Improving the Mechanical Properties of an Expansive Soil using Polyethylene Terephthalate and Recycled Concrete Aggregate

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THIS THESIS IS

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MY BELOVED PARENTS

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ABSTRACT

A million tons of concrete are thrown away in the environment after the demolition of civil structures, each year. Similarly, polyethylene terephthalate is extensively used in plastic bottles, which is also discarded in the environment without any proper disposal system. This study tests the efficacy of polyethylene terephthalate and recycled concrete aggregate waste materials to improve the mechanical properties of expansive soil. To attain the study objectives, laboratory tests such as grain size, Atterberg limits, standard compaction, California Bearing Ratio, direct shear, and XRD tests were employed. The XRD test results show that the soil contains minerals such as montmorillonite and illite, which have a high affinity for water. The treated soil shows peak strength and CBR value at 15% PET and 15% RCA, which is due to the percentage increase in calcite after the treatment which is clearly observed in the XRD analysis of treated soil. The strength decreases with the wet-dry cycles, initially but it provides insignificant changes after 7th cycles. The treated soil provides maximum CBR of 17.1% at the optimal concentrations of additives, which is almost 76.68% more than the untreated soil. The untreated soil provides a California bearing ratio of 9.67 %, marginal to the road criteria for a minimum wet CBR of 7%. The study findings show that polyethylene terephthalate and recycled concrete aggregate materials are effective in improving the mechanical behaviour of the soil.

Keywords**:** *recycled concrete aggregate (RCA), polyethylene terephthalate (PET), expansive soil*, shear strength

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Chapter 1

INTRODUCTION

1.1 General

Expansive soils are widespread in Pakistan. These soils experience significant volume changes on wetting and drying. The main issue with expansive soils is that their behaviour cannot be predicted using traditional elastic or plastic theories. Although removing and replacing these soils with good soil is always considered a better option but it is not a feasible and economical solution in some situations. Stabilization of soil is a technique which makes a way for an economical and effective solution to geotechnical engineering related problems. There is always an uncertainty associated with the underground soil characteristics. Hence the different stabilization techniques cannot be generalized for all the sites.

Therefore, researchers are trying to find out alternatives for the stabilization of problematic soils. The additives such as cement, lime, bagasse ash, gypsum, and some others are being trialled now a days in soil stabilization. According to research, polyethylene terephthalate and recycled concrete aggregate can be employed in combination to enhance the performance characteristics of problematic soils. To determine how well expansive soil performs with Polyethylene Terephthalate (PET) and Recycled Concrete Aggregate (RCA), the study examines this topic. The used waste materials are cheaper, environment friendly and are easily available in Pakistan. Every year, tons of thousands of concretes are wasted after the demolition of structures in the country. Similarly, polyethylene terephthalate is used in plastic bottles, and discarded extensively each year with adverse effects on the environment. It is the best possible way to reuse these waste materials for soil stabilization. The applicability of using these two additives in combination in soil stabilization has not been tested so far.

So, the scope of the work involves examining the mechanical behavior of RCA and PET treated soils. Pakistan is a country with diverse atmospheric conditions, consisting of wet-dry cycles throughout the year which alternately modify the soil properties. The study also simulates the natural environmental conditions, examining the engineering properties of an expansive soil for wet – dry cycles. Different tests such as California Bearing Ratio (CBR), grain size distribution, modified compaction, strength, and others are performed for various wet - dry cycles to achieve the study objectives. Finally, the study provides some useful conclusions of practical interest for scientists, engineers and practitioners.

1.2 Relevance to national needs

In many areas of Pakistan, the problematic soils have caused a lot of damages to roads and infrastructure, foundations, retaining walls and other structures. A lot of work is being done now a days in

Pakistan on the development of infrastructure as a part of CPEC and other mega projects. As a part of this work, motorways, highways, and connecting roads are being constructed in a large number. To replace the problematic soil with good quality soil is not practically feasible in some situations, hence the only option is to enhance their strength. The second problem is to find some soil stabilizers, for a developing country to accommodate large volumes of cement for construction and for soil stabilization is tedious task and it has adverse environmental effects. Pakistan is a country which is major contributor to the carbon emission and greenhouse gases, so it is very important to find environmentally friendly solutions. Hence, in this study the environmentally friendly additives such as, RCA and PET are selected to modify the engineering properties of soil.

1.3 Objectives

- To examine the mechanical behaviour of RCA and PET amended expansive soils for wet - dry cycles.

1.4 Scope and methodology

The scope and method of the research involves examining the engineering properties of treated and untreated soils using below mentioned tests and approaches.

1. Properties of untreated soil
    - Atterberg Limits
    - Particle size distribution
    - Specific gravity
    - Modified Proctor test
    - CBR test
    - Direct shear test
    - XRD test of natural soil, Polyethylene Terephthalate (PET) and Recycled Concrete Aggregate (RCA)
2. Optimization of Polyethylene Terephthalate (PET) and Recycled Concrete Aggregate (RCA)
    - Modified compaction test at various PET and RCA contents
    - CBR test at various PET and RCA contents
    - Direct shear test at various PET and RCA contents
    - XRD test at various PET and RCA contents.

3. Properties of treated soil at various wetting and drying cycles

    - Direct shear test at various wetting and drying cycles
    - CBR test at various wetting and drying cycles

Chapter 2

LITERATURE REVIEW

2.1 General

With a change in moisture content, expansive soils may undergo excessive deformation. These soils may substantially undergo differential settlement, when get wetted, which alternately results in the destruction of infrastructures. Any structure built on these soils produce cracks due to differential settlement, caused by moisture variations.

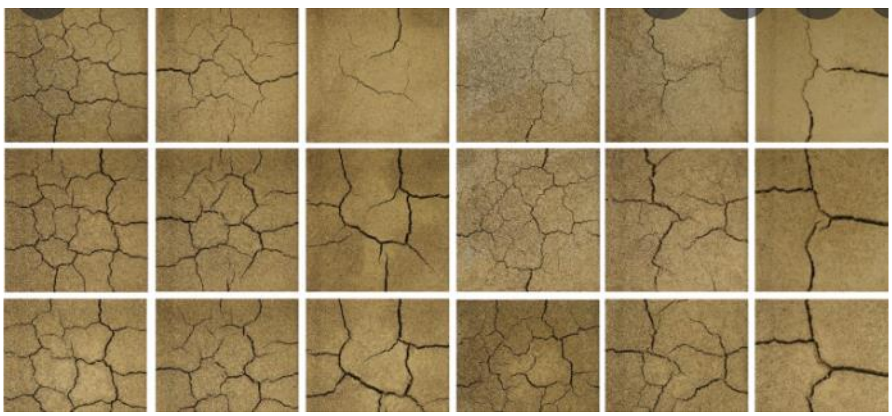


Figure 2.1: Cracks in expansive soils

2.2 Clayey soils

Clayey soil is defined as soil with particles smaller than 0.002 mm. In general, the clay mineral offers plasticity, a net negative electric charge, and lesser weathering resistance. The formation of clayey soils is alternately occurring due the weathering of rock. These soils have a low porosity with great potential for deformation. In comparison to sandy soils, clayey soils show higher permeability and swelling potential, and their strength is relatively low.

2.3 Properties of expansive soils

This soil may get wet due to leakage in water supply systems and sewage pipes, and with an increase in the groundwater table. These soils' alternate drying and wetting results in fissures at various locations. **Figure** 2.1 shows the crack propagation in the expansive soils. which alternately causse the structure to collapse because of differential settlement. Large particle sizes are less influenced by wet-dry cycles;

whereas higher percent of clay contents contribute to swelling and shrinkage of expansive soils **(Li, Wu, and Hou 2014).** Table 2.1 highlights the mineral components of expansive soil.

Table 2.1: Mineral components of expansive soils **(Li, Wu, and Hou 2014)**

Mineral Component	**% Content**
Na_2O	3.2
MgO	6.7
Al_2O_3	19.5
SiO_2	47.3
K_2O	8.4
Si_2O_3	12.8
SiO_2 /Al_2O_3	2.1

Table 2.2: Physical characteristics of expansive soils (Li, Wu, and Hou 2014)

Property	**Value**
Specific weight	19.7 kN/m^3
Liquid limit	37.9 %
Plastic limit	17.3 %
Plasticity index	20.6 %
Free swell ratio	54 %

The properties shown in Table 2.1 and **Table** 2.2 are related to specific type of expansive soil however every soil has its own minerology and physical properties. With montmorillonite dominating, kaolinite, illite, and other minerals make up most of the mineralogy of expansive soil. Tetrahedral and octahedral mineral sheets are layered in ratios of 1:1 or 2:1 in expansive soil. Octahedral sheets are sandwiched between two tetrahedral sheets in the 2:1 combination. The expansive soils have a strong propensity to absorb water due to montmorillonite's increased adsorption potential.

2.3.1 Grain size distribution

Particle size is the proportion of different particle sizes in a soil sample. The engineering behavior of all soils was significantly influenced by the soil particle size distribution **(Tyler and Wheatcraft, 1992).**

2.3.2 Atterberg limits

Water causes major changes on how fine-grained soils behave in engineering applications. Due to the varying ways that each soil can absorb water, different soils exhibit different Atterberg limits. To evaluate activity, the liquid limit and plastic limit are crucial features.

Table 2.3: Effect of liquid limit on soil classification

Soil Type	Liquid Limit
High plastic clay	LL > 50
Medium plastic clay	30 < LL < 50
Low plastic clay	LL < 30

2.3.3 Compaction characteristics

Typical and customized Proctor tests is frequently done to evaluate the ideal moisture content and maximum dry density of soil. When the earth is compacted, air is forced out, which improves soil strength. The compaction curve is connected to the OMC and MDD (Lindeburg and Drohan, 2019) demonstrates that superior quality soil is associated with higher unit weight and lower water content, and vice versa for lower unit weight and higher water content. The optimal moisture content and dry unit weight for each type of soil are also shown in Table 2.4.

Table 2.4: Relation between dry weight and optimum moisture content

Soil type	**Maximum dry unit weight (kN/m^3)**	**Optimum moisture content**
Well graded gravel	19.625	8-11
Poorly graded gravel	18.055	11-14

Silty gravel	18.84	8-12
Clayey gravel	18.055	9-14
Well graded sand	17.27	9-16
Poorly graded sand	15.7	12-21
Silty gravel sand	17.27	11-16
Clayey gravel sand	16.485	11-19
Non-plastic silt	14.915	12-24
Medium plastic clay	14.915	12-24
High plastic silt	10.99	24-40
High plastic clay	11.775	19-36
Organic clay	10.205	21-45

2.3.4 Swell potential

The swelling potential is a crucial characteristic to assess soil's engineering behavior. The more sensitive the soil is, which in turn leads to poor performance of the soil, the higher the swelling potential. **(Çimen, Keskin, and Yıldırım 2012)** developed the following equations for calculating the potential and pressures of swelling, respectively. According to the initial water content, dry unit weight, and plasticity index, the recommended expressions were produced by the multiple regression technique using the swell results of three samples repeated at least twice.

$$SP = (0.4768\Upsilon^{0.3888} - 0.0033\mathrm{w}^{1.6045})PI\text{^}0.7224 \quad (1)$$

$$Log\ Ps = 0.0239PI - 1285.3723\ \Upsilon^{-3.2768} - 0.0396W + 2.3238. \quad (2)$$

where, SP = proposed swelling potential, Log Ps = estimated swelling pressure, Y= maximum dry unit weight, w= initial water content, PI= Plasticity Index. As the plasticity index increases, swelling pressure and potential also do as well. The expanding potential of clay depends on its mineralogical composition

(Çimen, Keskin, and Yıldırım 2012). Table 2.5 represents a relation between soil type and swell potential. A significant correlation between dry density and liquid limit determines the swelling potential of soil.

Table 2.6: Relation between nature of soil and swell potential

Swell Potential	**Nature of Soil Sensitivity**
Greater than 25	Very High
5-25	High
1.5-5	Medium
Less than 5	Low

2.3.5 California Bearing Ratio (CBR)

CBR is the measure of quality of sub grade material of roads. The relation between CBR and quality of sub grade is presented in the table below.

Table 2.7: Subgrade classification based on CBR

Material Quality	**CBR (%)**
Good	>15
Moderate	7 – 15
Fair	3 – 7
Poor	< 3

2.4 Stabilization of Soil

Soil stabilization, which combines mechanical, chemical, and biological techniques, frequently enhances the expanding soil's engineering characteristics, such as shear strength, plasticity, bearing capacity, and consolidation property. The engineering qualities of the soil are enhanced using compaction, drainage, pre-loading, and other mechanical stabilizing techniques. Various synthetic and conventional chemicals are also used in chemical stabilization to strengthen soft soils. Since they are cementitious, these additives produce pozzolanic actions. The clay particles are typically negatively charged. The soil dispersion that results from these negatively charged particles repelling one another. The negatively charged soil particles can be held together by the positively charged cations, leading to flocculation or agglomeration of soil particles. There are three basic methods to stabilize the soils, such as chemical stabilization, mechanical stabilization, and biological stabilization. Compaction, preloading, drainage, and other procedures are used in mechanical stability. In Pakistan, mechanical stabilization is more prevalent and takes less time to complete than chemical stabilization. Numerous critical variables, such as stabilizer type and concentration, water content, temperature, mixing time, and curing period, have a significant impact on soil stability. Chemical stabilization is the process of adding different chemicals to soil to enhance its engineering qualities. Chemicals and soil particles react right away. These reactions can be categorized as cementitious or pozzolanic in origin. The incorporation of biological molecules, such as bio-enzymes, is a component of biological techniques.

2.5 Past studies on stabilization of soil

Stabilization of a soil is a technique which makes a way for an economical and effective solution to Geotechnical Engineering related problems. However, there is always an uncertainty associated with the underground soil characteristics. Hence the different stabilization techniques cannot be generalized for all the sites. For this reason, detailed laboratory testing is required before the recommendation of a stabilization technique for a particular site and type of soil.

Researchers have been trying to find new ways for the soil improvement which are economical as well as environmental friendly**. (Amakye et al. 2021)** reviewed the stabilization of expansive soils for improving sub grade properties of soils with processed industrial materials which include granulated blast furnace slag, polypropylene fiber, and brick dust. The study found that although cement and lime provide the best stabilization, these industrial byproducts offer alternatives that are more efficient, affordable, and environmentally beneficial. In the study presented by **(Aziz, Saleem, and Irfan 2015)** expansive soils have been stabilized by rice husk by performing Atterberg limits test, compaction test consolidation test and swell test, direct shear test, the results showed that adding rice husk may increase the shear strength have been observed up to a certain point and then its start to decrease, however swell potential and liquid limit is decreased**. (Tech- 2001)** employed Class C fly ash to lessen the tendency for expansive soils to expand. At an optimum percentage of 20% a maximum decrease in swell potential of a soil was observed.

(Mujtaba et al. 2018) used Granulated Blast Furnace Slag and calculated the optimum percentage of GBFS. The study reported that the optimum percentages for Compaction, CBR and swell potential were different, the research also reported different percentages of all the tests performed on different soil samples. Hence, it can be concluded that the optimum percentages cannot be generalized. **(Malekzadeh and Bilsel 2012)** Split tensile experiments were used to examine the effects of polypropylene fiber on the tensile behavior of expanding soils. **(S.Twinkle and M. K. Sayida 2011).** CBR, compaction, and unconfined compressive tests were carried out using polypropylene fiber and lime. The results showed a rise in CBR and unconfined compressive strength in contrast to a decline in Maximum Dry Density. In the study of **(K.Y and K 2016)** as a soil stabilization strategy, sisal fiber, bagasse ash, and glass powder were employed to increase the CBR value and unconfined compressive strength. The results showed that glass powder can raise CBR and compressive strength more successfully. Sugarcane Bagasse Ash is the leftover of this fibrous waste, and it is used as a fire fuel to heat the boilers (SCBA). The study of **(Payá et al. 2002)** also came to the conclusion that the impurities in the ash generally control parameters like the degree of silica crystallinity and bagasse ash's reactivity.

2.6 Stabilization using Recycled Concrete Aggregate (RCA)

Development and demolition (C&D) wastes are being landfilled in greater and greater quantities because of the extensive development and renovation of urban structures in both emerging and industrialized nations. Recycling construction and demolition debris for use in non-structural building materials and pavement construction reduces environmental pollution while protecting natural resources. Given inescapable phenomena like climate change and global warming, sustainable development is more important than ever in the 21st century. Construction material production, consumption, and the consequent environmental contamination are ongoing issues on a global scale **(Kianimehr et al. 2019).** It is well known that reusing and recycling C&D trash will reduce the amount of this waste material disposed of in landfills and reduce the demand for limited virgin natural resources **(Arulrajah et al. 2013).** Due to a rise in earthquake rates and the number of buildings that must be demolished, as stipulated by the new legislation, a sizable number of debris has been accumulating in recent years.

Building demolition wastes (CDW) is the term used to describe these wastes. There are certain techniques that are being thought about for the removal of this waste. Use of demolition and building debris in soil enhancement techniques is one of the strategies described. Land that is suitable for infrastructure development is getting harder to find. There are few expensive lands with desired geotechnical characteristics. Therefore, in order to enhance the soils underneath the specified problematic locations and utilize them for construction purposes, a variety of ground improvement procedures are taken into consideration, such as stabilization, grouting, and compaction **(Bagriacik and Mahmutluoglu 2020).** Because some natural resources, like gravel, are nonrenewable, it is imperative to utilize them less frequently and swap them out for recycled, cost-effective, and ecologically friendly alternatives. Crushed concrete aggregates generated from leftover concrete blocks and demolished old structures are considered as an alternative of natural crush (**Karkush and Yassin 2019).** The aggregates produced by recycling demolition waste fall under the category of local materials replacement, and the study by **(Melbouci 2009)** makes them more valuable in the field of civil engineering, particularly in roads. Based on the characteristics of the recycled aggregates (sand and gravel) after sorting and selection, the physical and mechanical behavior of recycled aggregates and natural materials can be compared. Research will significantly contribute to the creation of a more sustainable global environment by addressing the barriers to C&D material reuse in applications for pavement and road building. The only way to develop a framework for utilizing novel and distinctive kinds of waste materials in civil engineering applications is ultimately through research like this **(Arulrajah et al. 2013).**

2.6.1 Impact of (RCA) on specific gravity

The classification of soil and whether it is suitable for use in construction projects are significantly influenced by its physical properties. The soil samples were subjected to specific gravity tests, which revealed a considerable increase in the Gs value from 2.62 to 2.72 **(Karkush and Yassin 2019).**

2.6.2 Impact of (RCA) on Atterberg limits

Atterberg's limits experiments revealed that when the amount of crushed concrete increased, the liquid limit (LL) rose but the plastic limit (PL) showed no variation. The increased liquid limit could be a result of the crushed concrete absorbing water (Karkush and Yassin 2019)**.**

2.6.3 Impact of (RCA) on dry density and optimum moisture content

The optimal moisture content (w%) and maximum dry density (ρdmax) increase with an increase in RCA, according to the compaction curves for clay soil and RCA-clay mixtures. The maximum decrease is observed at a percentage of 15% (**Kianimehr et al. 2019**). The maximum dry density, as determined by the compaction curve, initially declines at a crushed concrete content of 5% before increasing to a maximum of 1.81 g/cm3 at a 15% crushed concrete content. The value of optimal water content increased somewhat for crushed concrete contents of 5 and 10%, but at 15% crushed concrete content, it falls to a minimum value of 15.2%. The highest possible dry density and the lowest optimal water content are evidently achieved with 15% crushed concrete **(Karkush and Yassin 2019).**

2.6.4 Impact of (RCA) on compressive strength

As RCA content increases, so does the UCS of RCA-clay blends. In compared to the clay soil for the specimen with RCA = 15%, the UCS has increased by 67%. Additionally, the axial strain (UCS) that corresponds to the peak axial stress decreases as %RCA rises. These findings show that practically immediately following their injection into clay soil, RCA increase soil stiffness and raise elastic modulus. For specimens that have undergone moist curing, a considerable increase in UCS is seen **(Kianimehr et al. 2019).**

2.6.5 Impact of (RCA) on cohesion(C) and friction angle (ϕ)

By including construction waste, it was possible to increase the ϕ and c measurements by up to 1.11 and 26.69 times, respectively, as compared to sandy soil. The 16% ratio with just the inclusion of construction demolition trash produced the highest strength value and was chosen as the ideal ratio **(Bagriacik and Mahmutluoglu 2020).**

2.6.6 General findings of stabilization using Recycled Concrete Aggregate (RCA)

(Bagriacik and Mahmutluoglu 2020) utilized a method involving cement and demolished concrete on sandy soils to alter a soil's bearing capacity and lessen settlement. After 28 days of curing, the maximum improvement in bearing capacity was seen. **(Arulrajah et al. 2013)** used different kinds of materials obtained from the demolished construction activities for the soil stabilization and gave the optimum percentages for the CBR, hydraulic conductivity and direct shear strength values**. (Hasan et al. 2016)** presented a study on the use of Granulated Blast Furnace Slag (GBFS) and building waste as soil stabilizers to determine the optimum percentage at which the maximum increase in soil compressive strength was observed, which were 5% for slag and 20 & for RCA.

2.7 Stabilization using Polyethylene Terephthalate (PET)

The pursuit of alternatives that place a high priority on the recycling of materials with a hard deterioration that hurt the environment throughout their life cycle makes a significant contribution to the mitigation of environmental effects. Environmentalists have been particularly concerned about polyethylene terephthalate (PET) bottles among the products of hard degradation since projections show increased consumption **(Castilho, Rodrigues, and Lodi 2021).** As per latest data discussed **in** (NAPCOR (National Association for PET Container) 2018) substantiate that in 2016, the US drank 2799.6 kilotons, or 6.172 billion pounds, of PET bottles. (Million tonnes). Due to the close relationship between production costs, mechanical properties, and thermal properties, PET, also known as polyethylene terephthalate, is a thermoplastic polymer that is a member of the polyester family **(Louzada, Malko, and Casagrande 2019).** One of the safest and most effective choices is to use plastic trash in civil engineering construction since it is environmentally friendly and will provide safe disposal. In addition, engineers are constantly looking for cost-effective resources, and plastic waste is almost free. Additionally, including these components could enhance the construction materials' qualities (**Iravanian and Haider 2020) .**

Using different waste items to stabilize soil has become a popular practice all over the world. The main reason for this is the widespread generation of hazardous wastes that are also difficult to get rid of, like fly ash, plastic, various types of slag, and foundry sands. The reuse of these materials in construction projects will substantially reduce the issue of their safe disposal **(Mishra and Kumar Gupta 2018).** In many nations today, a solid waste dump serves as the destination of solid wastes in the best-case scenario **(Botero et al. 2015).** The manufacturing of plastic bottles has dramatically increased during the last 60 years in the industrial sector. This quick production has produced a lot of waste plastic bottles, polluting the environment. Waste from plastic bottles could be put to use stabilizing soils with subpar engineering qualities **(Niyomukiza et al. 2021).**

It was found that the liquid limit of modified soil increases as the concentration of PET fiber increases when combined with fly ash. The observed changes are thought to be the result of fly ash and PET fibers replacing the soil grains. Reinforced soil has a higher liquid limit than unreinforced soil because it retains greater continuity than unreinforced soil and because recycled PET fibers don't concurrently absorb rainwater. Data show that when combined with fly ash, the reinforced soil's plastic limit rises as the amount of fiber increases **(Mishra and Kumar Gupta, 2018) .**

2.7.1 Effect of PET on dry density and optimum moisture content

It has been noted that the maximum specific dry mass and ideal moisture content of the material are both decreased when the finely crushed PET is added **(Louzada, Malko, and Casagrande 2019).** The ideal moisture content and maximum dry density were shown to decrease with increasing PET fiber content. The maximum dry density falls for samples with maximum dry densities of 1.74 gm/cc, 1.72 gm/cc, 1.68 gm/cc, 1.64 gm/cc, and 1.60 gm/cc, respectively. Due to the PET fibers' elastic response, which decreased compaction effectiveness, clay-PET fiber-fly ash mixtures' maximum dry densities fell. (Mishra and Kumar Gupta 2018)**.** The values are 1946, 1960, 1970, 1981, and 1972 kg/m^3 for the dry densities of the soil samples reinforced with PET plastic bottle fibers in the range of 0% to 0.4%, respectively. This upward trend shows that soil density rose as plastic inclusion % climbed **(Niyomukiza et al. 2021).**

2.7.2 Effect of PET on compressive strength

A correlation between the length and composition of the PET strip and the maximum Unconfined Compression Strength (UCS) has been found. The combination of a strip length of L = 20 mm and a content of 1.5% yields the maximum UCS value for sandy soil. The combination of strip length L = 30 mm and 1.5% content results in the greatest UCS value for the clayey soil. **(Castilho, Rodrigues, and Lodi 2021).**

2.7.3 Effect of PET on California Bearing Ratio (CBR)

On samples that had been immersed in for four days, the CBR test was conducted. While expansive clayey soil that wasn't fortified had a CBR of 12.2%, soil reinforced with PET plastic bottle strips had a CBR of 16.2%. An increase in CBR is an important indicator of increasing soil strength **(Niyomukiza et al. 2021).**The findings show that the CBR value of both wet and dry samples is increased by the addition of PET fiber blended with fly ash. The combinations of soil + PET Fiber 1.2% + fly ash 15% (S3) by weight of soil increased the highest CBR values for both soaked and unsoaked samples from 5.8% to 13.2% and from 4.91% to 11.86%, respectively **(Mishra and Kumar Gupta 2018).**

2.7.4 Impact of PET on cohesion(C) and angle of friction (ϕ)

When the strips are added, the behavior of the soil starts to change at the maximum applied stress levels, according to the analysis of direct shear curves. The substance starts to behave more ductility. With CD = 100% and CD = 95%, the cohesion of sand soil reinforced with strips increased by 66.4% and 55.5%, respectively, while the internal friction angle decreased by 3.5% and 1.7%, respectively. For clayey soil with strips, the cohesive intercept decreased by 7.6% and the internal friction angle increased relatively by 2.9% and 7.3% with CD = 100% and CD = 95%, respectively **(Castilho, Rodrigues, and Lodi 2021).** The similar trend of results were observed by **(Louzada, Malko, and Casagrande 2019),** where by increasing the PET content resulted in the decrease of cohesion and increase in angle of friction. However, **(Mishra and Kumar Gupta 2018)** demonstrated that as the percentage of PET increases, the values of both cohesion and angle of friction begin to rise.

2.7.5 General findings of stabilization using PET

The use of poly ethylene terephthalate is a new technique for soil stabilization**. (Castilho, Rodrigues, and Lodi 2021)** used different sizes of polyethylene terephthalate strips on the UCS and concluded that for sandy soils 20 mm strips gave the most value of UCS and for clayey soils 30 mm strips were the most effective in enhancing the compressive strength**. (Louzada, Malko, and Casagrande 2019)** The findings of a direct shear test utilizing PET in fine powder form revealed that the soil is changing into coarse grained soils with improved shear strength because the angle of internal friction rose while the cohesiveness decreased. PET is a new additive which is being introduced as a soil stabilizer. Many researchers are working to find its optimum percentage for different types of soil. However, using this additive in the combination of RCA is a new idea and it can be very economical and environment friendly solution.

2.8 Wetting and drying cycles

Due to shifting climatic circumstances, periods of cyclic wetting and drying frequently precede embankment failure in cohesive soils. Based on the test data, relationships of strength for various drying and wetting cycles were supplied since the strength analysis showed that the unsoaked strength, prior to the wetting and drying cycles, was closely related to the durability **(Kampala et al. 2014)**. **B. T. Wang et al. 2015)** examined UCS and swelling potential of OTAC-KCI-modified swelling soil for various water content changes, and they discovered that the admixture made it possible to raise the unconfined compressive strength while also lowering the swelling potential. **(D. Y. Wang et al. 2016**); in studies using a micro-penetrometer, the effect of water fluctuations on the strength profile of silty clay soil was evaluated. It was discovered that the strength tended to decrease as the number of W-D cycles rose. After the third W-D cycle, the penetration curves also underwent a change, transitioning from the typical mono-peak pattern to a multi-peak pattern. Researchers found that changes in water worsened the soil's mechanical behavior and that changes in the performance of the soil samples were typically controlled by the initial water content after observing the mechanical behavior of saturated and unsaturated soil specimens for three drying and wetting cycles **(Tang et al. 2016).** Studies on expansive soil treated with iron tailing sands and calcium carbide slag for drying-wetting cycles revealed that the unrestrained compression strength and Atterberg limits declined throughout gradually longer soaking and drying cycles **(Ye et al. 2018).**

Test protocols are used to measure the mass losses brought on by repeated wet-dry cycles and brushing motions. Each cycle begins with a 42-hour oven drying phase at a temperature of 71 °C 2 °C. The specimens are then repeatedly stroked with a force of around 15 N after that. Lastly, samples are immersed for five hours at 23 2 °C **(Consoli et al. 2017).** The amount that soil can expand throughout cycles of wetting and drying is greatly influenced by the soil fabric. On both the dry and wet sides of the compaction curve, samples with variable initial water contents (different textiles) and a certain dry density showed the same swelling potentials after they achieved equilibrium **(Estabragh, Parsaei, and Javadi 2015).**

Chapter 3

MATERIALS AND METHODOLOGY

3.1 General

Laboratory research was conducted to investigate the mechanical behavior of treated expansive soil. Various laboratory testing techniques were used in this regard. A description of the research's materials and methods are described in this chapter.

3.2 Materials

The materials such as expansive soil, PET, and RCA) are used in the study.

3.3 Soil

The study's soil was collected from Nandipur, Gujranwala, famous for its problematic potential in the area. This soil is typically utilized to prepare cricket pitches. Because of its tendency to swell and contract, the soil has an expansive nature.

Figure 3.1 : Nandipur soil sample

3.4 Polyethylene Terephthalate (PET)

PET is the abbreviation for the chemical name of polyester, polyethylene terephthalate. PET may be entirely recycled. Recycled PET is frequently utilized to create new PET bottles and jars, carpet, apparel, industrial strapping, rope, automotive parts, fiberfill for winter jackets and sleeping bags, construction materials, and protective packaging. The energy efficiency of PET is mostly due to its great strength in relation to its light weight, which enables the delivery of more items with less packaging and less energy. The recyclable, high strength and light weight nature of PET are the important factors for its consideration to be used as a soil stabilization material. In this research PET in a coarse form was obtained from Al Hafeez Crystoplasts Peshawar, Pakistan. The PET was then converted into fine grained form using crushers. This crushed PET was used in this research at different percentages in combination with Recycled Concrete Aggregate (RCA). The used percentages of PET were 5%, 10%, 15% and 20%.

Most food manufacturers across industries are switching to PET bottles for product packaging due to PET bottles' reduced cost and superior preservation, which is driving up demand for them. The following items are frequently packaged in PET bottles or containers. Soft Drinks and Carbonated Drinks, drinking water, edible oil, and containers for household food, Paints, lubricating oils, and detergents, Baby Bottles for Feeding (SMEDA 2011)**.** Lahore produces 1.97 million tons of trash a year, of which 0.6895 million tons, or 30–35% of the total, is not collected. As a result, there are 1.2805 million tons of trash that is readily available, of which 21.2% is recyclable, or 0.27 million tons annually. To boost revenues, the report also discovered that 0.04 million tons, or 15% of the total recyclables, are sold directly to industry each year. Additionally, it was discovered that 20% of them, or 0.054 million tons, are recycled by families. This shows that scavengers still have access to 0.086 million tons of recyclables annually (Batool, Chaudhry, and Majeed 2008)**.** The PET is shown in the figure below.

Figure 3.2 : Polyethylene Terephthalate

3.5 Recycled Concrete Aggregate (RCA)

In different concrete laboratories which are operational all over the Pakistan, large quantity of concrete is produced and wasted due to excessive amount of cylinder and cube testing of concrete specimens to determine its compressive strength. These laboratories are the continuous source of waste concrete. The Recycled Concrete Aggregate for this research was obtained from the Labs of HITEC University Taxila.

These were then crushed into fine powder by manual compaction. The RCA used for the given research was in fine form which was obtained after passing from sieve No. 40, the sample was then oven dried for 24 hours at 110ºC which is shown in the figure below. When concrete buildings were restored or demolished in the past, the concrete waste was typically trucked to landfills for disposal. Recycling has grown more appealing as a method of dealing with the debris in the current period of more environmental consciousness, more environmental legislation, and the need to cut construction costs **(Sajjad et al. 2014)**

Figure 3.3: Recycled Concrete Aggregate

3.6 Phase 1: Properties of untreated soil

The first goal of this research was to identify the characteristics of natural, untreated soil devoid of any admixtures. The qualities of the soil taken from Nandipur were assessed in their natural state.

3.6.1 Sample Collection

The soil sample was taken in Gujranwala's Ballewale village, which is close to Nandipur. Clayey dirt for cricket fields is famously exported from this area around the world. One of these places is where the sample was taken. To lessen the possibility of biological materials, roots, etc., a sample from 3 feet depth was taken while the excavation was still ongoing.

3.6.2 Particle size distribution

Following the procedures outlined in ASTM standards, the mechanical examination of soil was carried out by performing sieve analysis and hydrometer tests. A soil sample was first dried for 24 hours in the oven. The earth was crushed by hand and pounding once it had dried. First, the sieve analysis was carried out in accordance with the steps outlined in (**ASTM D422 2007**) for the method.

After that, the hydrometer test was conducted in accordance with **(ASTM D7928-17 2017)** standard, and the soil that had passed through a # 200 sieve was employed as the test material. A dispersing agent like sodium hexa-meta-phosphate was employed to spread out soil particles prior to hydrometric examination.

Figure 3.4: Sieve analysis in progress

3.6.3 Specific gravity test

As per ASTM standard 854 **(ASTM 2000)**, the soil's specific gravity was calculated. Air spaces were removed using a hotplate, and specific gravity was computed in accordance with this.

Figure 3.5: Specific gravity test

3.6.4 Atterberg limits of soil

4 For the determination of the liquid and plastic limits of soil, **(ASTM D4318, ASTM D 4318-10, and D4318-05 2005)** standards were used. The test soil was soil that passed through sieve #4 0. The classification was done using both AASHTO and USCS (uniform soil classification system). First, the liquid limit was determined using 50 grammes of natural soil that was run through sieve # 40. The soil adhered to the finger when water was added to create the test paste, and it had to be scraped off with a sharp knife.

Figure 3.6: Liquid limit and plastic limit test

4.1.1 Compaction test

For both natural and reinforced soils, the modified compaction tests were used to determine the moisture-density relationships. These procedures were carried out in accordance with the **(ASTM D1557-07 2014)** standard. 04 kg of soil that had passed through sieve #4 was first placed in a tray, and water was slowly and carefully added to the soil sample to ensure homogeneous soil-water composition. A knife was used to remove the soil from the fingers after it had stuck to them while mixing water with the soil. The combination was then transferred to the compaction mold once the uniformity of the soil and water had been confirmed. The test was then finished according to the standard instructions. Like that, the natural soil compaction curve was finished.

Figure 3.7: Compaction tests

4.1.2 California Bearing Ratio (CBR)

According to **ASTM D 1883-99 (Method 2010)**, a one-point CBR test was conducted. The OMC prepared the CBR samples and compacted them in five layers using 56 blows for each layer. A mold with an interior diameter of 6 inches and a height of 7 inches, a spacer disc with a thickness of 2 inches, and a surcharge weight of 5 kg make up the apparatus.

Figure 3.8: CBR test

4.1.3 Direct shear test

According to **(ASTM D3080/D3080M 2011)** standard **,** cohesion and angle of internal friction, two shear strength characteristics, were measured using direct shear testing on both treated and untreated soils. The samples were then transferred to the shearing box after being prepared at 95% of the maximum dry density indicated by the compaction curve. The direct shear test was conducted in a box that measured 6.032 by 6.032 by 2.58 cm^3. The samples were originally consolidated at 53 kPa until they attained their maximum consolidation potential before being sheared at normal stresses of 53, 106, and 160 kPa. The test data was then used to illustrate the correlations between the stress-strain and shear strength parameters. When processing the samples, it was discovered that a knife was necessary because the stickier dirt particles could not be handled with fingers.

Figure 3.9: Preparation and failure of direct shear samples

4.1.4 X-Ray diffraction (XRD)

The XRD tests were performed to identify the minerals present in the natural soil along with the ones existing in RCA and PET. The tests were performed in XRD lab located in U.S. Pakistan Center for Advanced Studies in Energy (UP CASE) in NUST Islamabad.

3.7 Phase 2: Optimization of polyethylene terephthalate (PET)

The second phase of this research is the optimization of PET content for the given sample of Nandipur soil. However, the optimization of RCA was not done in this study since ample amount of research was available in the past in which different researchers have optimized the content of RCA for the stabilization of expansive soils i.e., 15 %. The optimized 15% of RCA was used in combination of different percentages of PET to find the value at which maximum increase of strength was observed.

3.7.1 Moisture density relationships at various PET contents

The soil and 15% recycled concrete aggregate (RCA) were swapped out for 5%, 10%, 15%, and 20% polyethylene terephthalate (PET) for the modified compaction tests. The optimal moisture content (OMC) and maximum dry density (MDD) for each specimen were established using modified proctor tests. Five layers of earth are compacted, and a 10-pound hammer with an 18-inch drop height strikes each layer 25 times.

3.7.2 CBR value at various PET contents

Following the assessment of the optimum moisture content and maximum dry density at each PET content combined with 15% RCA. The PET content of 5%, 10%, 15%, and 20% was combined with RCA. Samples were produced for the one-point CBR test, which was run under dry condition. 56 blows were used to condense the samples into five layers, one layer at a time. The apparatus consists of a mold with an internal diameter of 6 inches and a height of 7 inches, a spacer disc with a 2-inch thickness, and a surcharge weight of 5 kg.

3.7.3 Direct shear test at various PET contents

A total of 12 samples were generated for the direct shear testing, 3 for each of the 5%, 10%, 15%, and 20% PET utilized in conjunction with 15% RCA. These samples were made at 95% of the maximal dry density and with the ideal moisture content. For each percent of PET content, the cohesion and internal friction angles were calculated. The samples were originally consolidated at 53 kPa until they attained their maximum consolidation potential before being sheared at normal stresses of 53, 106, and 160 kPa. The relationships between the stress-strain and shear strength parameters were then shown using the test data.

Figure 3.10: Soil, PET, and RCA for direct shear test

3.7.4 XRD test of improved soil

To identify the change in mineralogical composition in the soil after reinforcing it with admixtures XRD test of improved soil was conducted. A total of three tests were conducted with minimum, optimum and maximum percentage of PET reinforced with 15% RCA. The results of the test were interpreted in the form of a graph between intensity and angle.

3.8 Phase 3: Wetting and drying cycles

The final stage of the research examined the values of cohesiveness, angle of friction, and CBR under various wetting and drying cycles. Swelling and shrinking of the soil under examination was one of its most significant characteristics. The impact of these characteristics on soil strength must therefore be investigated. To stabilize the soil, researchers will employ the optimal ratio of recycled concrete aggregate and polyethylene terephthalate that was determined during phase 2 of the study.

3.8.1 Shear strength and CBR under wetting and drying action

The prepared samples for the performance of direct shear tests were wrapped in cotton bandages to prevent their direct contact with water and soaked with in water with the help of a bucket such that the tip of the samples touches the water. The total height of samples was 2 cm. They were immersed in water in such a way that total 0.5 cm of sample is in direct contact with water. Capillary motion helps the water rise so that it may saturate them. The image below depicts the method for saturating the samples. For 24 hours, the samples were submerged in water. To complete the first cycle of wetting and drying after 24 hours, they were first dried at ambient temperature for 3 hours, then put in an oven set at 35°C for 24 hours. The moisture content of the samples that had been soaked for 24 hours was measured to determine the level of saturation that had been reached, using below equations. The pictorial representation of the methodology adopted to achieve the required degree of saturation is shown in the figure below; S = degree of saturation, w = water content, e = void ratio, and Gs = specific gravity

$$Se = wG_s \qquad (3)$$

Figure 3.11: Wetting and drying action

Chapter 4

RESULTS AND DISCUSSIONS

4.1 Phase 1: Properties of untreated soil

4.1.1 Particle size distribution

While silt and clay percentages were established by hydrometer examination of the soil, grain size distribution of expansive soil was carried out using wash method to ascertain percentage passing sieve # 200. The soil gradation curve is shown in **Figure 4.1**. The gradation curve of soil indicates that nearly 80% of the soil consists of fine-grained particles.

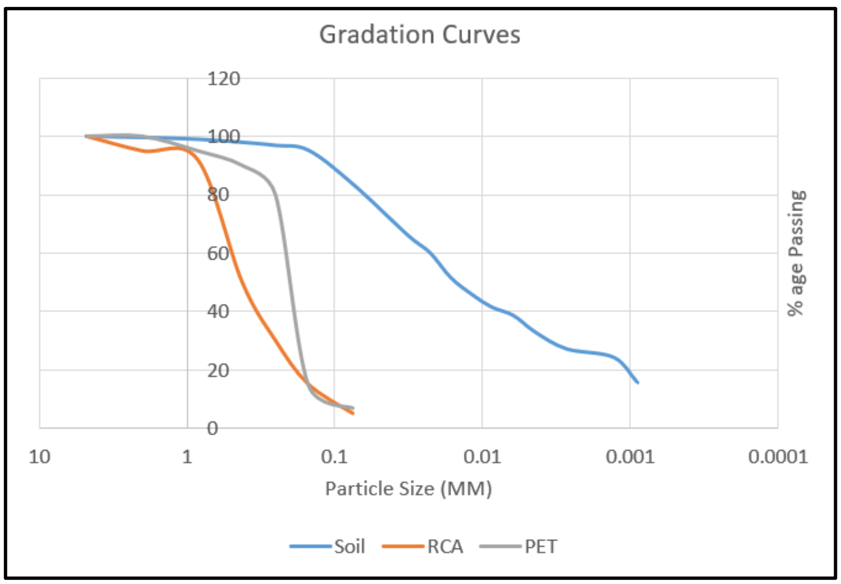


Figure 4.1: Gradation curve of Soil, RCA and PET

4.1.2 Specific gravity

The soil's specific gravity was calculated in accordance with ASTM D 854-98 standard. The soil was found to have a specific gravity of 2.63.

4.1.3 Atterberg limits

The Casagrande gadget was used to ascertain the soil's liquid limit, and threads made to the ASTM-required thickness of 1/8" were used to establish the plastic limit. Liquid limit of soil comes out to be 48 % and plastic limit value is 33%. According to the USCS system, it is categorized as CL, and the AASHTO system classifies it as A-7-5.

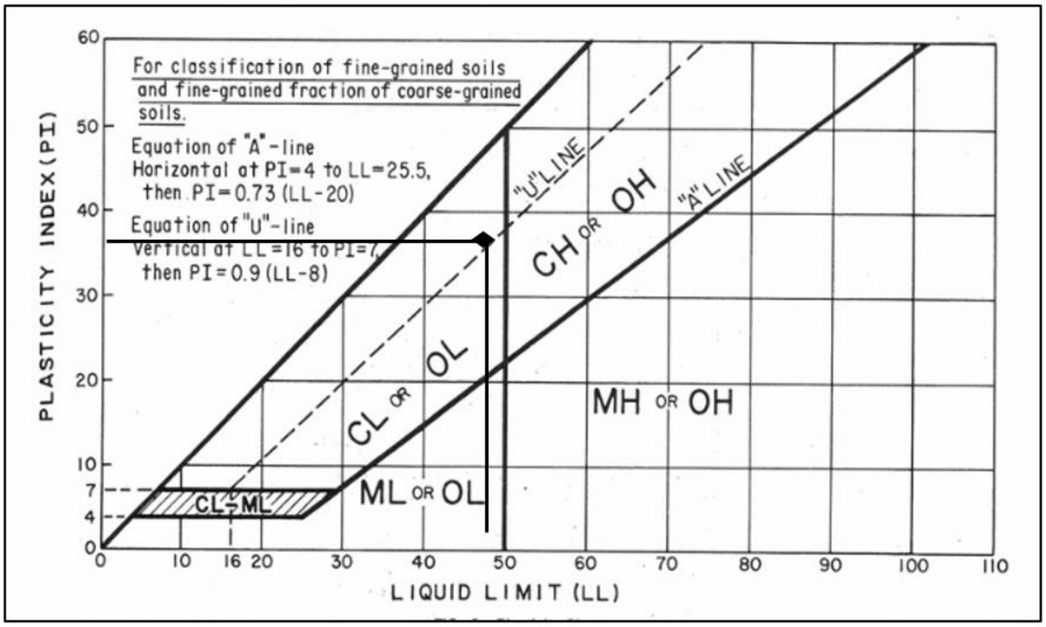


Figure 4.2: USCS soil classification chart

4.1.4 Compaction curve

A modified Proctor test was performed to determine the compaction characteristics of soil. The maximum dry density (MDD) of the soil is found to be 1591 kg/m^3 at an optimum moisture content (OMC) of 15.63%.

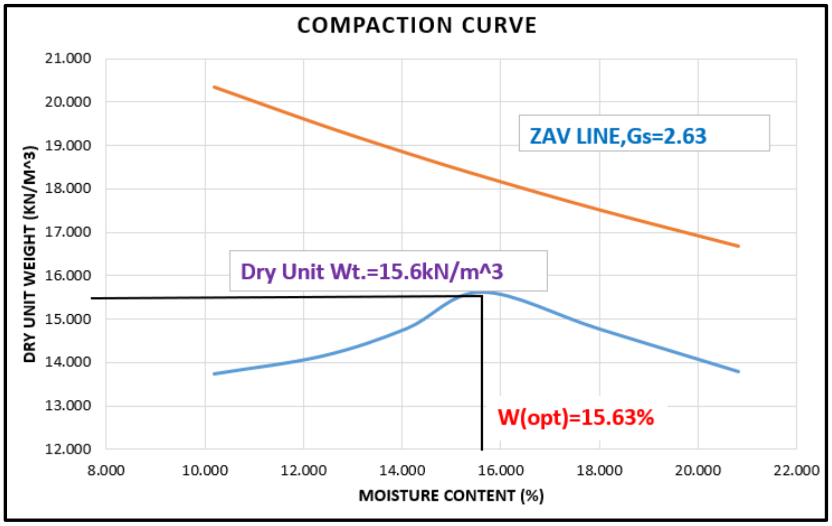


Figure 4.3: Compaction curve

The compaction curve is shown in **Figure 4.3.** The curve also shows the zero-air void line at a specific gravity value of 2.63.

4.1.5 California Bearing Ratio (CBR)

According to ASTM D 1883-99(Method 2010), a one-point CBR test was conducted. The OMC prepared the CBR samples and compacted them in five layers using 56 blows for each layer. The calculated value of CBR of the given soil sample is 9.67%.

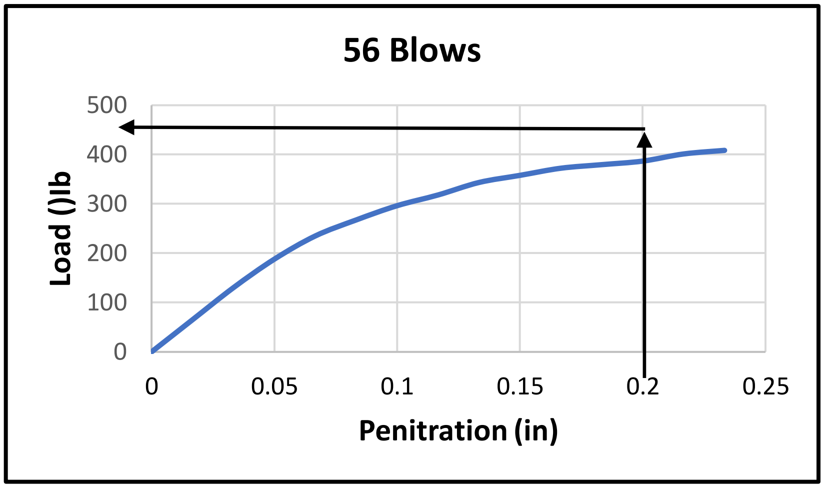


Figure 4.4: Penetration vs load graph

Table 4.1: CBR calculation

CBR Calculation				
CBR at 0.1 in		=	290/3000*100	
		=	9.67	%
CBR at 0.2 in		=	400/4500*100	
		=	8.888889	%

CBR at 0.1 in > CBR at 0.2 in

Figure 4.4 shows the results of CBR and the calculation of its value is done in **Table 4.1**. The value was greater at 0.1” which was selected as 9.67%.

4.1.6 Direct shear test

The findings of a direct shear test on natural soil are shown in Figure 4.5, and they demonstrate that the soil has an angle of internal friction of 6.63 degrees and a cohesiveness of 17 kPa under dry conditions. The normal stress of 53 kPa, 106 kPa and 160 kPa was applied in the set of conditions required to perform this test. **Figure 4.5** presents the relationship between normal stress and shear stress at the maximum value of normal stress that is 160 kPa, whereas **Figure 4.6** shows the graph between shear stress and displacement where at approximately 4 mm displacement shear stress almost becomes constant.

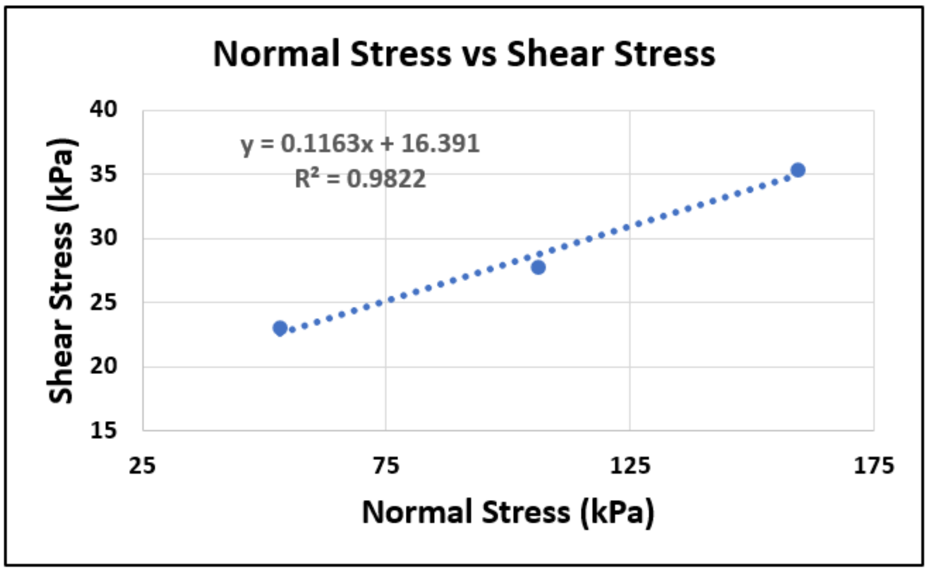


Figure 4.5: Normal stress vs shear stress (untreated soil)

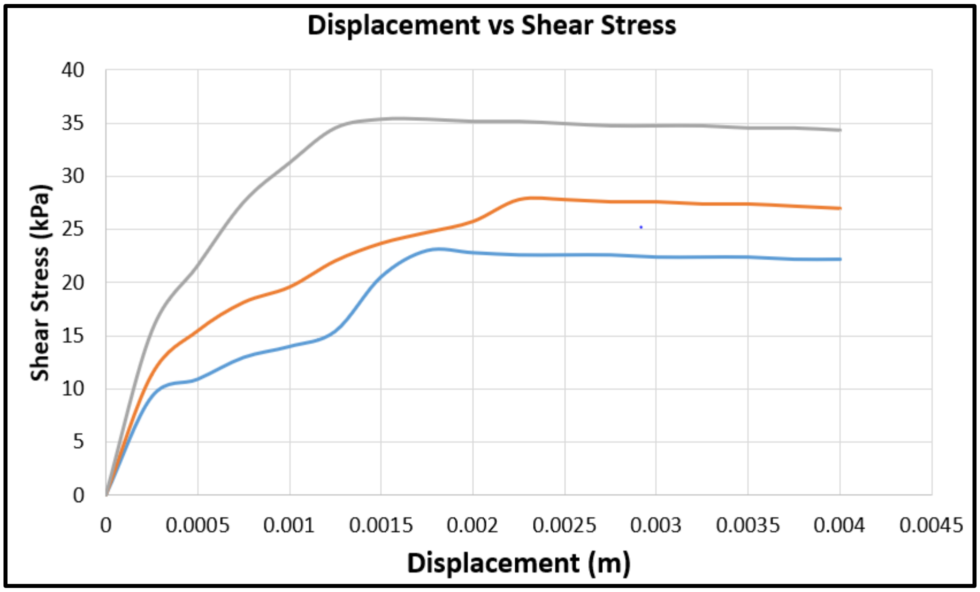


Figure 4.6: Displacement vs shear stress (untreated soil)

Table 4.2 provides a brief review of the characteristics of natural/undisturbed soil; subsequent paragraphs provide a full analysis of the test results.

Table 4.2: Properties of untreated soil

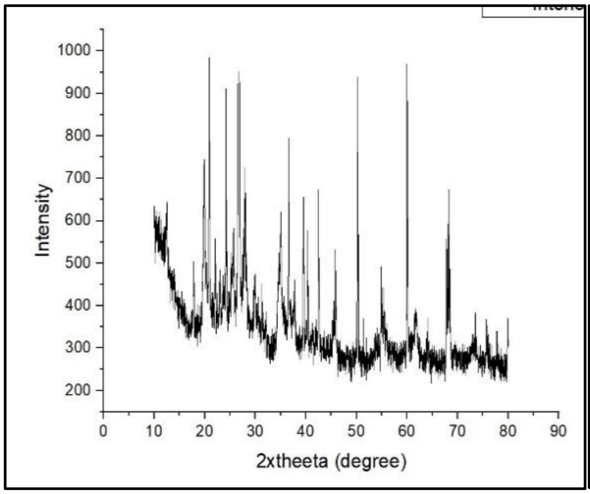
Liquid limit	48%
Plastic limit	33%
Plasticity index	15%
Specific gravity of soil	2.63
Specific gravity of PET	1.5
Specific gravity of RCA	2.9
% fines	83.5%
USCS soil classification	CL
AASHTO soil classification	A-7-5

Maximum dry unit weight (MDW	15.6 kN/m^3
Optimum moisture content (OMC)	15.63%
Hydraulic conductivity	0.000079 cm/s
California Bearing Ratio (CBR)	9.67%
Cohesion (c)	17 kPa
Angle of internal friction (ϕ)	6.63^o
Shear strength	25.07kPa

A CBR value of less than 10% is unsatisfactory because engineers for California Transportation are required to build subgrades with a Bearing Ratio (CBR) of at least 10%. According to studies, if the subgrade has a CBR value < 10, the subbase material will bend under traffic loads similarly to the subgrade, which will cause the pavement to deteriorate **(Schaefer et al. 2008)**. In addition, a very low value of shear strength also makes this soil unsuitable for the foundation construction. A very low value of angle of friction and slightly more value of cohesion indicates the soil is predominantly fine grained which can also be proved from soil classification results shown in table above.

4.1.7 XRD test of natural soil, RCA, and PET

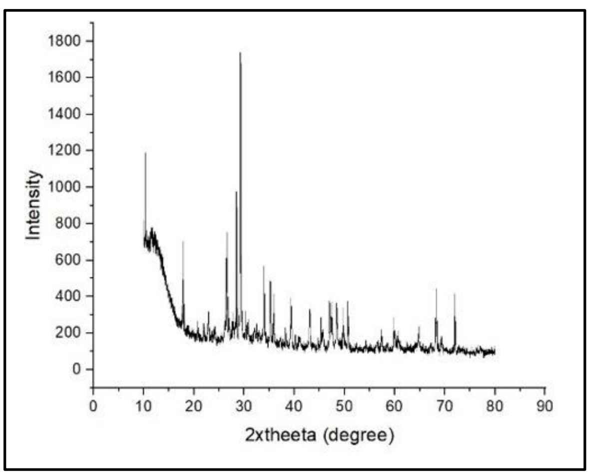
In the case of montmorillonite, the distinctive peak at about 8 to 10 degrees 2 theta correlates to the mineral's layer spacing since this is the angle at which the mineral's layer spacing causes X-rays to be diffracted (Marsh et al. 2018). Illite has two other characteristic peaks at around 20-22° and 30-32°. Illite's XRD pattern shows two peaks that result from X-rays interacting with the mineral's layers at different angles **(G. Wang, Wang, and Zhang 2017)**. These peaks were also observed in XRD analysis of Nandipur soil which is under study as shown in **Figure 4.7(a).** Quartz and SiO2 (silica) are two typical soil minerals that can increase the overall hardness and strength of the soil. Soil most likely contains water in the form of hydrogen. Due to its ability to reduce soil cohesiveness and enhance soil slipperiness, carbon graphite may have a detrimental effect on soil strength and stability **(Daniel-Mkpume et al. 2019).** The large percentage of carbon graphite along with quartz and silicon oxide makes this soil low ins hear strength. The percentages of different compounds are shown in **Figure 4.7(b).**



Formula	Matched phase	Quant.(%)
O2 Si	Silicon oxide $-alpha Quartz low	58.5
C	Carbon Graphite 2H	31.6
O2 Si	Quartz	.4
Al0.5 Li0.5 O...	i O4))0.5	2.2
H2	Hydrogen	1.3

Figure 4.7: (a) XRD test results (b) Matched phase from XRD test

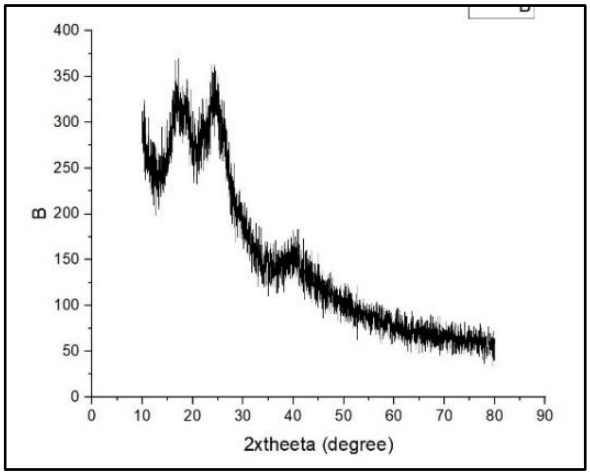
The XRD tests of recycled concrete aggregate indicate the presence of calcite since calcite is a common mineral found in natural and recycled concrete aggregates. RCA shows distinctive peak at 29.4°, showing existing of calcite, significantly **(Limbachiya, Marrocchino, and Koulouris 2007).** The peak at similar angle was observed in the case of RCA which was under this study as shown in **Figure 4.8 (a).** Furthermore, the XRD graph analysis shows that the mineral composition of RCA contains 59% calcite, which acts as a binder to reinforce the soil. In addition to this, RCA contains 18.8% calcium hydroxide and 18.8% silicon oxide which are also useful minerals to strengthen the soil properties as shown in the XRD results in the form of percentages (**Figure 4.8b**)

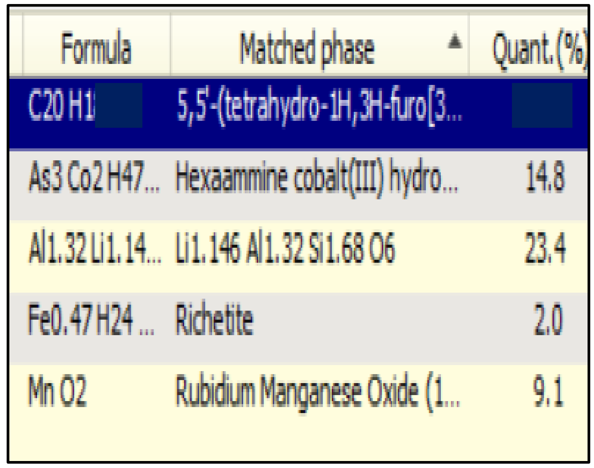


Formula	Matched phase	Quant.(%)
Ca H2 O2	Ca(OH)2	18.8
C Ca O3	Calcite	59.2
Si	Silicon oxide $-alpha Quartz low	22.0

Figure 4.8 : (a) XRD test results of RCA **(b)** Matched phase from XRD test

When subjected to XRD analysis. (PET) is a polymer and typically does not show characteristic diffraction peaks in XRD (Kevin Eiogu, Ibeneme, and Aiyejagbara 2020). A similar scenario was observed for the PET under study as shown in **Figure 4.9 (a)** where no characteristic peak is seen in the XRD test results. Large polymers present in PET are chemically inert and do not interact chemically with soil to improve its strength. The specific feature of PET is to replace the weak soil particles with PET crushed particles.





Formula	Matched phase	Quant.(%)
C20 H1[redacted]	5,5'-(tetrahydro-1H,3H-furo[3...	[redacted]
As3 Co2 H47...	Hexaammine cobalt(III) hydro...	14.8
Al1.32 Li1.14...	Li1.146 Al1.32 Si1.68 O6	23.4
Fe0.47 H24 ...	Richetite	2.0
Mn O2	Rubidium Manganese Oxide (1...	9.1

Figure 4.9: (a) XRD test results of PET (b) Matched phase from XRD test

4.2 Phase 2: Optimization of polyethylene terephthalate (PET)

In the second phase of the research different percentages of PET were mixed with soil using constant RCA content. 5%, 10%, 15% and 20% PET was mixed separately with 15% RCA and the sample of expansive soil.

4.2.1 Relationship between dry unit weight and moisture content

The research indicates the link between moisture density and various PET content levels while maintaining a constant RCA content of 15%. PET was added to soil samples in amounts of 5%, 10%, 15%, and 20%. For each sample, required parameters were calculated using the Modified Proctor test. The highest unit weight for natural soil is 15.6 kN/m^3, and the OMC is 15.63%, as shown in **Figure 4.3**. The maximum value of unit weight in dry state steadily declines after reinforcing with additives between 5% and 10% PET content but starts to rise between 15% and 20% PET content as seen from the compaction curves in **Figure 4.10**. The maximum dry unit weight has dropped because of soil flocculation and agglomeration, as well as the lower density and specific gravity of PET in contrast to soil. Moreover, as the PET concentration increases, the soil's optimum moisture level decreases. This is true because while RCA particles are coarser than soil, PET particles are finer. Smaller surface areas will result in reduced water content at lower PET percentages while RCA content is higher, but as PET content approaches or exceeds RCA content, more water will be needed to lubricate the larger surface area. Consequently, the ideal moisture content starts to rise. The relationships between PET content with OMC and dry density are presented in **Figures 4.11 and 4.12**.

The pattern changes in a way that is almost identical to previous findings when the addition of PET decreases the unit weight, and the addition of RCA increases the unit weight. PET that has been coarsely crushed is added, lowering the maximum specific dry mass of the material (Louzada, Malko, and Casagrande 2019)**. (Iravanian and Haider 2020)** researched the works of numerous writers and concluded that the maximum dry density and optimal moisture content both decreased in all pertinent tests when plastic waste was employed to stabilize soil. Similar trend was observed by **(Mishra and Kumar Gupta 2018)**. However**, (Niyomukiza et al. 2021)** and **(Al-Taie, Al-Obaidi, and Alzuhairi 2020)** showed that even with extremely small percentages of PET, there was a very minor increase in maximum dry density. The optimal water content rises while the maximum dry density decreases as the RCA component increases, according to the compaction curves for clay soil and RCA-clay combinations **(Kianimehr et al. 2019). (Karkush and Yassin 2019)** demonstrated that MDD lowers at lower percentages of recycled concrete before beginning to rise at greater percentages. However, in the current study, when both materials are used together, the dry unit weight initially decreases and then starts to climb to 15% PET and 15% RCA. This is contrary to past studies that found that using PET or RCA reduced the dry unit weight of soil.

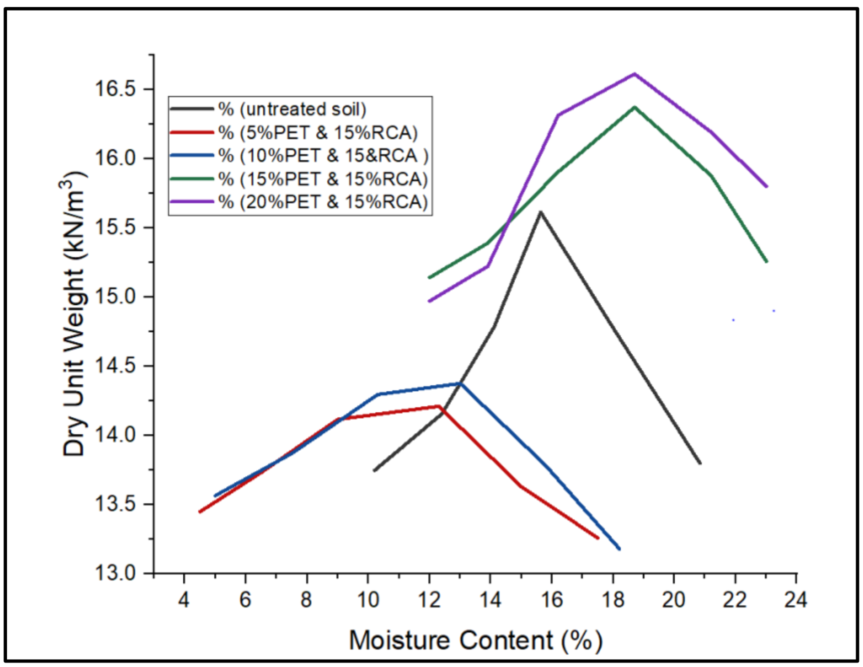


Figure 4.10: Moisture density relationships at various PET content and 15% RCA

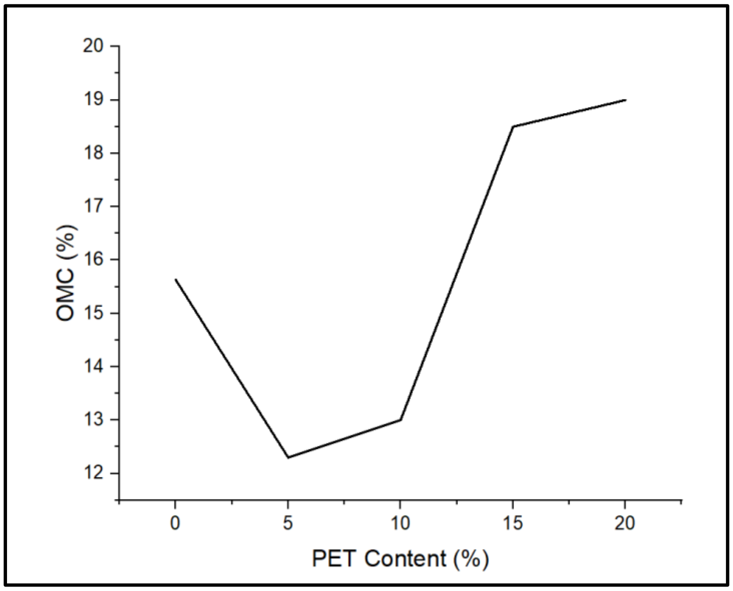


Figure 4.11: Relationship between PET content & OMC at 15% RCA

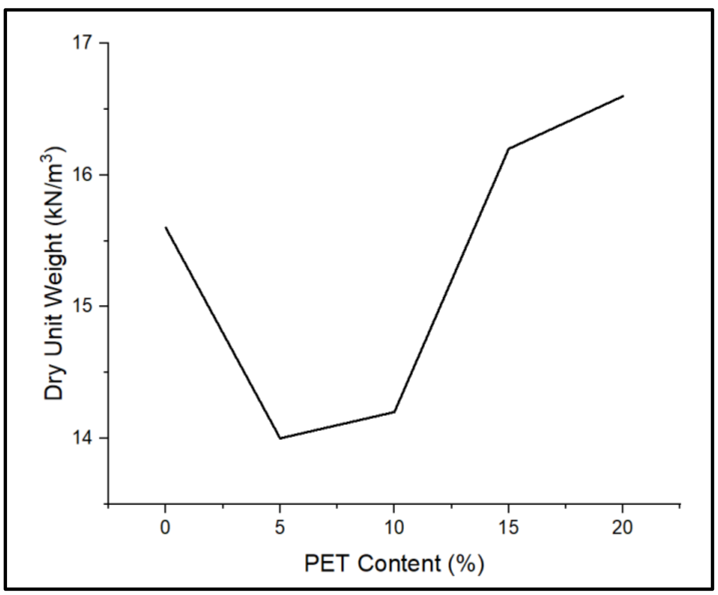


Figure 4.12: Relationship between PET content & unit weight at 15% RCA

4.2.2 California Bearing Ratio (CBR)

Since the original CBR value was less than 10% which is quite low. In this study the effect of PET and RCA was checked to see whether they can improve the CBR value or not. For this reason, a one-point CBR method test was performed on four different PET contents mixed with standard RCA content of 15% and the results are shown in **Figure 4.13**. At PET content of 5% a very small increase in CBR value was observed, however it jumped from 9% to approximately 17% at 15% PET content. This increase is not as significant when the PET percentage was changed to 20%. This trend is depicted in the form of a bar chart in **Figure 4.14** where approximately 100% increase in CBR value was observed. In one of the study, the CBR value was increased by 345% when discarded concrete fines were mixed into the soil at a 40% ratio (Singh and Singh 2017). The CBR values rise to 16.2% at 0.3% after adding various PET plastic bottle percentages to the soil as reinforcement (Niyomukiza et al. 2021). In this study, the CBR value is increased up to 17%, as a result, these soils meet the National Highway Authority's (NHA) criteria for a wet CBR of 7%, which is the minimal required (Government of Pakistan, 1998**) (Mujtaba et al. 2018).**

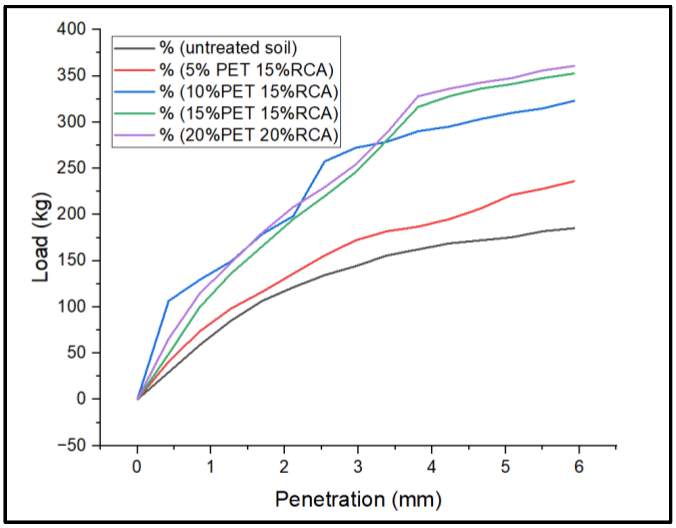


Figure 4.13: Load vs penetration at various PET content & 15% RCA

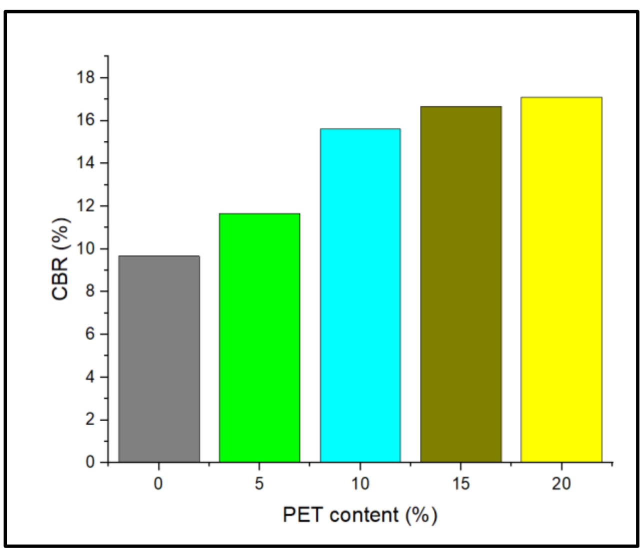


Figure 4.14: Relationship between CBR and % PET content at 15% RCA

4.2.3 Direct shear test

The numbers below show that the addition of PET and RCA consistently decreased cohesiveness and increased the ϕ. Additives, according to the compaction curves, decreases the soil's plasticity index (PI), which lowers the quantity of clay in the soil and changes how it behaves. As the fraction of additives increases, the cohesiveness declines and the ϕ increases correspondingly. The direct shear test results of different PT contents for the maximum normal stress value of 160 kPa are shown in **Figures 4.15-4.18**. The cohesiveness and ϕ altered the most dramatically at 15% PET and 15% RCA. Beyond this point, as the PET concentration grew, the cohesiveness and angle of friction reached a stable condition and did not vary much as shown in **Figure 4.19** and **Figure 4.20**. The prediction that larger particles will have a higher ϕ than smaller particles is supported by the observed rise in this angle. With increasing additive percentages, the PI also dropped, which caused the clay content to drop and the size of the soil particles to rise. As more additives are applied, the moisture level rises, which can loosen the connections between particles and cause the loss of cohesion. The theory is that the addition of chemicals educes the cohesion of the soil and consequently the amount of clay in it.

The shear stress is likely to be the same given the failure displacements in both situations, i.e., natural soil and treated soil, however this is not the case. Like this, after failure, the specimens with lower percentages of additives behave differently from those with larger percentages of additives, also displaying notable differences in residual strength. Similar conclusions were made by (Sabat 2012)**.** Indicating an increase in the shear strength of the poorly graded soil, the application of 2.0% DRPET increased the ϕ from 35° to 41.42°. mostly as a result of the expansion of the barrier between soil particles **(Al-Taie, Al-Obaidi, and Alzuhairi 2020).** ϕ increases and the cohesiveness slightly reduces when PET strips are introduced to a clayey soil, but as the proportion of PET increases, a noticeable improvement is observed **(Castilho, Rodrigues, and Lodi 2021).** The examined materials, however, differed differently from previous studies in terms of composition because of changes in additives and soil types. As the proportion of RCA in clay mixtures rises, shear strength increases along with higher cohesion (c) and peak internal friction angle **(Kianimehr et al. 2019)**. By including building waste, it was possible to increase the soil's internal friction angle and cohesiveness values by up to 1.11 and 26.69 times, respectively, as compared to just sandy soil. The ratio of 16% for the inclusion of solely building waste was found to have the highest strength value and was chosen as the best ratio **(Bagriacik and Mahmutluoglu 2020).**

It is normal for larger particles to experience more internal friction than smaller ones, which in turn increases the ϕ. As the percentage of additives rises, the PI likewise falls, which alternately lowers the clay content and causes the smaller grains to enlarge into larger ones. Additionally, a loss in cohesiveness is very normal because as the number of additives increases, so does the moisture content, which may alternately loosen the links between particles. Another explanation is that adding chemicals causes the soil's clay content to drop, and a fall in clay content directly reflects a decrease in soil cohesiveness.

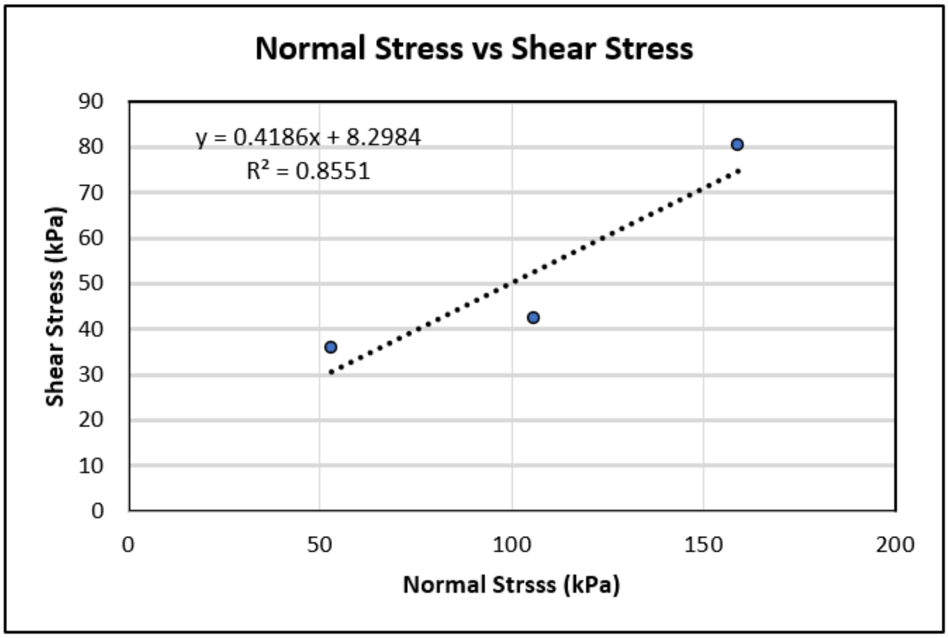


Figure 4.15: Direct shear test at 5% PET & 15% RCA

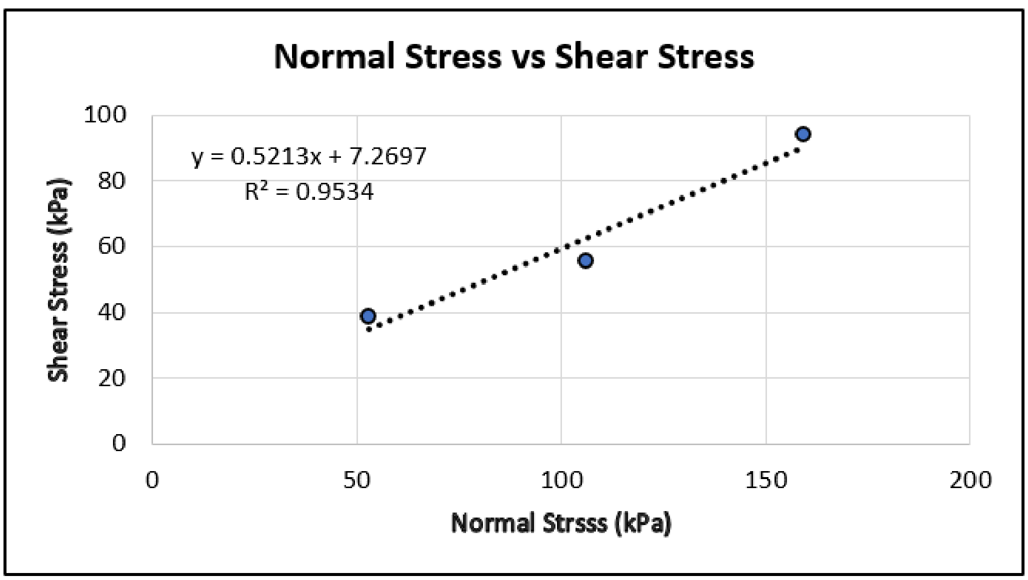


Figure 4.16: Direct shear test at 10% PET & 15% RCA

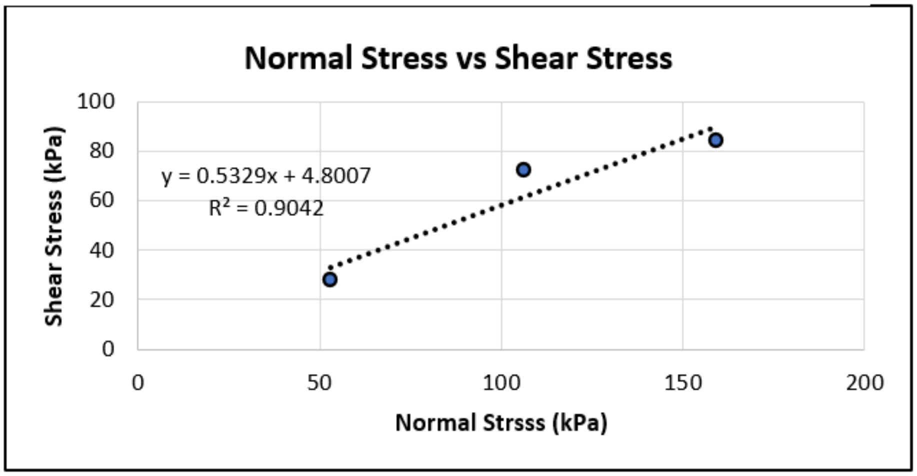


Figure 4.17: Direct Shear Test at 15% PET & 15% RCA

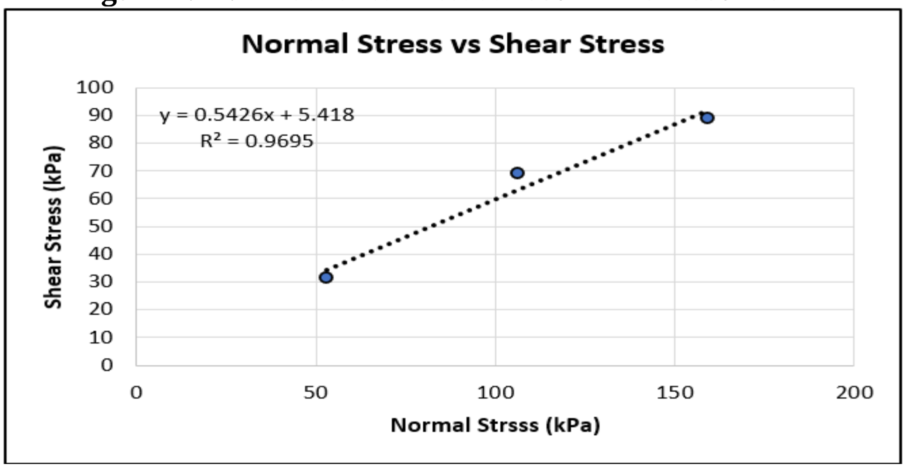


Figure 4.18: Direct shear test at 20% PET & 15% RCA

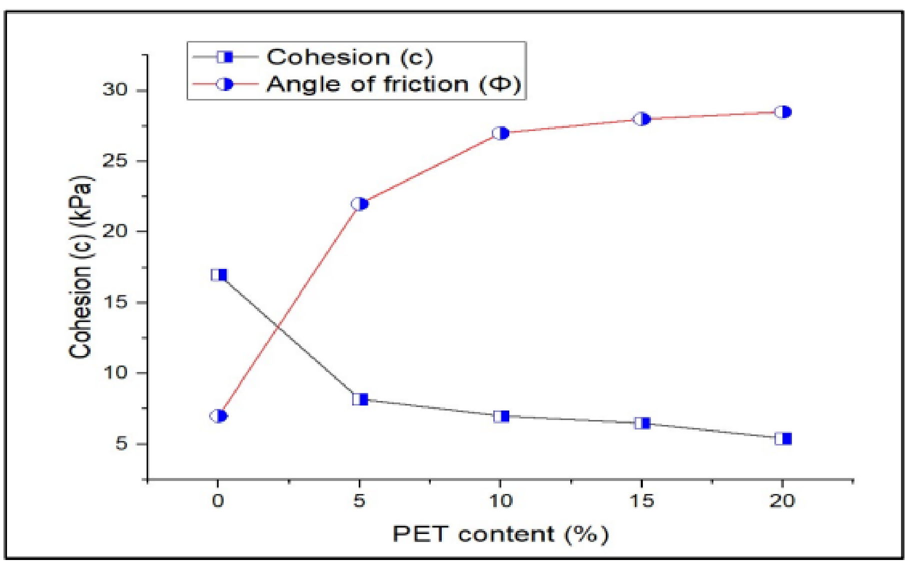


Figure 4.19: c and ϕ at various PET contents and 15 % RCA

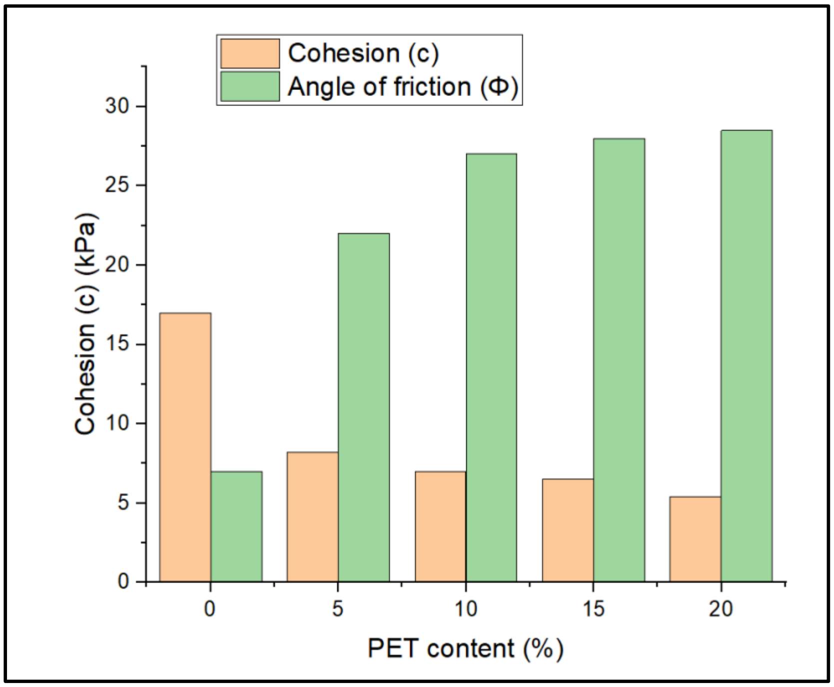


Figure 4.20: c and ϕ at various PET contents and 15 % RCA

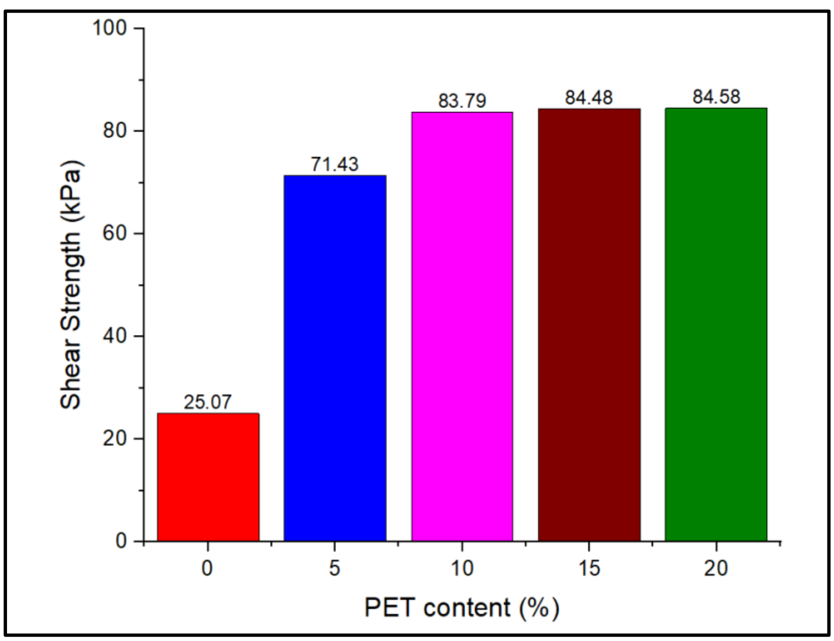


Figure 4.21: Increase in shear strength at different PET contents

The shear stress is likely to be the same given the failure displacements in both situations, i.e., natural soil and treated soil, however this is not the case. Like this, after failure, the specimens with lower percentages of additives behave differently from those with larger percentages of additives, also displaying notable differences in residual strength. Similar conclusions were made by **(Sabat 2012),** study showed that changes in the concentration of ceramic dust steel fibers caused the cohesiveness to decrease and the ϕ to increase.

However, the examined materials had a somewhat different composition from earlier studies because of variances in additives and soil types. The interlocking of the soil particles caused by the cementitious effects of the additives in combination with the expansive soil causes the increase in ϕ when the dry unit weight decreases with an increase in the percentage of the additives, which may cause the angle of internal friction to decrease. However, the cementitious effect of the additives with soil is the only factor that makes this increase in ϕ conceivable. As a result of which the shear strength is also enhanced to 85 kPa as compared to that of original soil which was only 25 kPa showing almost 300% increase in shear strength also shown in **Figure 4.21.**

Considering the test results at all percentage contents of PET at 15% RCA content. The optimum percentage calculated is 15% PET and 15% RCA. The properties of treated soil at this optimum percentage are illustrated in the table below. It has been observed that liquid limit is decreased, and plastic limit is increased resulting in the lower plasticity index. Dry Unit Weight and optimum moisture content were increased. Cohesion decreased and angle of friction increased. CBR value also showed some considerable improvement.

Table 4.3: Properties of treated soil

Liquid Limit	28%
Plastic Limit	20%
Plasticity Index	08%
Specific Gravity	2.72
Maximum Dry Unit Weight (MDD)	16.2 kN/m^3

Optimum Moisture Content (OMC)	18.5%
California Bearing Ratio (CBR)	16.67%
Cohesion (c)	6.5 kPa
Angle of internal friction (ϕ)	28.05^{o}
Shear Strength	84.48 kPa

4.2.4 XRD Test

The presence of a mineral known as calcite, which is a common component of both recycled concrete aggregates. Calcite has a characteristic XRD peak at around 28 degrees, which explain the peak observed in XRD analysis (Derkani et al. 2019). Calcite is a mineral with a high compressive strength, reinforcing the soil matrix to improve its strength. The presence of calcite also reduces the soil's susceptibility to deformation, occurred due to changes in moisture content. This is because calcite has a low water absorption capacity, which means that it can help reduce the amount of moisture that the soil absorbs, reducing the potential for swelling and deformation **(Zamer et al. 2017)**. In the improved soil sample, XRD tests have generated the peak at similar angle as that of calcite which proves the presence of calcite that is the major contributor for increased strength. (PET) is a polymer and typically does not show characteristic diffraction peaks in XRD. The removal of carbon graphite in the improved soil sample indicates the clear reason for improved strength because problematic mineral has been removed because no peak is observed at 26 degrees in any of the samples.

The presence of carbon graphite is still evident at approximately 26 degrees **(Figure 4.23)** when using a combination of 5% PET and 15% RCA, suggesting its continued existence. When the PET content increases to 20% alongside 15% RCA, calcite begins to be replaced by PET, resulting in a reduction in the intensity of the calcite peak at 29 degrees **(Figure 4.24)**. However, an optimal composition of 15% PET and 15% RCA eliminates all peaks associated with problematic minerals and maximizes the intensity of calcite **(Figure 4.22)**.

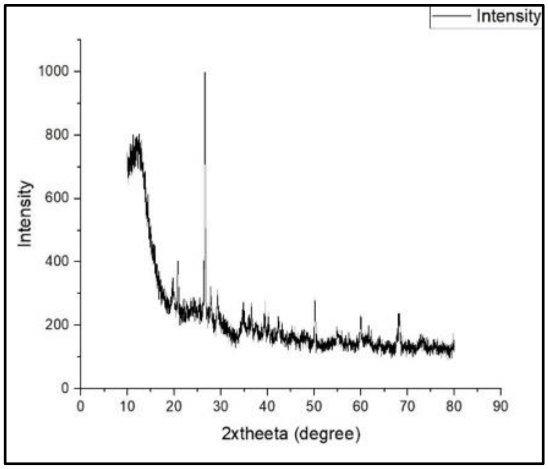


Figure 4.22: XRD test at 15% PET and 15% RCA

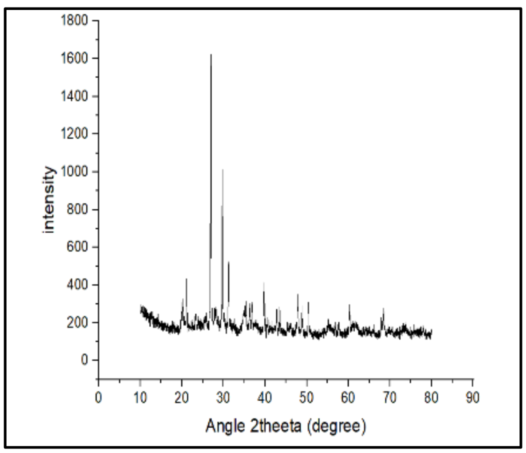


Figure 4.23: XRD test at 5% PET and 15% RCA

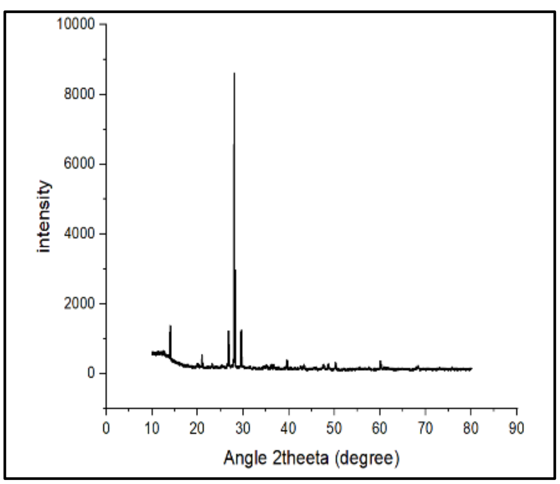


Figure 4.24: XRD test at 20% PET and 15% RCA

4.4 Phase 3: Wetting and drying cycles

4.4.1 Shear strength under wetting & drying cycles

To replicate field circumstances, soil samples were wetted and dried during the research's final phase. To determine the cohesiveness and angle of friction, the direct shear test was used to samples that had been wetted and dried. With an increase in the ages of additives, the cohesiveness declines and ϕ rises, exhibiting behavior akin to - circumstances. The cohesiveness and internal friction angle of the natural soil are 16.63 kPa and 6.63 degrees, respectively (after first cycle of wetting & drying). From the test results, cohesion decreases, and angle of internal fiction increases in the soaked condition. This is because the soaked soil offers less cohesion than samples tested under similar conditions without the wetting & drying action condition, and the decrease in cohesion is caused by the loss of adhesion between soil particles because of the soaking. The higher angle of internal friction during soaking and drying action conditions is attributed to the sample's increased consolidation, which alternatively packs the particles more tightly and causes the particles to interlock more. The figures below represent the outcomes of direct shear testing conducted during various wetting and drying cycles. The outcomes show that strength is decreased throughout this procedure. The properties of soil under soaking and drying are also enhanced by soil stabilization.

The test results demonstrate that, as would be expected, dry specimens offer greater cohesiveness than samples that have been wet and then dried, and that there are fewer changes in the angles of internal friction under both conditions. The test findings demonstrate that, in contrast to this option, the shear stress of unsaturated specimens is consistently higher than the shear stress of moist specimens. For 15% PET and 15% RCA, both soaked and unsoaked specimens often offer more strength compared to all other alternatives, making them the greatest alternative so far in the study. In comparison to natural soil, specimens reinforced with chemicals often offer increased strength.

It has also been observed that a major reduction in the strength is observed at initial wetting and drying cycles and later the decrease in strength is minimum. When the wetting and drying cycles are increased soil samples begin to lose their shear strength with the decrease in angle of friction. After the 7^{th} wetting-drying cycle shear strength is reduced from 85 kPa to 50 kPa as shown in **Figure 4.31.**

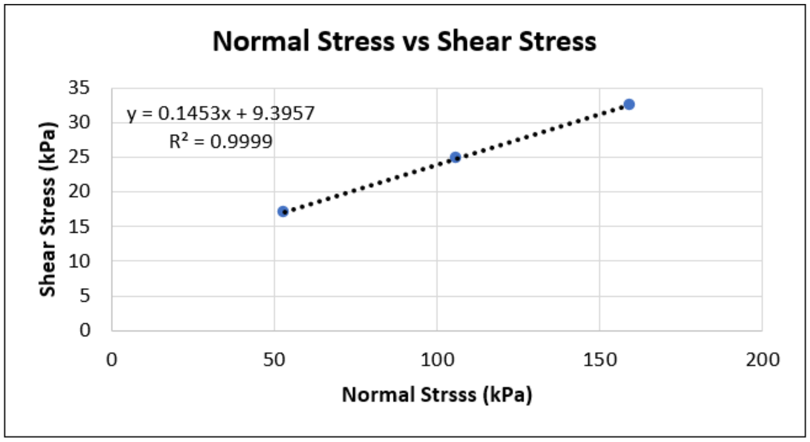


Figure 4.25: Direct shear test untreated soil (1st wetting & drying cycle)

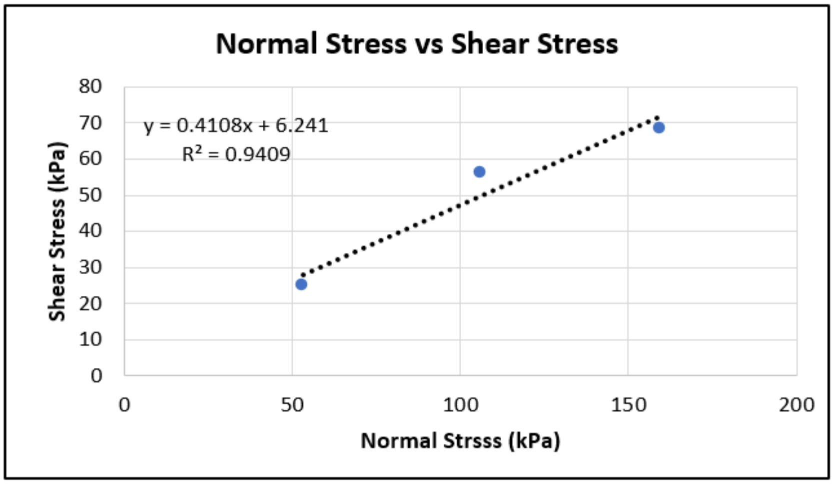


Figure 4.26: Direct shear test treated soil (1st wetting & drying cycle)

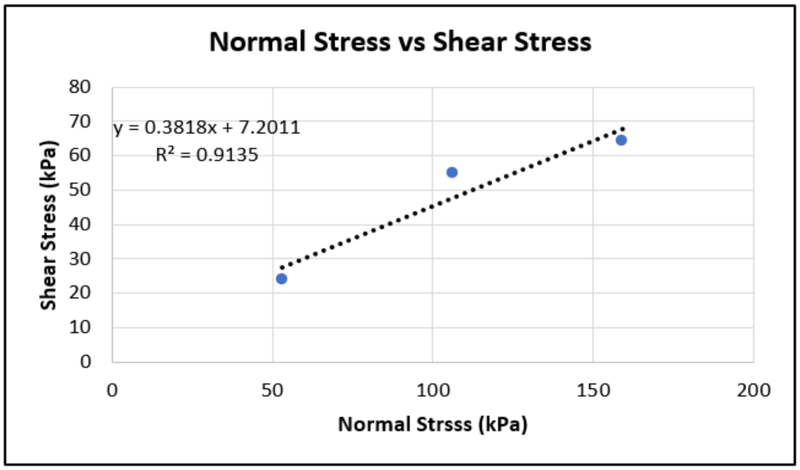


Figure 4.27: Direct shear test treated soil (3rd wetting & drying cycle)

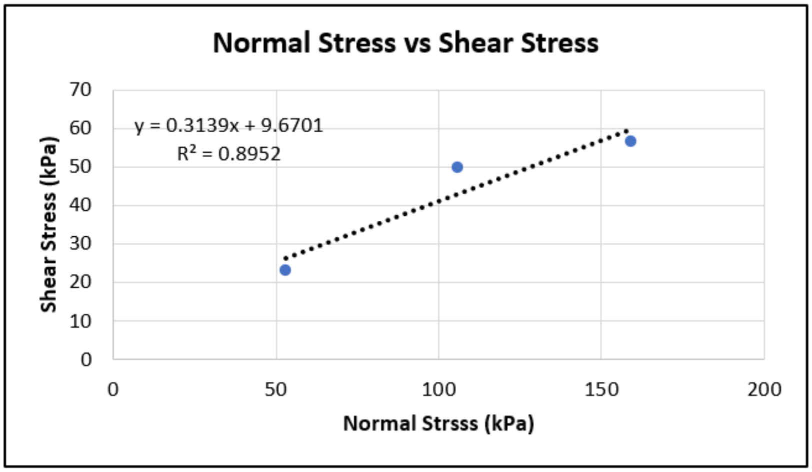


Figure 4.28: Direct shear test treated soil (5th wetting & drying cycle)

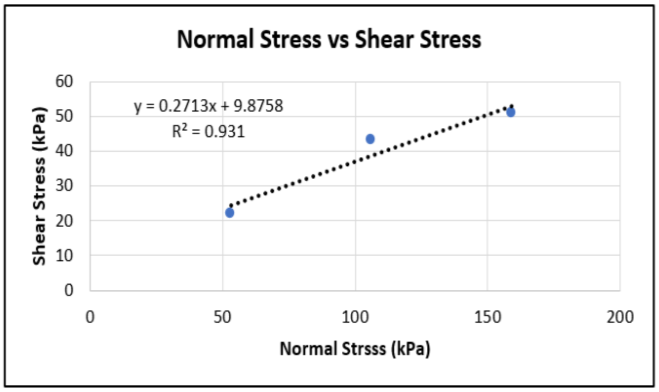


Figure 4.29: Direct shear test treated soil (7th wetting & drying cycle)

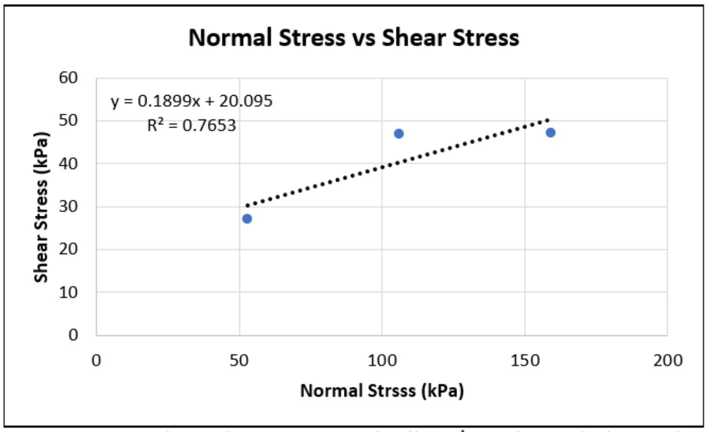


Figure 4.30: Direct shear test treated soil (10th wetting & drying cycle)

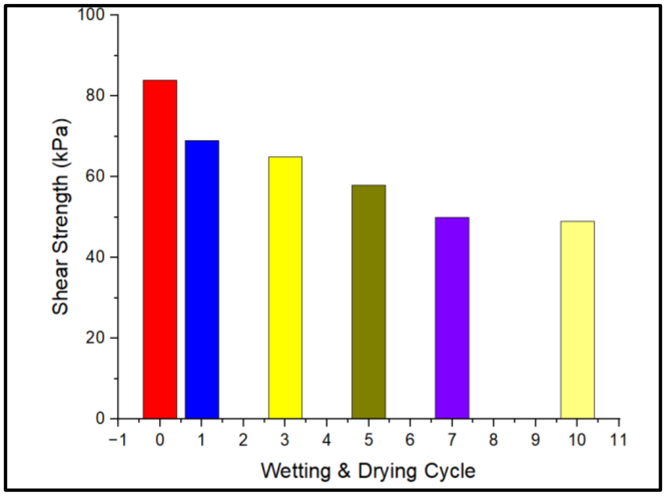


Figure 4.31: Decrease in shear strength at different wetting drying cycles

4.4.2 CBR under wetting & drying Cycles

Additionally, the value of CBR was assessed for various wetting and drying cycles. After each soaking stage, the California Bearing Ratio (CBR) decreases as depicted in **Figure 4.32**. The rise in CBR brought on by drying for the same cycle is less than the comparable decrease brought on by soaking. The CBR value of expansive soil with lime stabilization decreases by 30% till 3rd wet dry cycle but it becomes stable after the fifth wet-dry cycle **(Ye et al. 2018)**. this study the CBR value was evaluated till 3rd wetting-drying cycle and a very small decrease in CBR was observed. It decreases from the value of 16.67% to 13.3% at the third wet-dry cycle which was also proved by **(Stuti Maurya 2016)** and **(Ye et al. 2018)**. After the third dry cycle a small change is observed in CBR value on the 5th cycle, and it almost becomes constant in the 7th cycle **(Figure 4.33).**

California Transportation and **(Government of Pakistan, 1998)** (Mujtaba et al. 2018) even after 7 cycles of wetting and drying. After the first two cycles, the sample shows a noticeable increase in the fracture cracks and dimensions, and after subsequent cyclic events, the sample tends to reach an equilibrium condition **(Oluwaseun Sunday Bamgbopa 2016).** Similarly dominant vertical cracks were observed in CBR sample after 3rd cycle of drying.

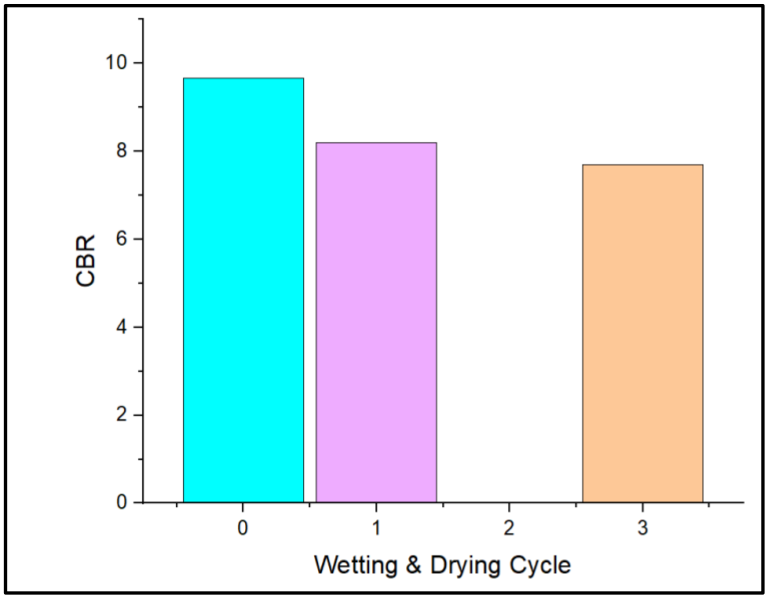


Figure 4.32: Influences of wetting-drying cycles on CBR for untreated soil

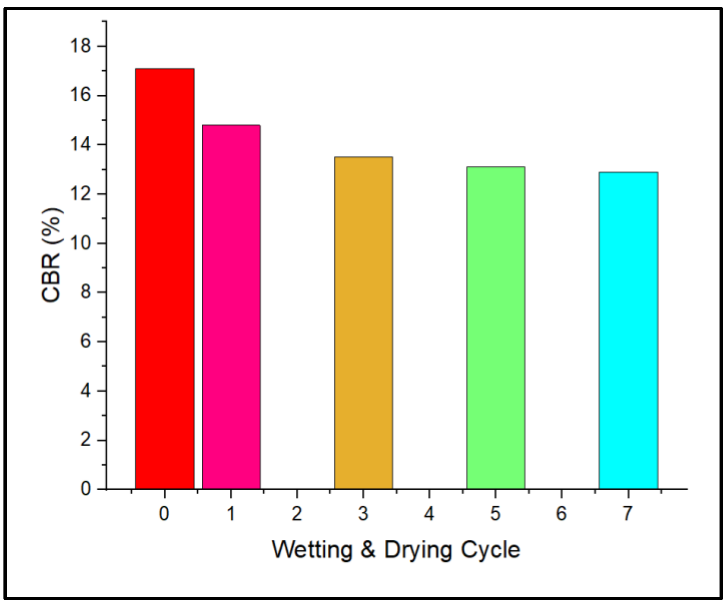


Figure 4.33: Influences of wetting-drying cycles on CBR for untreated soil

Chapter 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

- The soil's liquid and plastic limits changed with changes in the concentrations of PET and RCA, and it provides a liquid limit of in natural state. The soil's high plastic clay concentration was reduced by the addition of reinforcements, turning it into low plastic clay. Additionally, the soil's plasticity index fell as the proportion of additives rose, suggesting that the soil's clay content dropped and its capacity for swelling was constrained.
- Illite and montmorillonite were found in natural soil, according to an XRD examination. In addition, analysis results also revealed a large amount of carbon graphite i.e., 32%. After reinforcing the soil with RCA and PET, distinguished peaks for calcite were observed which was the major contributor for increased strength.
- With an increase in PET contents, the maximum dry unit weight and ideal water content of the soil decline and then increase; nevertheless, after a certain concentration, the dry unit weight and ideal water content significantly rise. This is the study's optimal concentration.
- Due of PET's reduced density and specific gravity when compared to natural soil, this occurred. When the ratio of PET and RCA was balanced, the increase in dry unit weight resumed. At lower PET percentages, smaller surface areas with higher RCA content will have less water and less ideal moisture content, but when PET content increases to equal or exceed RCA content, more water will be required to lubricate the greater surface area. As a result, the optimal moisture level starts to increase.
- At an optimal concentration of RCA (15%) and PET (15%) content, the treated soil provides a CBR value of 16.7%, which is almost double than the CBR of the natural soil (9.67%). This improvement was attributed to the presence of aggregates and sand in RCA and plastic powder, which provided greater resistance to penetration in the treated soil.
- For an optimized concentration of 15% RCA and 15% PET, the cohesion decreases from 17 kPa to 6 kPa and angle of internal friction increases from 7 to 28o, showing almost 300% increase in shear strength. This demonstrates that when the RCA transforms the soil into a coarser state, its impact on soil stabilization is more significant. The weakened connections between the soil particles were the cause of the decrease in cohesiveness. Due to the alteration in particle size and the increased

particle interlocking brought on by higher preconsolidation pressure, the angle of internal friction increased.

- It was found that the angle of friction started to decrease while only a slight rise in cohesiveness was seen when the samples, made with the ideal amounts of PET and RCA, were put through wetting and drying cycles. Shear strength did, however, decrease by 50% at the 7th cycle before becoming constant.
- The CBR values also declined when soil reinforced with optimum RCA and PET was subjected to different wetting and drying cycles. The value of CBR dropped from 17.1% to 12.9% at 7th cycle before it became constant.

5.2 Recommendations

- The research may be extended to shear strength testing on triaxial test.
- The research may also be extended to un-confined compressive strength and consolidation test.

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