

Figure 3.8: UCS test performed in the laboratory

3.3.6 Hydraulic conductivity tests

Falling head tests were conducted to examine the hydraulic conductivity of soils, as per guidelines in the ASTM D2434-68 standard. The specimens were prepared in the permeator at 95% of maximum dry density as per the standard Proctor test for both natural and treated soils. The samples got stuck with the steel permeator and damaged while getting out of it. The samples need to get out of the mold for their wetting and drying. To resolve this issue, a special mold was manufactured with plastic pipes of 4 cm diameter and 6 cm depth. The mold was longitudinally cut with a sharp cutting device to facilitate the samples out of the permeator, easily. To fix the sample in a modified mold, a steel wire was used as a clamp (Figure 3.9). After preparing the samples, the wire was untied and the samples were taken out of the plastic mold, easily.

The wetting and drying cycles were completed as per the procedure discussed in Section 3.6. After then, the prepared samples were transferred to a hydraulic conductivity permeator. It was noted that the samples got shrink after wetting and drying cycles, and there was a slight gap between the sample and permeator wall. So, sealant silicon as shown in Figure 3.9 was used to fill this gap to prevent any seepage of water adjoining the permeator wall. Figure 3.10 shows a few pictorial views of hydraulic conductivity tests in the laboratory. Finally, Equation 3-4 was used to determine the hydraulic conductivity of the soil. In Equation 3.4, A and a=x-sectional areas of specimen and standpipe respectively, L=length of the specimen, t=elapsed time during the test, h_1 and h_2 are heads at the beginning and end of the test.

$$k = 2.3\frac{aL}{At}log\frac{h1}{h2} \qquad \text{Equation 3-4}$$

Figure 3.9: Special molds with sealant

Figure 3.10: Pictorial views of hydraulic conductivity tests in the laboratory

3.4 Terrazyme selection

The amount of terrazyme generally depends upon the plasticity index, percentage fines, and the maximum dry density of the soil. Based on the %age fines, plasticity index, and maximum dry density of soil, Table 3.1 and Table 3.2 were used to estimate the concentration of terrazyme for a specified volume of soil. The terrazyme is a water-soluble enzyme, so it was first dissolved in a given amount of water to prepare a water terrazyme suspension. The water terrazyme admixture was carefully prepared, ensuring its dispersion and dilatancy with water. After then the prepared solution was added to the soil and mix it uniformly with a brush. The UCS and k tests were carried out for different concentrations of the terrazyme.

Table 3.1: Relation of soil volume with its PI and percentage fines

PI						
40	24 m³	22m³	20 m³	18 m³	16 m³	14 m³
35	27 m³	25 m³	23 m³	21 m³	19 m³	17 m³
30	30 m³	28 m³	26 m³	24 m³	22 m³	20 m³
25	33 m³	31 m³	29 m³	27 m³	25 m³	23 m³
20	36 m³	34 m³	32 m³	30 m³	28 m³	26 m³
15	39 m³	37 m³	35 m³	33 m³	31 m³	29 m³
10	42 m³	40 m³	38 m³	36 m³	34 m³	32 m³
5	45 m³	43 m³	41 m³	39 m³	37 m³	35 m³
0	**15**	**50**	**85**	**120**	**155**	**190**
	% Fines					

Table 3.2: Terrazyme concentration in liters for given soil volume

m3 soil/ Litr. TZ conc.		**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**
Soil density (kg/m3)	**1400**	3.35	3.25	3.15	3.05	2.95	2.85	2.75	2.65	2.55	2.46	2.38
	1500	3.1	3.01	2.92	2.83	2.74	2.65	2.56	2.47	2.38	2.3	2.22
	1600	2.87	2.79	2.71	2.63	2.55	2.47	2.39	2.31	2.23	2.16	2.08
	1700	2.74	2.66	2.58	2.5	2.42	2.34	2.26	2.18	2.1	2.03	1.96
	1800	2.62	2.54	2.46	2.38	2.3	2.22	2.14	2.06	1.98	1.92	1.85
	1900	2.44	2.37	2.3	2.23	2.16	2.09	2.02	1.95	1.88	1.81	1.75

3.5 Sample preparation

The UCS and hydraulic conductivity tests of both natural and treated soils were performed for different wetting and drying cycles. Figures 3.11 and 3.12 show the samples of natural soil prepared for UCS and hydraulic conductivity tests.

Figure 3.11: Samples of natural soils for UCS tests

Figure 3.12: Samples of natural soil for hydraulic conductivity tests

3.6 Wetting-drying action

The prepared samples were wrapped in cotton bandages to prevent their direct contact with water to prevent the disturbances of the samples, as shown in Figure 3.13 and Figure 3.14.

Figure 3.13: UCS wetting-drying cycles samples

Figure 3.14: Hydraulic conductivity wetting-drying cycles samples

The wrapped samples were placed in the porous plastic tubs vertically in such a way that the lower end of the sample was touched with water, which started to saturate the sample using capillary action as shown in Figure 3.15. After saturation, the specimen was oven dried for 24 hours. In this way, 1st wetting-drying cycle for a sample was completed. Similarly, the 3rd, 5th, and 7th wetting-drying cycles were completed for the particular sample, and the same procedure was repeated for all the samples, for both natural and treated soils. Duplicate samples were prepared for each sample to ensure the repeatability of the test data.

Figure 3.15: Saturation process is in progress

Chapter 4

4 RESULTS AND ANALYSIS

4.1 Introduction

This chapter reports the results to discuss the hydro-mechanical behaviour of natural and treated soils for different wetting–drying cycles in addition to some other index properties.

4.1.1 Grain size analysis

The grain size distribution curves of Nandipur, Kallar Kahar, and Lodhran are shown in Figure 4.1. The test results show that Nandipur soil contains 8% sand, 48% clay, and 44% silt. Kallar Kahar soil contains 88% silt and 12% clay and Lodhran soil contains 27% sand, 73% silt, and 0% clay contents. It means that Lodhran soil relatively contains coarser particles than other soils, and comparatively, the Kallar Kahar soil profile shows a more consistent nature, providing a wide range of particles (Figure 4.1). The outcome of the current research work is in line with the previously published work (Mosa, 2017; Saride, 2013).

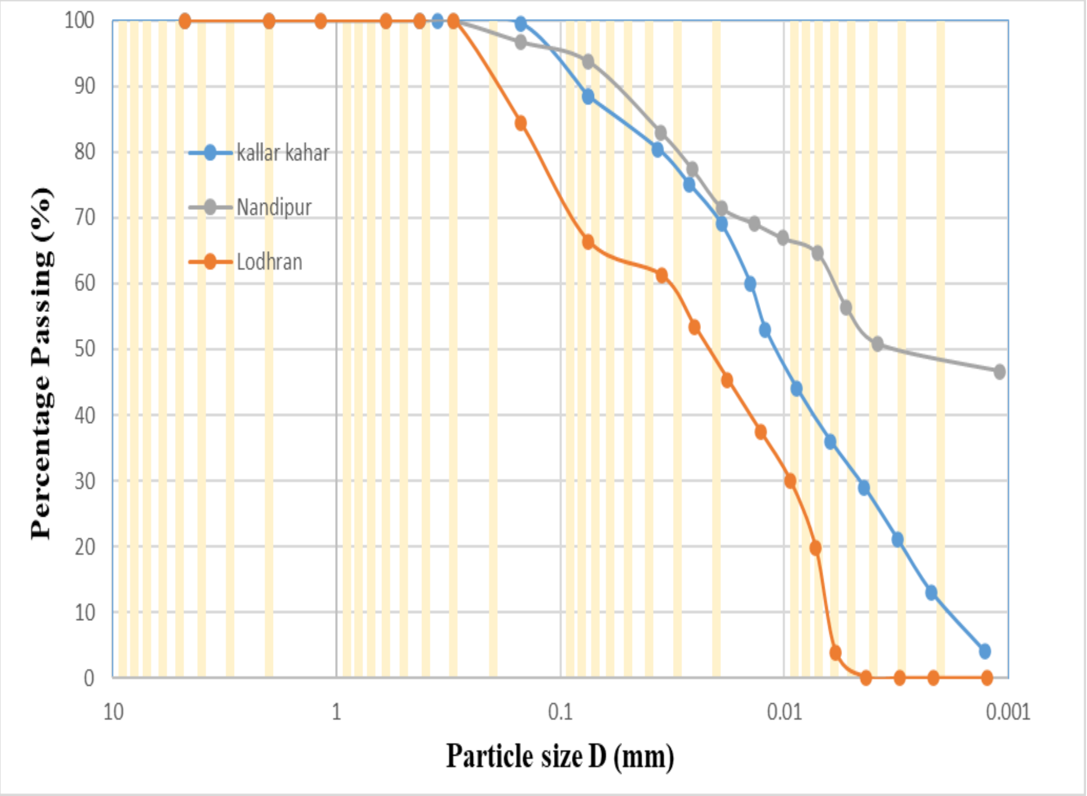

Figure 4.1: Particle size distribution curves for Nandipur, Kallar Kahar, and Lodhran soils

4.1.2 Atterberg's limits

Figure 4.2 shows liquid limit test results and Figure 4.3 shows the relationship between plasticity index and liquid limit. Nandipur soil shows a liquid limit of 60%, plastic limit of 21.95%, and shrinkage limit of 21.22%, respectively with a P.I of 38%. Kallar Kahar soil shows a liquid limit of 42%, a plastic limit of 26%, and a shrinkage limit of 14.5%, respectively with a P.I of 16%. Lodhran soil shows a liquid limit of 28%, a plastic limit of 22%, and a shrinkage limit of 11.54%, respectively with a P.I of 6%. It means that Nandipur soil shows more PI than other soils, which alternately may provide more swelling potential. The outcome of the current research work is in line with the previously published work (Saride, 2013; Wan, 2018).

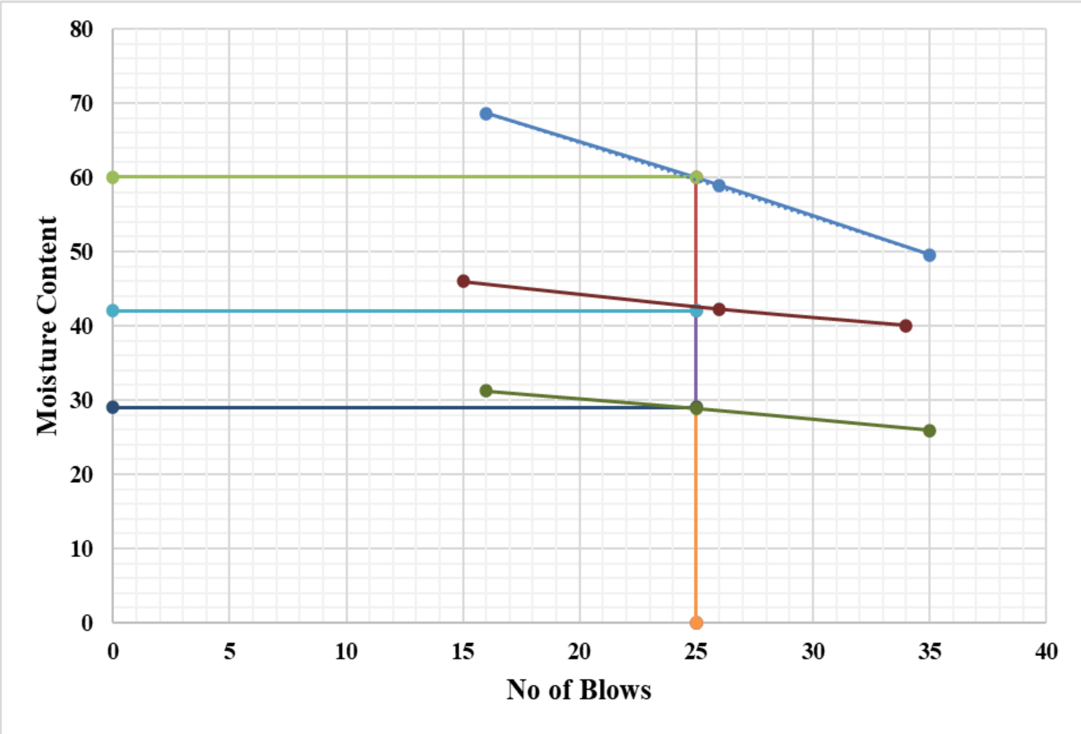

Figure 4.2: Liquid limit test results of Nandipur, Kallar Kahar & Lodhran soil

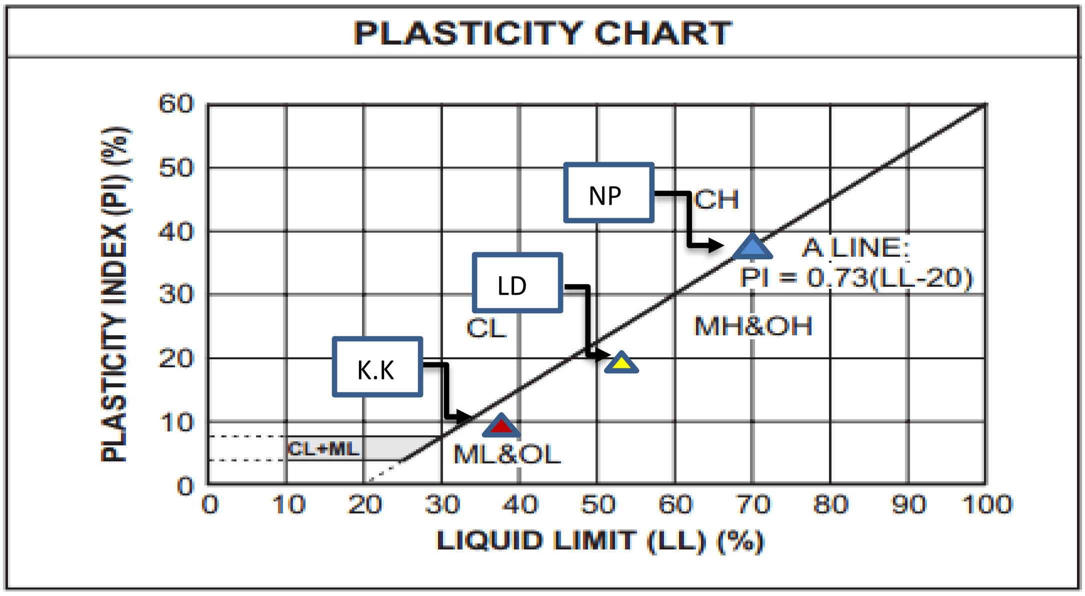

Figure 4.3: USCS Classification of Nandipur, Kallar Kahar & Lodhran soil

It can be seen from Table 4.1 that Nandipur soil falls in highly plastic clay with the A-7-6 group (AASHTO SCS). Kallar Kahar and Lodhran soil are low plastic clay according to AASHTO Soil Classification System and fall in A-4 and A-7-6 groups.

According to the soil classification system and consistency limit test results, the Kallar Kahar soil relatively seems a better soil than others.

Table 4.1: Liquid limit, plastic limit, shrinkage limit, and classification of soils

Property	**Unit**	**Nandipur Soil**	**Kallar Kahar Soil**	**Lodhran Soil**
Liquid Limit	Moisture (percent)	60	29	42
Plastic Limit	Moisture (Percent)	22	21	26
Plasticity Index	Moisture (Percent)	38	08	16
AASHTO Classification		A-7-6	A-4	A-7-6
USCS Classification		CH	CL	CL

4.1.3 Specific gravity

The Nandipur soil, Kallar Kahar soil, and Lodhran soil show a specific gravity of 2.68, 2.67, and 2.7 respectively, and are shown in Figure 4.4.

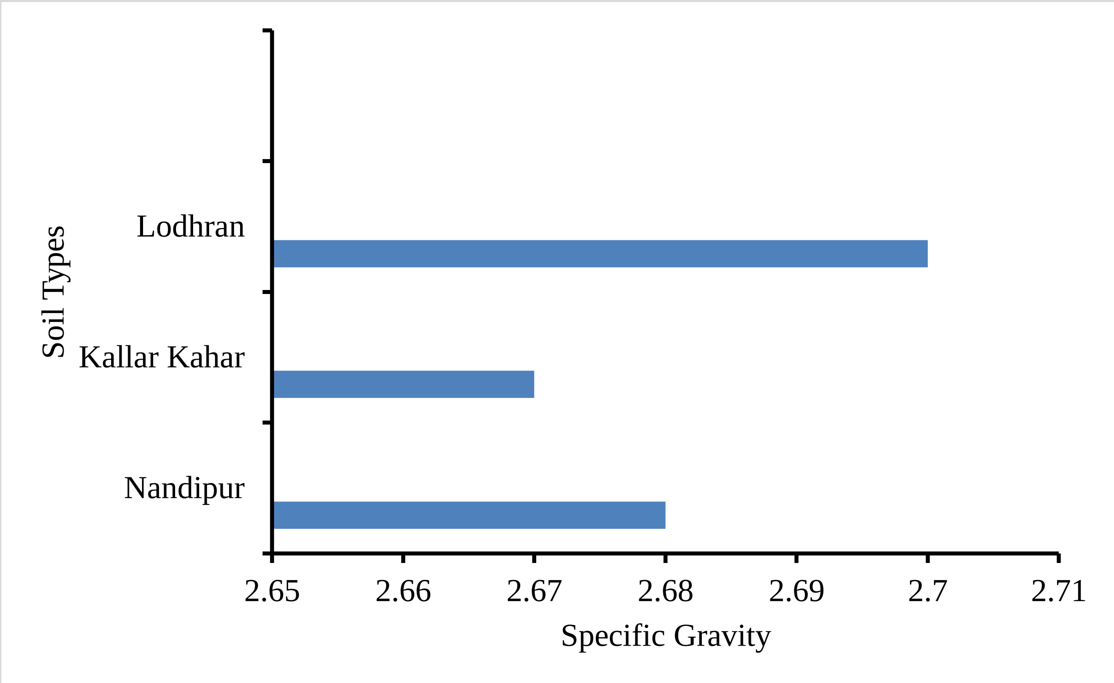

Figure 4.4: Specific gravity results for soil samples

4.1.4 Moisture-density relationship

Figure 4.5 shows the relationship between optimum moisture content and maximum dry density for different soils. The maximum dry density for Nandipur soil, Kallar Kahar soil, and Lodhran soil was 15.7 kN/m^3, 18.6 kN/m^3, and 16.9 kN/m^3 at 22.95%, 14.7%, and 17.5% moisture content, respectively. As in Figure 4.5, the Nandipur soil shows a lower peak than other soils which is due to differences in liquid limit and grain size distribution. Similarly, findings were reported by

(Saride, 2013) while working on 08 different samples in which each specimen provided a different compaction curve.

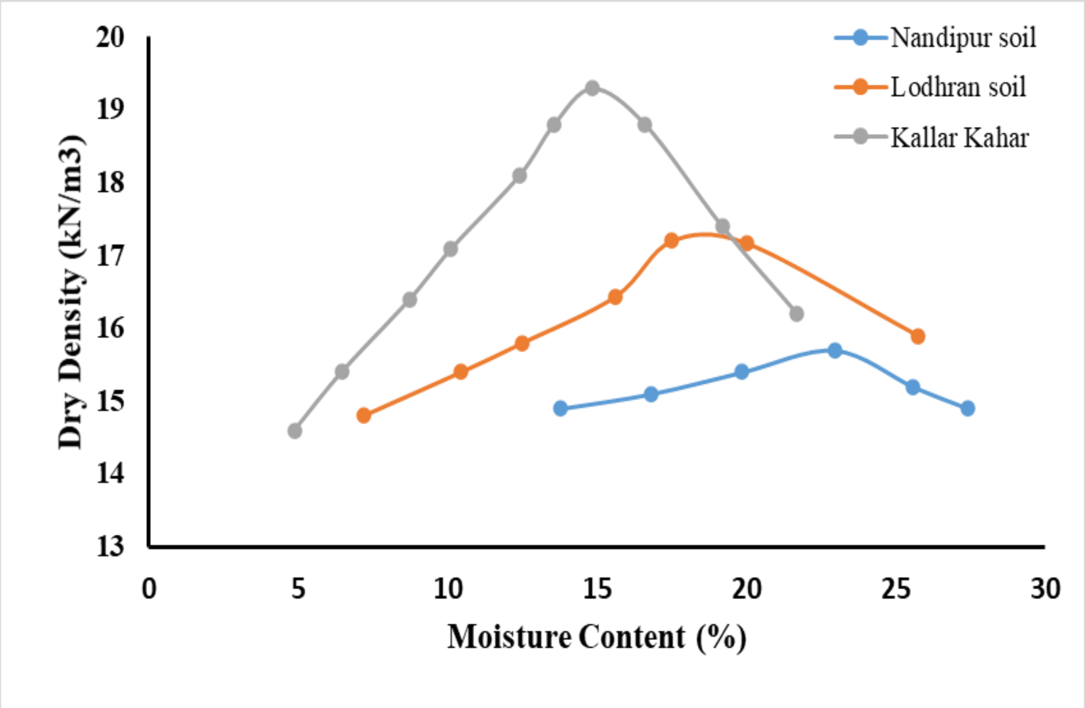

Figure 4.5: Moisture-density relationship of Nandipur, Kallar Kahar, and Lodhran soil

4.1.5 Unconfined compressive strength

The UCS of Nandipur, Kallar Kahar, and Lodhran soils are 44.6 kPa, 160.9 kPa, and 135.9 kPa respectively showing that Kallar Kahar soil provides more strength than other soils which is due to its well-graded grain size distribution profile and A-4 group. Figure 4.6 shows the test results for UCS for these soils.

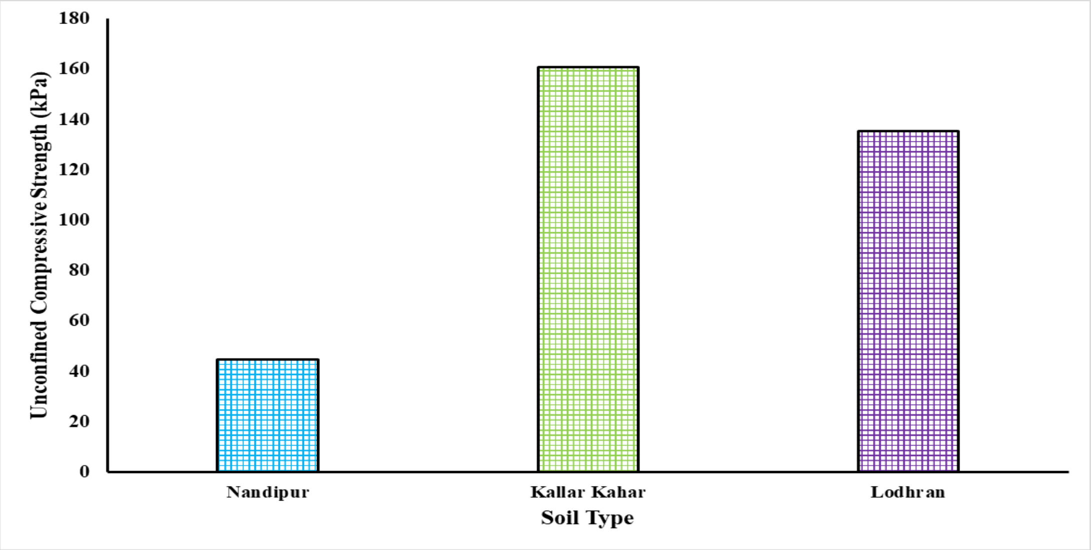

Figure 4.6: UCS results of Nandipur, Kallar Kahar, and Lodhran at OMC

4.2 Terrazyme selection

4.2.1 Terrazyme dosage

Terrazyme dosage was calculated as per the company's protocols.

4.2.2 Preparation of dosages

Table 4.1 shows the percentage fines and PI for different soils in relation to soil volume and Table 4.2 highlights the terrazyme dosage in relation to soil volume and soil density. The %age fines and PI for Nandipur, Kallar Kahar, and Lodhran vary from 85-120 percent, 35-40 percent, 85-120 percent and 5-10 percent, and 50-85 percent and 15-20 percent, respectively. The maximum dry density of Nandipur, Kallar Kahar, and Lodhran soils are 1600, 1870, and 1750 kg/m^3 as per moisture density relationships, respectively. Using these values in relation to Table 4.1 and 4.2, the reference concentrations of terrazyme per kg for Nandipur, Kallar Kahar, and Lodhran soils are estimated as 0.0231 ml, 0.0162 ml, and 0.0174 ml, initially. The samples were prepared for these terrazyme proportions, initially, and after then the specimens were tested for different doses to determine the best dose. The UCS test results for Nandipur soil are reported in Figures 4.7 and 4.8. The test results show that the dose (TR-0.0271) provides maximum compressive strength (80 kPa) as compared to other alternatives. The UCS test results for Kallar Kahar soil are presented in Figures 4.9 and 4.10 and as per test data. The results indicate that terrazyme concentration (TR-0.06) provides maximum compressive strength (205 kPa) as compared to other alternatives. The variations in UCS for various terrazyme concentrations are presented in Figures 4.11 and 4.12 for Lodhran soil. The test data shows that the dose (TR-0.08) provides maximum compressive strength (210 kPa) as compared to other alternatives. It means that the Kallar Kahar and Lodhran soil provides quite higher strength than Nandipur soil. However, the Nandipur soil needs quite a lower dose for maximum strength as compared to others. The low strength of Nandipur soil is associated with its low compaction curve peak at higher water content. Furthermore, its liquid limit is also quite higher than other soils.

The addition of terrazyme in the soil increases the bonding capacity of the soil particles. For doses beyond a certain limit, a decrease in strength is due to the fact that repulsive forces dominate the attractive forces due to a higher concentration of terrazyme. Furthermore, the extra amount of terrazyme increases the quantity of liquid producing slippage among the clayey particles, which reduces the cohesion within the soil particles, and alternately the soil loses strength. The chemical action of the enzyme helps to fuse the soil particles providing a more packed structure which alternately results in an increase in the soil strength (Marasteanu, Hozalski, Clyne, & Velasquez, 2005). Another reason for an increase in UCS is that the thickness of the the double layer minimizes due to the reorientation of soil particles, which alternately provides a denser soil matrix. Furthermore, for lower doses, the concentrations are insufficient to provide a strong bond among colloids due to which the soil provides lower strength.

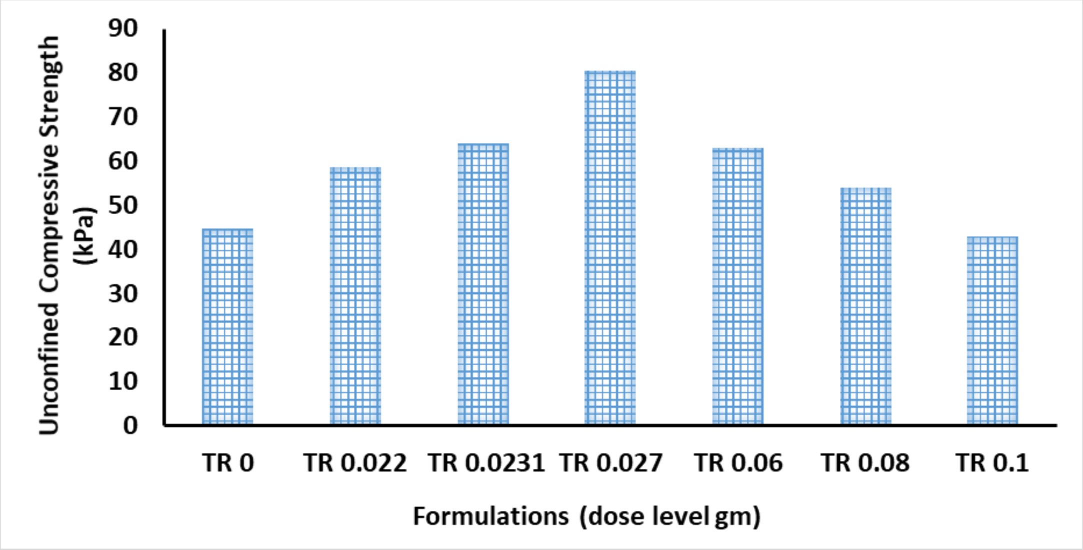

Figure 4.7: Variation in strength for different dosages of terrazyme

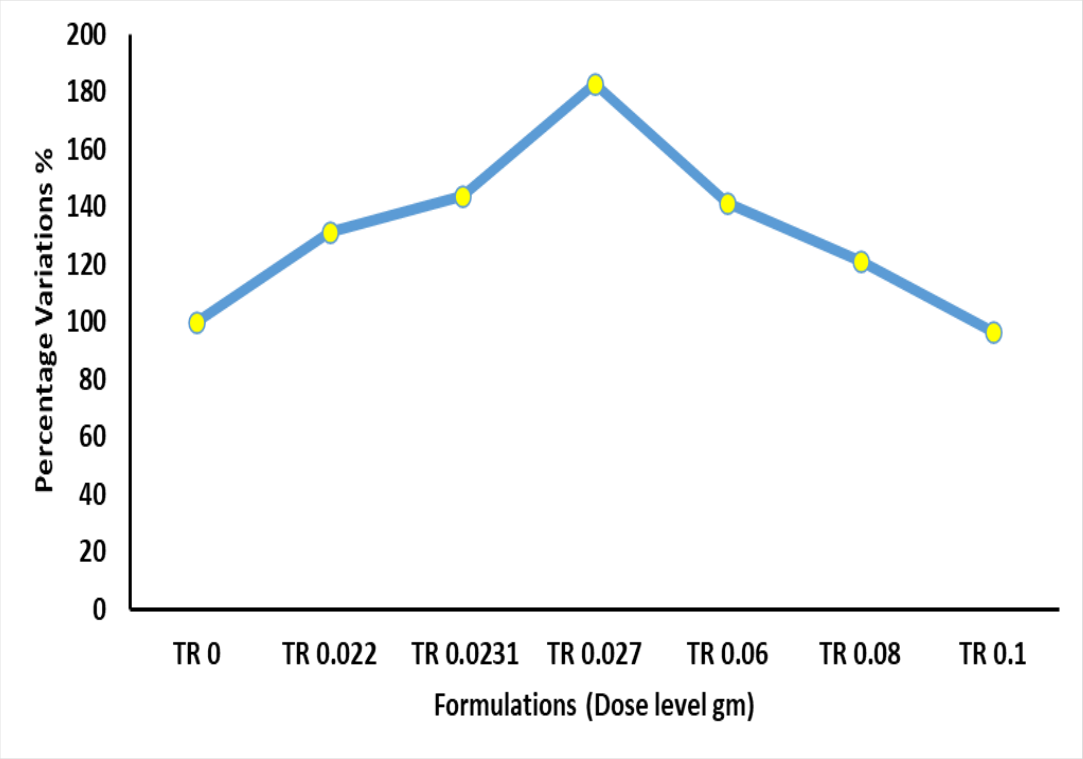

Figure 4.8: Percentage variation in strength for different dosages of terrazyme

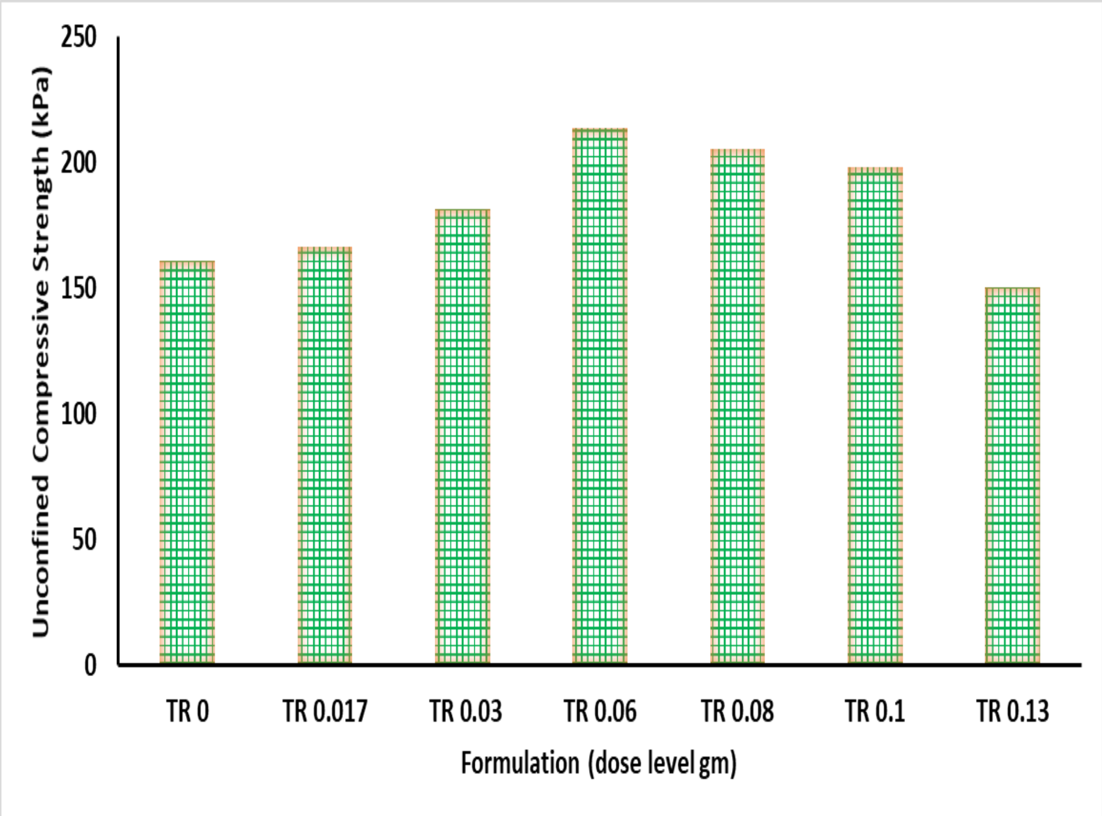

Figure 4.9: Variation in strength for different dosages of terrazyme

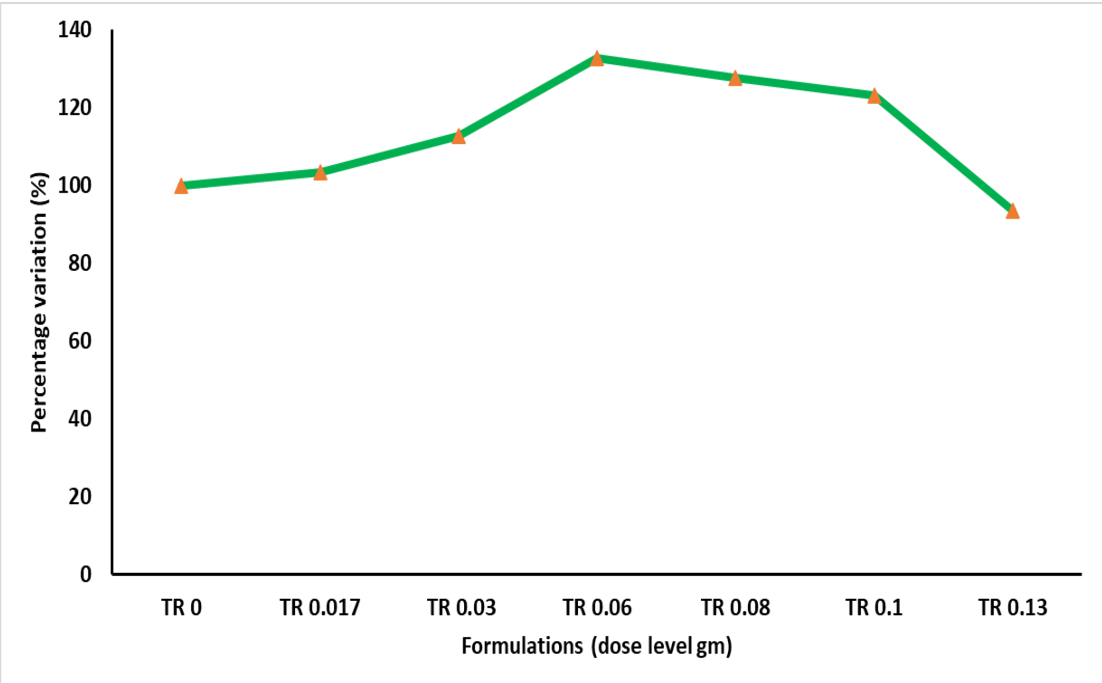

Figure 4.10: Percentage variation in strength for different dosages of terrazyme

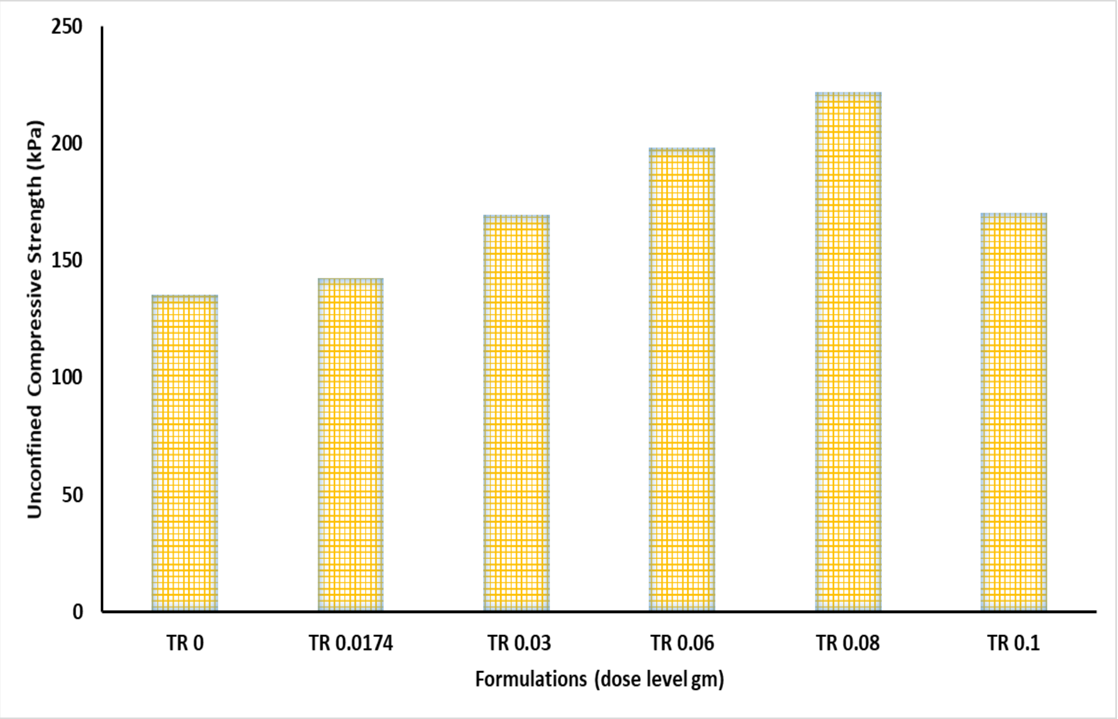

Figure 4.11: Variation in stresses w.r.t different dosages of terrazyme

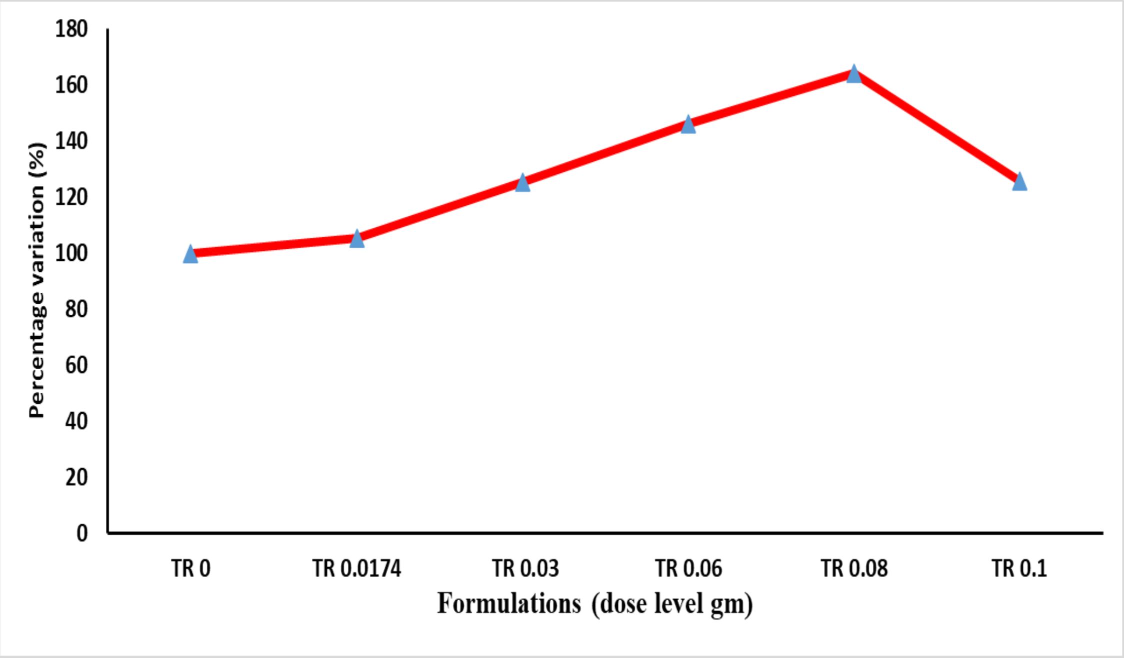

Figure 4.12: Percentage variation in stresses w.r.t different dosages of terrazyme

4.3 Effects of wetting-drying cycles on soil behavior

4.3.1 Unconfined compressive strength

4.3.1.1 Nandipur soil

The test results show that the soil strength decreases with a gradual increase in the wetting and drying cycles. The variations in the UCS after different wetting and drying cycles are shown in Figure 4.13. The test results indicate that unconfined compressive strength for the 3^{rd}, 5^{th}, & 7^{th} wetting & drying cycles of untreated soil is approximately 15%, 31%, & 45% less than 1st cycle. Similarly, the treated Nandipur soil shows 11%, 22%, & 37% less unconfined compressive strength for 3^{rd}, 5^{th}, & 7^{th} wetting & drying cycles than 1st cycle.

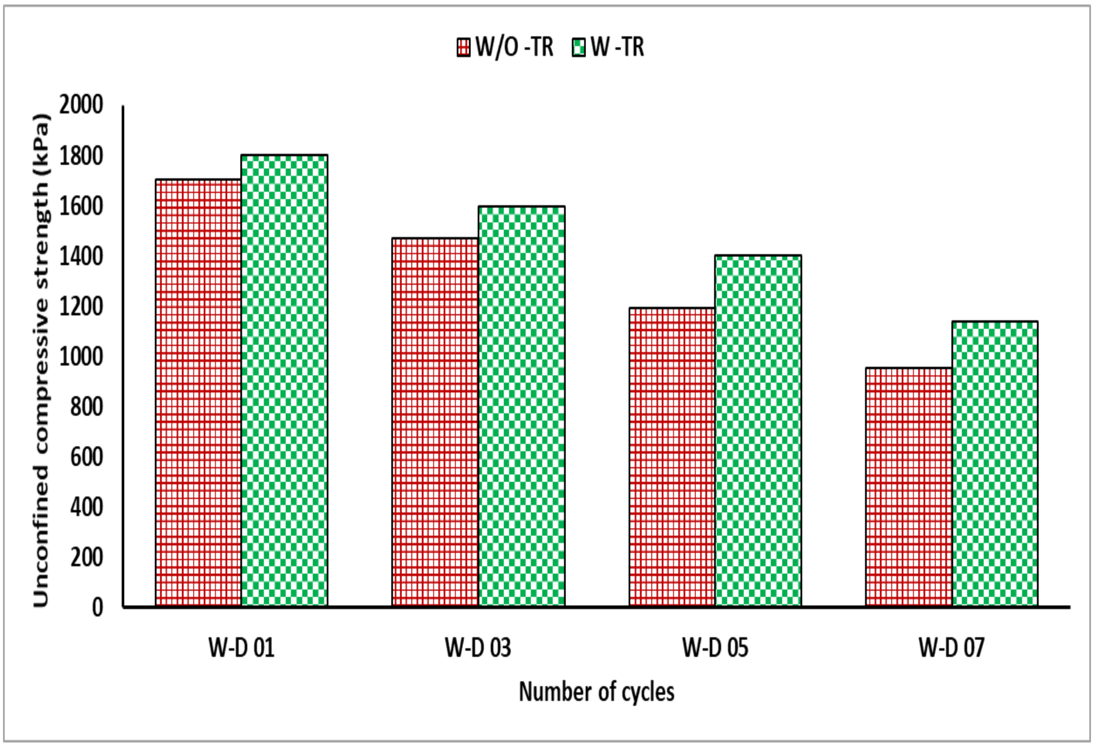

Figure 4.13: Variation of UCS of treated & untreated Nandipur soil for wetting-drying cycles

Comparatively, the treated soils provide 5%, 9%, & 8% higher strength than untreated soils for 3rd, 5th, and 7th wetting and drying cycles respectively. This increase in UCS of treated soil is due to the fact that terrazyme reacts with the absorbed water layer around the clay particles which causes a reduction in the double layer around the soil particles, which alternately reduces the L.L and P.I of soil. Another reason for this increase in strength is that the soil particles come closer to each other due to a reduction in the double layer, which alternately provides tight bonding among colloid particles. These results are consistent with the previous research work in which terrazyme enabled to increase the strength, considerably (Ramesh, 2015).

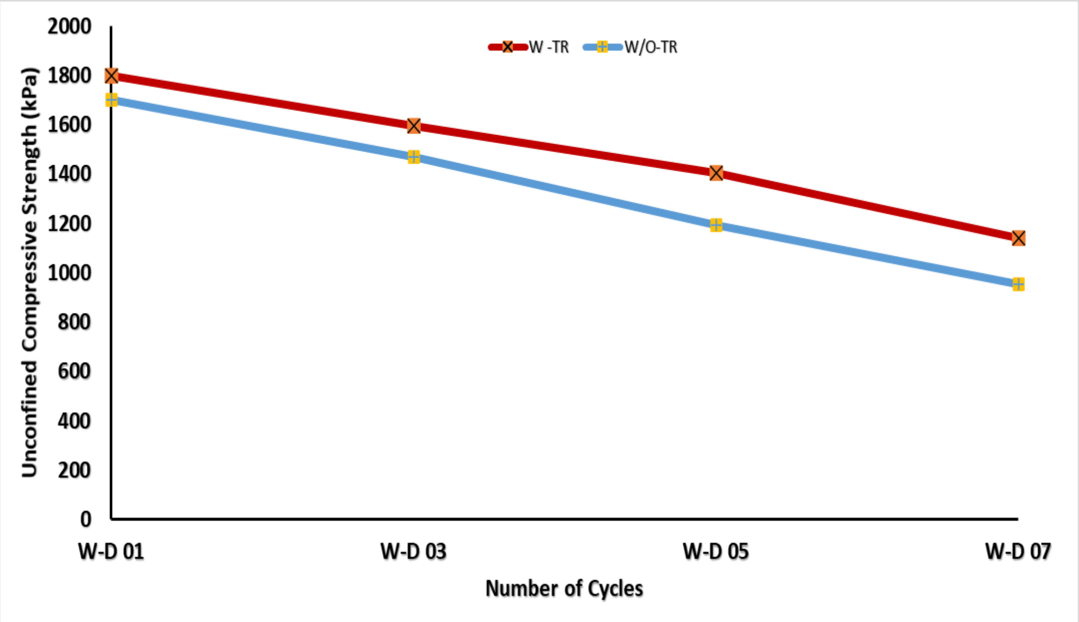

Figure 4.14: Strength loss chart for different wetting-drying cycles

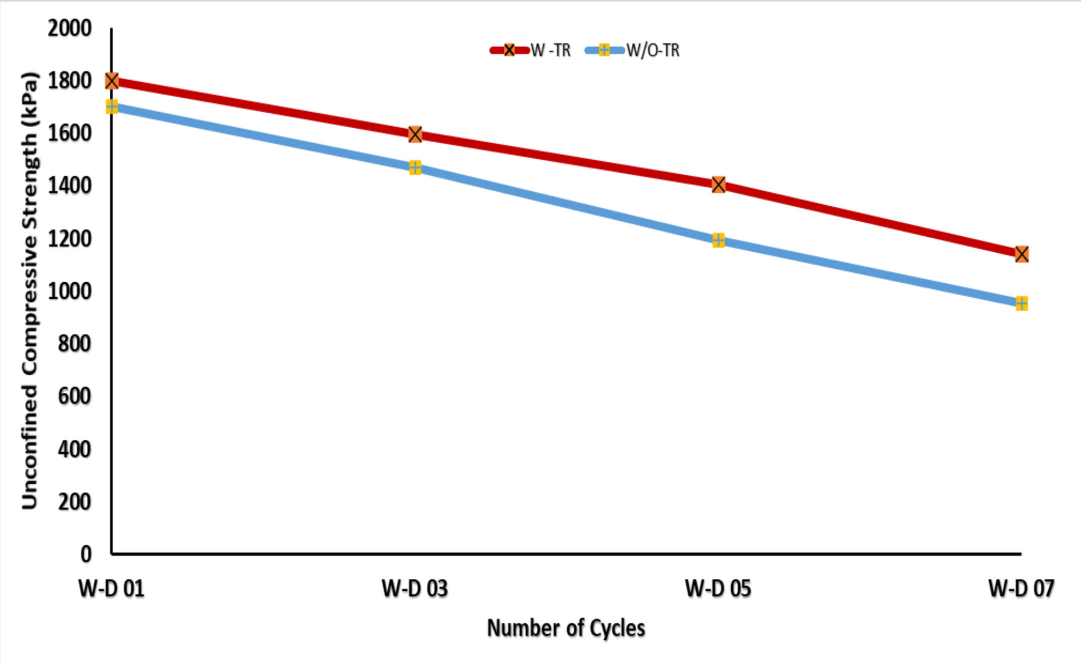

Figure 4.15: Percentage variations in strength for wetting-drying cycles

4.3.1.2 Kallar Kahar soil

The Kallar Kahar behaves similarly to that of Nandipur soil as the UCS reduces with an increase in the number of wetting and drying cycles. The variations in UCS for different wetting and drying cycles are shown in Figure 4.16. The results indicate that unconfined compressive strength for 3rd, 5th, & 7th wetting & drying cycles of untreated soil is approximately 12%, 20%, & 29% less than 1st cycle. Similarly, for treated Kallar Kahar soil, the unconfined compressive strength for 3rd, 5th, & 7th wetting & drying cycles is approximately 7.5%, 16%, & 23% less than the 1st cycle.

From the test results of treated Kallar Kahar soil, the strength is approximately 6%, 5%, & 4% higher than untreated soil for the 3rd, 5th, and 7th cycles. This increase in UCS of soil is due to the binding action of terrazyme as the addition of terrazyme provides cementitious activities which alternately enhances hydrogen ions within the soil matrix, and consequently, the soil strength increases (Ramesh, 2015).

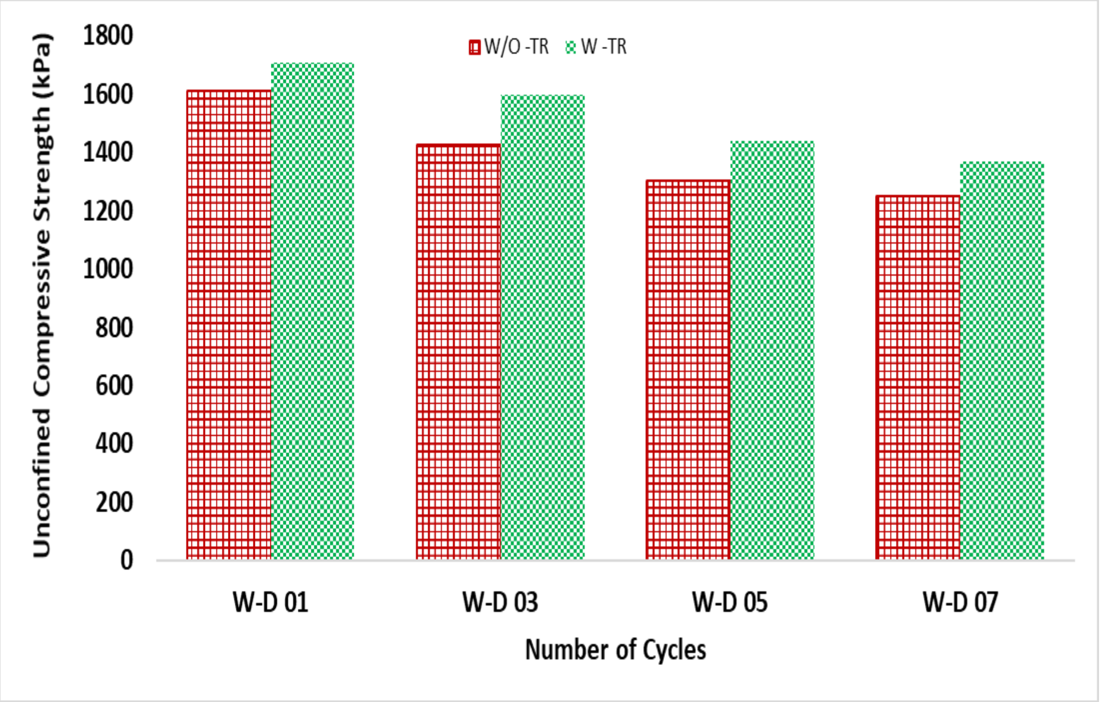

Figure 4.16: Variation in UCS of treated & untreated Kallar Kahar soil for wetting-drying cycles

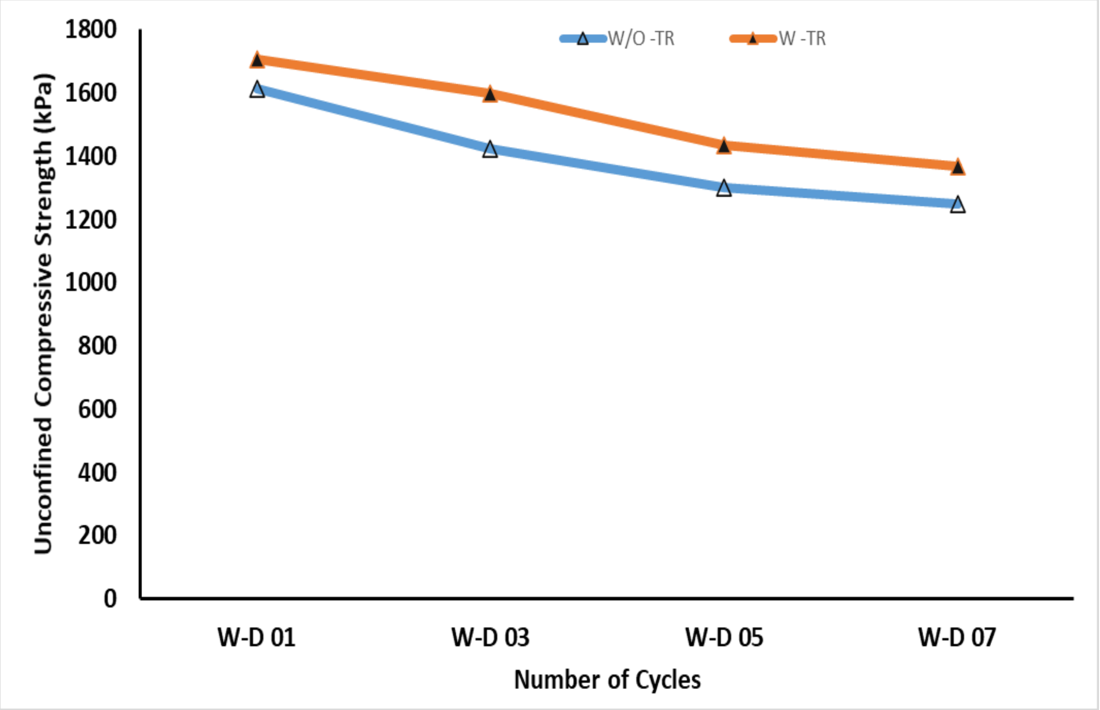

Figure 4.17: Strength loss chart for different wetting-drying cycles

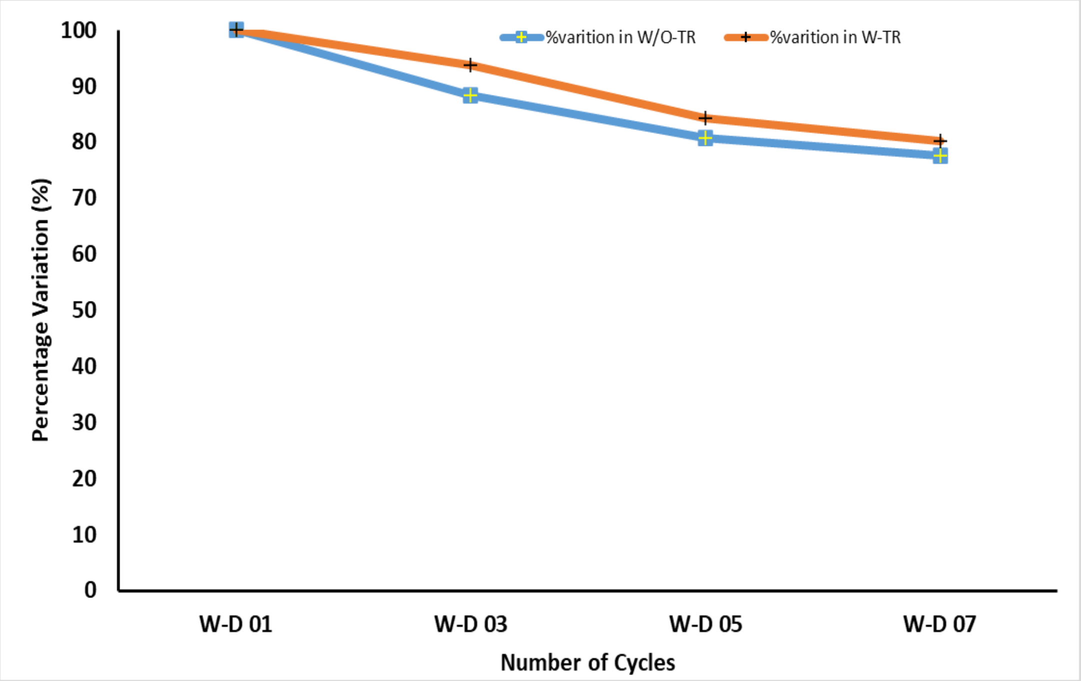

Figure 4.18: Percentage variations in strength for wetting-drying cycles

4.3.1.3 Lodhran soil

The variations in the UCS for different wetting and drying cycles are shown in Figure 4.19. The results show that the unconfined compressive strength of untreated soil for the 3^{rd}, 5^{th}, & 7^{th} wetting & drying cycles is 12%, 24%, & 40% less than 1^{st} cycle. Similarly, the unconfined compressive strength of treated soil for the 3^{rd}, 5^{th}, & 7^{th} wetting & drying cycles are approximately 7.5%, 16%, & 29% less than 1st cycle. Resultantly, the treated Lodhran soil provided 5%, 4%, & 3% higher strength than untreated soil. The findings of the present work show a good agreement with the data sets of (Consoli, 2017), in which compacted clay-fly ash-carbide lime mixes were used as reinforcing materials.

Figure 4.19: Pictorial views of samples after wetting-drying cycles

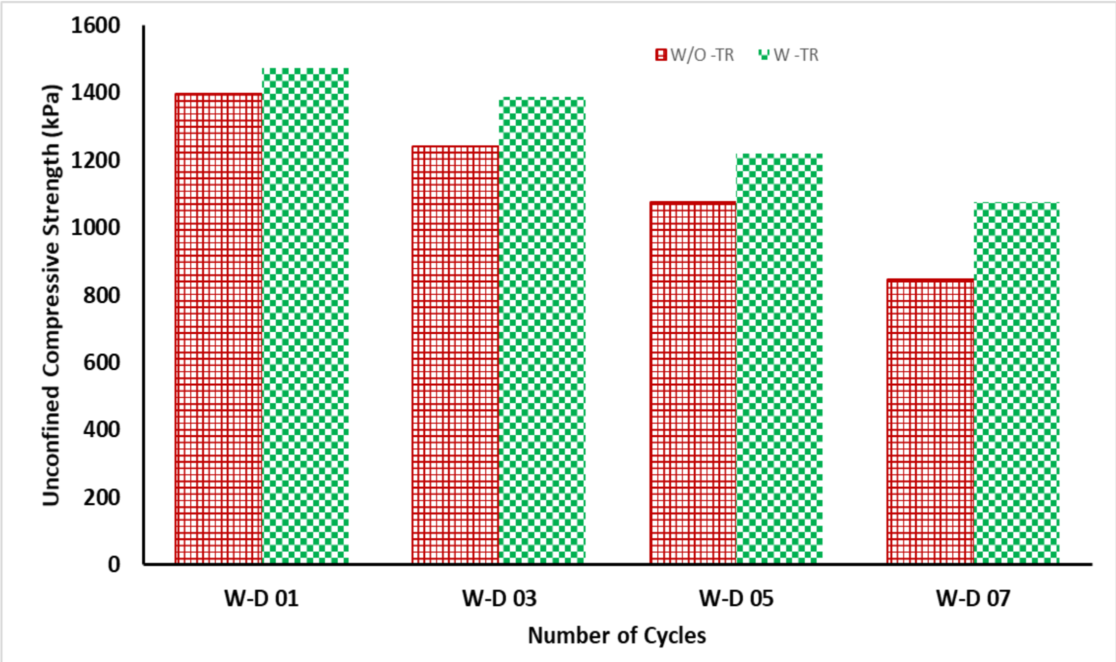

Figure 4.20: Variations in UCS of treated and untreated Lodhran soil for wetting-drying cycles

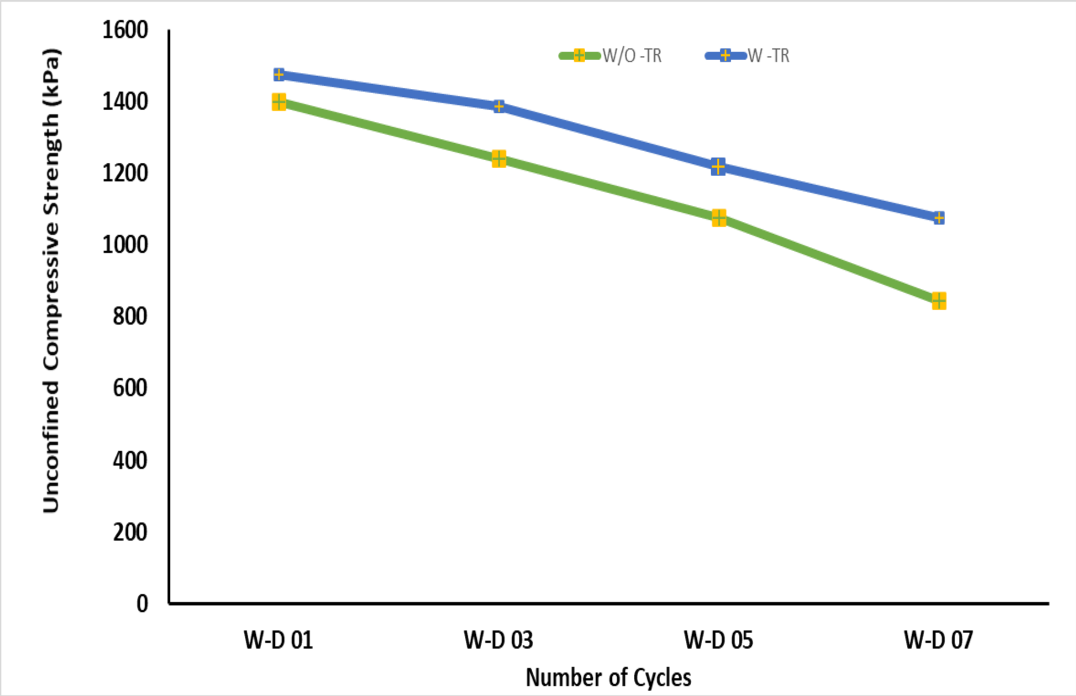

Figure 4.21: Strength loss chart for different wetting-drying cycles

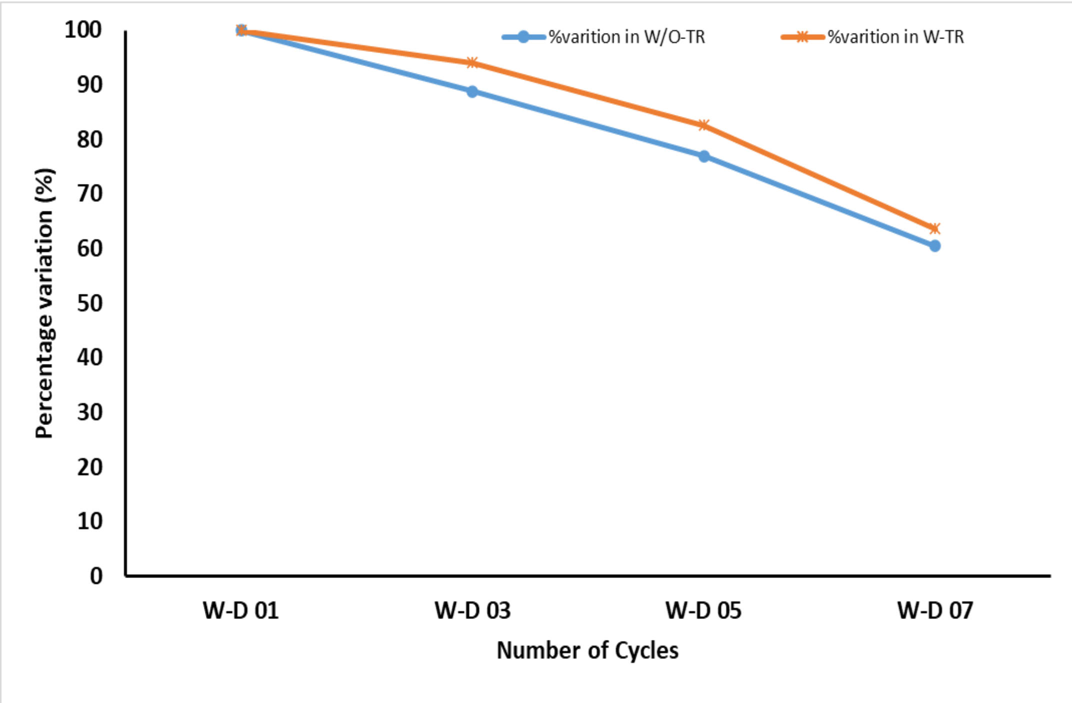

Figure 4.22: Percentage variations in strength for wetting-drying cycles

Figure 4.23 shows a comparative evaluation of untreated soils for various wetting and drying cycles, which indicates that the strength of Nandipur and Lodhran soils varies significantly with the wetting–drying cycles. However, Kallar Kahar soil shows fewer changes in strength for the 5th and 7th cycles.

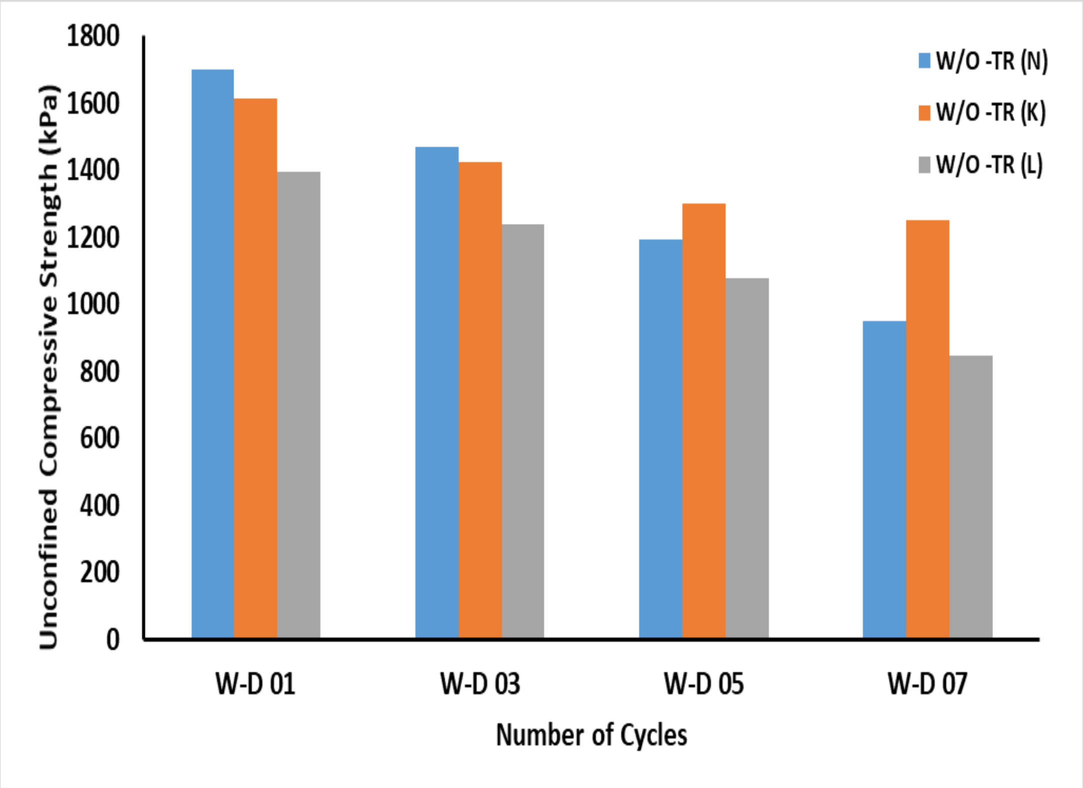

Figure 4.23: Variations in UCS of untreated soils for different wetting-drying cycles

Figure 4.24 shows a comparative evaluation of treated soils for various wetting and drying cycles, which indicates that the strength of Nandipur and Lodhran soils changes with changes in wetting–drying cycles significantly, while Kallar Kahar soil relatively shows fewer changes for 5th and 7th cycles, similar to that of untreated soils. Similar findings were reported by (Wang B. T., 2015; Tang C. S., 2016; Kampala, 2014) while working on lime, cement, and gypsum reinforced soils.

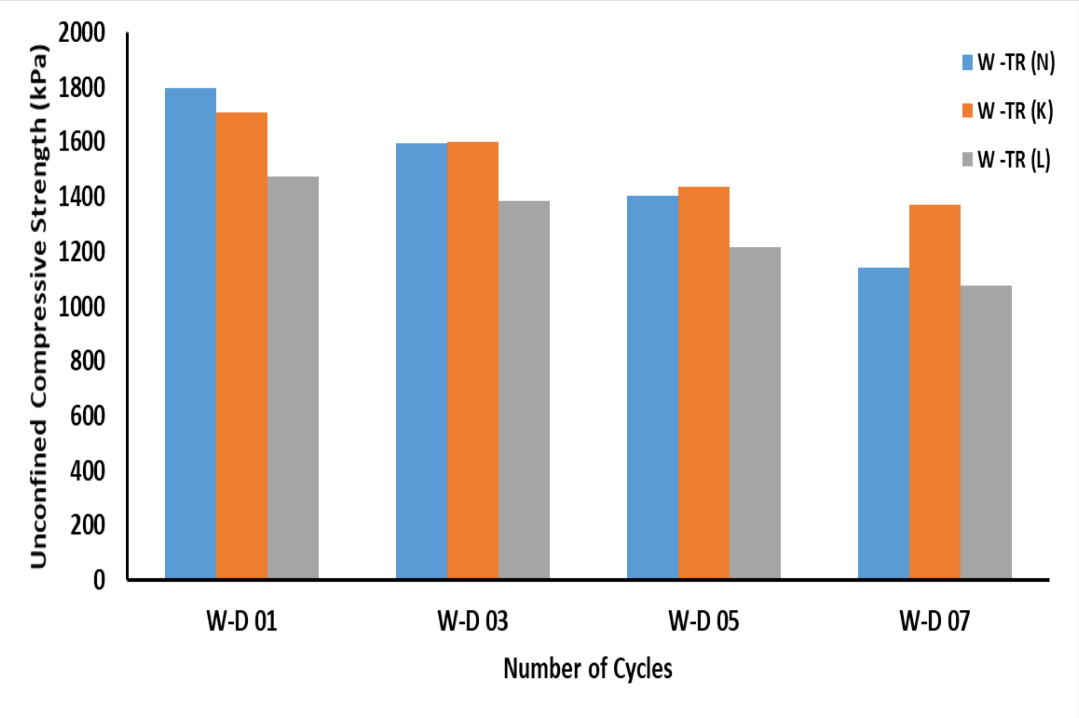

Figure 4.24: Variations in UCS of treated soils for different wetting-drying cycles

4.3.2 Hydraulic conductivity

The hydraulic conductivity of Nandipur soil, Kallar Kahar soil, and Lodhran soil at optimal water contents are $1.3x10^{-6}$ cm/sec, $2.01x10^{-6}$ cm/sec, and $2.6x10^{-5}$ cm/sec respectively. The hydraulic conductivity test results for different wetting and drying cycles of natural soils are shown in Table 4.4, which shows that the hydraulic conductivity increases with a gradual increase in wetting and drying cycles. This increase in hydraulic conductivity is due to an increase in the porosity of the soil specimens. Furthermore, the wetting drying cycles result in the formation of tiny cracks in the soil matric which can be seen in Figure 4.25. These cracks result increase the hydraulic conductivity of soils, permitting more water to seep through the soil matrix. (Omidi, 1996) reported similar findings stating that the hydraulic conductivity of soil increased with an increase in wetting and drying cycles

Figure 4.25: Pictorial views of soil samples

Nandipur soil relatively shows low hydraulic conductivity than other soils. Lodhran soil shows higher hydraulic conductivity, which is due to the higher %age of fine sands in it. Similar to that of natural soil, the hydraulic conductivity of treated soil increases for different wetting and drying (Figure 4.25), which is due to changes in porosity / void ratio of the soil specimens. The comparative evaluation of hydraulic conductivity of treated and natural soils shows that the treated soils show lower hydraulic conductivity than untreated soil for respective cycles, which is relatively due to its lower porosity. Furthermore, the addition of terrazyme provides cementitious activities which alternately packs the soil matrix more, and consequently, the treated soil provides lower hydraulic conductivity than untreated soil, corresponding to a particular wetting-drying cycles. Similar findings were reported by (Cuisinier, 2020; Wan, 2018) showing that the treated soils provided less hydraulic conductivity than untreated soil for different wetting and drying cycles.

Table 4.2: Hydraulic conductivity of treated and untreated soil samples

k (cm/sec)								
Soil Type	**1st Cycle**		**3rd Cycle**		**5th Cycle**		**7th cycle**	
	Untreated	**Treated**	**Untreated**	**Treated**	**Untreated**	**Treated**	**Untreated**	**Treated**
Nandipur	$1.6 x10^{-6}$	$1.48 x10^{-6}$	$1.91 x10^{-6}$	$1.71 x10^{-6}$	$2.29 x10^{-6}$	$1.89 x10^{-6}$	$2.56 x10^{-6}$	$2.15 x10^{-6}$
Kallar Kahar	$2.09 x10^{-6}$	$1.85 x10^{-6}$	$2.44 x10^{-6}$	$2.10 x10^{-6}$	$2.95 x10^{-6}$	$2.57 x10^{-6}$	$3.65 x10^{-6}$	$3.00 x10^{-6}$
Lodhran	$2.85 x10^{-5}$	$2.54 x10^{-5}$	$3.21 x10^{-5}$	$2.94 x10^{-5}$	$3.65 x10^{-5}$	$3.15 x10^{-5}$	$4.01 x10^{-5}$	$3.81 x10^{-5}$

Chapter 5

5 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

Based on the laboratory tests following conclusions are drawn from the study:

- The optimum dosages of terrazyme for Nandipur soil, Kallar Kahar soil, and Lodhran soil were 0.0271 ml, 0.06 ml, and 0.08 ml respectively.
- Nandipur soil provided a lower peak moisture density relationships as compared to other soils, which was due to differences in their liquid limits.
- For untreated soils, the compressive strength decreased up to 45% in Nandipur soil, 34% in Kallar Kahar, and 40% in Lodhran soil after the 7^{th} cycle.
- For treated soil, the compressive strength decreased up to 37% in Nandipur soil, 20% in Kallar Kahar, and 35% in Lodhran soil after the 7^{th} cycle.
- The treated soil relatively showed more strength than untreated soil for a particular wetting & drying cycle.
- The hydraulic conductivity of both treated and untreated soils gradually increased for an increase in the number of cycles, and comparatively, the treated soil showed less hydraulic conductivity than untreated soil. The reduction in Nandipur, Kallar Kahar, and Lodhran hydraulic conductivity was 15%, 10%, and 12% respectively.
- The compressive strength of both treated and untreated soils decreased and hydraulic conductivity increased for a gradual increase in wetting and drying cycles.

5.2 Recommendations

- The terrazyme can also be tested in combination with other additives, such as lime, rice husk, fly ash, etc.
- This study can also be extended further by testing alternate wetting and drying methods.

REFERENCES

Agarwal, P., & Kaur, S. (2014). Effect of bio-enzyme stabilization on unconfined compressive strength of expansive soil. *International Journal of Research in Engineering and Technology, 3*(5), 30-33.

Ahangar-Asr, A. F. (2011). Modeling of permeability and compaction characteristics of soils using evolutionary polynomial regression. *Computers & Geosciences, 37*(11), 1860-1869.

Arabani, M. &. (2020). The effect of polymeric fibers on the mechanical properties of cement-stabilized clay soils in Northern Iran. *International Journal of Geotechnical Engineering, 14*(5), 557-568.

ASTM-D2166-00. (n.d.). *Standard test method for unconfined compressive strength of cohesive soil.* American Society for Testing and Materials.

ASTM-D5084-16a. (n.d.). *Standard test methods For measurement of hydraulic conductivity of saturated porous materials using a flexible wall permeameter.* American Society for Testing and Materials.

Benson, C. H. (1995). Hydraulic conductivity of thirteen compacted clays. *Clays and Clays minerals, 43*(6), 669-681.

Boynton, S. S. (1985). Hydraulic conductivity tests on compacted clay. *Journal of Geotechnical Engineering, 111*(4), 465-478.

Bremer, M. G. (2004). Electrostatic interactions between immunoglobulin (IgG) molecules and a charged sorbent. *Colloids and Surfaces A: Physicochemical and Engineering Aspects, 250*(3), 29-42.

British-Standards. (1990). *BS 1377-4:1990, Methods of test for soils for civil engineering purposes. Compaction-related tests.* BSi Group.

Butt, W. A. (2016). Strength behavior of clayey soil stabilized with saw dust ash. *International Journal of Geo-Engineering, 7*(1), 1-9.

Carpenter, G. W. (1986). Permeability testing in the triaxial cell. *Geotechnical Testing Journal, 9*(1), 3-9.

Consoli, N. C. (2017). Compacted clay-industrial wastes blends: Long term performance under extreme freeze-thaw and wet-dry conditions. *Applied Clay Science, 146*, 404-410.

Cui, Y. J. (2008). Determining the unsaturated hydraulic conductivity of a compacted sand–bentonite mixture under constant-volume and free-swell conditions. *Physics and Chemistry of the Earth, 33*, 462-471.

Cuisinier, O. &. (2020). Impact of wetting/drying cycles on the hydromechanical behaviour of a treated soil. *E3S Web of Conferences, 195*.

Daniel Ribeiro, R. N. (2016). Influence of water content in the UCS of soil-cement mixtures for different cement dosages,. *Procedia Engineering,, 143*, 59-66. doi:https://doi.org/10.1016/j.proeng.2016.06.008.

Datta, R. A. (2017). How enzymes are adsorbed on soil solid phase and factors limiting its activity. *International Agrophysics, 31*(2), 287-302.

Degens, B. P. (1995). Repeated wet-dry cycles do not accelerate the mineralization of organic C involved in the macro-aggregation of a sandy loam soil. *Plant and Soil, 175*(2), 197-203.

Denef, K. S. (2001). Importance of macroaggregate dynamics in controlling soil carbon stabilization: short-term effects of physical disturbance induced by dry–wet cycles. *Soil Biology and Biochemistry, 33*(15), 2145-2153.

Estabragh, A. R. (2015). Laboratory investigation of the effect of cyclic wetting and drying on the behaviour of an expansive soil. *Soils and Foundations, 55*(2), 304-314.

Estornell, P. &. (1992). Hydraulic conductivity of three geosynthetic clay liners. *Journal of Geotechnical Engineering, 118*(10), 1592-1606.

Francisca, F. M. (2010). Long term hydraulic conductivity of compacted soils permeated with landfill leachate. *Applied Clay Science, 49*(3), 187-193.

Gillott, J. E. (1986). Some clay-related problems in engineering geology in North America. *Clays and Clay Minerals, 21*(3), 261-278.

Gupta, A. S. (2017). Review paper on soil stabilization by terrazyme. *International Journal of Research in Engineering and Technology, 7*(4), 54-57.

He, Y. C. (2017). Effects of wetting-drying cycles on the air permeability of compacted Téguline clay. *Engineering geology, 228*, 173-179.

Hu, Z. P. (2019). Effect of wetting-drying cycles on mechanical behaviour and electrical resistivity of unsaturated subgrade soil. *Advances in Civil Engineering*.

Jjuuko, S. K. (2011). The use of locally available sand in stabilization of Ugandan clayey soils: Case study of clayey soil from Busega area. *In Uganda Institution of Professional Engineers 16th National Technology Conference*.

Jones Jr, D. E. (1973). Expansive soils-the hidden disaster. *Civil Engineering, 43*(8).

Kampala, A. H. (2014). Influence of wet-dry cycles on compressive strength of calcium carbide residue–fly ash stabilized clay. *Journal of Materials in Civil Engineering*, *26*(4), 633-643.

Khan, S. I. (2019). Coupled effect of wet-dry cycles and rainfall on highway slope made of yazoo clay. *Geosciences, 9*(8), 341.

Lacuoture, A. &. (1995). Usage of organic enzymes for the stabilization of natural base soils and sub-bases in Bagota. *Pontificia Universidad Jevariana, Faculty of Engineering.*

Liu, H. &. (2010). Eliminating inhibition of enzymatic hydrolysis by lignosulfonate in unwashed sulfite-pretreated aspen using metal salts. *Bioresource Technology*, *101*(23), 9120-9127.

Liu, J. Q. (2017). Study on the permeability characteristics of polyurethane soil stabilizer reinforced sand. *Advances in Materials Science and Engineering*.

Lundquist, E. J. (1999). Wet–dry cycles affect dissolved organic carbon in two California agricultural soils. *Soil Biology and Biochemistry*, *31*(7), 1031-1038.

Maghsoodi, S. C. (2020). Thermal effects on mechanical behaviour of soil–structure interface. *Canadian Geotechnical Journal, 57*(1), 32-47.

Marasteanu, M. O., Hozalski, R. M., Clyne, T. R., & Velasquez, R. (2005). *Preliminary laboratory investigation of enzyme solutions as a soil stabilizer.* University of Minnesota Twin Cities.

Md, S. H.-w. (2016). Effect of drying-wetting cycles on saturated shear strength of undisturbed residual soils. *American Journal of Civil Engineering, 4*(4), 143-150.

Mosa, A. M.-J. (2017). Improvement of poor subgrade soils using cement kiln dust. *Case Studies in Construction Materials, 7*, 138-143.

Muntaha, M. (2017). The effect of drying-wetting cycle's repetition to the characteristic of natural and stabilization residual soils Jawa Timur-Indonesia. *Conference Series: Materials Science and Engineering, 267*(1).

Nabil, M. M. (2020). Impact of wetting—drying cycles on the mechanical properties of lime-stabilized soils. *International Journal of Pavement Research and Technology, 13*(1), 83-92.

O'Connor, D. P. (2019). Microplastics undergo accelerated vertical migration in sand soil due to small size and wet-dry cycles. *Environmental Pollution, 249*, 527-534.

Olshansky, Y. R. (2018). Wet–dry cycles impact DOM retention in subsurface soils. *Biogeosciences, 15*(3), 821-832.

Omidi, G. H. (1996). Effect of desiccation cracking on the hydraulic conductivity of a compacted clay liner. *Water, Air, and Soil Pollution, 89*(1), 91-103.

Patel, U. S. (2018). Effect of bio enzymeterrazyme on compaction, consistency limits and strength characteristics of expansive soil. *International Research Journal of Engineering and Technology, 5*(3), 1602-1605.

Phani Kumar, B. R. (2004). Effect of fly ash on engineering properties of expansive soils. *Journal of Geotechnical and Geoenvironmental Engineering, 130*(7), 764-767.

Puppala, A. J. (2000). Effects of fiber reinforcement on strength and volume change in expansive soils. *Transportation Research Record, 1736*(1), 134-140.

Rajaram, G. &. (1999). Effect of wetting and drying on soil physical properties. *Journal of Terramechanics,, 36*(1), 39-49.

Rajoria, V. &. (2014). A review on stabilization of soil using bio-enzyme. *International Journal of Research in Engineering and Technology, 3*(1), 75-78.

Ramesh, H. N. (2015). Effect of drying on the strength properties of terrazyme treated expansive and non-expansive soils. *Indian Geotechnical Conference, Pune, India*.

Ren, X. Z. (2016). A relation of hydraulic conductivity—void ratio for soils based on Kozeny-Carman equation. *Engineering Geology, 213*, 89-97.

Ribeiro, D. N. (2016). Influence of water content in the UCS of soil-cement mixtures for different cement dosages. *Procedia engineering, 143*, 59-66.

S. B. Ikizler, M. V. (2014). Prediction of swelling pressures of expansive soils using soft computing methods. *Neural Computing and Applications, 24*(2), 473-485.

Saini, V. &. (2015). Soil stabilization by using terrazyme. *International Journal of Advances in Engineering & Technology, 8*(4), 566.

Samarasinghe, A. M. (1982). Permeability and consolidation of normally consolidated soils. *Journal of the Geotechnical Engineering Division, 108*(6), 835-850.

Saride, S. P. (2013). Swell-shrink and strength behaviors of lime and cement stabilized expansive organic clays. *Applied Clay Science, 85*, 39-45.

Sarkar, J. M. (1984). Synthesis and properties of β-d-glucosidasephenolic copolymers as analogues of soil humic-enzyme complexes. *Soil Biology and Biochemistry, 16*(6), 619-625.

Schofield, R. K. (1954). Flocculation of kaolinite due to the attraction of oppositely charged crystal faces. *Discussions of the Faraday Society, 18*, 135-145.

Scholen, D. E. (1995). Stabilizer mechanisms in nonstandard stabilizers. *Transportation Research Board Conference Proceedings*.

Shiel, R. S. (1988). The effect of successive wet/dry cycles on aggregate size distribution in a clay texture soil. *Journal of Soil Science, 39*(1), 71-80.

Tang, A. M. (2008). Thermo-mechanical behaviour of a compacted swelling clay. *Géotechnique, 58*(1), 45-54.

Tang, C. S. (2016). Effect of wetting–drying cycles on profile mechanical behavior of soils with different initial conditions. *Catena, 139*, 105-116.

TxDOT. (1999). *TxDOT online manuals.* Retrieved from ftp://ftp.dot.state.tx.us/pub/txdot-info/cst/TMS/100-E_series/

Wan, Y. X. (2018). Relationship between the shrinkage crack characteristics and the water content gradient of compacted clay liner in a landfill final cover. *Soils and Foundations, 58*(6), 1435-1445.

Wang, B. T. (2015). Research on wetting-drying cycles' effect on the physical and mechanical properties of expansive soil Improved by OTAC-KCl. *Advances in Materials Science and Engineering*.

Wang, D. F. (2020). Impacts and interactions of biochar and biosolids on agricultural soil microbial communities during dry and wet-dry cycles. *Applied Soil Ecology, 152*.

Wani, K. S. (2020). Unconfined compressive strength testing of bio-cemented weak soils: a comparative upscale laboratory testing. *Arabian Journal for Science and Engineering, 45*, 8145-8157.

Weber, C. (2015). *On the characterization of electric double layers of clay minerals and their relevance for macroscopic transport phenomena.*

Ye, H. C. (2018). Experimental studies on drying-wetting cycle characteristics of expansive soils improved by industrial wastes. *Advances in Civil Engineering*.

Yusoff, S. A. (2017). Laboratory investigation of terrazyme as a soil stabilizer. *AIP Conference Proceedings, 1892*(1).

Zhai, Q. R. (2019). Role of the pore-size distribution function on water flow in unsaturated soil. *Journal of Zhejiang University-Science, 20*(1), 10-20.

Zhang, Z. &. (2008). Durability of cement stabilized low plasticity soils. *Journal of Geotechnical and Geoenvironmental Engineering, 134*(2), 203-213.

Zhou, W. H. (2014). Estimation of soil–water characteristic curve and relative permeability for granular soils with different initial dry densities. *Engineering Geology, 179*, 1-9.

Zimmerman, A. R. (2010). Organo-mineral–enzyme interaction and soil enzyme activity. *Springer, Berlin, Heidelberg*, 271-292.

Zoungrana, T. F. (1997). Structure, stability and activity of adsorbed enzymes. *Journal of Colloid and Interface Science, 190*(2), 437-448.