GEOTECHNICAL PROPERTIES OF WASTE PLASTIC SHRED REINFORCED CEMENTED SOIL FOR HIGHWAYS CONSTRUCTION

A THESIS SUBMITTED TO THE INSTITUTE OF GRADUATE STUDIES OF NEAR EAST UNIVERSITY

By
SHIVAN JALAL ALI ALI

In Partial Fulfilment of the Requirements for the Degree of Master of Science in Civil Engineering

NICOSIA, 2021

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Approval of Institute of Graduate Studies

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I hereby declare that all information in this document has been obtained and presented in accordance with academic rules and ethical conduct. I also declare that, as required by these rules and conduct, I have fully cited and referenced all material and results that are not original to this work.

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ACKNOWLEDGEMENTS

I would like to express my deepest thanks to my supervisor Assist. Prof. Dr. Anoosheh Iravanian for her guidance, valuable advices, contribution, and supports during this thesis. I am thankful that I was given the chance to work with her.

Great thanks go to my co-supervisor Assist. Prof. Dr. Abdullah Ekinci as well for his help, guidance, and contribution.

I would like to thank the Technical College of Engineering, Duhok Polytechnic University (DPU), Duhok, Iraq, for their support and for offering me the ability to work at their Soil Laboratory through the difficult times of COVID-19. In addition, special thanks go to Dr. Mudhafer H. Selman the Head of Department of Highways and Bridges Engineering at DPU for his contribution, help, and guidance.

Finally, I would like to offer my special thanks, love and respect to my family especially my parents and not enough words can be said to express my gratitude. I would like to acknowledge every single person who was supportive or helpful through this study.

To my family…

ABSTRACT

Highways are high-cost structures which are considered as one of the country developments factors. The soil underneath the highways contributes significantly for the structure to serve as required. However, sometimes the available soil is weak and it needs hardening and stabilization. One of the popular stabilization methods is adding cement to the soil, but it has several undesirable side effects. On the other hand, the disposal of plastic wastes causes harmful effects on the environment. A known waste component is waste plastic bottles, which the use and disposal of them are increasing annually worldwide. As it is known, civil engineers always try to use economical materials and eco-friendly. This study investigates the ability of polyethylene terephthalate (PET) shreds to be used as soil reinforcement and to improve the strength of soils in terms of California Bearing Ratio (CBR). The PET shreds were added at ten different percentages from (0.1 to 1.0) with an interval of 0.1% molded at the maximum dry density to find the optimum PET shred contents to be added to cemented soil. The study also investigates the ability of PET shreds to be used conjoined with cement in soil stabilization to reduce the amount of cement used, in terms of CBR, initial shear modulus (Stiffness), and microstructure. Additionally, it examines the effect of using such soils on the design of pavement thickness. For this purpose cement was added at three different percentages (5, 7, and 10)% and the PET shreds also were added at three different percentages as well (0.6, 0.7, 0.8)% and the samples were molded at a dry density of 1.4 g/cm^3. Results demonstrated that using PET shreds as soil reinforcement increases the strength of soils. The addition of PET shreds to cemented soil is effective as it increased the strength of soil compared to cemented soil and also it reduced the brittleness. PET shreds also reduced the thickness of pavement compared to plain and cemented soil. The relationships among the porosity/binder index, CBR, and stiffness were detected and the index was found to be highly correlated to both CBR and stiffness. Finally, the XRD test show that with time the quartz and calcite were increased for cemented soil with PET shreds which indicates an increase in strength. Also, the SEM tests revealed that there are cement hydration byproducts stock on the PET shreds surface which indicate increased strength and also the pores in the PET shreds reinforced cemented soil were reduced due to the cement byproducts which fill the pores with time.

Keywords: PET shreds; soil-stabilization; CBR; stiffness; microstructure; porosity/binder index.

ÖZET

Karayolları, ülke kalkınma faktörlerinden biri olarak kabul edilen yüksek maliyetli yapılardır. Otoyolların altındaki toprak, yapının gerektiği gibi hizmet vermesine önemli ölçüde katkı sağlamaktadır. Ancak bazen mevcut zemin zayıftır ve sertleşmeye ve stabilizasyona ihtiyaç duyar. Popüler stabilizasyon yöntemlerinden biri, toprağa çimento eklemektir, ancak bunun birkaç istenmeyen yan etkisi vardır. Öte yandan, plastik atıkların bertarafı çevre üzerinde zararlı etkilere neden olmaktadır. Bilinen bir atık bileşeni, kullanımı ve bertarafı dünya çapında her yıl artan atık plastik şişelerdir. Bilindiği üzere inşaat mühendisleri her zaman ekonomik ve çevre dostu malzeme kullanmaya çalışırlar. Bu çalışma, polietilen tereftalat (PET) parçalarının zemin takviyesi olarak kullanılabilme ve zeminlerin mukavemetini California Rulman Oranı (CBR) açısından iyileştirme özelliklerini araştırmaktadır. Çimentolu toprağa eklenecek optimum PET parça içeriklerini bulmak için maksimum kuru yoğunlukta kalıplanmış %0,1'lik bir aralıkla (0.1 ila 1.0) on farklı yüzdede PET parçaları eklendi. Çalışma ayrıca, kullanılan çimento miktarını CBR, ilk kesme modülü (Sertlik) ve mikro yapı açısından azaltmak için toprak stabilizasyonunda çimento ile birleştirilmiş PET parçalarının kullanılabilme kabiliyetini de araştırmaktadır. Ayrıca, bu tür zeminlerin kullanılmasının kaplama kalınlığı tasarımına etkisini inceler. Bu amaçla %3 farklı oranda (%5, 7 ve %10) çimento ve %0,6, 0,7, 0,8 oranında PET parçaları da ilave edilmiş ve numuneler 0,8 kuru yoğunlukta kalıplanmıştır. 1.4 g/cm3. Sonuçlar, zemin takviyesi olarak PET parçalarının kullanılmasının zeminlerin mukavemetini arttırdığını göstermiştir. Çimentolu zemine PET moloz ilavesi, zeminin çimentolu zemine göre mukavemetini arttırdığı ve kırılganlığı azalttığı için etkilidir. PET parçaları, düz ve çimentolu toprağa kıyasla kaplamanın kalınlığını da azalttı. Gözeneklilik/bağlayıcı indeks, CBR ve sertlik arasındaki ilişkiler tespit edildi ve indeksin hem CBR hem de sertlik ile yüksek oranda ilişkili olduğu bulundu. Son olarak, XRD testi, mukavemette bir artışa işaret eden PET parçalı çimentolu toprak için zamanla kuvars ve kalsitin arttığını göstermektedir. Ayrıca SEM testleri, PET parça yüzeyinde artan mukavemet gösteren çimento hidratasyon yan ürünleri stoğu olduğunu ve ayrıca zamanla gözenekleri dolduran çimento yan ürünleri nedeniyle PET parça takviyeli çimentolu topraktaki gözeneklerin azaldığını ortaya koydu.

Anahtar Kelimeler: Atık plastik (PET) parçaları; Zemin iyileştirmesi; CBR; sertlik; mikro yapı; porozite/bağlayıcı indeksi.

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LIST OF ABBREVIATIONS

PET:	California Bear Ratio
CBR:	American Society for Testing and Materials
ASTM:	Standard Specifications Road and Bridges
G_0:	Maximum Shear Modulus
SORB:	Standard Specifications Road and Bridges
AASHTO:	American Association of State Highway and Transportation Officials
UPV:	Ultrasonic Pulse Velocity
SEM:	Scanning Electron Microscopy
EDX:	Energy-Dispersive X-ray Spectroscopy
XRD:	X-Ray Powder Diffraction
PCA:	Portland Cement Association
USACE:	US Army Corps of Engineers
UFC:	Unified Facilities Criteria
IS:	Indian Standards
IRC:	Indian Road Congress
EOAC:	Engineer Officer Advanced Course
UFGS:	Unified Facilities Guide Specifications
FHWA:	Federal Highway Administration
PI:	Plasticity Index
MDD:	Optimum Moisture Content
OMC:	Maximum Dry Density
USCS:	Unified Soil Classification System
UCS	Unconfined Compression Test
R^2:	Coefficient of Defemination
Q:	Quartz
C:	Calcite
CSH:	Calcium Silicate Hydrate

CHAPTER ONE
INTRODUCTION

1.1 Preface

For the development of any country, highways and roads play a critical role because highways serve as the main facility for traveling by the public between destinations. So that, the long-term performance of a highway requires constructing of a structure that is capable of carrying the imposed traffic loads (Okonkwo and NW, 2015). The highways' structure transfers the loads to the subgrade.

The subgrade is the bottommost layer in the highway structure and serves as the foundation of the highway structure which is usually the naturally existing soil materials. The properties of the subgrade control the structure of the highway system (Shafabakhsh et al., 2014). Since the subgrade is made of natural soil, the soil has a significant role to sustain the whole system, as that soil supports the whole highway structure. As a result, the stronger the subgrade materials the better the structure performance and the longer the service life of the structure (Salahudeen and Ja'afar, 2019; Iravanian and Ali, 2020).

However, it is very common that subgrade is made or composed of clay soil. In the north of Iraq, most pavements are constructed on compacted fine-grained soil (Rasul, 2016). The problem with clay soil is that it can be a weak soil type (Cristelo et al., 2013; Senol et al., 2006). In Iraq around 35% of the Iraqi clay soils are problematic soils (Ahmed, 2015). Construction on such soils is highly risky and can affect the construction and stability of structures (Buhler and Cerato, 2007; Clayton et al., 2010; Bahmani et al., 2016; Tabarsa et al., 2018; Kulanthaivel et al., 2020). The problems with this type of soil are that they lack the mechanical and geotechnical properties required for the construction projects (Choobbasti et al., 2019), as they are susceptible to differential settlements, poor strength and volume change either in compressibility or swelling (Alzaidy, 2019; Ghadir and Ranjbar, 2018; Prusinski and Bhattacharja, 1999; Tang et al., 2007; Kumar and Gupta, 2016). Hence, the clayey subgrade would require higher thicknesses of pavement layers.

One of the well-known treatment techniques to gain the required mechanical properties of the soil is soil stabilization techniques (Choobbasti et al., 2015; Haeri et al., 2006; Majeed and Taha, 2012; Kutanaei and Choobbasti, 2015; Consoli et al., 2011; 2011a; Bahmani et al., 2014). Soil stabilization is the operation of enhancing the soil properties to make it satisfy the required engineering requirements (Attoh-Okine, 1995). Moreover, soil improvement techniques by mixing soil with binding agents is considered one of the most utilized ways (Ekinci et al, 2020), especially cement soil stabilization (Consoli et al., 2019; Walker, 1995; Ingles and Metcalf, 1972; Consoli et al., 2019a; Amhadi and Assaf, 2018; Suddeepong et al., 2018; Jayasinghe and Kamaladasa, 2007; Kariyawasam and Jayasinghe, 2016; Mitchell, 1981; Lu et al., 2020; PCA, 1971). However, the production process of cement is a harmful process to the environment as this process releases considerable quantities of carbon dioxide (CO_2) (Schneider et al., 2011; Rahla et al., 2011; Siddique et al., 2019; Andrew, 2019). In addition, cement itself is not a very effective stabilizer because it is subjected to sulfate attack which causes cracks (Mitchel, 1986). Thus, it is necessary to use small percentage of Portland cement and mix it with other stabilizer materials (Abdulsattar, 2015). Due to these setbacks of cement stabilization of soil, many studies have done to seek for alternative approaches to reduce cement usage and also carbon gas (Ekinci, 2019; Cheah et al., 2017; Frías et al., 2017; Siddique, 2012; Shearer and Kurtis, 2015). Therefore, the development of alternative ways that reduce cement usage can be a proper way.

In spite of that, all over the world there are waste disposal problems that needs to be managed (Iravanian and Haider, 2020). Solid waste is becoming a critical issue to manage (Psomopoulos et al., 2009; Mukherjee et al., 2020), and the quantity is increasing highly compared to previous years (Islam et al., 2014; Tarun et al., 2019). Poly-Ethylene Terephthalate (PET) is a polyester which has board plastic applications because of its properties (El Essawy et al., 2017; Zander et al., 2018; Islam et al., 2016; Subramanian, 2000). PET has been widely used in single use products. Waste PET bottles make up the largest portion of plastic waste (Akçaözoğlu et al., 2021). Therefore, their disposal has led to serious environmental problems (Zhang and Wen, 2014; Zhang, 2020). The other problem with PET waste is that it is considered as non-degradable as it needs more than 100 years to degrade (Akçaözoğlu et al., 2010; Silva et al., 2005). Therefore, there is a need to seek for reasonable disposable methods. In the literature there are many applications of PET bottles for structural materials (Foti, 2013; Thomas and Moosvi, 2020; Foti, 2011; Alani et al., 2019; Al-Tulaian et al., 2016; Ochi et al., 2007; Yin et al., 2015; de Oliveira and Castro-Gomes, 2011; Borg et al., 2016).

Cemented soil reinforcement with waste plastic bottles (PET) shreds as soil stabilization may provide effective waste plastic disposal ways and reduce the cement employed in the soil improvement and therefore reduce the CO_2 emissions. Waste plastic bottles (PET) mixed with soil behave similar to fiber-reinforced soils, fiber improve the strength of soil (Nsaif, 2013).

By reviewing the previous works as will be seen in next chapter, just a limited amount of data is available on the PET fiber reinforcement of cement stabilized soils for geotechnical purposes (Sobhan and Mashnad, 2002). Moreover, there is a gap considering the clay stabilized with cement and PET, therefore this research tries to cover this gap.

1.2 Problem statement

- Clay soil causes difficulties in construction with its low strength and stiffness. This may cause serious problems in geotechnical engineering.
- Stabilization with cement is a reasonable way but it has considerable side effects on environment due to its CO_2 emissions, and cement is subjected to sulfate attack, which may cause a pavement failure as it causes cracks. Thus, it is necessary to use small percentage of cement.
- There are environmental problems around the world due to plastic waste such as PET bottles which needs to be managed.

1.3 Idea and Solution Statement

Because cement is commonly used and it is known that it improves the properties of soils the idea of this study is to add PET shreds to cemented soil as a mean of reinforcement, therefore if it improves the properties then the amount of used cement in soil stabilization can be reduced as a result it will reduce the environmental impacts and enhance the mechanical performance of cemented soil. Figure 1.1, shows the new composed material after mixing soil, cement, PET shreds, and water.

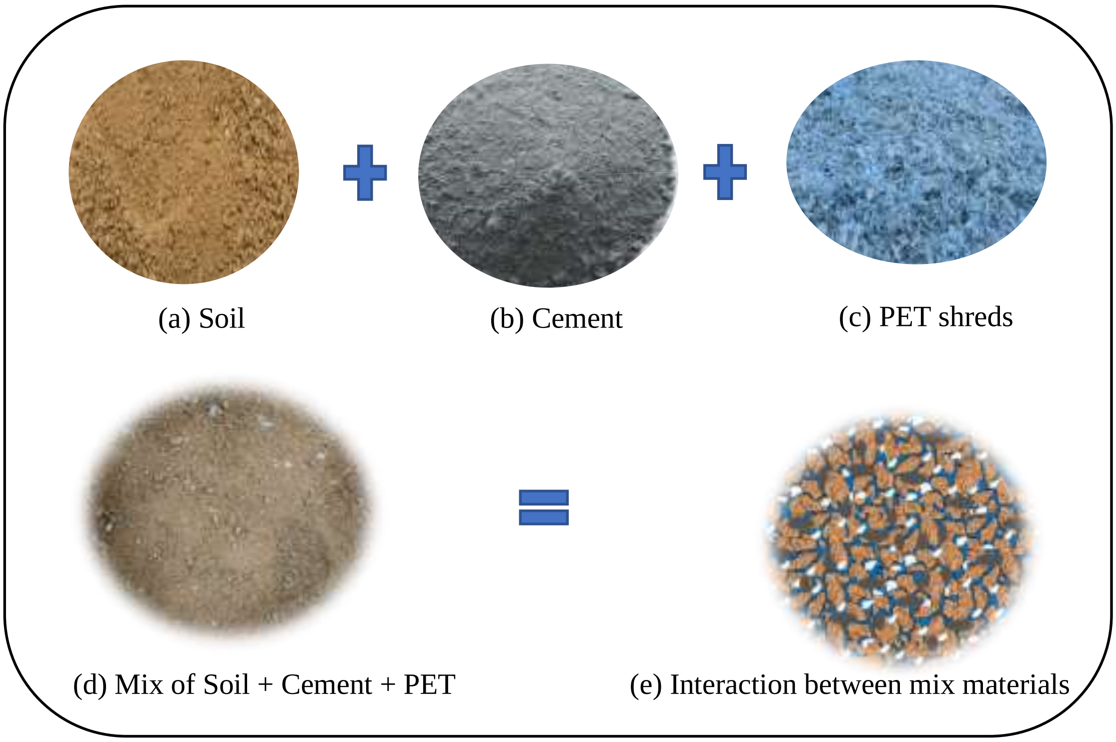

Figure 1.1: Process of mixing soil, cement, and PET shreds

1.4 Thesis Objectives

The major aim of this thesis is to analyze the behaviors of PET shreds reinforced soil and soil stabilized with cement and reinforced with PET shreds. Generally, the major aims of this study can be summarized in the following points:

- Study the effects of adding PET shreds on the properties of soil and cemented soil.
- Study the effectiveness of using PET shreds as soil reinforcing material in reducing pavement design thickness.
- Study the influence of the porosity/binder index on the mechanical behavior of the mixes to try to develop formulas to predict the (Strength and Stiffness).
- Investigating the effect of PET shreds as reinforcement on cracks development by visual inspection.

- Study the microstructure of soil stabilized with cement and reinforced with PET shreds in terms of scanning electron microscope (SEM) and X-ray powder diffraction (XRD).

1.5 Thesis Justification

- Meet the challenges of society and reduce the quantity of waste plastic that lead to eco-friendly safe environment as it provides an alternative plastic waste management solution as it can help get rid of waste materials. Also, it can reduce the cement employed in the soil improvement and therefore reduce the CO_2 emissions.
- Economical technique as it uses unwanted waste materials and reduces the amount of cement used in soil stabilization, which means less cement consumption.
- Improve properties of soil to achieve standard requirements for design.
- In highways it can reduce the design thickness of pavement to be more economic as it reduces the use of raw materials.

1.6 Thesis Layout and Methodology

For achieving the main aims of this research, this study was concentrated on a state-of-the-art literature review and practical studies with a laboratory testing. Therefore, the thesis was divided into five chapters as following:

Chapter 1: This chapter introduces a general background and the thesis problem and idea also it presents the thesis main objectives and justification and finally it introduces the outline of this thesis.

Chapter 2: The second chapter presents the theoretical studies where a thorough review of the available literature on correlated fields was performed. The literature review started with introducing highways and subgrade and its effect on the pavements' design. Also, the ways of improving soil are presented in this chapter. The chapter presents the mechanical and chemical behaviors of cemented soil, fiber reinforced soil, and fiber reinforced cemented soils. The plastic waste problem and the ability of using it as soil reinforcement presented in this chapter. Eventually, the last sections introduce other terms related to this study as porosity binder index.

Chapter 3: This chapter includes a description of the materials used and the tests performed in the study. Furthermore, various procedures followed in this research and calculations/corrections are presented in this chapter.

Chapter 4: The testing outcomes of this study are introduced and discussed in this chapter. The available literature was evaluated, together with the results obtained from this study. This was used as a background to the analysis of the obtained tests results.

Chapter 5: The last chapter presents this study's conclusions and gives some recommendations.

CHAPTER TWO
LITERATURE REVIEW

2.1 Introduction

This chapter presents past experimental studies of many authors regarding this thesis. It starts with introducing highways and subgrade and its effect on the pavements' design. Also, the ways of improving soil are presented in this chapter. The chapter presents the mechanical and chemical behaviors of cemented soil, fiber reinforced soil, and fiber reinforced cemented soils. The plastic waste problem and the ability of using it as soil reinforcement presented in this chapter. Eventually, the last sections introduce other terms related to this study as porosity binder index.

2.2 Background about Highways and Pavement

Highway is a main road for travel by the public between important destinations, such as cities, large towns, and states as shown in Figure 2.1. Highways play an important role in making travel easier and more expedient. Daily human activities depend on the highways. This is of great assistance for traveling for work or transporting goods. Where, highways make a crucial contribution to economic development and growth and bring important social benefits. They are of vital importance in order to make a nation grow and develop. For those reasons, highways infrastructure is the most important of all public assets. Highways provide the quickest route from Point A to Point B, meaning that those who must use this method of delivery will need to utilize the fastest and most direct means of road travel. This is where the highway system becomes very important. Since time equals money, the shortest and most direct route will prove to be the most lucrative (Garber and Hoel, 2014).

Highways need to be of a high performance because they are expensive to construct where the United States spends about $200M/year on highway construction (TRB, 1999). Highways consists of a number of elements but the most important element is pavement, where it is the element that holds all the loads, therefore the better the pavement is the better the highway is.

The word 'Pavement' refers to a hard surface of flat stones or a mixture of aggregate, sand and soil or without soil to support the load of traffic plying on it as well as to facilitate the movement of traffic. The pavement consists of a few layers of pavement materials over a prepared soil subgrade to serve as a carriage way. The pavement carries the traffic loads and transfers the load through a wider area on the soil subgrade below. The surface of the pavement should be stable and non-yielding under heaviest road traffic (Thom, 2008).

Generally, pavements are divided to two main categories: flexible pavements and rigid pavements (Huang, 2004). Flexible pavements are composed of bitumen layers placed on granular materials which have subgrades. Rigid pavements are composed of plain or reinforced concrete layers placed on soil subgrades and rigid pavements may have granular bases (Huang, 2004).

Highway pavement is complex structures supported by foundations of soil layers. During the service life of pavement systems, soil layers beneath a pavement surface course are subjected to different intensities of loads by the wheels of moving vehicles. The weight of this traffic is finally transmitted and carried by the subgrade itself, which in turn provides support to the pavement structure. The behavior of subgrades under different loading conditions must be thoroughly investigated before a rational pavement design or analysis is conducted (Ahelah, 2016). As a result, the design of a pavement is mostly dependent on the subgrade soil characteristics representing the strength behavior. Therefore, subgrade is a controlling element in highways design and performance.

Figure 2.1: A highway example in Iraq (Erbil-Makhmour Highway) **(**Anadolu Agency, 2018)

2.2.1 Requirements of a pavement design

Adeyeri (2014) an ideal pavement should meet the following requirements: Sufficient thickness to distribute the wheel load stresses to a safe value on the sub-grade soil, Structurally strong to withstand all types of stresses imposed upon it, adequate coefficient of friction to prevent skidding of vehicles, smooth surface to provide comfort to road users even at high speed, produce least noise from moving vehicles, impervious surface, so that sub-grade soil is well protected, and long design life with low maintenance cost. As per different standards there are CBR requirements for highways' pavement components which are presented in Table 2.1.

Table 2.1: CBR Requirements for highways' pavement components

Purpose	CBR (%)	Standard/Research
Subgrade	Minimum 2	Kent County Council (2001)
Subgrade	Minimum 3	Indian Roads Congress (IRC) (2012)
Subgrade	Minimum 3	Guidelines for Human Settlement Planning and Design
Subgrade	Minimum 3	Army Corps of Engineers (1984)
Subgrade	Minimum 10	Schaefer et al. (2008)
Subgrade	Minimum 4	Iraqi Standards for Roads and Bridges (SORB), (SORB R5-16, 1983)
base and subbase class A	Minimum 45	Iraqi Standards for Roads and Bridges (SORB), (SORB R5-16, 1983)
base and subbase class B	Minimum 35	Iraqi Standards for Roads and Bridges (SORB), (SORB R5-16, 1983)
base and subbase class C	Minimum 30	Iraqi Standards for Roads and Bridges (SORB), (SORB R5-16, 1983)
Subbase	Minimum 30	Unified Facilities Criteria (UFC) (2014)
Road subbase, formation backfill for trenches	20–80	Ingles and Metcalf (1972)
Road subbase, base for light traffic	50–150	Ingles and Metcalf (1972)
the subbase for the heaviest traffic	Minimum 20	Maclean and Lewis (1963)
Subgrade	Minimum 10	Amadi et al. (2018)
Subbase	Minimum 30	Amadi et al. (2018)

2.2.2 Pavement design

Flexible pavements are structures as seen in Figure 2.2 which are designed to carry the traffic loads and to resist environmental conditions during their design life (McElvaney and Snaith, 2002). The pavement design is the process of determining the thickness of pavement to provide comfort and safe transportation and which should be adequate to become economic and eco-friendly.

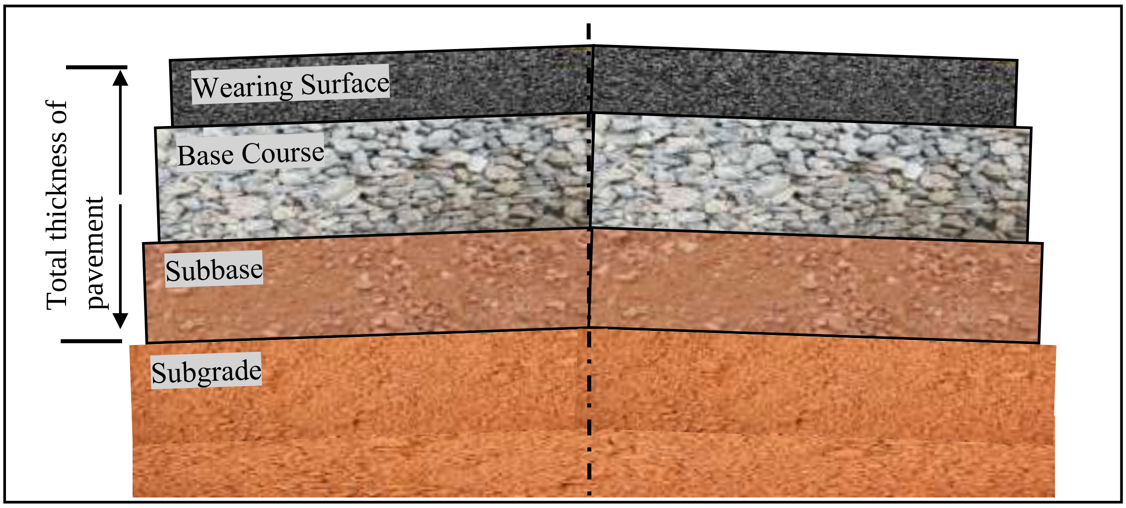

Figure 2.2: Pavement structure

2.2.2.1 Pavement design by CBR method for highway

During the early 1920s, the California Bearing Ratio (CBR) test was developed by O. J. Porter for the California State Highway Department to evaluate the bearing capacity of pavement materials in laboratory. After that, many countries developed methods of pavement design on the basis of materials CBR (Nguyen and Mohajerani, 2015). The CBR is the most common used strength parameter for fine-grained subgrade soils in flexible pavement design, while research into the use of the resilient modulus in pavement design continues (Design, 2012).

The method combines a load penetration test performed in the laboratory or in-situ with the empirical design charts to determine the thickness of pavement and of its constituent layers (AS 1289.6.1.1; AS 1289.6.1.3; ASTM D1883-05; ASTM D 4429-04). This is the most commonly used way for flexible pavement design. The thickness of the elements comprising a pavement is determined by CBR values. The CBR test is a small-scale penetration test in which a cylindrical plunger of diameter of (5 cm) cross-section is penetrated into a soil mass (i.e., subgrade material) at the rate of 1.27 mm/min. (Nguyen and Mohajerani, 2015). The CBR value is the ratio of the applied load to the standard load. The standard load is the value of standard crushed rock and is presented in Table 2.2 (Aytekin, 2000).

$$CBR = \frac{Applied\ Load}{Standard\ Load} \times 100 \tag{2.1}$$

Table 2.2: Standard crushed rock loads with CBR value of 100%, (BS 1377-4, 1990)

Penetration depth (mm)	**Load (kN)**
2.5	13.24
5	19.96

The CBR test is conducted in laboratory on compacted soil specimens as shown in figure 2.3, and it is conducted on the ground surface, excavation surface, or bulldozer cut surface (Day, 2001).

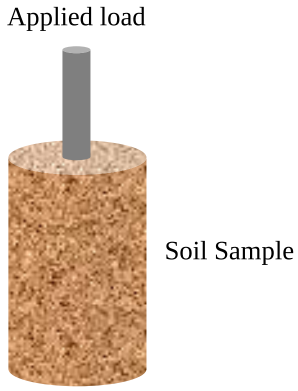

Figure 2.3: Applied load on the soil sample

The CBR test method is most appropriate and gives the most reliable results for fine-grained soils. It can also be used to characterize the strength of pavement materials. In cohesionless soils, especially those that include large particles, the reproducibility of the test is poor (Rollings and Rollings, 1996).

Flexible pavement design by CBR method is used to determine the total thickness of pavement. Generally, there are two methods to design the pavement from California bearing ratio (CBR) value.

2.2.2.1.1 CBR method recommended by California State highways department

Figure 2.4 is the curve of the highways pavement thickness design which is suggested by the California State highways department, in which the thickness of pavement calculated based on the CBR of the subgrade and the load of the traffic (Davis, 1994).

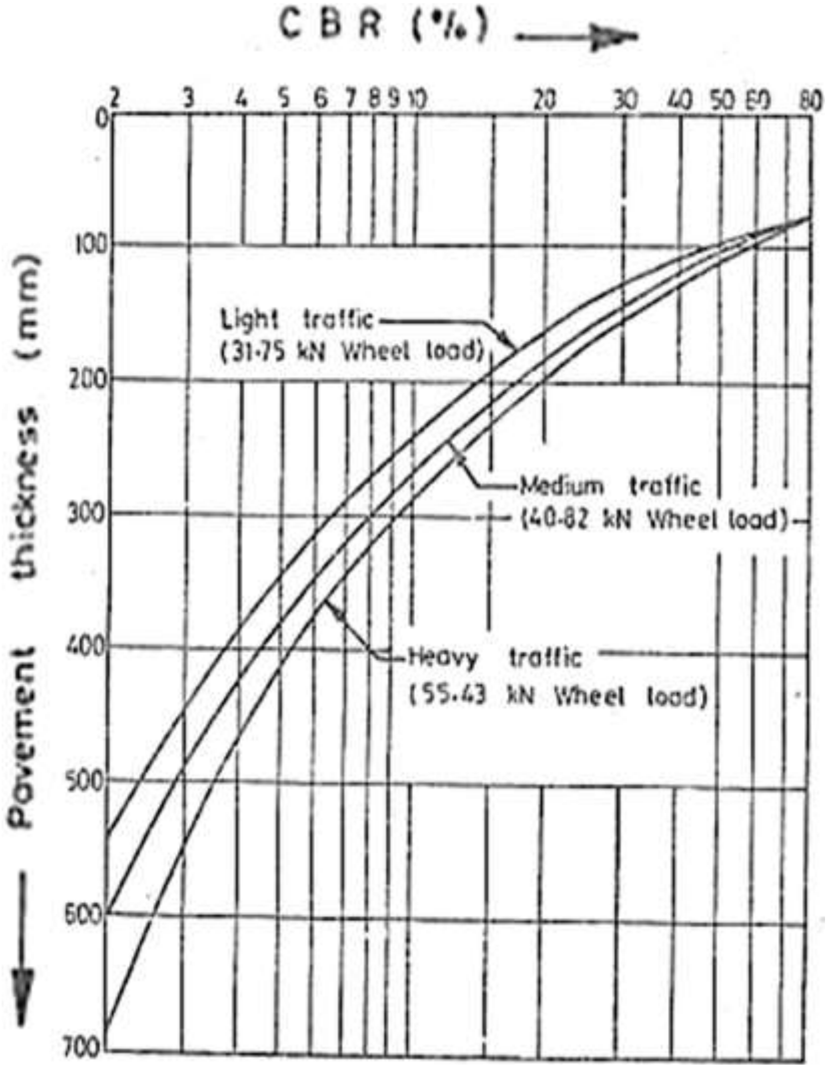

Figure 2.4: Pavement design by CBR method for highway (California State of highways)

2.2.2.1.2 CBR method adopted by Indian road congress (IRC)

Figure 2.5 gives the design curves for determining the appropriate thickness of construction required above a material with a given CBR, for different wheel loads and traffic conditions. These design curves for roads have been proposed by the Road Research Laboratory, England, and are also followed in India by Indian Roads Congress (Punmia et al., 2005).

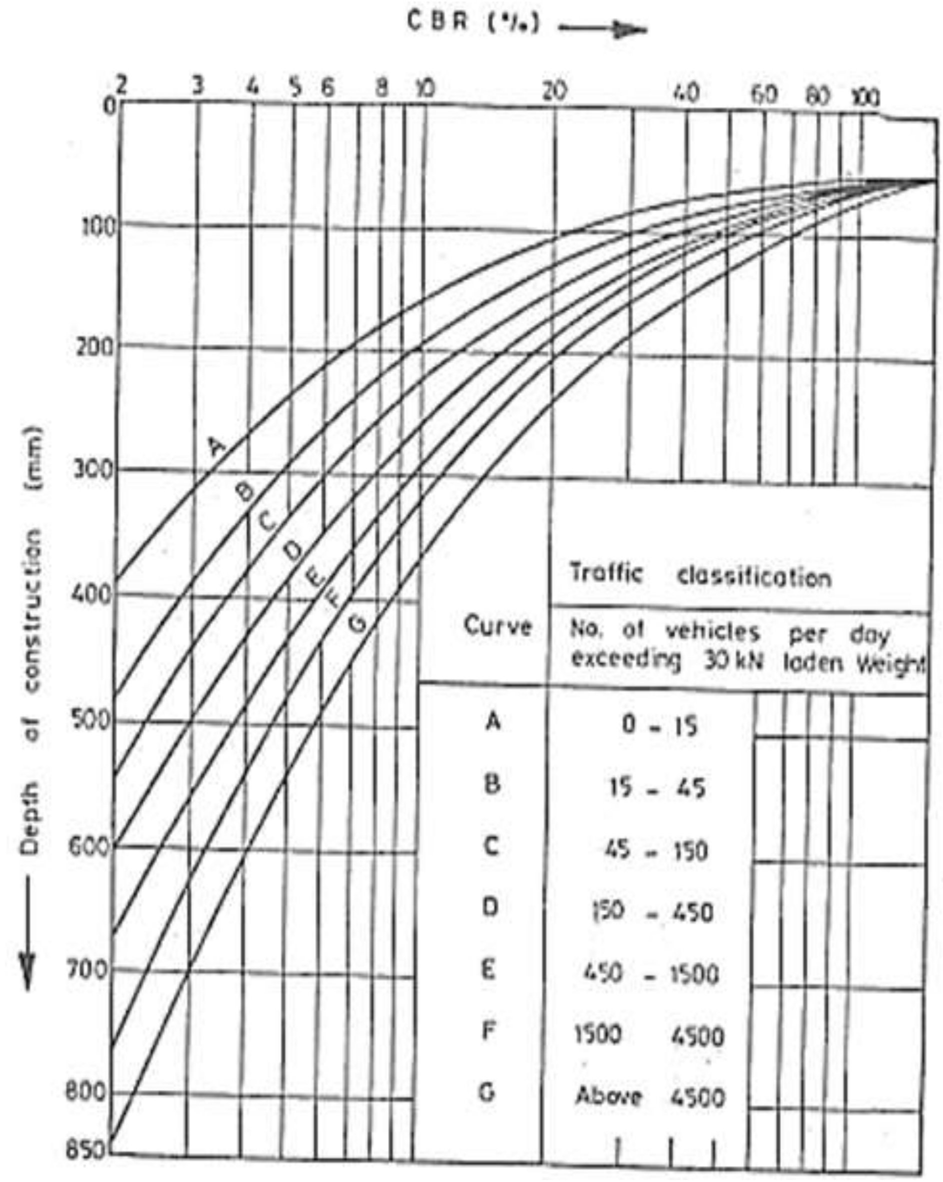

Figure 2.5: CBR design curves adopted by (Indian Roads Congress)

2.2.2.2 Airport (runway) pavement design

Federal Aviation Administration (FAA) recommends the usage of a curve which was developed by them. Calculation of total thickness from Figure 2.6 for given CBR value of soil subgrade, cross aircraft weight, and annual departures (Mallik and El-Korchi, 2009).

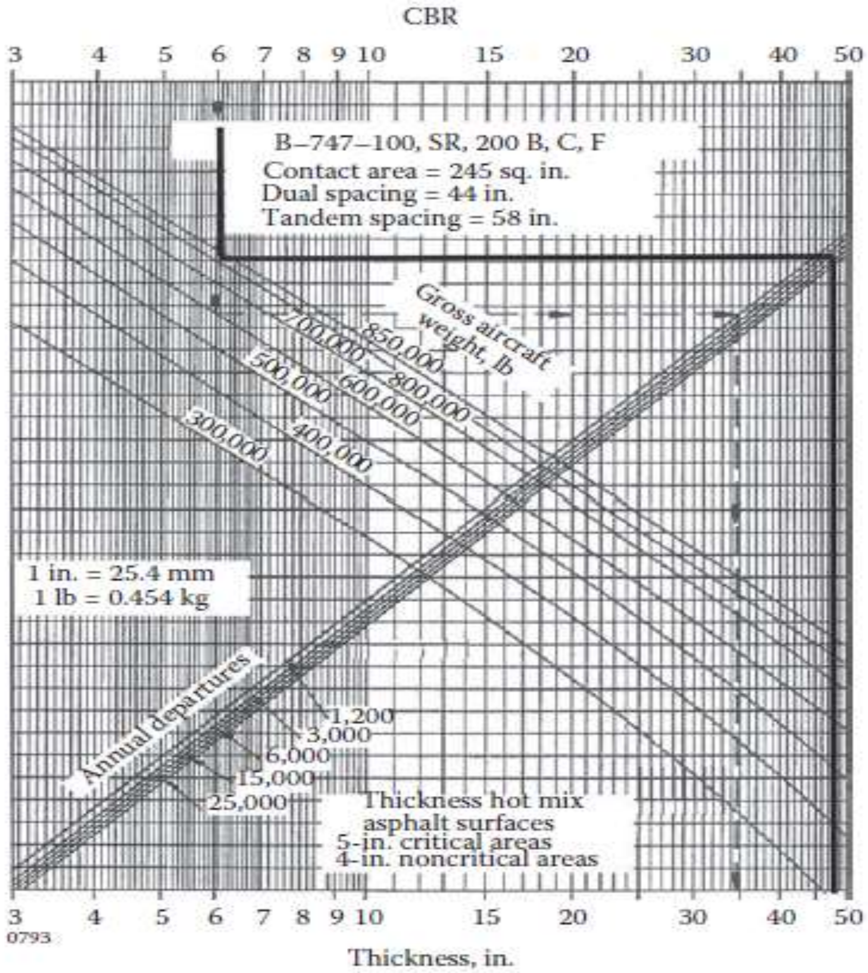

Figure 2.6: Pavement design by CBR method for Airport Runway (Adapted from FAA, 1995). (Mallik and El-Korchi, 2009)

2.3 Subgrade

2.3.1 Introduction to subgrade

The upper layer of the Embankment or natural ground whether in cut or fill is termed as subgrade Load from the traffic is ultimately distributed on subgrade through other component layers. The subgrade is a soil layer of natural formation which can bear wheel loads transporting from vehicles as well as from pavement layers. The subgrade soil works as the foundation that supports the road (Yousif, 2015) as shown in Figure 2.7. Therefore, the success or failure of any pavement system is more often dependent upon the strength of the underlying subgrade upon which the pavement structure is built. The main functions of subgrade soils are principally based on several parameters, such as load-bearing capacity and stiffness (George, 2000).

In the pavement design process, the strength characteristics of the subgrade on which the pavement is placed, are essential design parameters that need to be considered and determined (JAMESON, 2008). Subgrades are typically characterized by their resistance to deformation under wheel load actions, which can be either a measure of strength or a measure of stiffness (Marradi et al, 2014; Ping and Sheng, 2011). The higher the subgrade strength and stiffness the better the pavement performance. Therefore, the pavement design concentrates on economic and efficient usage of subgrade soils to get the best possible performance (Mokwa and Akin, 2009; Sadeeq et al., 2014a; 2014b).

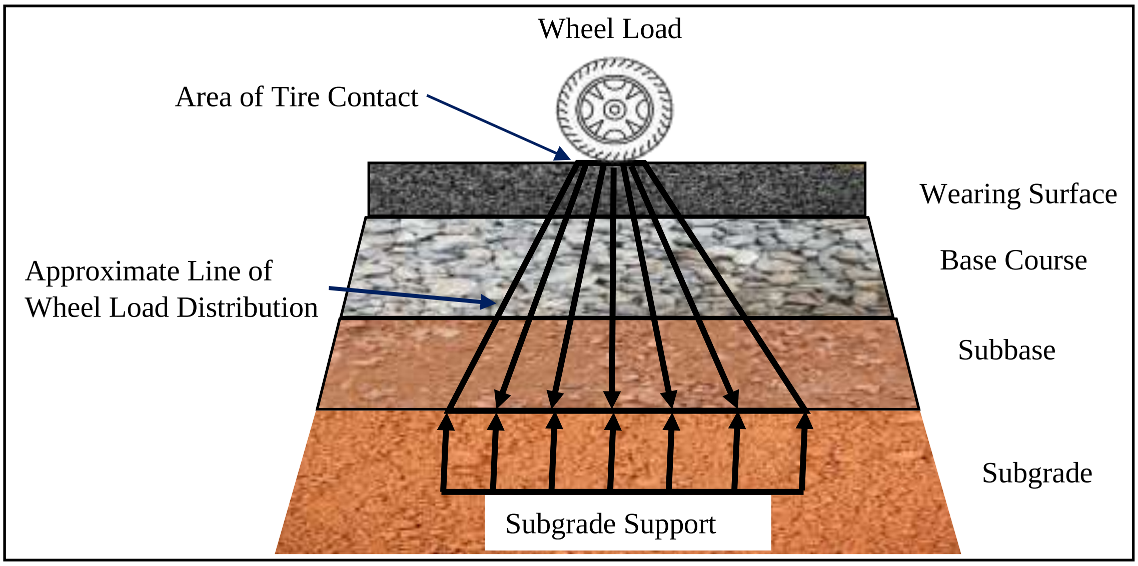

Figure 2.7: Load Distribution in Pavement Structure

2.3.2 Weak subgrade and treatment

Subgrade is composed of different natively existing soils which could be soft and having low strength and stiffness to carry loads. In flexible pavements, subgrades are often more subjected to failure when traffic loads are applied, because this pavement type does not distribute the loads uniformly. Subgrades do not get as much attention as the other layers of pavement get, in spite of the reality that most pavements failures are results of subgrades failure. Many difficulties may be faced during the construction works, but finding the subgrades to be composed of soft clay is one of the most difficult issues. Soft clay soils usually display decreased shear strength, high swelling potential, and high compressibility especially if raising water content happens (Chen, 1981). As water content increases, plasticity of the clay increases and strength decreases (Li and Selig, 1996). Support of the pavement base layer by the clay subgrade is dramatically reduced and often results in poor pavement performance such as base failure, alligator cracking, uneven pavement, rutting, and potholes (Cokça, 1999; Prusinski and Bhattacharja, 1999).

Mechanical compaction is the most commonly used technique to improve soil subgrades. When first compacted clayey soils usually have considerable bearing strength. However, shortly after the pavement is placed and the clayey subgrade is exposed to moisture, CBR strength decreases (Hopkins and Sun, 2006). The loss of bearing strength of subgrade soil affects pavement performance.

There are several ways to solve the weak soil problems which involve:

- Replacing weak soils suitable soils.
- Additional base layers.

Nevertheless, such solutions can lead to increased costs, construction works delay, and wasteful because they require the use and transportation of additional virgin materials (Prusinski and Bhattacharja, 1999; da Fonseca et al., 2009). Therefore, many studies reveal that the stabilization is the most economic and environmental option to be used. The improvement of such soil with a stabilizer may be a superior solution for permanent deformation resistance (Rasul et al., 2015).

2.4 Clay Soil

2.4.1 Introduction to clay soil

A clay soil in civil engineering means a soil that is mainly composed of clay minerals, has plasticity and is cohesive. Clays are fine-grained soils but it cannot be simply said that all of fine-grained soils are clays (Zuber et al., 2013). Depending on the soil's content in which it is found, clay can appear in various colors from white to dull grey or brown to deep orange-red (Firoozi et al., 2016). In addition, clay minerals are called secondary silicates, because they are formed from the weathering of primary rock-forming minerals. Clay minerals occur in small particle sizes (<0.002 mm) and they are separated from sand, gravel and silt due to the negative electrical load on the crystal edges and positive electrical load on the surface.

Clay is very common on the earth's surface so that they appear almost in all sedimentary rocks (Obianigwe and Ngene, 2018).

2.4.2 Clay mineralogy

Clay minerals are composed of aluminosilicates along with molecules of water and commutable cations like calcium (Ca++). Clay minerals are fundamentally aqueous aluminosilicates in addition to magnesium (Murthy, 2002). Based on of XRD, clay minerals are structured of two-dimensional sheets, that are placed one each other (Holtz and Kovacs, 1981):

A-Tetrahedral (T) sheet is basically a combination of silica tetrahedral units which are consist of four oxygen atoms at the corners, surrounding a single atom. Figure 2.8a shows a single silica tetrahedron, Figure 2.8b shows how the oxygen atoms at the base of each tetrahedron are combined to form a sheet structure.

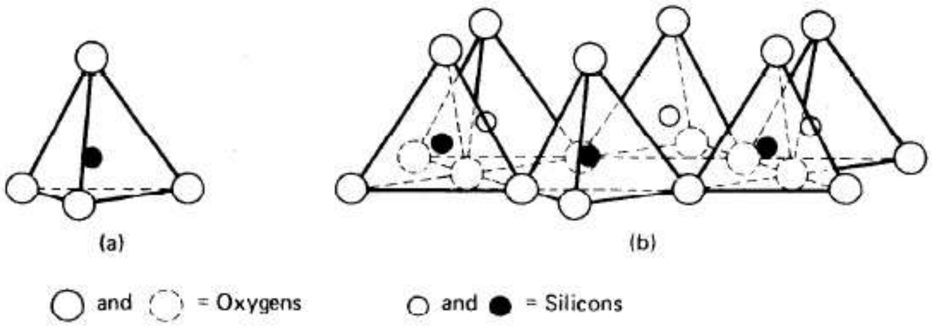

Figure 2.8: (a) Single silica Tetrahedron, and (b) Isometric view of the Tetrahedral or silica sheet (Grim, 1959).

B- The octahedral (O) sheet is basically a combination of octahedral units consisting of six oxygen or hydroxyls enclosing an aluminum, magnesium, iron, or other atom. Figure 2.9a shows a single octahedron, Figure 2.9b shows how the octahedrons combine to form a sheet structure. The rows of oxygens or hydroxyls in the sheet are in two planes.

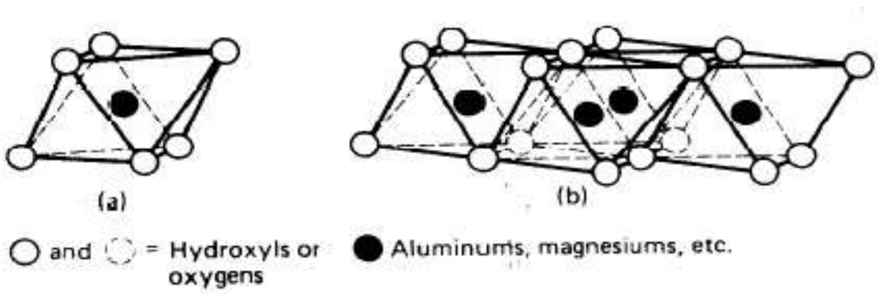

Figure 2.9: (a) Single aluminum Octahedron, and (B) Isometric view of the Octahedral sheet (Grim, 1959)

To describe the effect of the clay minerals on the soil properties there is a need to understand the microstructure of these minerals. The major minerals are as following (Budhu, 2010):

A. Kaolinite: Kaolinite structure is composed of repeated layers and each layer is a tetrahedral sheet of silica and an octahedral sheet of aluminum and each layer has a thickness of 0.72 nm. The layers are held together by hydrogen (H) bonds. Figure 2.10 shows atomic structure of kaolinite.

B. Illite: It is composed of frequent layers and each single layer is composed of one octahedral sheet of aluminum surrounded by two tetrahedral sheets of silicate. In addition, every layer has a thickness of 0.96 nm, are bonded together with ions of potassium (K). Figure 2.10 shows atomic Structure of illite.

C. Montmorillonite: It has a structure like the one of illite, the only difference is that the layers bonding is done by weak forces of van der Waals and exchangeable ions; easily infiltrated by water (H_2O). Figure 2.10 shows atomic Structure of montmorillonite.

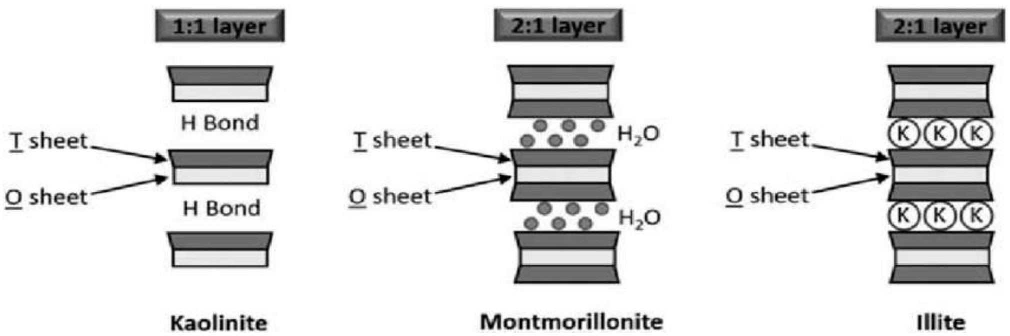

Figure 2.10: A schematic diagram of the structures of kaolinite, montmorillonite, and illite (Zhang, 2016)

Table 2.3: CEC, SSA, and chemical formulas of Clay minerals (Firoozi Et Al., 2016).

Clay Mineral	SSA (m2 /gm)	CEC (meq/100g)	Typical Chemical Formula
Kaolinite	(7-10)	3-15	$Al_2Si_2O_5(OH)_4$
Illite	(80-100)	10-40	$(K,H_3O)(Al,Mg,Fe)_2(Si,Al)_4O_{10}[(OH)_2, (H_2O)]$
Montmorillonite	(800-1000)	80-150	$(Na,Ca)0.3(Al,Mg)_2\ Si_4O_{10}\ (OH)_2 * nH_2O$

CEC: Cation exchange capacity, SSA: Specific surface area.

On the surface of a clay particle there are net negative charges and that is due to the fracture of the mineral structure's continuity at the edges (Das, 2010). These negative charges attract ends of water molecules that have positive charges. A clay particle schematic is presented in Figure 2.11.

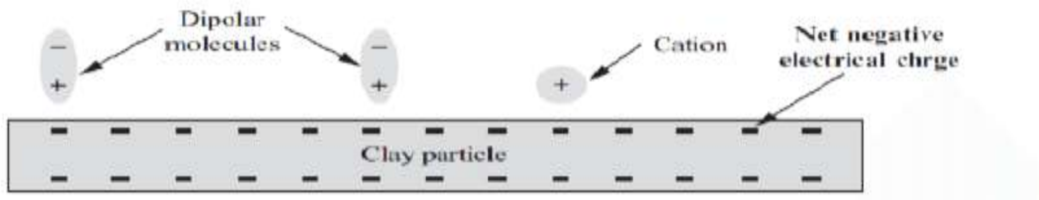

Figure 2.11: Clay Particle Schematic (Nicholson, 2015)

2.4.3 Clay water interaction

The presence of water highly affects the clay properties, as a result there is a need to understand the clay water interaction mechanism. The clay particles have counter ions as salts when they are dry. When they are wet that leads to the hydration of the counter ions on the clay particles surfaces. The hydrated counter ions are attracted to the clay particles because the clay particles are charged. Water attaches to the remaining counter ions on the particles' surfaces. Mitchell (1993) summarized the clay water interaction reasons can be epitomized in bonding of hydrogen, osmosis attraction, exchangeable cations hydration, dipole attraction, and dispersion force presence as shown in Figure 2.12.

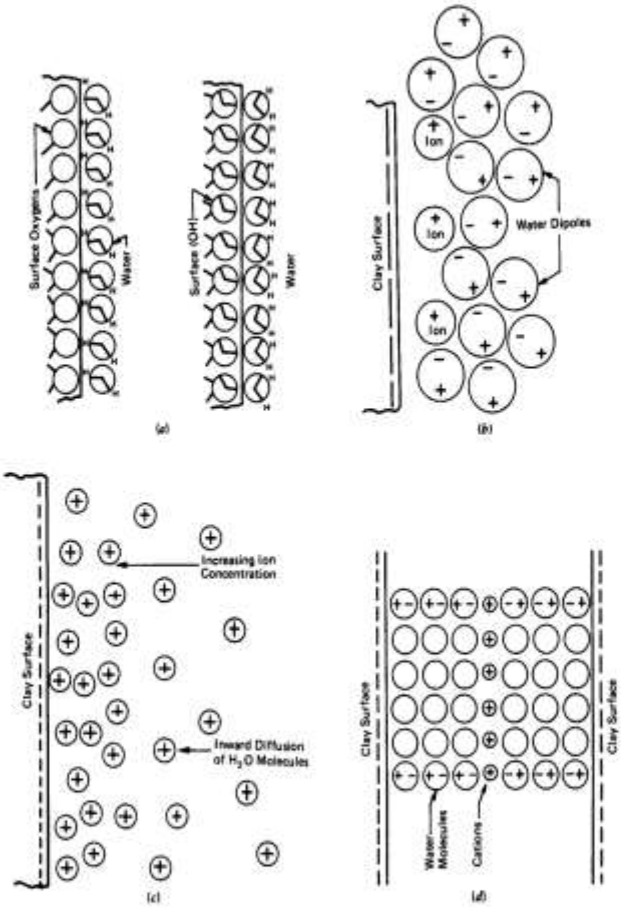

Figure 2.12: Clay water interaction reasons (a) bonding of hydrogen (b) hydration of ion (c) Osmosis attraction (d) attraction of dipole (Mitchell, 1993)

2.4.4 Problems of clay soil

Clayey soils suffer from different problems. In clay soils variation of water content leads to noticeable changes in volume which in turn can result in significant problems structures. The swelling potential and shrinkage is affected by many variables in clay soils as mineral's kind, density, water content and changes of climate (Firoozi et al., 2016; Prusinski and Bhattacharja, 1999). Construction of any buildings such as highways and other civil engineering structures on clayey soil is considered risky, because such soil is susceptible to differential settlements and poor strength and volume change either in compressibility or swelling. (Alzaidy, 2019; Ghadir and Ranjbar, 2018; Prusinski and Bhattacharja, 1999). Property changes of the clays are also problematic, moisture increases, plasticity of the clay increases and therefore the strength and also the stiffness decrease (Firoozi et al., 2007; Prusinski and Bhattacharja, 1999).

2.4.5 Possible solutions for clay soils

- Replacing the existing weak soils with soil that have better properties.
- Treating naturally existing soils to improve their properties.

2.5 Soil modification/stabilization

2.5.1 Introduction to soil modification/stabilization

Soil stabilization or modification is the process of altering some soil properties by different methods in order to produce an improved soil material which has all the desired engineering properties (Nicholson, 2014; Hausmann, 1990). Soils are generally stabilized to increase their strength and durability or to prevent erosion and dust formation (Senol et al., 2002). The main aim is the creation of a soil material or system that will hold under the design use conditions and for the designed life of the engineering project (Sivapullaiah et al., 2004). Various methods are employed to stabilize soil and the method should be verified in the laboratory with the soil material before applying it on the field (Sai and Srinivas, 2019). Stabilizing process needs choosing of stabilizing agent for getting the needed strength and stiffness (Sai and Srinivas, 2019), the basic concepts of soil stabilization are: To evaluate the soil behaviors, to decide the soil property lack, and to select an efficient and inexpensive form of soil stabilization.

2.5.2 Methods of soil improvement

The soil improvement's principles did not change from the beginning of the human history (Ahmed, 2015). However, during time due to new technologies and materials they have been developed (Terashi and Juran, 2000). When difficulties are faced like the non-availability, high price, and economical side-effects of certain materials to be used in soil improvement then there is a need to look at the factors that will determine which solution will be suitable to get the best properties needed (Nicholson 2014; Hausmann, 1990). The improving of soil can be done by several techniques, as follows:

2.5.2.1 Mechanical modification

Mechanical Stabilization is the process of improving the properties of the soil by changing its gradation. Where, mechanical energy is required to enhance the density of soil, involving compacting soil by several ways such as static compaction and dynamic compaction (Nicholson 2014; Hausmann 1990).

2.5.2.2 Chemical admixture stabilization

In this method of soil stabilization, chemical reactions occur between the minerals in soil and the different admixtures added to the soil (BISHT, 2018). Admixtures may be natural materials, by-products of industries or waste materials, which in proper quantities enhances the quality of the soil. The admixture substance's type to be utilized depends on a couple of variables as soil type, desired behaviors, materials obtainability, issues regarding prices and environment (Shareef, 2016).

2.5.2.3 Thermal modifications

Enson (1999) stated that ground freezing and heating are two major thermal stabilization methods. Both heating and freezing can be used for ground improvement. Heating evaporates water and causes permanent changes in the mineral structure of soils. Freezing solidifies part or all of the water and bonds individual particles together.

2.5.2.4 Hydraulic modification

This method includes getting groundwater out which leads to the reduction of water and therefore better properties and this way is applicable to both fine-grained soils and coarse-grained soils. In the case of fine-grained soils this can be done by several ways like preloading and in the case of coarse-grained soils drains can be utilized (Nicholson, 2014).

2.5.2.5 Soil reinforcement

This method involves the process of strengthening soil by adding materials as meshes, bars, strips, fibers, and fabrics. These materials are added to withstand tensile strength. The added materials interact with soil by friction and adhesion (Hausmann, 1990). Generally, this process improves the soil stability and strength and reduces settlements (Abdi and Zandieh, 2014; Liu et al., 2014; Bayormy et al., 2007; Lajevardi et al., 2014).

Figure 2.13 summarizes methods of soil improvement.

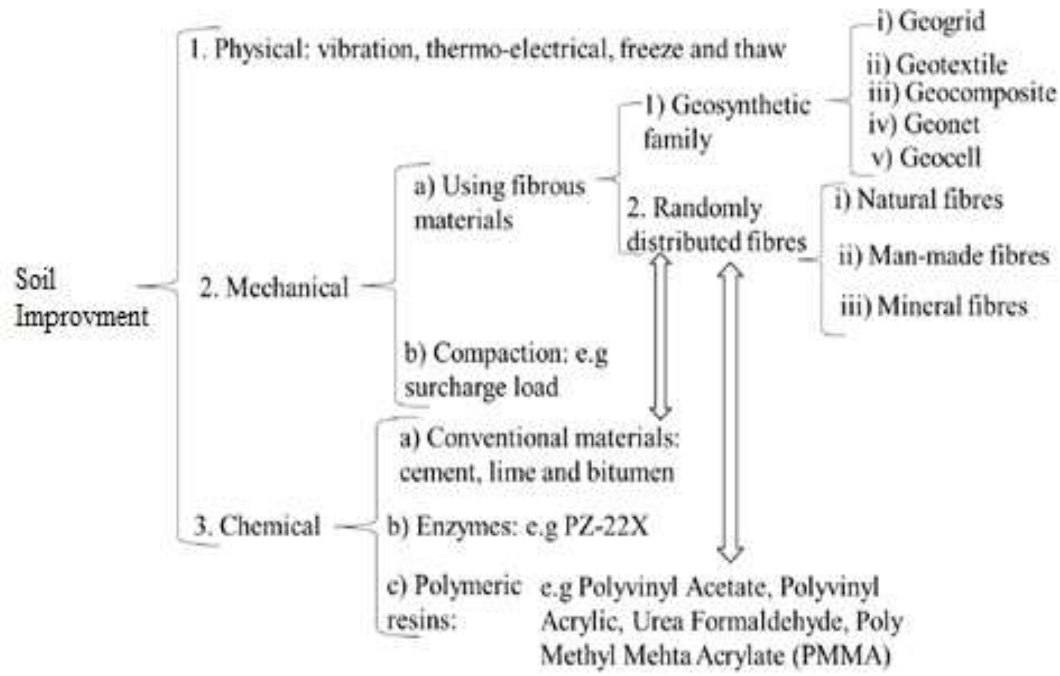

Figure 2.13: Soil Improvement Methods (Hejazi Et Al. 2012)

2.5.3 Factors affecting choice of improvement method

Nichloson (2015), there are many factors controlling the selection of improvement methods and these are as following:

A. Soil type.

B. Area, depth, and location of treatment required.

C. Desired / required soil properties.

D. Availability of materials.

E. Environment.

F. Economic.

2.6 Cement Stabilization

2.6.1 Introduction to cement stabilization

One of the common methods of chemical stabilization is to mix soil with cement to form a product named as soil–cement (Croft, 1967). Cement is considered as the most ancient stabilizer since the nineteen-sixties. Cement is able to provide the needed action of stabilization (Sherwood, 1993). This stabilizer is commonly utilized for improving the clay properties (Xiao and Lee, 2008; Feng et al, 2001; Lorenzo and Bargado, 2004; Broms, 1999). What makes cement that common is that it reacts with both minerals of soil and water to provide stabilization (EuroSoilStab, 2002).

2.6.2 Mechanism of soil – cement stabilization

Prusinski and Bhattacharja. (1999) and PCA. (2020) the treatment of clay soils with Portland cement involves four discrete processes:

I. Cation Exchange

- Clay surfaces exhibit a negative charge from the silica & alumina layers.
- Sodium ions inherent in high plastic clays are monovalent +1 cation charge.
- Calcium in Portland cement is divalent with a +2 cation charge replaces the weaker dipolar water molecules.
- Calcium ions exchange results in a thinner layer of water between the clay layers which reduces the capacity of the clay to hold water resulting in a lower plasticity.

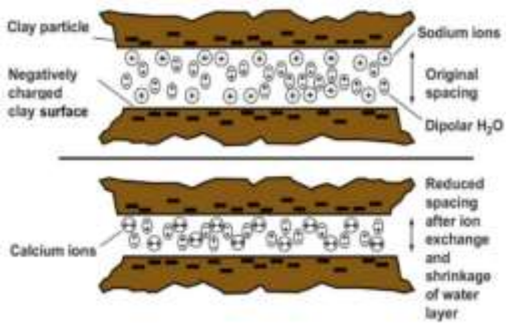

Figure 2.14: Cation Exchange (PCA, 2020)

II. Flocculation and Agglomeration

- The cation ion exchange also causes changes in the texture of the clay.
- Clay particles alter their arrangement from flat and slick to a more resistant alignment through random edge-to-face orientation.
- The material changes from plastic to friable.

- Agglomeration refers to the weak bonding at the edge-surface interface, forming large aggregate size particles from the finely divided clay.
- Result is higher shear strength and improved texture.

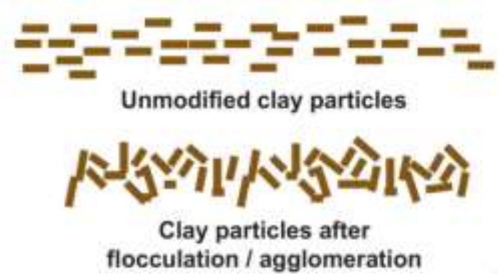

Figure 2.15: Flocculation and Agglomeration (PCA, 2020)

III. Cementitious Hydration

- Cement hydration products of calcium silicate hydrate (CSH) and calcium aluminum hydrate (CAH) act as the “glue” that bounds the clay particles.
- This bonding between the hydrated cement and agglomerate clay forms still larger particles from the fine-grained particles.
- This process happens between a one day and one month.

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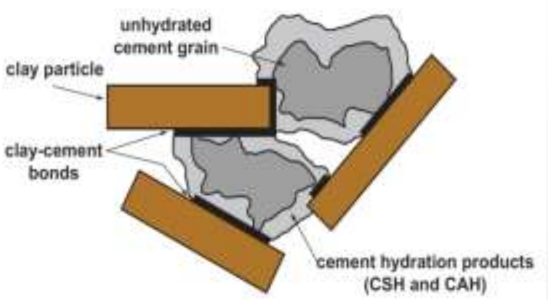


Figure 2.16: Cementitious Hydration (PCA, 2020)

The Cementitious Hydration process is presented in Figure 2.16. Adding cement into soil makes it react with existing water in soil which means starting hydration process which leads to initiation of beneficial products as calcium silicates and hydrated lime that increase the strength of soil (Herzog and Mitchell, 1965) as seen in equations bellow (Bergado et al, 1996):

$C_3S + H_2O \rightarrow C_3S_2H_x + Ca(OH)_2$ (2.2)

(Primary cementitious products)

$Ca(OH)_2 \rightarrow Ca^{2+} + 2(OH)^-$ (2.3)

(Hydrolysis of lime)

IV. Pozzolanic Reaction:

- In addition to CSH and CAH, cement also forms calcium hydroxide, Ca (OH)2 which enters into a pozzolanic reaction.
- This secondary soil modification takes calcium ions and combines them with the dissolved silica and alumina from the clay to form additional CSH and CAH.
- The pozzolanic reactions take place slowly, over months and years, and can further strengthen the modifies soil as well as reduce its plasticity and improve its gradation. Process happens between one day and one month.

These secondary soil modifications are presented in equations bellow:

$Ca^{2+} + 2OH^- + SiO_2 \rightarrow CSH$ (2.4)

(Secondary cementitious products)

$Ca^{2+} + 2OH^- + Al_2O_3 \rightarrow CAH$ (2.5)

(Secondary cementitious products)

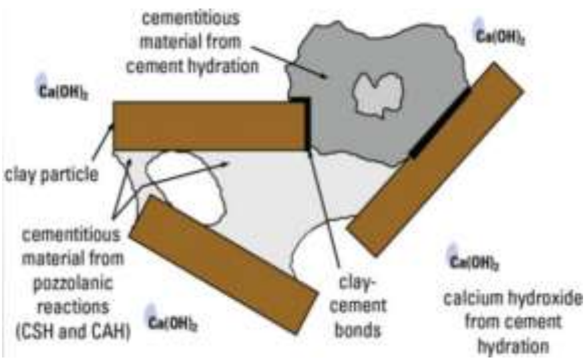


Figure 2.17: Pozzolanic Reaction (PCA, 2020)

2.6.3 Factors affecting the strength of soil stabilization with cement

Several researchers found that many variables affect the strength of soil stabilization with cement, the first ones are soil particles properties like shape, dimensions, and roughness and secondly the cement properties, quality, and quantity in addition to the period of curation (Catton 1962; Clough et al., 1981; Nagaraj et al., 1996). The variables influencing can be summarized as in Table 2.4 (Terashi, 1997).

Table 2.4: Influencing variables on the soil stabilized with cement strength (Terashi, 1997)

Property	**Factor**
I. Stabilizer characteristics	○ Stabilizer type. ○ Stabilizer quality. ○ Blending water and additives.
II. Soil Properties and conditions	○ Soil chemical and physical properties ○ Amount of organic materials ○ Amount of water
III. Conditions of mixing	○ Blending degree ○ Mixing time ○ Stabilizer content
IV. Conditions of curing	○ Temperature ○ Curing period. ○ Humidity ○ Freezing and thawing.

2.6.4 Previous studies on soil stabilized with cement

2.6.4.1 Mechanical properties of soil stabilized with cement

The cement stabilization of clay was investigated by many researchers (Rahman et al., 2010; Horpibulsuk, 2012; Ekinci et al., 2020; Gallavresi, 1992; Uddin et al., 1997). More recently, it has been found that cement addition improves cemented clays strength (Ekinci, 2019; Hanafi et al., 2020; Horpibulsuk, 2012; Gallavresi, 1992; Uddin et al., 1997; Asano et al. 1996; Gallavresi, 1992; Kauschi;nger et al., 1992; Matsuo et al., 1996; Nagaraj et al., 1998).

Several researchers (Consoli et al., 1999; Uddin et al., 1997; Consoli et al., 2006; Kawasaki et al., 1981; Xiao et al., 2009; Kamruzzaman, 2002) demonstrated that as the cement quantity increases, both the strength and stiffness increases. Lee et al. (2005) stated that, for fine-grained soils stabilized with cement, the strength is correlated to the water/cement ratio of the mixture. Kamruzzaman et al. (2009) revealed that clay stabilized with cement's strength gets higher as the curation period increases.

Basha, et al. (2005) and Balkis, et al. (2019), studied the effect of cement amount on CBR values of different soil type, they found that cement can increase the CBR value of each type of soil. Mousavi et al. (2015), found that the CBR value of stabilized clay increased drastically in comparison with the CBR of untreated soil specimen.

Haralambos (2009) stabilized different types of soil (CL, ML, SM, GP-GM, and GC) with cement in different percentages of 3%, 5% and 7. The author found that the classification of soil significantly affects the increase of strength, as a result of cement addition to the different soil types mentioned both the compressive strength and stiffness increased.

Experimental works performed on cemented soil are summarized in Table 2.5.

Table 2.5: Previous Studies on Soil Stabilized with Cement

Researcher	**Soil Type**	**Percent of cement by soil mass (%)**	**Conclusions**
da Fonseca et al. (2009)	Sand	1,3,5,7,9, and 12	• Porosity reduced. • Strength increased.
Oyediran and Kalejaiye (2011)	lateritic soil	2, 4, 8, 10, and 20.	• By adding cement: • MDD and CBR increased. • OMC decreased. • Addition of cement more than 10%: • MDD and CBR decreased. • OMC increased.

Researcher	Soil Type	Percent of cement by soil mass (%)	Conclusions
Al-zoubi and Mohammed Shukri (2008)	Clay	0 to 25	• The higher cement quantity the higher the shear strength gets.
Okonkwo and NW. (2015	sandy clay	5.0, 5.5, 6.0, 6.5, 7 and 7.5	• The addition of 5.36% and 6.48% of cement help the soil meet the CBR requirement for sub-base and base course respectively.
Arshad et al. (2018)	silty clay	3, 4, and 5	• The strength and the density increased by cement addition.
Kumar and Sumanth (2020)	Sand	2, 4, and 6	• With a higher cement a higher CBR value was gained.
Udo et al. (2015)	river sand	From 2 to 10	• Cement addition improved CBR of soil by (26-127) %.
Balkis, et al. (2019)	GC-GM, CL, ML, and CL-ML	3, 7 and 10	• Cement addition increased CBR values of different soil types by the rate of 22-69%.
Ujjawal and Yadav (2017).	Gravelly Soil	From 0 to 6	• 6 % of cement content increased CBR value from 30 to 90 %.
Sariosseieri and Muhunthan, (2009)	Clay	2.5,5,7.5 and 10	• Higher percentage of cement led to reduction in plasticity index. • The addition of cement increased OMC and decreased MDD of the soils. • Increase in strength can be achieved with high percentages of cement.
Jauberthie et al. (2010)	Silt	1.5,3,4,5 and 7	• Soil properties improved.

Researcher	Soil Type	Percent of cement by soil mass (%)	Conclusions
Suárez et al. (2019)	Clay (high plasticity)	1.2, 4, and 6	• It was demonstrated that it is not necessary to improve it with cement for its use as a subgrade.
	clay (low plasticity)	1.2, 4, and 6	• 4%, and 6 % having similar characteristics but underlining that to be used as a subgrade.
Sharo et al. (2019)	expansive clayey	3, 5, 8 and 12	• Plasticity index and the swelling potential have decreased. • UCS and MDD increased

2.6.4.2 Chemical properties (SEM and XRD) of soil stabilized with cement

Kamruzzaman et al. (2009) and Chew et al. (2004) studies were held using SEM to analyze the cemented clay microstructural modification and they demonstrated a decrease in the deflocculation level with a high amount of cement.

Buritatun (2020)'s study, demonstrates the SEM image of cement-stabilized coarse-grained soil after 7 days of curing at 3%, 5%, and 7% of cement by weight of soil. The cementitious products are observed in the pore space. The highest cementitious products are found at the 7% cement as shown in figure 2.18. These cementitious products not only fill up the pore space to reduce the void ratio but also enhance the interparticle bonding strength, which results in the significant strength development (Horpibulsuk et al. 2010).

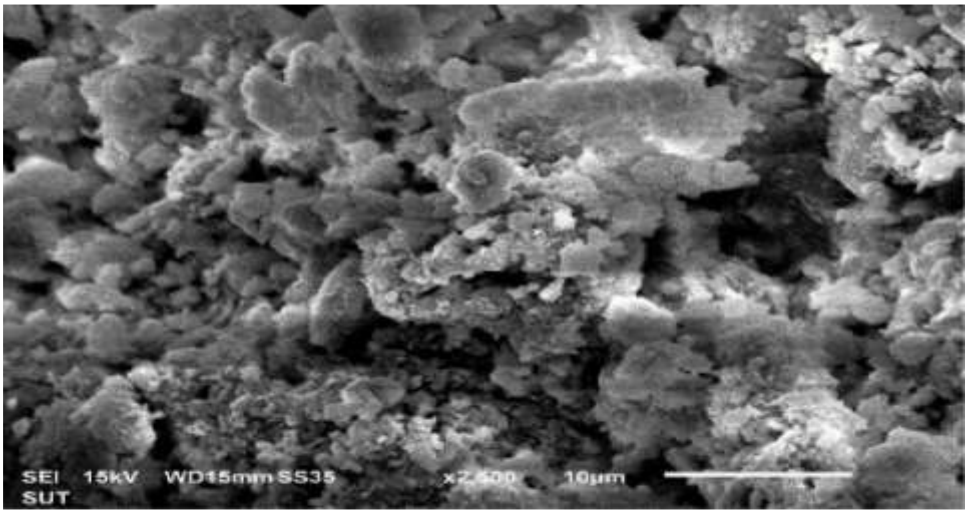


Figure 2.18: SEM Images of Cement-Stabilized Soil After 7 Days of Curing At 7% of Cement by Weight of Soil (Buritatun, 2020)

Mutaz and Dafalla (2014) studied X-ray diffraction assessment of a stabilized clay soil with cement. The addition of cement had a pronounced effect on the soil which changed the mineralogy of the soil. The formation of both CAH in the former and CSH in the latter appears to be responsible for the stabilization of the soil. An increase in aluminum cations (Al+3) happens due to treatment, and since aluminum is more reactive than silica cations (Si+4), CAH and CSH and calcite are produced in the clay soil. Adding 3% cement increased the concentrations of Si+4, Al+3 and K+ as shown in figure 2.19.

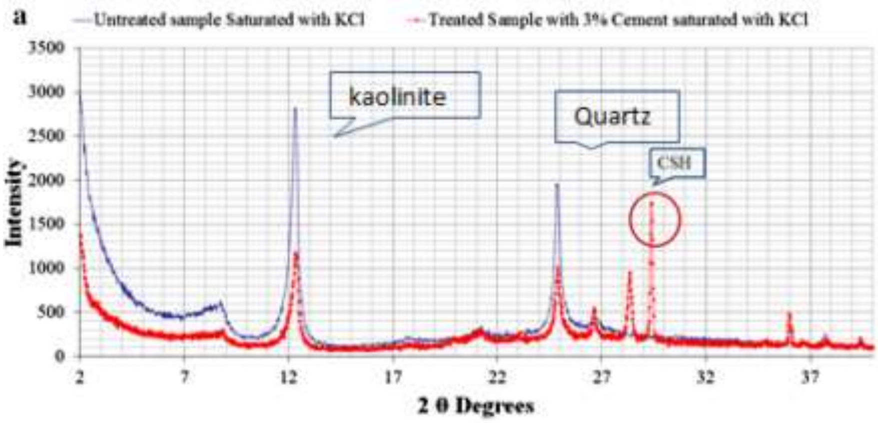


Figure 2.19: Identification of Minerals For 3 % Cement Treated Clay Soil (Mutaz and Dafalla, 2014)

Kamruzzaman et al. (2009) studied the XRD of clay stabilized with cement. The results showed as shown in Figure 2.20 that new peaks were obtained in comparison to plain clay such peaks mean that there are new crystalline materials in mixes.

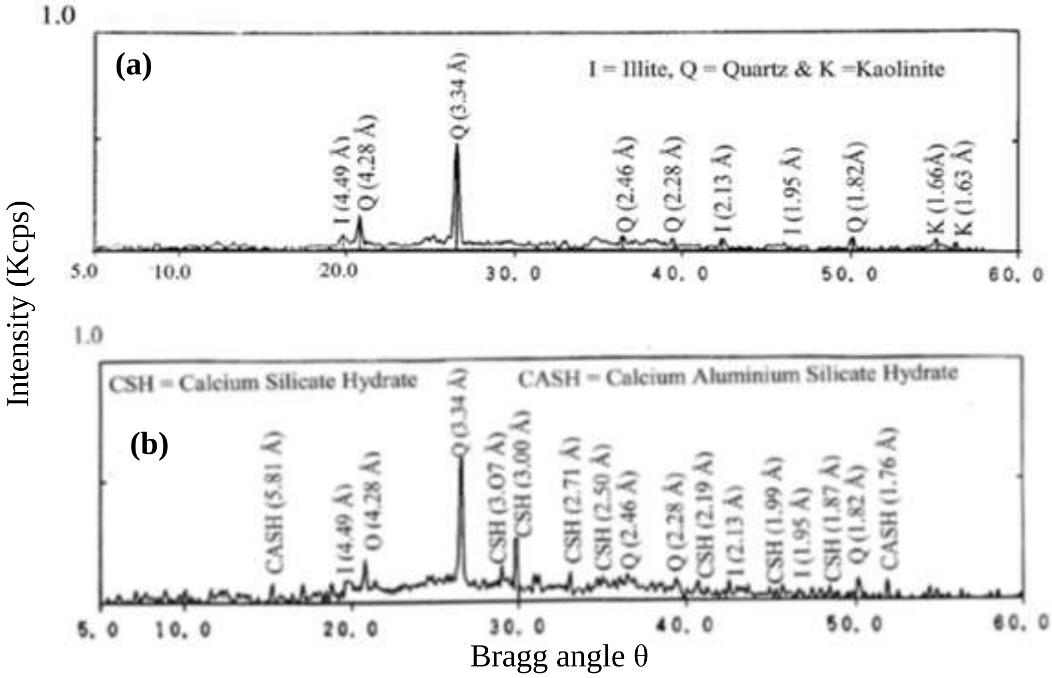


Figure 2.20: XRD of (a) plain clay, and (b) clay stabilized with 10% cement (Kamruzzaman et al., 2009)

2.6.5 Problems associated with soil stabilization with cement

Despite the many benefits, there are problems associated with cement stabilized materials:

A. Negative environmental impact

Global warming is a serious threat which our planet is facing (Aksan and Çelikler, 2012). Carbon dioxide (CO_2) is one of the main factors for this warming (Taha et al., 2013; Zhang et al., 2012; Ali et al., 2011; Du et al., 2015). Cement manufacturing is a process which emits CO_2 in large amount (Taha et al., 2013; Mikulčić et al., 2012; 2013; Gao et al., 2015). Cement industry alone produces about 10% of total CO_2 emission (Liska and Al-Tabbaa, 2008). Cement manufacturing emits CO_2 through decarbonisation of limestone, burning fossil fuels, electricity, and transportation (Firoozi et al., 2017). Where, this process discharges about nine hundred kilograms of CO_2 for each thousand kilograms of produced cement (Mahasenan et al., 2003). The European Cement Association states that every thousand kilograms of cement produced needs sixty to a hundred thirty kilograms of fuel and about a hundred five-kilowatt hour of electricity (Oggioni et al., 2011). Andrew (2019) stated that the CO_2 emissions due to cement production in 1928 was about 50 Mt and by time it increased to be about 1500 Mt in 2018 as shown in figure 21.

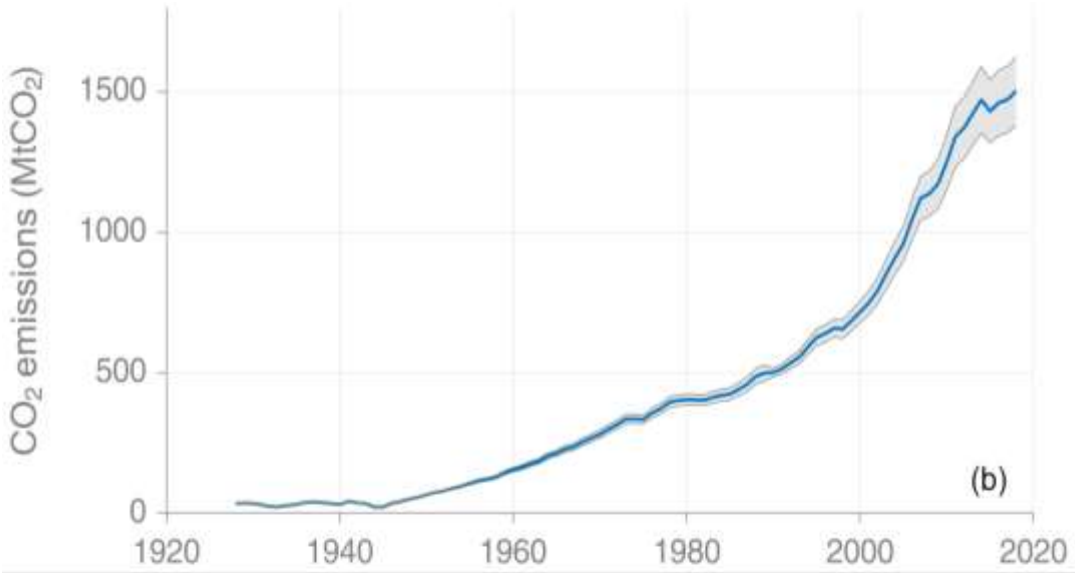


Figure 2.21: Global Process Emissions from Cement Production, (Andrew, 2019)

B. Cracks

The higher cement content added means more heat released due to the increased hydration processes which in turn can lead to cracking in mixtures (Khattak and Alrashidi, 2006).

2.6.6 Trials of cement reduction used in soil stabilization with cement

Due to these setbacks of cement stabilization of soil, many studies have been done to seek for alternative approaches to reduce cement usage and carbon gas (Ekinci, 2019; Cheah, et al., 2017; Frías et al., 2017; Siddique, 2012). Therefore, the development of alternative ways that reduce cement usage can be a proper way. Studies tried to reduce cement usage by replacing cement with other alternatives.

Ekinci et al. (2020) used wood-ash as a cement replacement for stabilization of marine deposited clays. It was found that that the replacement of cement with 5% wood-ash improved cohesion.

Ghadir and Ranjbar (2018) compared the potential of volcanic ash (VA) based geopolymer as an alternative environmentally friendly clayey soil stabilizer to cement. VA was added with percentages of (0, 5, 10, and 15) %. The untreated clayey soil specimen's strength could be improved from 2 to 12 MPa, when the soil partially replaced with 15% of the binders by weight.

Marir et al. (2019) aimed to quantify the influence of cement and zeolite as well as recycled PET fiber on the strength of loess soil. The results indicated that the strength of samples stabilized with 4% and 8% cement were substantially enhanced by increasing zeolite replacement. Additionally, soil stabilization with a combination of cement, zeolite, and PET fiber significantly increased the strength. The addition of PET to a zeolite-cement-loess mixture caused an increase in failure strain. To overcome the brittle behavior of cemented loess, the combination of PET and zeolite in a cement-loess mixture is very effective.

2.7 Fiber Reinforced Soil

Fiber reinforced soil, the soil reinforced with random fibers is a way to treat soils. The fiber reinforcing includes random addition of fibers not like the traditional reinforcement methods. Fibers utilized could be natural or synthetic (Hejazi et al., 2012). These materials have a high resistance towards chemical and biological degradation and do not cause leaching in the soil (Puppala and Musenda, 2000). Fibers reinforcing of soils is found to be effective in improving strength of soils (Singh and Bagra, 2013; Muntohar et al. al., 2013; Gray etal., 1983; 1986; Maheshwari et al. al., 2011; Lirer et al., 2012; Puppala and Musenda, 2000; Yetimoglu and Salbas, 2003; Babu et al. al., 2008a; 2008b; Chauhan et al., 2008; Tang et al. al., 2010; Prabakar and Sridhar, 2002).

2.7.1 Mechanism of fiber reinforced soil

Tang et al. (2007) revealed that the fibers interlock the soil particles and holds the soil particles with each other. This interlock ability depends on the fibers resisting of sliding which depends on fibers coarseness (Frost and Han, 1999; Tagnit et al., 2005a; 2005b Shah, 1991a; 1991b;). Figure 2.22 shows the abilities of fiber surface pits in enhancing the interaction between the fibers and soil particles. When fibers and soil are blended, the soil particles get attached to the fibers, which leads to better interlock (Tang et al., 2007). Therefore, the fibers work as bridges that hold the soil particles together. Through this mechanism of fiber–soil interaction, the stresses and the incremental strains of fibers are related to that of the soil.

Tensile or compressive stress can be induced in a fiber, depending on the fiber's orientation with respect to the direction of the principal stresses. It is well understood that only fibers under tension, termed active fibers, contribute to the improvement of the behavior of fiber-reinforced soils (Zornberg, 2002).

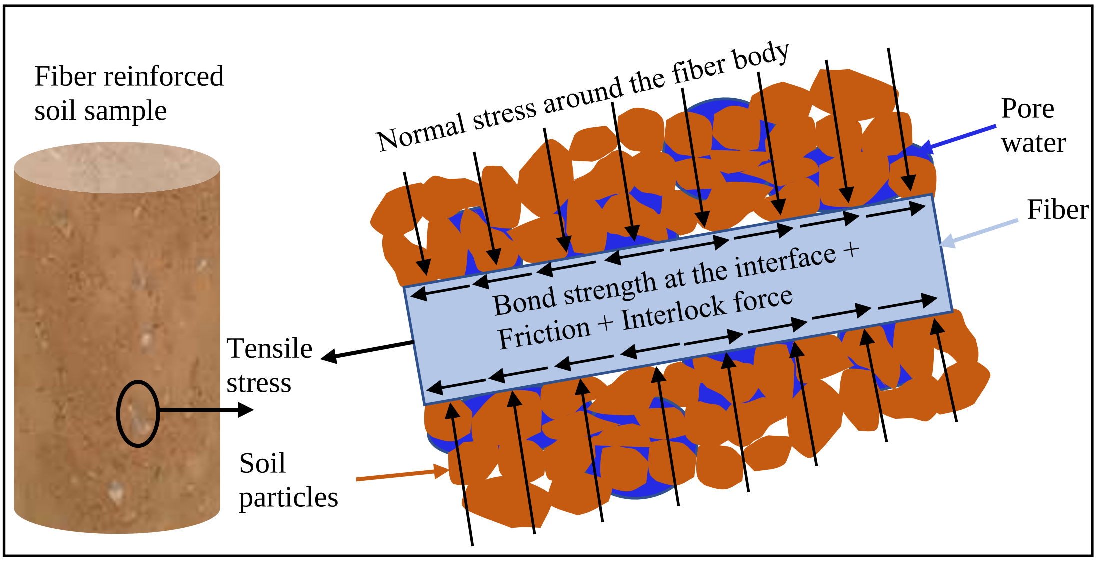


Figure 2.22: Interaction between a fiber and soil particles

2.7.2 Factors affecting soil reinforced with fibers strength

Many researchers (Gray et al., 1983; 1986; Maher and Ho, 1994; Santoni et al., 2001; Tang et al., 2007; Silva et al., 2010a; 2010b; Estabragh et al., 2012; Li and Zornberg, 2013) studied the strength properties of soil reinforced with fibers to declare what variables affect the strength. The efficiency of soil reinforced with fibers depends on various factors which are:

A. Soil characteristic

B. Fiber characteristics like length, aspect ratio, fiber percentage, and fibers material.

2.7.3 Types of fiber used in reinforcement of soil

As have been mentioned, the fibers can be natural or synthetic. Hejazi et al., (2012) stated that the fibers' kinds can be summarized as:

- Some common natural fibers such as: Coir fiber, Sisal fibers, Palm fibers, Jute fibers, Barley-straw fibers.
- Some synthetic (manmade) fibers such as: Polyvinyl alcohol fibers, Glass fibers, Plastic fiber (Polypropylene fibers (PP), Polyester fibers (PL), Polyethylene terephthalate fibers (PET)).

This research is about using waste plastic (PET) as soil reinforcement.

2.8 Plastics

2.8.1 Introduction to plastics

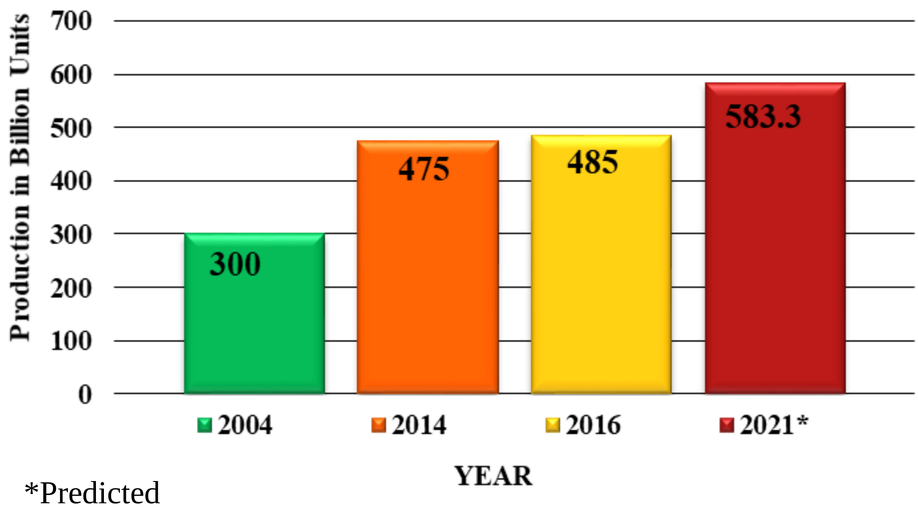
Plastic is a material which consists of synthetic or semi-synthetic organic compounds that can be molded into solid materials. Plastics are mostly derivative of petrochemicals. Due to their properties of impermeability to water, low cost, ease of production and versatility, plastics are used in a tone of products. Plastics have become an essential material for daily use. The world production reaches a hundred fifty million tons every single year (Peddaiah et al., 2018). The consumption of plastic in different forms is increasing by an average of 10% every year (Singh and Dixit, 2017). In 2016, the global annual production of plastics reached 330 million metric tons (Plastics Europe, 2017).

2.8.2 Plastic waste generation

In general, the quantity of plastics of all types consumed annually all over the world has been growing in a phenomenal way. The manufacturing processes, service industries and municipal solid wastes generate numerous waste plastic materials. The increasing awareness about the environment has tremendously contributed to the concerns related with disposal of the generated wastes. Disposal of these wastes produced from different industries and urban areas has become a great problem. Most of the wastes generated are non-biodegradable and possess severe environmental threat causing environmental pollution. The widespread generation of plastics waste needs proper end-of- life management (Mohammed et al., 2018).

2.8.3 Polyethylene Terephthalate (PET) plastic bottles

Plastic bottles made of Polyethylene Terephthalate (PET) are one of the most abundant plastics in solid urban waste (Abhishek Patil et al., 2016). The bottled water is the fastest growing beverage industry in the world. The international bottled water association (IBWA), demonstrated that bottled water sales increased by five hundred percent over the last 10 years and 1500 thousand tons of plastics are used for water bottling annually (Babu and Chouksey, 2011). As shown in Figure 2.23 the production in 2004 was only 300 billion bottles, while it is predicted to be 583.3 billion units in 2021 (Statista, 2017). In 2007, it is reported that a world's annual consumption of PET drink covers of approximately 10 million tons and this number grows up to 15% every year (Pal et al., 2018). Total PET used in the production of United States bottles in 2013 was also higher at 2.61 million kg, despite sales declines in some beverage market sectors (Louzada et al., 2019). Plastics comprise 12.3% of the total waste produced, most of which is from discarded PET water bottles (Ramadevi and Manju, 2012). On the other hand, recycling of plastic water bottles is very low. And hence there is need of reuse of the plastic water bottles (Abhishek Patil et al., 2016). The general survey shows that 1500 bottles are dumped as garbage every second. (Arpitha et al., 2017; Pal et al., 2018). Americans alone, throw away 35 billion plastic bottles every year (Plastics Europe, 2014). Every hour waste of PET Bottles is about 54.9 million pieces and if these are collected in a pile it would be higher than Christ the Redeemer (Christ the Redeemer 38 m) in Rio de Janeiro (Barrett, 2019), as shown in the figure 2.24.



*Predicted

Figure 2.23: Production of PET Bottles Worldwide (Statista, 2017)

Figure 2.24: Waste PET of an hour compared to Rio de Janeiro's Christ the Redeemer (Barrett, 2019)

2.8.4 Plastic waste management

Waste management is the process of controlling generation, storing, collecting, transferring, treating, and getting rid of waste in a way that it protects health, and which is environmentally acceptable (McDougall et al., 2008; Filemon, 2008). There are some methods of plastic waste disposal:

- Landfilling
- Incineration
- Recycling

An effective method to get the plastic wastes managed is to use waste in engineering applications. In the literature there are many applications of PET bottles for structural materials (Foti, 2013; 2011; Thomas and Moosvi, 2020; Alani et al., 2019; Al-Tulaian et al., 2016; Ochi et al, 2007; Yin et al., 2015; de Oliveira and Castro-Gomes, 2011; Borg et al., 2016). Many studies tried to use waste plastic in soil reinforcement of soil. In next section, the previous trials to use such materials in reinforcement of soil are presented.

2.8.5 Previous studies on PET bottles reinforced soil

There has been an evaluation of soil reinforced with fibers. Many authors investigated soil reinforced with fibers, herein summarizes a number of studies.

Several researchers have studied the properties of soil reinforced with PET shreds (Iravanian and Haider, 2020; Babu and Chouksey, 2011; Singh and Mittal, 2019; Arpitha et al., 2017; Louzad et al., 2019; Peddaiah et al., 2018; Consoli et al., 2002; Hafez et al., 2018; Botero et al., 2015; Ilieş et al., 2015; 2017; 2017a). The behavior of PET strips inclusion in soil was studied and it was found to be able to enhance the soil's strength (Babu and Chouksey, 2011; Singh and Mittal, 2019; Consoli et al., 2002).

Soil fiber composites were effective in improving the CBR value (Peddaiah et al., 2018; Fletcher and Humphries, 1991; Kumar et al., 1999; Yetimoglu et al., 2005). Louzada et al. (2019), studied the SEM of clay stabilized with PET and found that the PET enhances the interaction among particles of soil.

Ilieş et al. (2015; 2017; 2017a), stabilized clay soil with PET shreds and they found that properties of clay soils were improved by adding PET shreds.

In Gunaydin et al. (2019)'s study, various geotechnical tests were conducted on the clayey soil and soil-PET waste plastic mixtures. Soil was mixed with PET waste plastic fine and coarse granules in varying percentages. Results of tests demonstrated that the inclusion of PET waste plastic fine and course granules in soil with appropriate amounts improved strength and deformation behavior of clay soil.

Table 2.6 summarizes the studied experimental works carried on PET fiber reinforced soil.

Table 2.6: Experimental Works Carried on PET Fiber Reinforced Soil

Authors	**Soil Type**	**Percent of PET bottle by soil mass (%)**	**Size of PET bottle (mm)**	**Test carried out**	**Conclusions**
Mai et al. (2017)	Clay	1 and 2	10*1	direct shear, compaction, and UCS	• Optimum PET 2% • MDD, OMC increased • Direct shear increased116%. • UCS increased 175%

Authors	Soil Type	Percent of PET bottle by soil mass (%)	Size of PET bottle (mm)	Test carried out	Conclusions
Priya Dharshini et al. (2018)	red soil	0.25, 0.5, 0.75 and 1	20*3	CBR	• Optimum PET 0.75% • CBR value increased 211%
Singh et al. (2017)	Clay	2, 4, and 6	25*5, 35*10, and 50*15	Compaction, UCS, and CBR	• Optimum PET 6% • OMC increased • MDD decreased • CBR value improved 27.3 %.
Gangadhara et al. (2016)	Sand	0.3, 0.7, 1, and 2	5mm diameter	Direct Shear and Static load	• Optimum PET 0.7% • Settlement decreased • Load carrying capacity increased 179.5% • Shear strength increased 175%
Arpitha et al. (2017)	Clay	0.5, 1, 1.5, 2, and 2.5	random size	CBR	• Optimum PET 1.5%. • Strength and deformation improved. • CBR value increased 8.7%.
Mahali and Sinha (2015)	Stone dust	0.25 to 2	AR of 1, 2, and 3	Standard proctor and CBR	• Optimum PET 2%. • MDD increased. • OMC decreased. • CBR value increase 180%.
Abhishek et al. (2016)	black cotton soil	1	10*10	direct shear and tri-axial	• Optimum PET 1%. • Tri-axial test, cohesion increased 67.2%. • Direct shear test, cohesion increased 24%.

Authors	Soil Type	Percent of PET bottle by soil mass (%)	Size of PET bottle (mm)	Test carried out	Conclusions
Burman et al. (2018)	silty sand	0.2, 0.4, 0.6, and 0.8	15*15, 15*25, and 15* 35	Standard Proctor, Direct Shear and CBR	• Optimum PET 0.4%. • MDD increased. • OMC decreased. • Cohesion increased 78.9%. • Internal friction increased 42%. • CBR value increased 400%.
Alshkane (2017)	Sand	1, 2, and 4	long 16 and short 8	Direct shear	• Optimum PET 1%. • Bearing capacity of soil increased. • Settlement of soil decreased.
Babu et al. (2010)	Red soil	0, 0.5, 0.75, and 1	12*4	(CU) and one-dimensional compression	• Optimum PET 0.5%. • Strength of soil improved. • Compressibility reduced.
Paramkusam et al. (2013)	red mud soil	0.5, 1, 2, 3, and 4	passing sieve 20 mm	Standard Proctor, and CBR	• Optimum PET 2%. • MDD increased. • CBR value increase 233%.
YARBAŞI and Kalkan (2020)	Clay	0.1, 0.2, and 0.3	15*10	Freeze-thaw tests, and UCS	• Optimum PET 0.3%. • Strength values before and after freeze-thaw cycle increased.
Kirubakaran et al. (2018)	black cotton soil	3, 5, and 7	less than 0.5	Standard Proctor, UCS, and CBR	• Optimum PET 5%. • MDD and OMC Increased. • UCS increased 29.5% • CBR value increased 47%.

Authors	Soil Type	Percent of PET bottle by soil mass (%)	Size of PET bottle (mm)	Test carried out	Conclusions
Hotti et al. (2019)	Black cotton soil	2, 4, 6 and 8	Random size	standard proctor, CBR, and UCS	• Optimum PET 6%. • MDD increased. • CBR value increased 37%. • UCS increased 20.2%.
Ammaar et al. (2019)	Clay	0.5, 1, 1.5 and 2	35*8	Compaction and CBR	• Optimum PET 1.5%. • MDD decreased. • CBR value increased 100%.
Karmacharya et al. (2017)	Sand	0.5, 1, and 1.5	3*10	tri-axial	• Optimum PET 1.5%. • Shear strength increased 129%.
Ashraf et al. (2011)	Sand	0.2, 0.4, 0.6, 0.8, and 1	Random size	CBR and Plate load	• Optimum PET 0.6%. • CBR value increased 31.6%. • Settlement decreased 70.9%.
Laskar and Pal (2013)	Sandy Clay	0.25, 0.5, and 1	10*5, 10*2.5, and 10*1.2	compaction and consolidation	• Optimum PET 0.5%. • MDD increased. • Settlement decreased.
Naeini and Rahmani (2016)	Silty	0.25, 0.5, 0.75, 1, and 1.25	4*4, 8*4, 12*4	tria-xial (CU)	• Optimum PET 1.25% • MDD and OMC decreased. • Cohesion and friction angle increase.
Mohammed et al. (2018)	Clay	0.5, 1.5, 3, 6, 12 and 15	7.5*4	Proctor compaction and tri-axial	• Optimum PET 1.5% • MDD decreased. • OMC increased. • Maximum shear strength observed at 1.5% of plastic bottle content.

Authors	Soil Type	Percent of PET bottle by soil mass (%)	Size of PET bottle (mm)	Test carried out	Conclusions
Saravanan and Jose (2018)	sand	0.2, 0.4, 0.6, 0.8, and 1	random size	CBR	• Optimum PET 0.6%. • CBR value increased 26%.
Pal et al. (2018)	Clay	0.25, 0.5, and 0.75	10*10, and 20*10	compaction and CBR	• Optimum PET 0.25%. • MDD increased. • OMC decreased. • CBR value increased 34.9%.
Harish and Ashwini (2016)	Black cotton	0.2, 0.4, 0.6, 0.7, 0.8, and 1	random size	Proctor Compaction, and CBR	• Optimum PET 0.5%. • CBR value increased 22.2%.
Harish and Ashwini (2016)	Red soil	0.2, 0.4, 0.6, 0.7, 0.8, and 1	random size	Proctor Compaction, and CBR	• Optimum PET 0.7%. • CBR value increased 26.1%.
Gowthami et al. (2017)	Clay (CH)	0.5, 1, 1.5, and 2.	Passing sieve 10 mm	Atterberg's limit, Compaction, CBR, and UCS	• Optimum PET 2% • LL, PL, and OMC decreased. • MDD increased. • CBR increased 317.5%. • UCS increased 27.8%.
Jin et al. (2019)	Sandy and Cape Flats Sandy	2.5 to 20	2-4.75, 4.75-5.6, and >5.	Direct shear	• Optimum PET 12.5% and10% for Sandy and Cape flats Sandy. • Cohesion and friction angle increased.

Authors	Soil Type	Percent of PET bottle by soil mass (%)	Size of PET bottle (mm)	Test carried out	Conclusions
Nsaif (2013)	Clay	2, 4, 6, and 8	(1-2) diameter and 5mm thick.	Compaction and Direct shear	• Optimum PET 8%. • MDD and OMC decreased. • Cohesion increased 1.8%. • Friction angle Increased 52%.
Nsaif (2013)	Sand	2, 4, 6, and 8	(1-2) diameter and 5mm thick.	Compaction and Direct shear	• Optimum PET 8%. • MDD and OMC decreased. • Cohesion increased. • Friction angle increased 48.6%.
Bhattarai et al. (2013)	Silty	0.25, 0.5, and 1	AR of 1, 2, 3, and 4	CBR	• Optimum PET 0.5%. • CBR value increased.
Babu and Chouksey (2011)	Sand and Red soil	0.5%, 0.75%, and 1	12*4	tri-axial, compressibility, and UCS	• Optimum PET 1%. • Strength parameter increased. • Compressibility parameters decreased.
Sai and Srinivas (2019) (1(11) imp	Clay	0.5, 1, 1.5, and 2	passing sieve 4.75mm	compaction, CBR and UCS	• Optimum PET 0.5%. • CBR value increased 12.5%. • Shear strength increased 15%.
Gangadhara et al. (2017)	silty	1, 2, and 3	diameter 5 and AR 1	direct shear, and Static load	• Optimum PET 1%. • Strength parameter increased. • Settlement decreased 20%.
Khan and Pachghare (2015)	Sand	from 0 to 6	12*12, 24*12, and 36*12	compaction, direct shear, and CBR	• Optimum PET 5%. • MDD and OMC decreased. • Maximum shear stress increased 57%. • CBR value increased 67%.

Authors	Soil Type	Percent of PET bottle by soil mass (%)	Size of PET bottle (mm)	Test carried out	Conclusions
Louzada et al. (2019)	Clay	10, 20, and 30	fine crushed bottles	Compaction and Tri-axial	• Optimum PET 30%. • MDD and OMC decreased. • Cohesion increased 11.2%.
Louzada et al. (2019)	Clay	3 and 5	flakes bottles	Compaction and Tri-axial	• Optimum PET 5%. • MDD and OMC decreased. • Cohesion increased 1.2%.
A Mishra (2016)	Clay	0.2, 0.4, 0.6, and 0.8	length 35 and diameter 25	Atterberg limit and CBR	• Optimum PET 0.6%. • Plasticity index decreased. • Shear strength improved. • CBR value increased.
Alzaidy (2019)	Clay	0.25, 0.5, and 1	20*1.5	direct shear, UCS, and CBR	• Optimum PET 1%. • Strength properties increased. • Reduction of swelling potential.

The outcomes clarify that plastic bottle have the ability to perform as a soil reinforcement additive very effectively. It is observed that the properties of soil reinforced with plastic strips are very sensitive and can change with addition of small increments of plastic, with different size and different gradation of soils (sand, silt and clay etc.). Overall, it is inferred that, with addition of plastic strips at particular percentage and for particular gradation of soil there is considerable enhancement in the soil strength.

2.9 Fiber Reinforced Cement Treated Soil

As have been mentioned before, cement stabilization of soil is considered to be good however the literature showed that it has problems such as brittleness cracks and also it has environmental issues. Therefore, an idea was developed to mix cement soil stabilization technique with fiber reinforcement of soil technique together so that the brittleness and cracks of cemented soil can be reduced and the strength to be increased. In this way, the cement used can be reduced so that the environmental issues will possibly solved. Many authors studied cemented soils reinforced with fibers (Gray et al., 1983; 1986; Maher & Gray, 1990; Nataraj and McManis, 1997; Consoli et al., 1998; Zornberg, 2002; Diambra and Ibraim., 2014). In the next section the literature available on fiber reinforced cemented soil is presented.

2.9.1 Previous studies on fiber reinforced cemented soil

2.9.1.1 Mechanical properties (strength and stiffness) of fiber reinforced cemented soil

Fatahi et al. (2012), Park (2009), Liu & Starcher (2013), Cristelo et al. (2015) and Khattak & Alrashidi, (2006) showed that adding fibers to cemented soil increased strength and reduced stiffness.

Correia et al. (2015) noted that the behaviors of soil stabilized with cement have not been affected with the variation of the added fibers quantity. Sobhan et al. (1999) and Gaspard et al. (2003) showed that fiber reinforcement has no considerable impact on cemented soil strength.

Kaniraj & Havanagi (2001) and Fatahi et al., (2012) concluded that the more cement added the higher the strength of fiber reinforced soil.

Consoli et al. (1997) investigated the impacts of fiber reinforcing on cemented soil, cement percentages varying from 1 to 5%. Fiber lengths were of 3.2 mm, 6.4 mm and 12.8 mm, in content varying from 0 to 3%. Test results indicated that fiber reinforcement may increase the strength of cemented soil but definitely reduces soil stiffness. Inclusion of fibers also contributed to reduce the brittleness index of cemented soil. Consoli et al. (1998), studied the behavior of fiber-reinforced cemented and uncemented sandy soils. The results of the tests show the behavior of both plain soils and cemented ones to be significantly influenced by fiber reinforcement. In general strength was increased and stiffness was decreased. The major benefit of fiber reinforcing, especially for soils stabilized with cement, is reducing brittleness. Consoli et al. (2002), investigated the behavior of fibers reinforced sand. They revealed that the polyethylene terephthalate fiber reinforcement somewhat improved the strength of both cemented and uncemented soil and reduced the brittleness of the cemented sand. In addition, the initial stiffness was not significantly changed by the inclusion of fibers. Consoli et al. (2004) evaluated the effects of using three different randomly distributed fibers (polyester, polypropylene and glass fibers) and rapid hardening Portland cement to improve the engineering behavior of a uniform fine sand. Fiber content between 0-5% by weight and cement content between 0-7% by weight. The cement addition considerably improves strength and brittleness of the sand. Inclusion of polyester and glass fibers (both relatively stiff) slightly reduced the stiffness and increased strength of both the cemented and uncemented sand, and also slightly reduced the brittleness of the cemented composite. On the other hand, relatively flexible polypropylene fiber reinforcement dramatically reduced the brittleness and stiffness, changing the mode of failure of the cemented sand from brittle to ductile for longer fibers, while increasing the strength of the cemented composite. Consoli et al. (2009) studied the behaviors of cemented sand reinforced with polypropylene fibers. The cement was added with different percentages of 0 to 10% together with fiber contents of 0% and 0.5%. Test results indicated that the addition of cement to sand increases stiffness, strength and brittleness. The fiber reinforcement increases strength just up to a certain cement content (up to about 5%), increases strength, decreases stiffness and changes the cemented sand brittle behavior to a more ductile one. Consoli et al. (2010), studied the properties of cemented soil with/without fibers. The results show that fiber insertion in the cemented soil, for the whole range of cement studied, causes an increase in unconfined compression strength. Consoli et al. (2011b; 2011c) added polypropylene fibers clayey sand. The results showed that fiber insertion causes an increase in strength in the cemented soil, the larger the fiber percentage inserted the greater the strength. The addition of cement, even in small amounts, greatly improves the soil strength of fiber reinforced and non-reinforced sandy soils.

Ojuri and Ozegbe (2016) considered the behaviors of PET shreds reinforced cemented sand, the authors found that PET shreds improved the cemented soils strength. Also, Tang, et al, (2007) reinforced cemented clay soil with polypropylene fibers, they revealed that fibers inclusion increased the strength and decreased the stiffness, also they found that adding fibers and cement together to clay improves the strength of clay much more than adding each of them individually. These findings were proven by Estabragh et al. (2012) and Xiao et al.

(2013) as well. Kim et al. (2008) added PET net to cemented clay and their findings showed that PET net adding enhanced the strength.

Aldaood et al. (2021) evaluated the effect of straw fibers and cement percentage on the mechanical properties of low plasticity clay soil. Straw fibers with 0.25, 0.5, 1.0 and 1.5% and cement percentages of 2, 4 and 6% were used. The test results show that the strength behavior of soil samples depends considerably on the percentages of both straw fibers and cement. Increase in the strength is linear with increasing cement percent. Further, the contribution of both straw fibers and cement percentages in increasing the strength is much more than the increase caused by them individually. The stress–strain behavior of soil samples changes from brittle behavior to ductile one with straw fiber addition.

Craig et al. (1987) modified the behavior of soil-cement by the addition of fiber reinforcing. A clayey sand was used. Four different types of fibers were examined; Straight steel, hooked steel, polypropylene, and fiberglass. Overall, fiberglass reinforcing was revealed to be most efficient in enhancing strength properties of the soil-cement. Ductility was greatly enhanced for all the fiber mixtures.

Maher et al. (1994) added fibers to clay soil, they found that fibers significantly increased the strength and ductility of clay. AI-Refeai (1991) added glass fibers to fine sand. Results indicated glass fibers improved strength of fine sand.

Chen et al. (2015) added polypropylene fiber to soft clay. The results show that fiber additive can significantly improve the strength and ductility of the cement treated clay.

Rathod (2019) studied coir fiber reinforced cement stabilized rammed earth they found that coir fibers can be used for improving the strength and ductility of the rammed earth.

Tang et al. (2019) reinforced contaminated soils with wheat straw fiber and cement. Fiber contents of 0.1%, 0.2%, and 0.3% together with cement contents of 5%, 7.5%, and 10%. The inclusion of fiber reinforcement within cemented soil caused an increase in the strength and changed the brittle behavior of cemented soil to a more ductile one.

Zhang et al. (2018) studied strength and water stability of fiber-reinforced cemented loess. Results indicated that the mixing of cement and fiber significantly improve the strength and the water stability of samples.

Park (2011) studied Polyvinyl alcohol (PVA) fiber cemented sand to evaluate how fiber inclusion affects the measured strength and ductility characteristics of cemented sand. Cement ratios used in the study were 2, 4, and 6% and the fiber ratios were 0, 0.3, 0.6 and 1%. The test results indicate that the inclusion of PVA fiber has a significant effect on the strength. The fibers inclusion increased the ductility of cemented soil.

Chegenizadeh and Nikraz (2011) added fiber in cemented soil. The results showed that fiber inclusion in the cemented soil composite increased strength and using of fiber caused increase in ductility of composite samples.

Janalizadeh Choobbasti and & Soleimani Kutanaei (2017) studied the effect of polyvinyl alcohol (PVA) fiber inclusion on deformation characteristics of cemented sand. The cement contents were 2, 4, and 6% by weight and. PVA fibers with percentages of 0.0, 0.3, 0.6 and 1%. Tests results showed that addition of cement to sand increased stiffness and strength.

Hamidi and Dehghan (2015) studied the effect of fiber inclusion on stiffness and deformation characteristics of sand-gravel mixtures. Fiber percentages used in the study were 0, 0.5 and 1.0%. The results show that fibers decreased initial tangent stiffness of the cemented sand-gravel mixture.

Piuzzi and Boszczowski (2019) reinforced cemented soil with polypropylene fibers. Results showed that the addition of polypropylene fibers alone did not result in significant gains in strength but provided an increase in soil ductility.

Ng (2018) studied strength and water stability of fiber-reinforced cemented loess. Results indicated that the mixing of cement and fiber significantly improve the strength and the water stability of samples.

2.9.1.2 Microstructure (SEM) of fiber reinforced cemented soil

Olgun (2013) evaluated the effects of polypropylene fiber on the characteristics of a clayey soil stabilized with cement and fly ash. Fiber content used were 0.25, 0.50, 0.75 and 1.0%. Strength values increased to a great extent following the addition of fiber into the stabilized soil, as there were traces of abrasion seen on the fiber surface in Figure 2.25 which indicate that the frictional strength between fiber and soil is the other important factor in increasing strength. The cementing gel remaining on the fiber surfaces after shearing is the most significant indicator of the importance of the interlocking between fiber and cement in increasing the frictional strength of the soil.

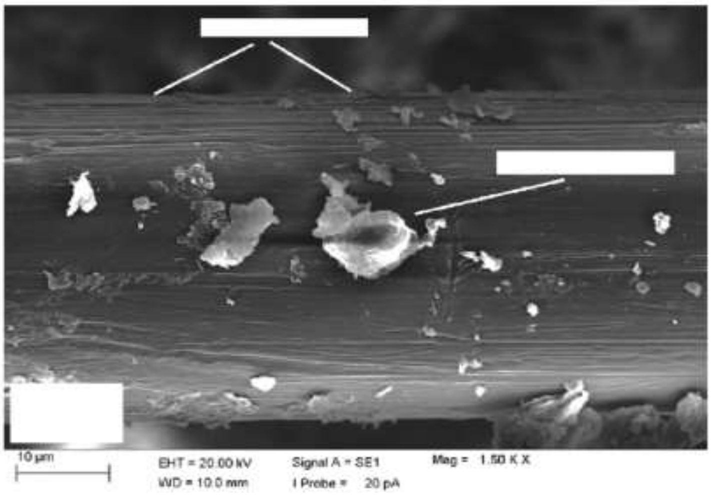


Figure 2.25: SEM image of Fiber Surface in Stabilized Soil

Tang (2007) investigated the effects of discrete short polypropylene fiber on the strength and mechanical behavior of un-cemented and cemented clayey soil. Fiber contents used were 0.05, 0.15 and 0.25% and cement content used were 5 and 8%. They found that fiber is attached to many products of cement hydration process and because these products have high strength, the interface strength of cemented soil reinforced with fibers is better than that of plain soil reinforced with fibers because they do not have such products.

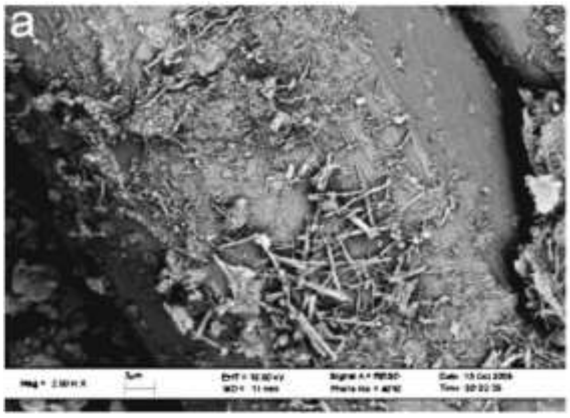
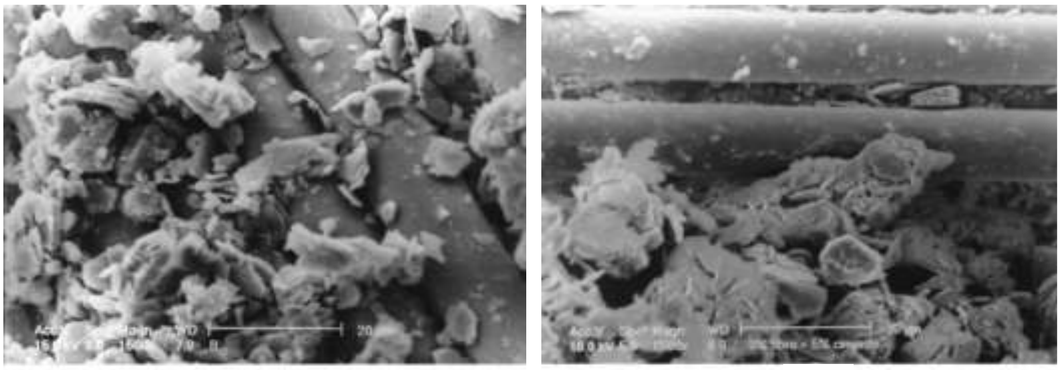


Figure 2.26: SEM image of fiber surface in cemented soil (Tang et al., 2007)

Consoli et al. (1999) evaluated the effect of glass fiber reinforcement on the response of a cemented sandy soil. Cement added amounts were between 0 and 5% and fiber was varying in a content from 0 to 3%. The fiber inclusion increased strength, the interactions between the fibers and cemented soil, has a primary role in the behavior of the composite material as shown in figure 2.27.



(a) (b)

Figure 2.27: SEM Microphotographs of fiber-reinforced Soils: (a) 0% cement; (b) 5% Cement (Consoli et al., 1999)

Wang et al. (2020), tried to add blast fibers to cemented soil and they found that soil reinforced with fibers had a higher strength. The microstructure in figure 2.28 showed that the basalt fiber having a rough surface is tightly wrapped by the soil and the hydration products, presenting a better interfacial bond between the cement soil and the basalt fiber.

This interfacial bond increases the interaction between the cement soil and the basalt fiber, and thus can explain the reason why the fiber improves the cemented soil strength.

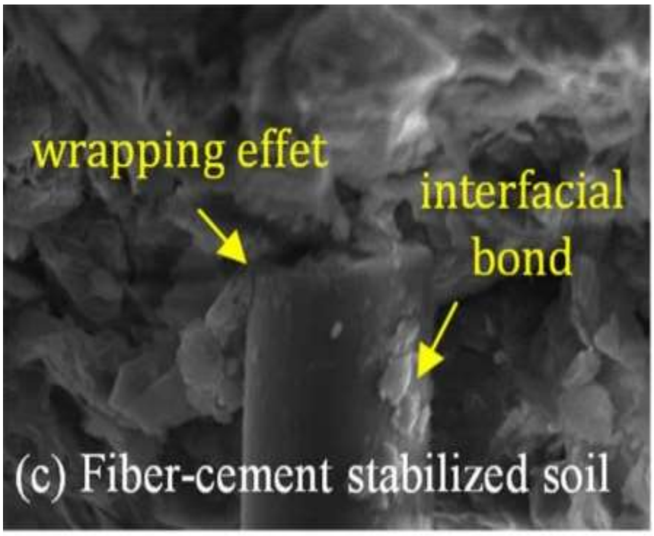


Figure 2.28: SEM image of fiber- cement stabilized soil (Wang et al., 2020)

2.9.1.3 Effect of fiber content on failure characteristics of cemented soil

Cemented soils have brittle characteristic where Tang et al., (2007) noted that when cemented soil fails big cracks were initiated. With addition of fibers in cemented soils, the cracks gets to be shorter as fiber content increases as shown in figure 2.29. Therefore, the fibers added to cemented soil changed the brittle behavior to ductile behavior. Freilich et al., (2010) found that at failure the plain soil sample separated a part while the fiber reinforced soil sample kept its integrity as shown in figure 2.30

(a)

(b)

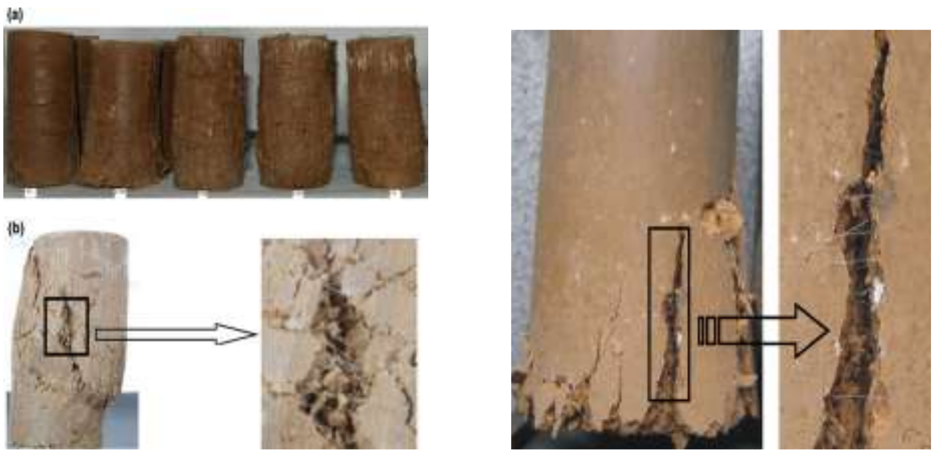
Figure 2.29: Effect of fiber failure characteristics of cement treated soil with 8% cement content: (a) without fiber content; (b) with fiber content (Tang et al., 2007).

(a) (b)

Figure 2.30: Soil sample at failure (a) with fiber and (b) without fiber (Freilich et al., 2010)

2.9.1.4 Crack Development in Fiber Reinforced Cemented Soil

As have been mentioned before, the fibers change the characteristics of cemented soils from being brittle to being more ductile, also the addition of fibers in cemented soil increases its strength. The main reason behind that is the bridging effect that the fibers introduce to the cemented soils. When the tension stress occur, the fiber serves as the bridge that carry the tension therefore reducing cracks in cemented soils. Tang et al. (2007) revealed that the fibers bridged cracks as shown in figure 2.31. Zaimoglu and Yetimoglu (2012) studied the impact of polyethylene fibers on silty soil. They revealed that increase in strength was as a result of bridge-influence of fiber that efficiently controls the deformation and development of failure planes and of the soil as shown in figure 2.31



(a) (b)

Figure 2.31: The bridge effect of fiber reinforcement in soil (a) Zaimoglu and Yetimoglu (2012), (b) Tang et al. (2007)

2.10 Porosity/Binder Index

Consoli et al. (2007) introduced a logical dosage index for cemented soil (Equation 1), taking into consideration the porosity/cement index (η/Civ) to assess a unique relationship related to the strength of cemented soil mixes. Where porosity/cement ratio controls the strength (Consoli et al., 2010; 2011; 2011a; 2011e; 2012; 2012a; 2017; 2020). Later researchers examined the capability of using porosity/cement ratio as stiffness parameters of cemented soil to evaluate the stiffness (Consoli et al., 2009). Where, studies proved that this ratio is proper for evaluating strength and stiffness of fine-grained soil-binder blend (Consoli et al., 2017). The cement/porosity index (η/Civ) that was generated by (Consoli et al., 2007) can just be used for cement. But, Ekinci, et al. (2019) introduced a general index (Xiv), which can be used for other binders. Also, regarding the external exponent, studies conducted for several kinds of soils revealed that the exponent varies between 0.28 and 0.35 (Consoli et al., 2017a; 2018).

$$\text{Porosity Binder Index } = \frac{\eta}{(C_{iv})} \qquad (2.6)$$

$$\text{Adjusted Porosity Binder Index } = \frac{Porosity}{Binder\ (X_{iv})} \qquad (2.7)$$

Where, X_{iv} is the adjusted general index for this study which could be any binder, while $C_{iv}$is the index of cement of cement only, and η is the porosity.

Several studies were carried out to examine the porosity binder index effectiveness in predicting the strength (Consoli et al., 2011; 2011a; 2011d; 2017; 2020) and they found that it is effective as high determination coefficient were achieved.

Other studies were carried out (Consoli et al., 2019a; 2012a; 2017a; 2018) to examine how the porosity binder index is effective in predicting the stiffness and they found that it is effective as high determination coefficient were developed.

In addition, the studies show that as porosity binder deceases, strength and stiffness increases.

Consoli et al. (2011) assessed the strength controlling parameters of two clays with distinct coarse-grained materials (silty clay and sandy clay) treated with cement and tried to show that the porosity/cement ratio plays a fundamental role in target strength assessment of clayey materials. The porosity/cement ratio is shown to be a key parameter in an evaluation of the unconfined compressive strength of the clayey soils, because high R^2 were gotten as shown in Figure 2.32.

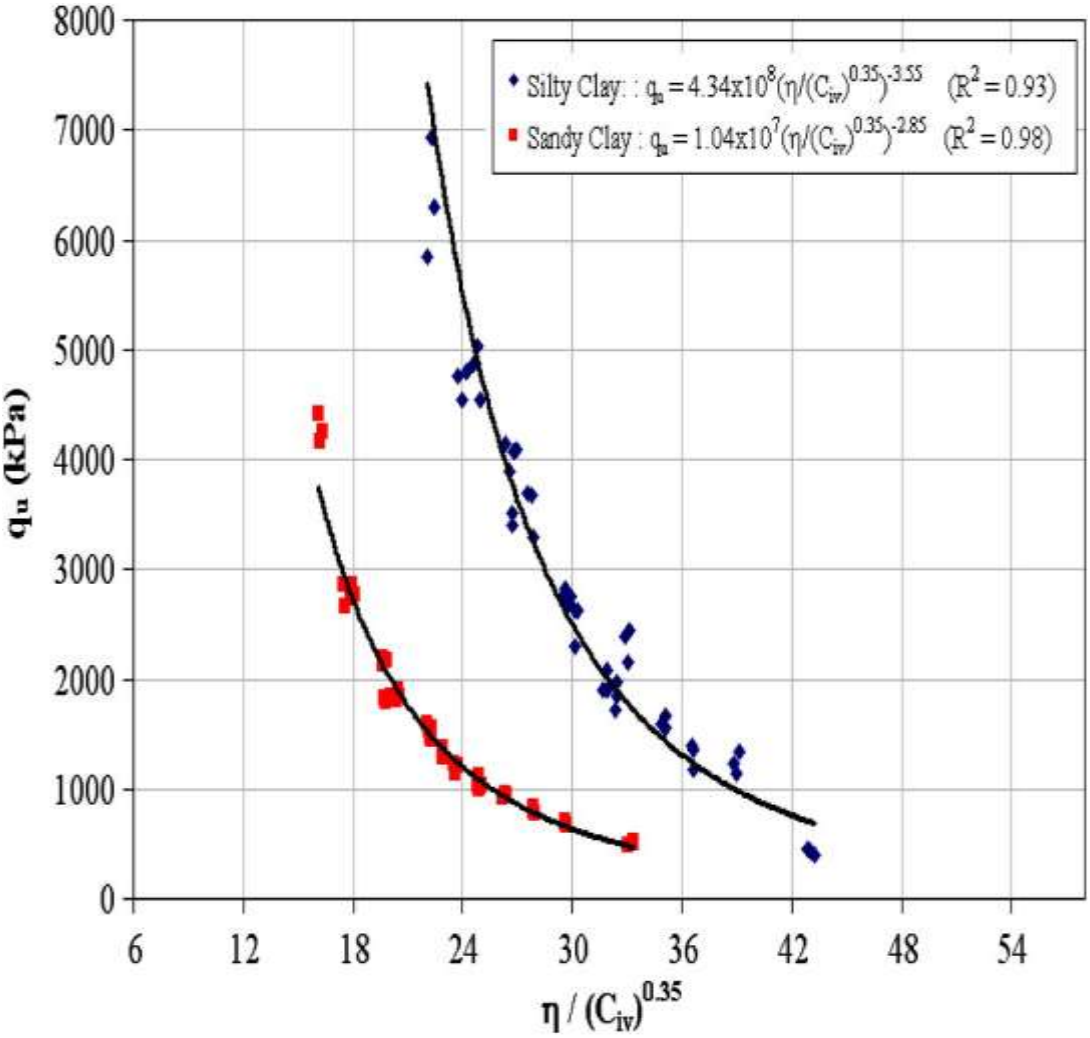


Figure 2.32: Relation between UCS and porosity binder index (Consoli et al., 2011)

Ekinci, et al. (2020) studied the stiffness of wood-ash and cement stabilized clay. The results showed that the adjusted porosity binder index (Xiv) can be used to predict the stiffness of soil with any binder, because of the high R^2 that were attained as shown in Figure 2.33.

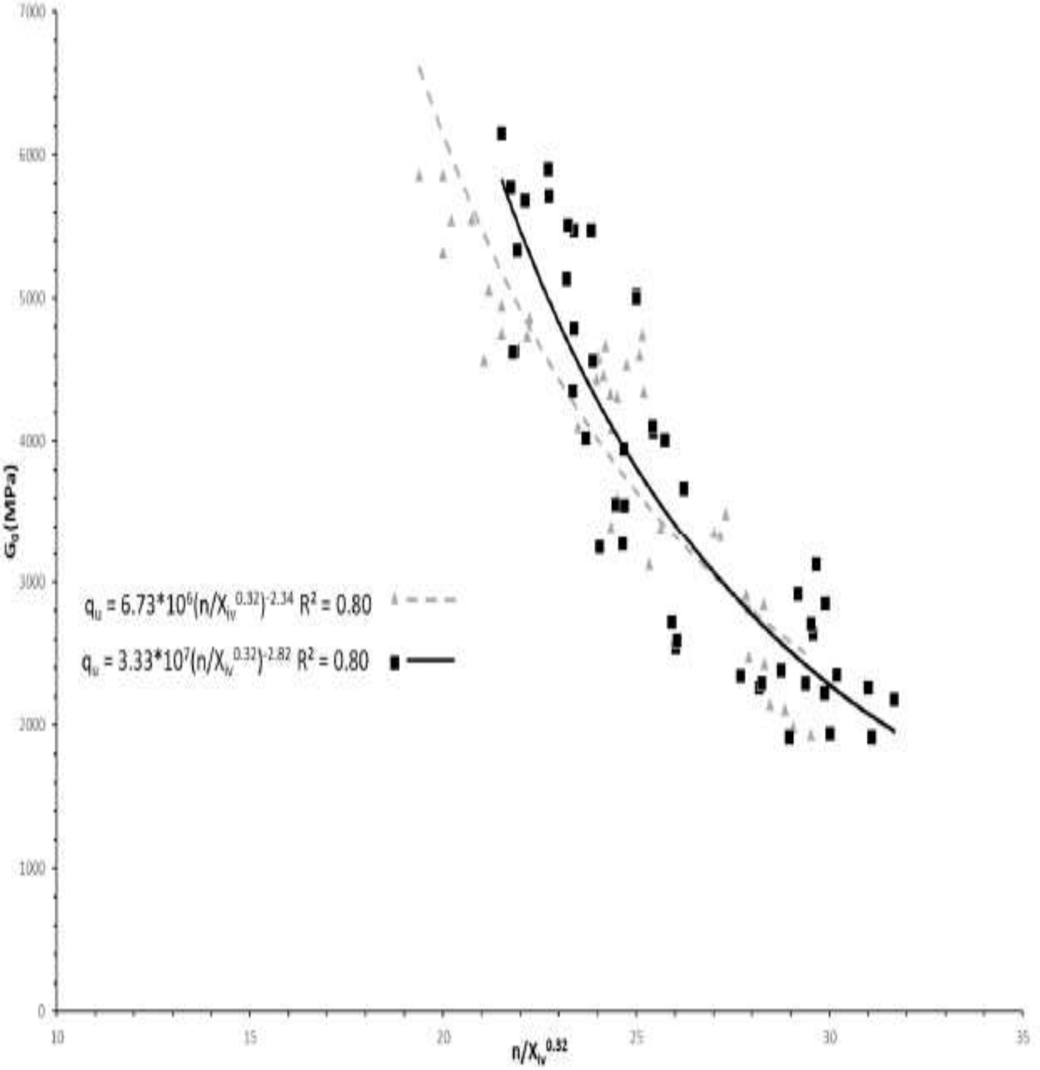


Figure 2.33: Relation between G_0 and porosity binder index (Ekinci, et al., 2020)

2.11 Stiffness (UPV) Prediction through Strength (UCS)

In engineering terms, stiffness means the ratio of applied stress to induced strain (Thom, 2008). Stiffness through initial shear modulus (G_0) can be determined by Ultrasonic Pulse Velocity (UPV) according to ASTM standards. The strength was tried to be used as an indicator of stiffness of soil. Consoli et al. (2020) did a study on low plasticity silty sand–clayey sand blended with a binder composed of coal fly ash and hydrated lime and proposed a correlation which relates the stiffness results through UPV and strength through UCS. The stiffness was presented as a function of UCS and a fair determination coefficient (R^2) was obtained as shown in Figure 2.34.

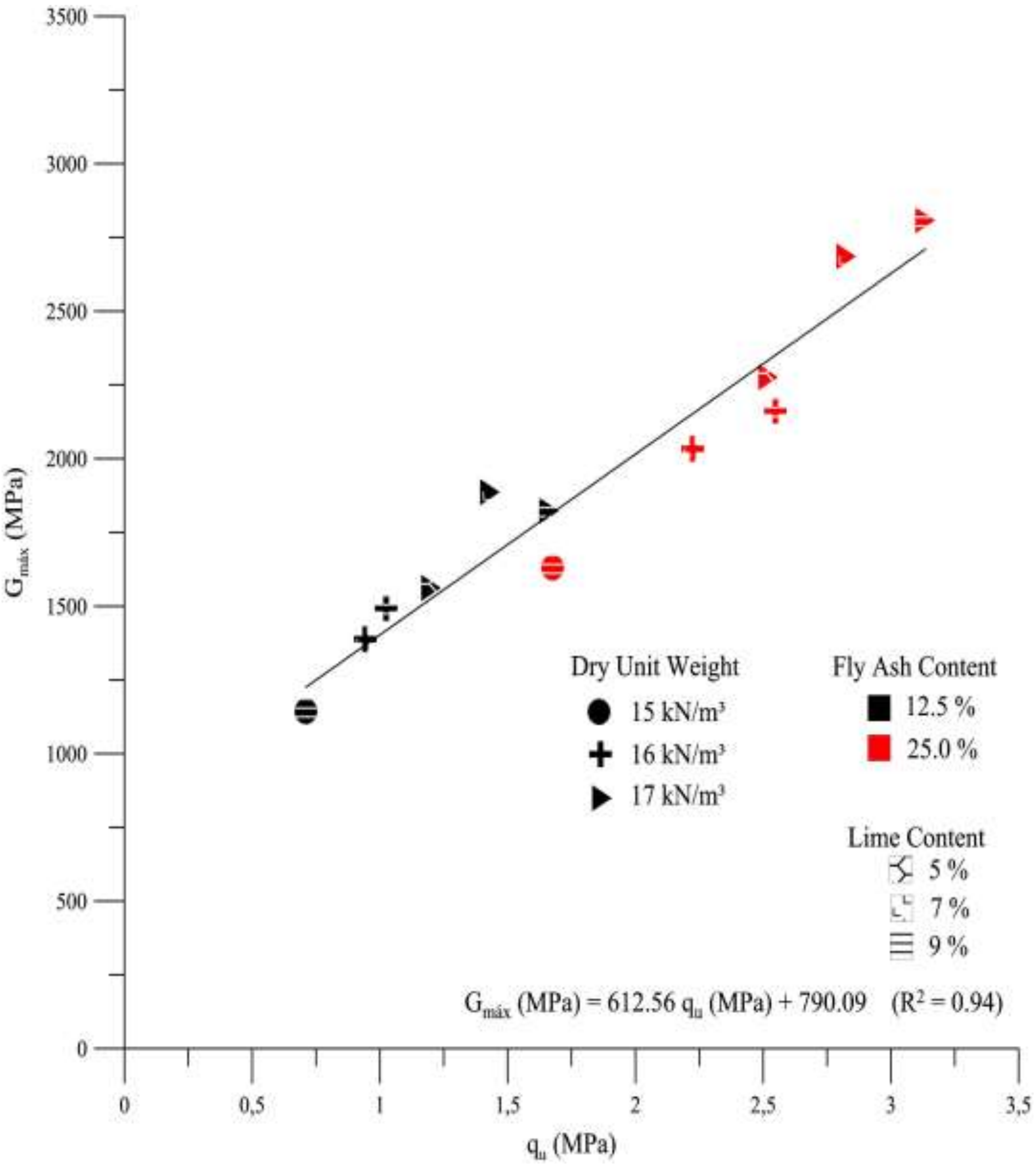


Figure 2.34: Relation between and Stiffness and UCS (Consoli et al., 2020)

CHAPTER THREE
MATERIALS AND METHODS

3.1 Introduction

This chapter explains the experimental section performed for achieving the objectives of this thesis. It introduces the work plan, materials utilized, and the experimental details and test procedures. The experimental work plan is summarized in Figure 3.1.

First of all, materials (soil, cement, plastic bottles, and water) were collected. Two sizes of PET shreds were chosen which are size 10 and 40 shreds and prepared. Size 10 is passing sieve No. 4 and remaining on sieve No. 10 and size 40 which passing sieve No. 20 and remaining on sieve No. 40.

Different PET shreds contents were selected to be added to soil as 0. 1, 0.2, 0.3, 0.4, 0.5, 0.6, 0.7, 0.8, 0.9, and 1.0% to find the suitable percentage and the materials collected were tested for basic characteristics tests. The soil was then reinforced with PET shreds and was tested for compaction and CBR. After finding the best PET shreds content range, three different cement percentages were chosen as 5, 7, and 10%. The cemented soil samples with and without PET shreds were then prepared and got cured for 7 and 28 days. Finally, the samples were tested for CBR, stiffness, XRD and SEM tests.

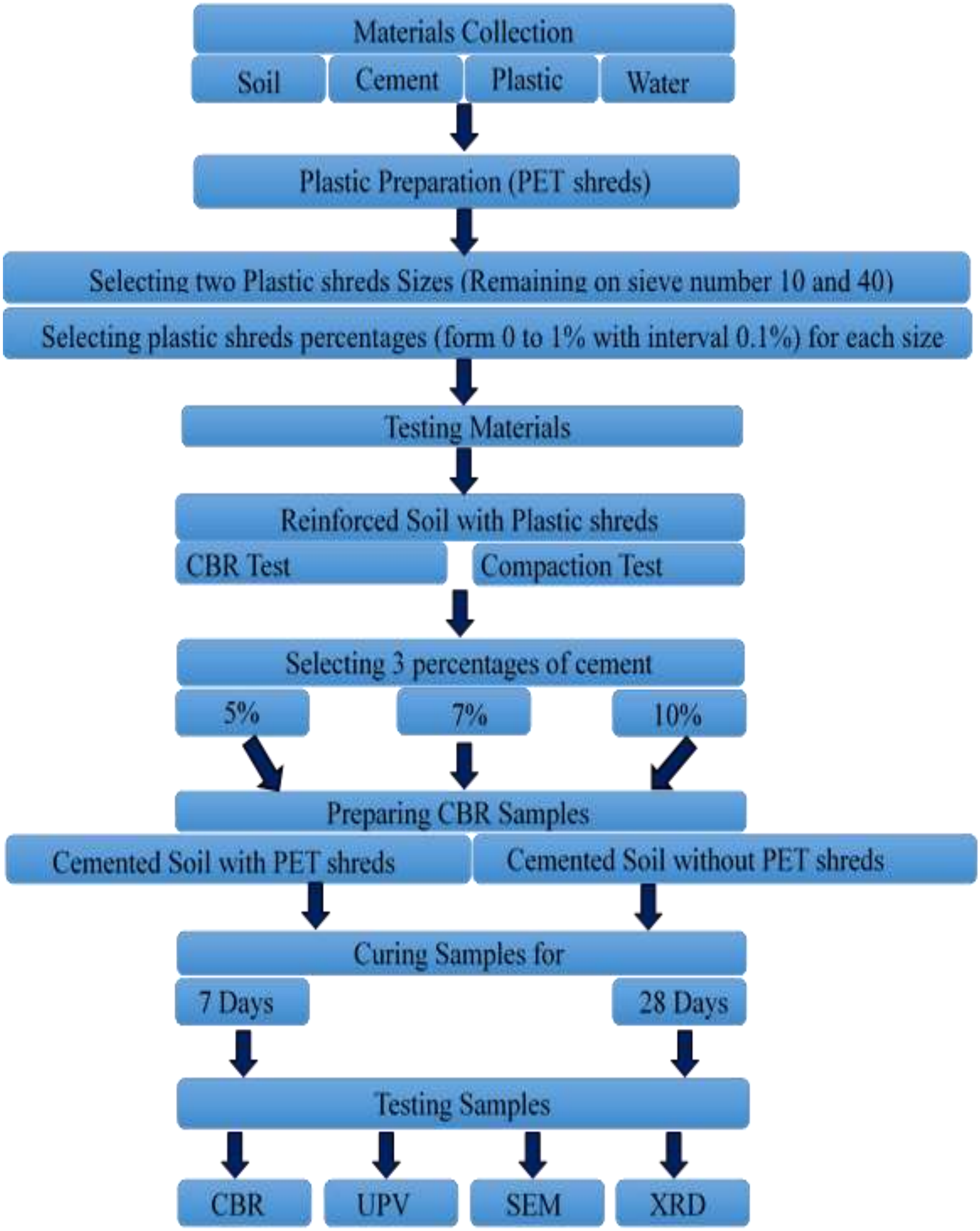


Figure 3.1: Experimental work plan

3.2 Materials

The materials used in this research included: clay soil, PET plastic waste bottles, cement, and water.

3.2.1 Soil

The soil sample used in this study has been brought from a site which is located in Duhok governorate in the north of Iraq (36°59'24.5"N and 42°39'20.7"E) about 500 km away from the Iraqi capital, Baghdad as shown in (Figure 3.2 and Figure 3.3).

Figure 3.2: A satellite map of location of the sample

Figure 3.3: Location of the sampling

The disturbed sample was obtained after removing 50 cm of the soil surface. In order to classify the type of soil and its various geotechnical properties the standardized tests were carried out as follows:

A. Specific Gravity Test of Soil

The test was carried out for a sample of soil according to ASTM D 854. By using a water pycnometer, the specific gravity of the soil was determined as shown in Figure 3.4.

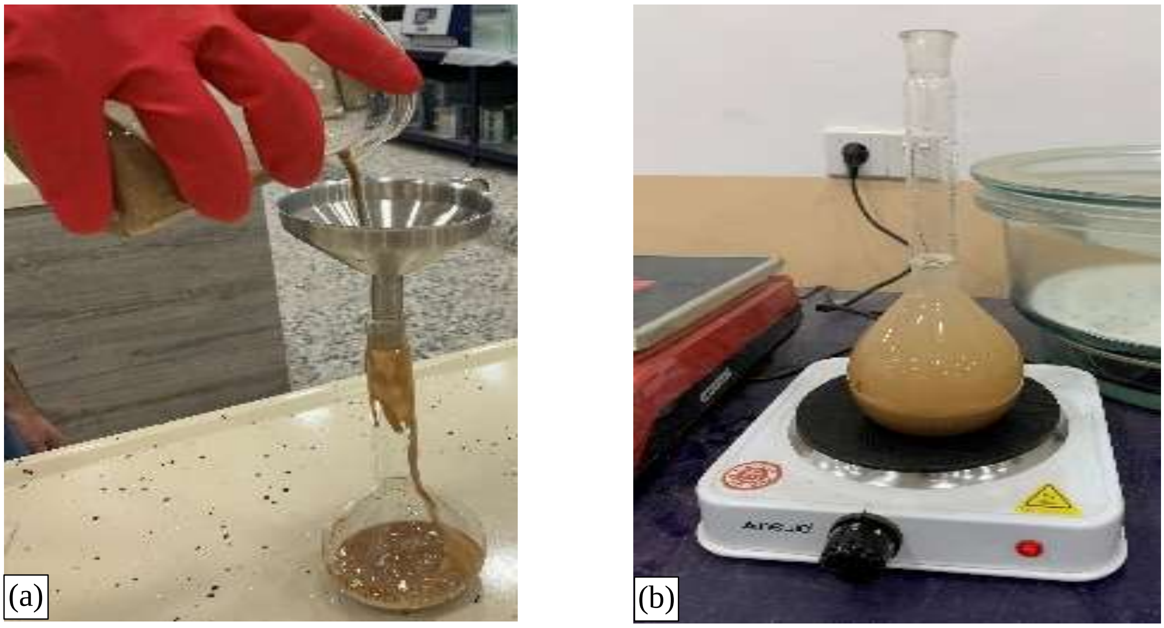


Figure 3.4: Specific gravity test of soil (a) Puring the mix into the pycnometer and (b) getting the bubles out of the mix

B. Grain Size Analysis

The test was performed on a soil sample in accordance with ASTM D 422. The sieve analysis is used to determine the gradation of the coarse particles as shown in Figure 3.5a, and the finer particle gradation is determined by using the hydrometer method as shown in Figure 3.5b

Figure 3.5: (a) Sieve analysis test of soil and (b) Hydrometer analysis test of soil

C. Atterberg Limits Test

The test was carried out for a sample of soil according to the procedure of ASTM D 4318-17e1 as shown in Figure 3.6, to establish the water contents at which fine-grained clay soil transitions between solid, semi-solid, plastic, and liquid states.

Figure 3.6: (a) Plastic limit test of soil and (b) Liquid limit test of soil

D. Standard Proctor Test

The Compaction Characteristic of the soils was determined using a standard proctor method that followed the ASTM D 698 procedure. The goal of this experiment is to determine the OMC at which the MDD can be achieved. The compaction mold could be seen in figure 3.7.

Figure 3.7: Compaction test of soil

The characterization tests results of natural soil are presented in Table 3.1. Figure 3.8 illustrates the soil grain-size distribution and Figure 3.9 presents plasticity chart for used soil.

Table 3.1: The characterization tests results of natural soil

Properties	Value	Standard
Liquid Limit (%)	37	ASTM D4318-17e1
Plastic Limit (%)	24	ASTM D4318-17e1
Plasticity Index (%)	13	ASTM D4318-17e1
Specific Gravity	2.70	ASTM D854-14
Classification	CL	ASTM D2487-17e1
MDD (kg/m^3)	1581	ASTM D698-12e2
OMC (%)	23.3	ASTM D698-12e2
CBR (%)	3.15	ASTM D1883-16

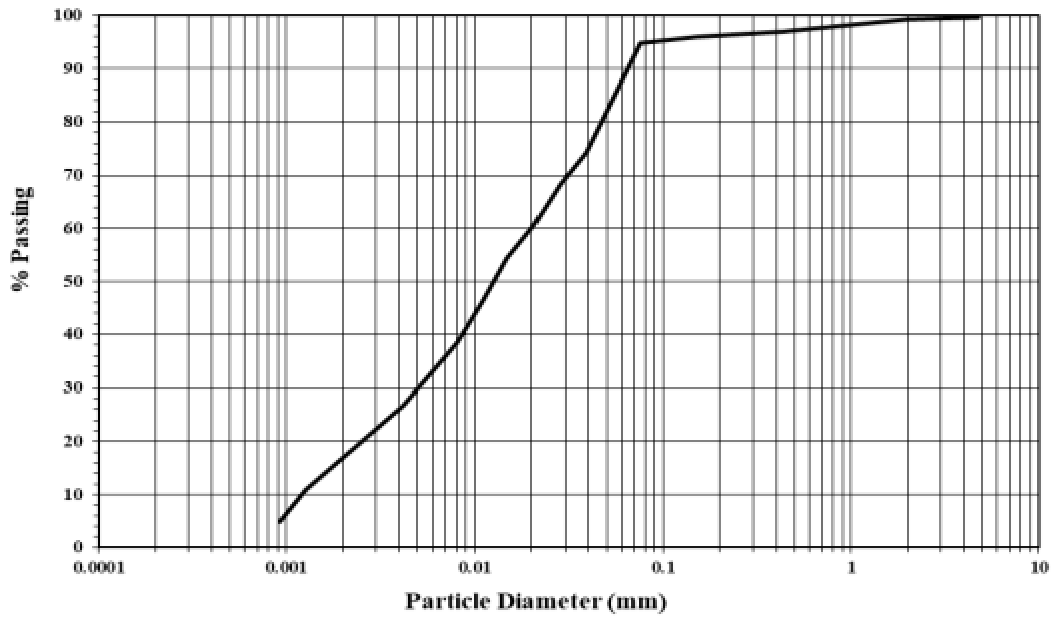


Figure 3.8: Grain size distribution of the Soil

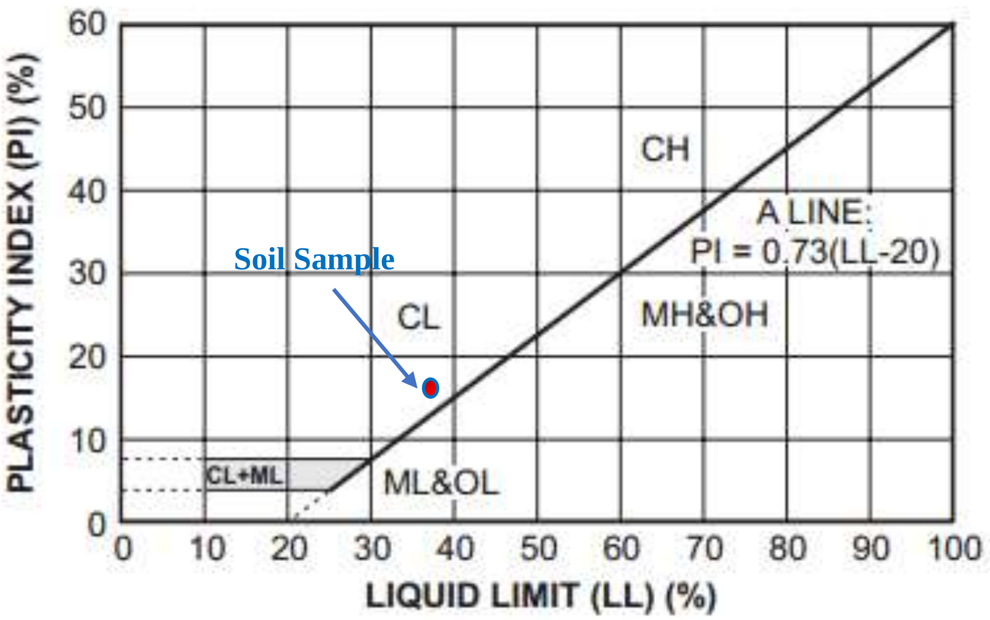


Figure 3.9: Plasticity Chart

The soil sample used for this research is specified as lean clay CL as per the Unified Soil Classification System (USCS). As shown in Table 3.1, the soil is weak since the CBR is less than 4%. Such subgrade requires special treatment before being used in construction. Hence, for pavement construction, stabilization is necessary.

Additionally, The Scanning Electron Microscopy (SEM) were carried out for the soil sample and it showed that the soil sample is rich in calcium and contains "hollow-like structures" as shown in Figure 3.10. Chemical characterization for the soil sample was conducted through Energy-dispersive X-ray spectroscopy (EDX) which is shown in in Figures 3.11.

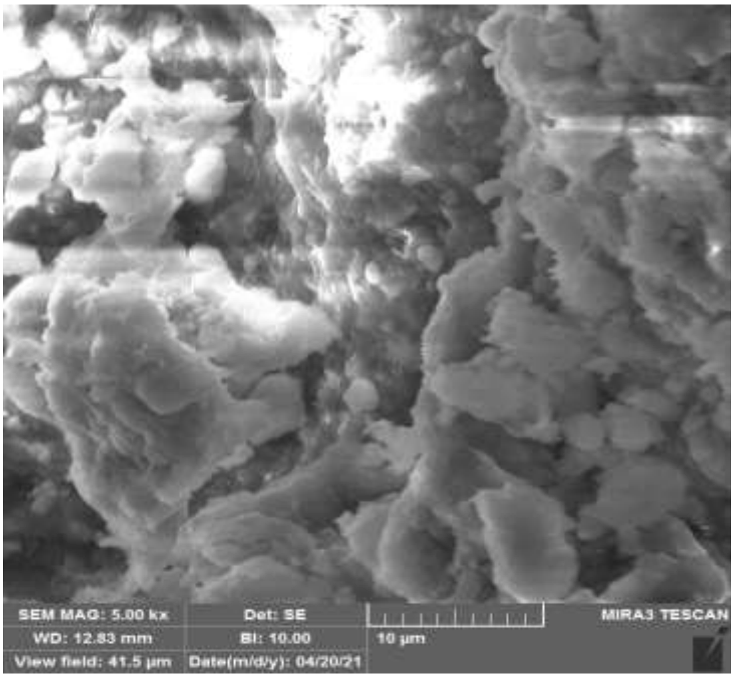


Figure 3.10: SEM of soil magnified x5000

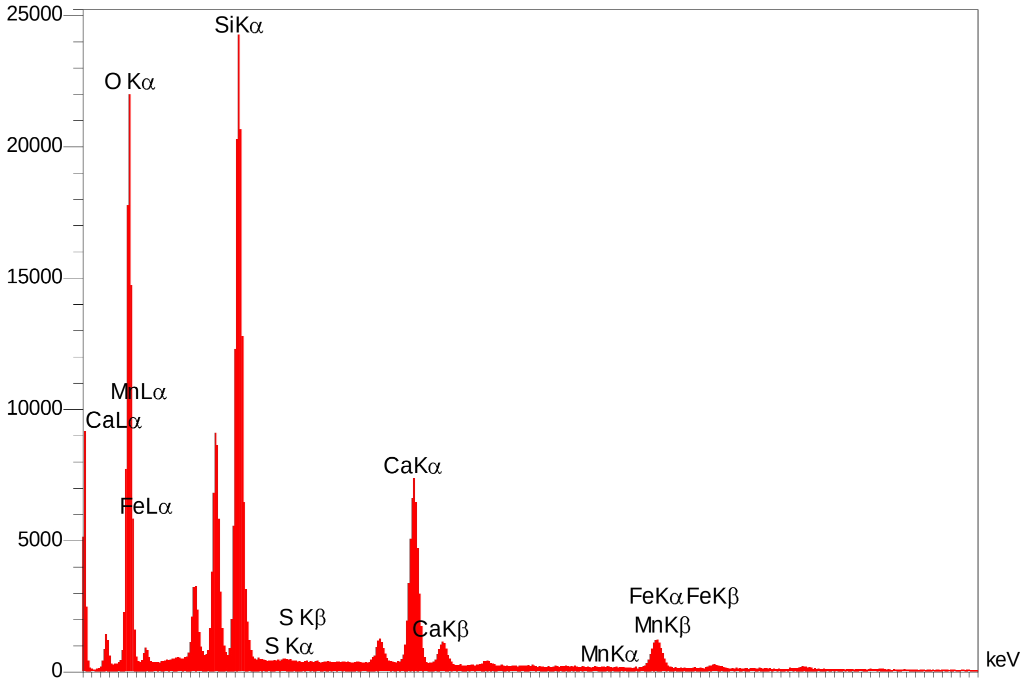


Figure 3.11: EDX of soil

3.2.2 Selection of Stabilizer

For determining the appropriate stabilizer agent for various soil types there are guidelines provided by various different standards. Virtually commonly used methods are provided in this section, which are Currin et al., (1976) method and US Army Corps of Engineers method.

3.2.2.1 Currin et al., Method

This method utilizes the content of fine-grained soils and the soil PI in choosing of stabilizing agent as seen in Figure 3.12. It was developed specially for subgrades stabilizing processes. As the soil utilized in this research is CL and from the chart, the proper stabilizer is shown as cement or lime.

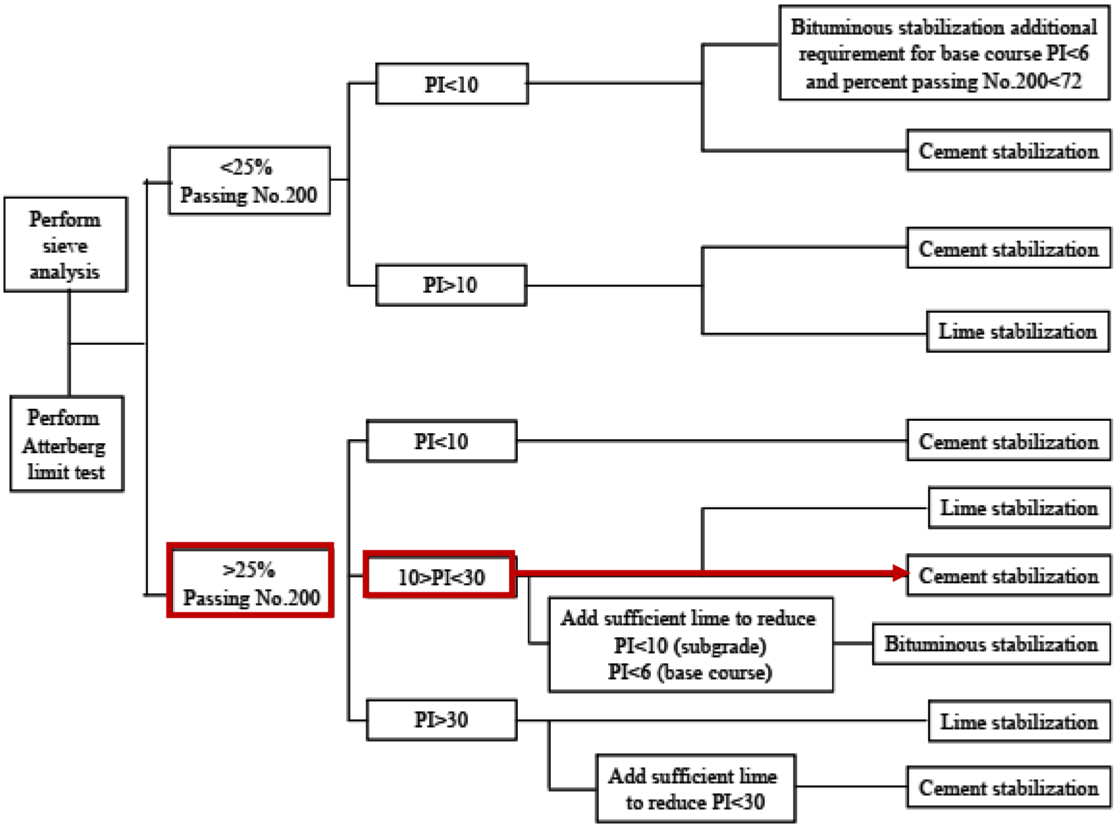


Figure 3.12: Determining of suitable agent (After Currin et al., 1976)

3.2.2.2 US Army Corps of Engineers Method

The US Army Corps of Engineers method supplies with instructions for soil treatment reasons. The types of stabilization are provided in Table 3.2. As the soil utilized in this research is CL, checking from the chart, the proper stabilizer would be cement.

Table 3.2: Determination of appropriate stabilizer (USACE, 1994)

Soils Class.[a]	Type of Stabilizing Additive Recommended	Restriction on LL and PI of Soil	on Percent Passing No. 200 Sieve[a]	Remarks
SW or SP	(1) Bituminous			
	(2) Portland Cement			
	(3) Lime-Cement-Fly Ash	PI not to exceed 25		
SW-SM or SP-SM or SW-SC or SP-SC	(1) Bituminous	PI not to exceed 10		
	(2) Portland Cement	PI not to exceed 30		
	(3) Lime	PI not less than 12		
	(4) Lime-Cement-Fly Ash	PI not to exceed 25		
SM or SC or SM-SC	(1) Bituminous	PI not to exceed 10	Not to exceed 30 percent by weight	
	(2) Portland Cement	----b		
	(3) Lime	PI not less than 12		
	(4) Lime-Cement-Fly Ash	PI not to exceed 25		
GW or GP	(1) Bituminous			Well-graded material only
	(2) Portland Cement			Material should contain at least 45 percent by weight of material passing No. 4 sieve
	(3) Lime-Cement-Fly Ash	PI not to exceed 25		
GW-GM or GP-GM or GW-GC or GP-GC	(1) Bituminous	PI not to exceed 10		Well-graded material only
	(2) Portland Cement	PI not to exceed 30		Material should contain at least 45 percent by weight of material passing No. 4 sieve
	(3) Lime	PI not less than 12		
	(4) Lime-Cement-Fly Ash	PI not to exceed 25		
GM or GC or GM-GC	(1) Bituminous	PI not to exceed 10	Not to exceed 30 percent by weight	Well-graded material only
	(2) Portland Cement	---b		Material should contain at least 45 percent by weight of material passing No. 4 sieve
	(3) Lime	PI not less than 12		
	(4) Lime-Cement-Fly Ash	PI not to exceed 25		
CH or CL or MH or ML or OH or OL or ML-CL	(1) Portland Cement	LL less than 40 and PI less than 20		Organic and strongly acid soils falling within this area are not susceptible to stabilization by ordinary means
	(2) Lime	PI not less than 12		

Based on both methods the cement is the proper stabilizing agent, as a result cement was chosen as the stabilizing agent.

3.2.3 Cement

The used cement in current research as a binding agent is Ordinary Portland Cement (OPC) Type I, according to ASTM C150 / C150M-18. Basic properties tests of cement such as fineness, specific gravity, and setting time were conducted according to ASTM C204-18e1, ASTM C188-17, and ASTM C191-19, respectively as shown in Figures 3.13-3.15.

Figure 3.13: Fineness of Hydraulic Cement

Figure 3.14: Specific gravity test of cement

Figure 3.15: Setting Time Test of cement

The cement used satisfied the ASTM C150 requirements for Type I cement, according to Portland Cement Association (PCA), the cement to be used in soil stabilization should fulfill the minimum given requirements in Table 3.3. Table. 3.3 also illustrates the results of the basic tests which were carried out on the cement. Additionally, the SEM was carried out for the used cement sample and it showed that the used cement is rich in calcium as shown in Figure 3.16. Chemical analysis for the cement was performed through EDX and which is shown in Figure 3.17

Table 3.3: Results of cement tests

Type	**Value**	**ASTM C150 Requirements**	**Standard**
Specific Gravity	3.15	-	ASTM C188-17
Fineness (m^2/kg)	403	Minimum = 260	ASTM C204-18e1
Initial setting time (min)	180	Not less than = 45	ASTM C191-19
Final setting time (min)	230	Not more than = 375	ASTM C191-19

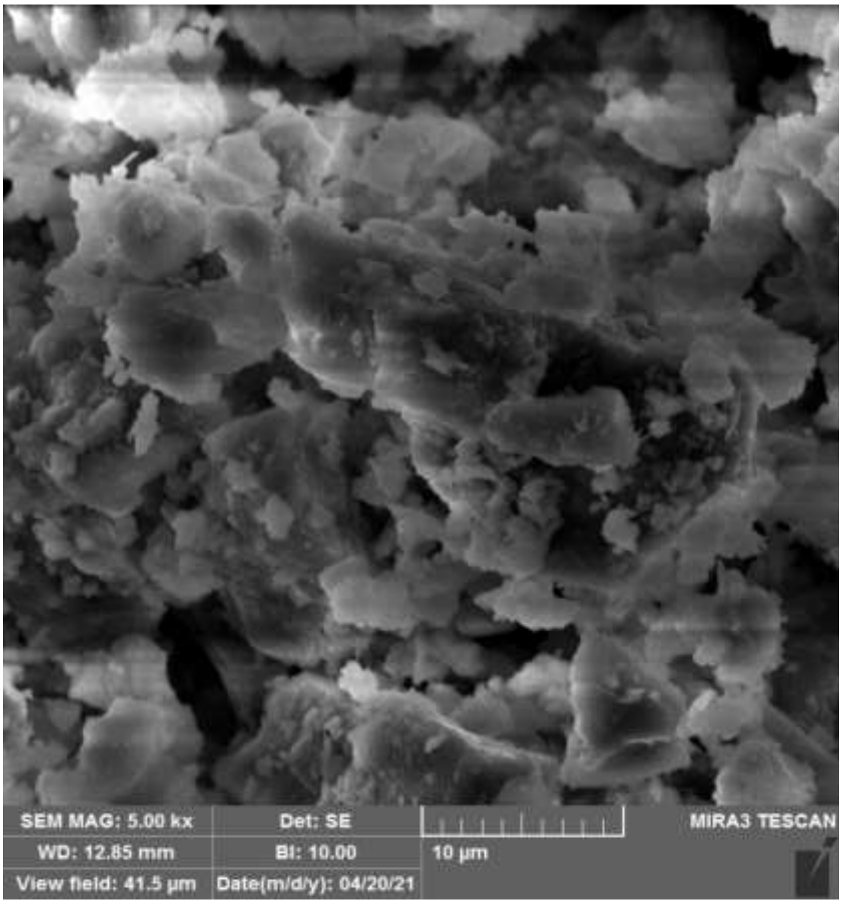


Figure 3.16: SEM of cement Magnified x5000

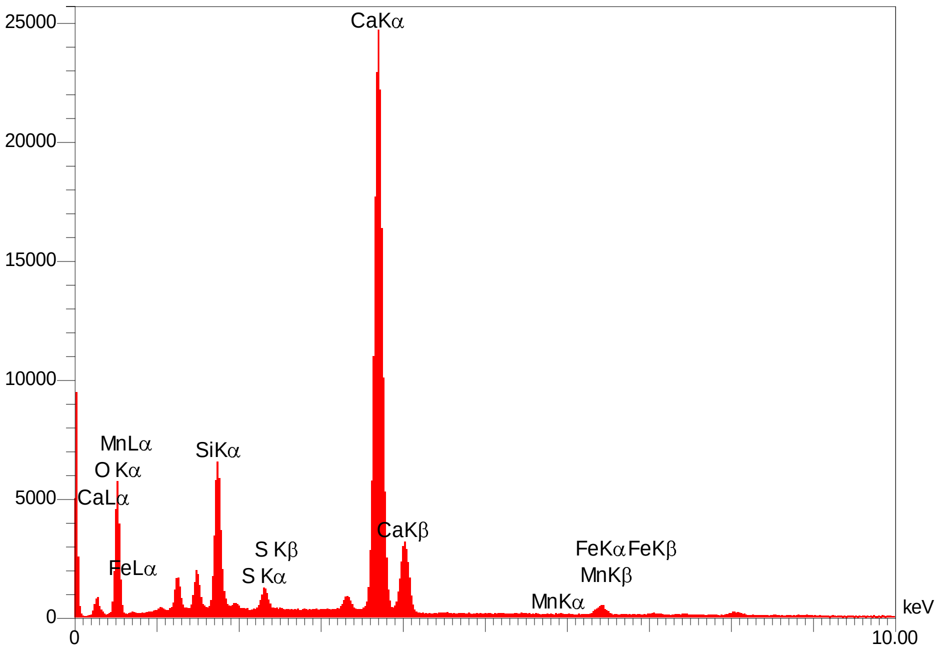


Figure 3.17: EDX of cement

3.2.3.1 Cement addition content

The content of cement to be added to soil for stabilizing purposes is considered to be a very critical issue, because if the content is high, it will not be economic neither eco-friendly, and if it is too low there will be no benefit from adding it.

3.2.3.1.1 Currin et al., method

Currin et al., method provides a table to select the usual cement content to be added on the bases of type of soil. As the soil in this research was CL, from table the usual content is about 9 to 15%.

Table 3.4: Determination of appropriate cement content, (After Currin et al., 1976)

AASHO Soil Classification	Unified Soil Classification[a]	Usual Range in Cement Requirement[b]		Estimated Cement Content Used in Moisture-Density Test (percent by weight)	Cement Content for Wet-Dry and Freeze-Thaw Tests (percent by weight)
		Percent by Volume	Percent by Weight		
A-1-a	GW, GP, GM, SW, SP, SM	5 to 7	3 to 5	5	3 to 5 to 7
A-1-b	GM, GP, SM, SP	7 to 9	5 to 8	6	4 to 6 to 8
A-2	GM, GC, SM, SC	7 to 10	5 to 9	7	5 to 7 to 9
A-3	SP	8 to 12	7 to 11	9	7 to 9 to 11
A-4	CL, ML	8 to 12	7 to 12	10	8 to 10 to 12
A-5	ML, MH, OH	8 to 12	8 to 13	10	8 to 10 to 12
A-6	CL, CH	10 to 14	9 to 15	12	10 to 12 to 14
A-7	OH, MH, CH	10 to 14	10 to 16	13	11 to 13 to 15

3.2.3.1.2 U.S. Army Corps of Engineers Method

The Army Corps of Engineers manuals gives a way to estimate the cement content to be added on the base of the AASHTO classification of soil and states that the process of identifying the cement content is based on the trial. As the soil in this research was CL, from Table 3.5 the estimated content of cement is about 10%.

Table 3.5: Determination of appropriate cement content (USACE, 1994)

Soil Classification[a]	Initial Estimated Cement Requirement Percent Dry Weight
GW-SW	5
GP, SW-SM, SW-SC, SW-GM, SW-GC	6
GM, SM, GC, SC, SP-SM, SP-SC, GP-GM GP-GC, SM-SC, GM-GC	7
SP, CL, ML, ML-CL	10
MH, OH	11
CH	10

Because both methods recommend to use 10%, this percentage was used in this research and the other trial percentages were selected as 5% and 7%. The reason of choosing these trial percentages is that this research tries to reduce the environmental problems and try to achieve the desired properties with lower amounts of cement and therefore provide a better economic solution. Also, the literature showed that the higher cement content can increase the risk of crack occurrence in the soil, as a result lower cement contents were tried.

3.2.4 PET Shreds

The PET shreds involved in this study were produced from waste PET plastic water bottles. Where two sizes were selected, the first size is size10, which is passing sieve No. 4 and remaining on sieve No. 10 and the second size is size (40) which passing sieve No. 20 and remaining on sieve No. 40. The characteristics of the PET were gotten from the manufacturer company and they are shown in Table 3.6. Moreover, the SEM was carried out for the used PET shreds as shown in Figure 3.18 and elemental analysis for the PET shreds was done through EDX and which are illustrated in Figure 3.19

Table 3.6: Properties of PET shreds

Type	Value
Water Absorption (%)	0.16
Specific Gravity	1.3 – 1.4
Melting Point (°C)	260
Modulus of Elasticity (GPa)	2.8– 3.1
Tensile Strength (GPa)	0.055 – 0.075

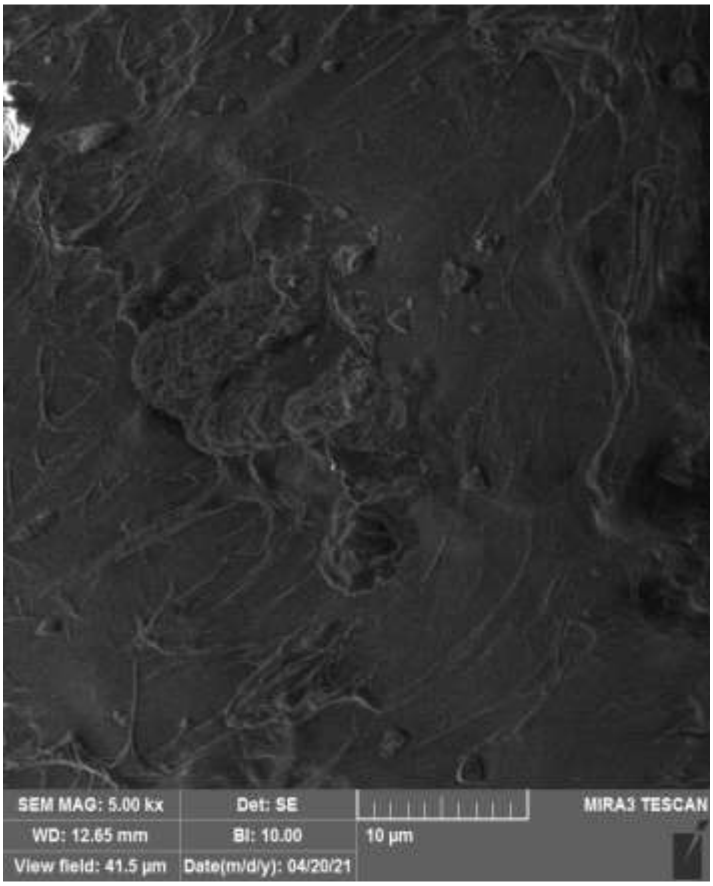


Figure 3.18: SEM of PET shreds maginfied x5000

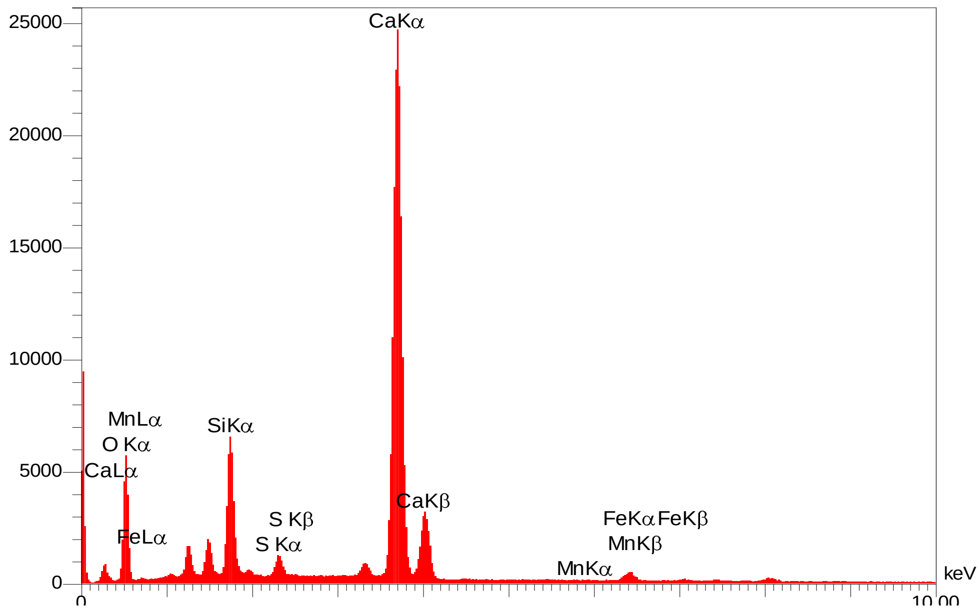


Figure 3.19: EDX of PET shreds

3.2.4.1 Plastic preparation

A. About 2000 PET bottles were collected through local shops and they were cleaned. Then the caps and bottom and label of the bottles were removed by scissors as shown in Figure 3.20.

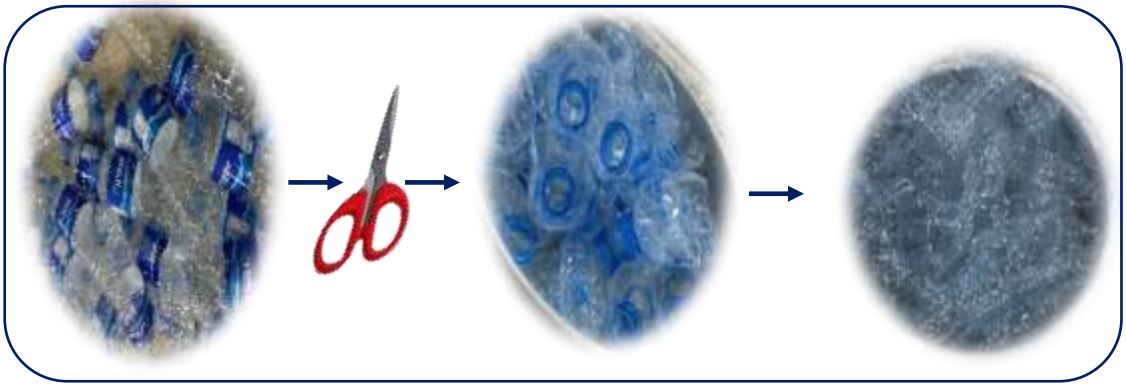


Figure 3.20: Removing the caps and bottom and label of the bottles by scissors

B. The bottles were cutting into strip with varying dimensions by scissors as shown in Figure 3.21.

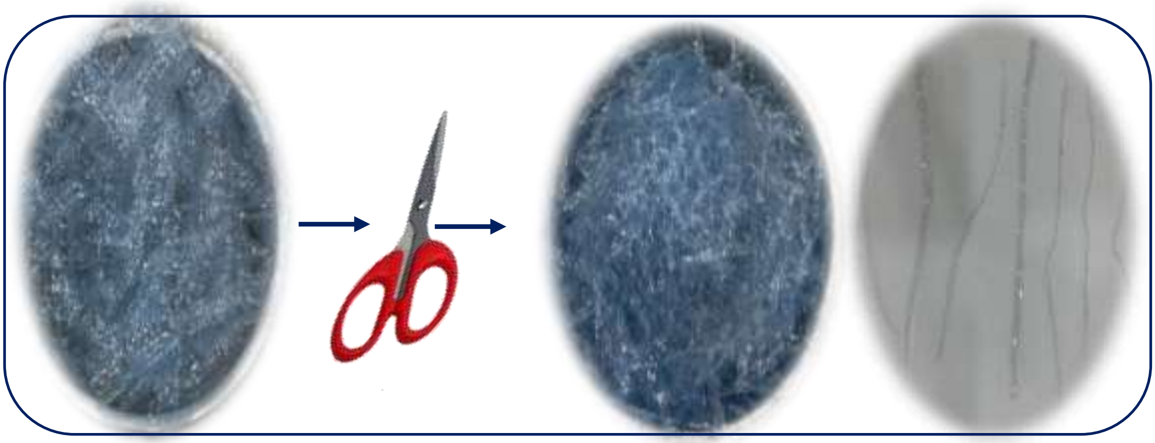


Figure 3.21: Cutting process of plastic bottles

C. Then the plastic strip were grinded into plastic shreds using grinder as shown in Figure 3.22.

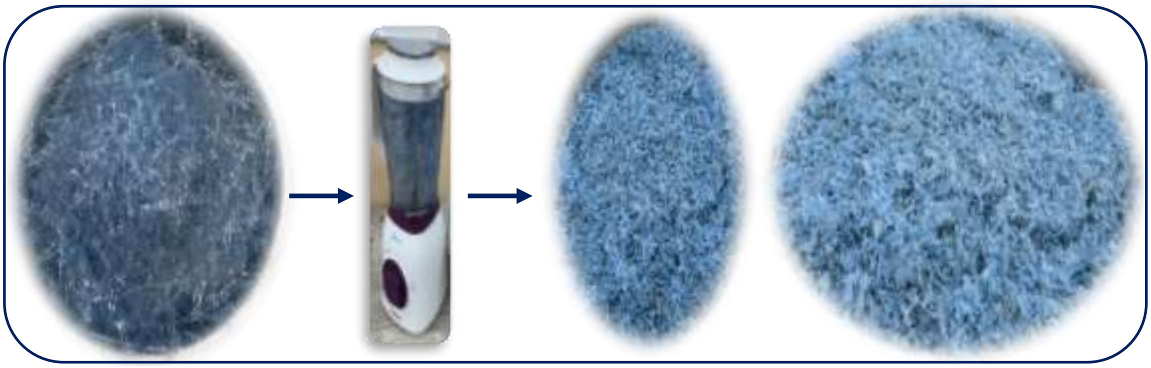


Figure 3.22: Grinding process of plastic bottles

D. Finally, the shreds were sieved to obtain the specified sizes. The first size is size 10 which is passing sieve No. 4 and remaining on sieve No. 10 and the second size is size 40 which passing sieve No. 20 and remaining on sieve No. 40 as can be seen in Figure 3.23. The percentages added were from 0.1 to 1.0% and that is because many studies in the literature recommend to use low percentages of PET.

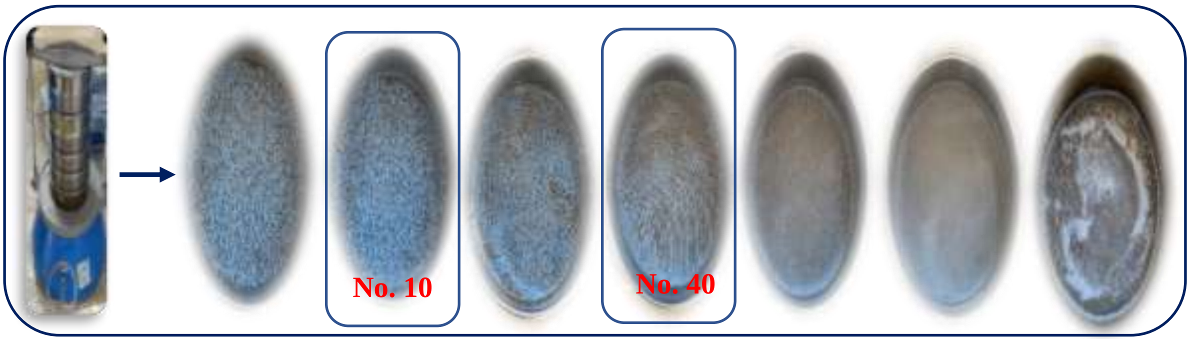


Figure 3.23: Sieving plastic bottles shreds

3.2.5 Water

Distilled water was used to mix and cure the samples which satisfies PCA requirements for water to be used in cement stabilization. Where, according to PCA, the water used in soil-cement should be relatively clean and free from harmful amounts of alkalies, acids, or organic matter. Water fit to drink is satisfactory.

3.3 Specimens Molding and Curing

For the purpose of studying the effects of PET shreds on soil strength was studied to find out the optimum percentages range of plastic bottle shreds, where California Bearing Ratio (CBR) was used as a strength indicator. Where, 11.62 cm high and 15.24 cm diametric cylindrical specimens were used according to ASTM D1883-16. The CBR tests specimens in this stage were prepared at maximum dry density (MDD) and optimum moisture content (OMC). After that, the quantities of clay and PET shreds were measured based on the MDD then blends were blended for at least 5 min and the water was added and the blends were blended well. Eventually, specimens were being tested for CBR. Figure 3.24 shows the process of reinforcing soil with PET shreds.

Figure 3.24: Reinforcing soil with PET shreds process (a) Soil, (b) Mix of soil and PET, (c) CBR mold, (d) Putting mix in CBR mold, (e) Compacting layers of mix, and (f) Molded sample

In addition, to study the effect of reinforcing cemented soil with PET shreds. Where, CBR and Ultrasonic Pulse Velocity (UPV) were conducted and for both tests cylindrical specimens which are 11.62 cm high and 15.24 cm diametric. Where, the chosen dry density was specified which was 1.4 kg/m3 based on soil's MDD at OMC. Then, the proportions of clay, cement, and PET shreds were measured based on the foregoing density. The dry materials were blended by hand for at least 5 min until a uniform blend was visually obtained. Then, the premeasured quantity of distilled water was added and mixed by hands mixing until a homogeneous paste in appearance was gotten. Each sample was molded in five layers inside a cylindrical mold statically. The blending and preparing of specimens were finished in less than initial setting time of the cement. After forming the specimens, they were removed out of molds and specimens' dimensions were measured. Finally, the samples were fastened in plastic bags, and cured according to ASTM C511-19. Figure (3.25-3.27) shows the process of stabilizing soil with cement and reinforcing with PET shreds. The details of sampling and curing data are presented in Table 3.7

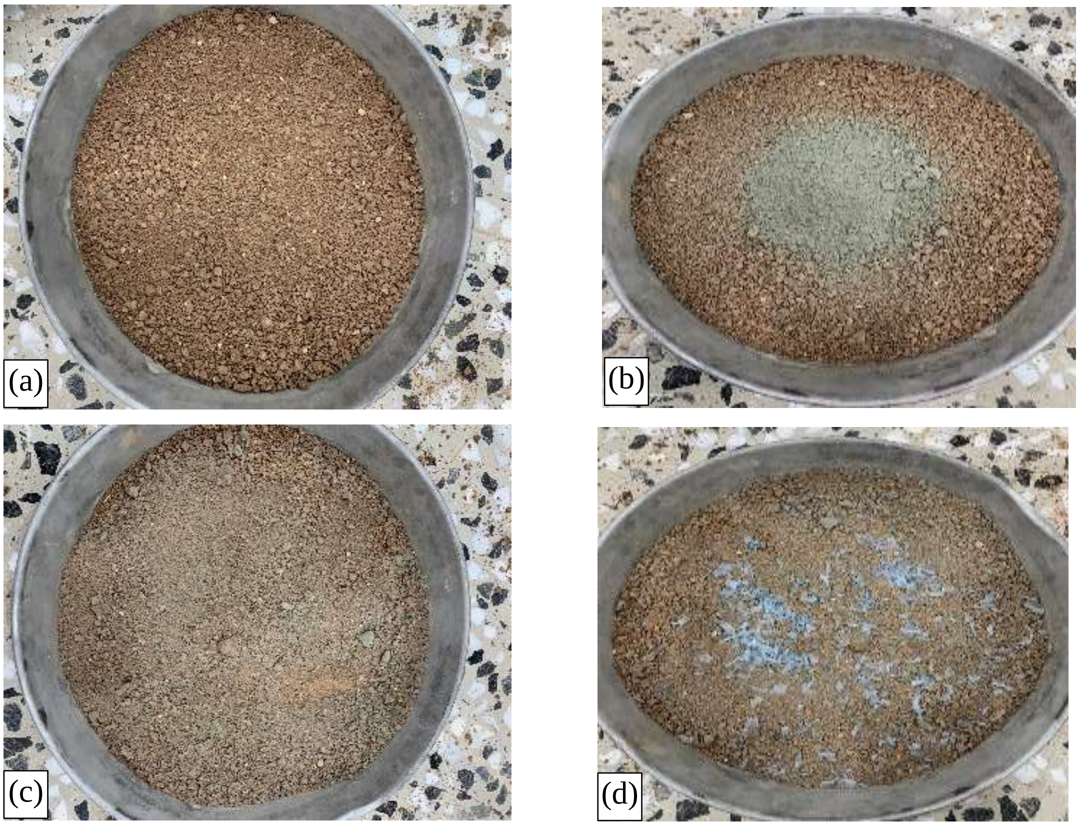


Figure 3.25: Process of stabilizing soil with cement and reinforcing with PET shreds (a) Soil, (b) Adding cement to soil, (c) Mixing soil and cement, and (d) Adding PET to cemented soil

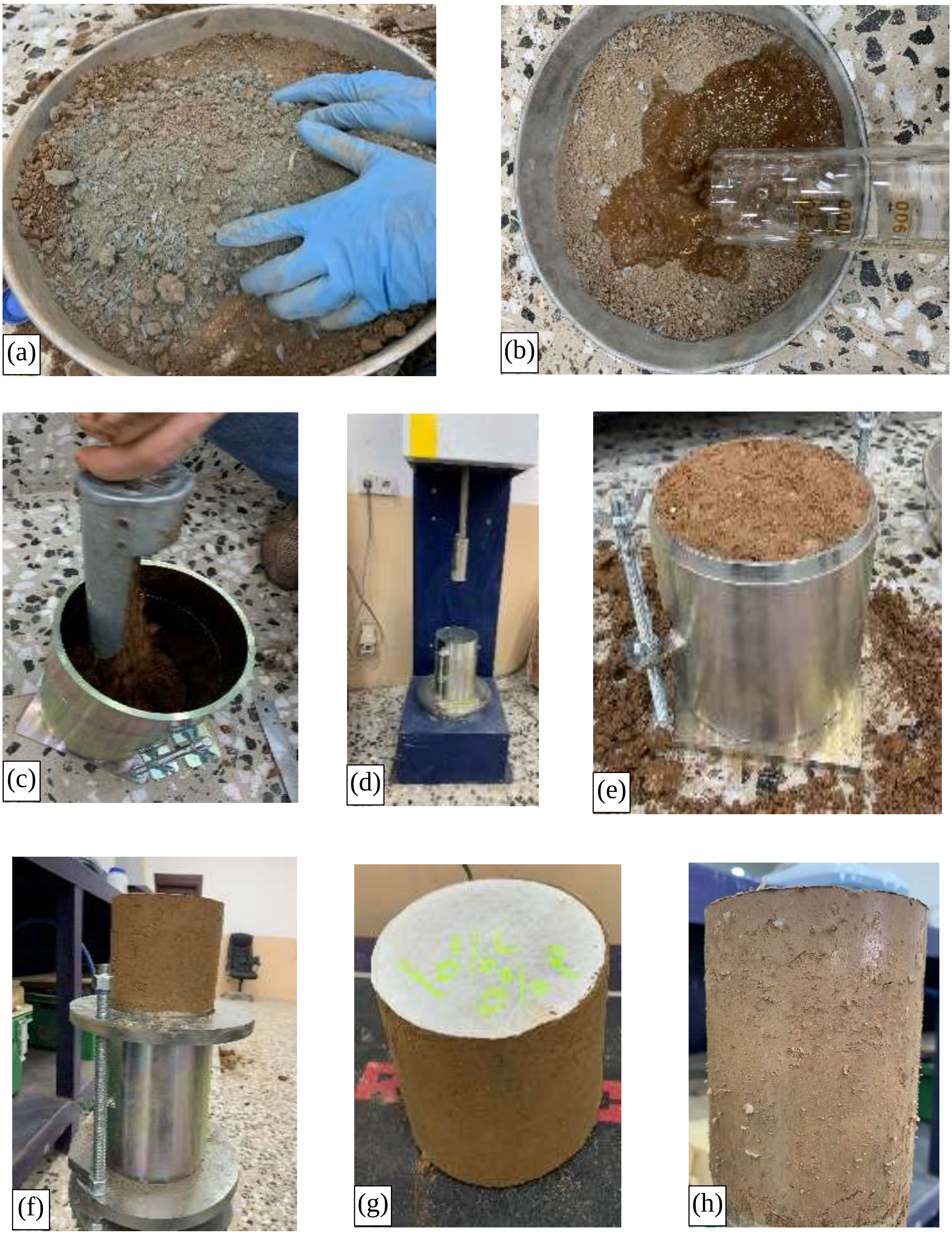


Figure 3.26: Process of stabilizing soil with cement and reinforcing with PET shreds (a) Mixing Pet and cemented soil, (b) Adding water to mix, (c) Putting mix in mold, (d) Compacting layers of mix, (e) Molded sample, (f) Sample extruding, (g) Cemented soil sample, and (h) PET- Cemented soil sample

Figure 3.27: Curing process of stabilizing soil with cement and reinforcing with PET shreds (a) Curing of Cemented soil sample for 7 days, (b) Curing of Cemented soil sample for 28 days, (c) Curing of PET- Cemented soil sample for 7 days, and (d) Curing of PET- Cemented soil sample for 28 days

Table 3.7: Details of sampling and curing data

Mix	Soil Type	Cement Content (%)	PET Shreds Content (%)	PET Shreds Size (Sieve No.)		Dry Molding Density (g/cm^3)	Curing Periods (Days)	Test Type
Soil + PET shreds	Clay	-	0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0	Passing No. 4 and Remaining on No. 10	Passing No. 20 and Remaining on No. 40	MDD	-	Compaction and CBR
Soil + Cement + PET shreds	Clay	5 7 10	0.6 0.7 0.8	Passing No. 4 and Remaining on No. 10	Passing No. 20 and Remaining on No. 40	1.4	7 & 28	CBR, UPV, and *SEM and XRD

* SEM and XRD were done to all the samples with 7% Cement, 0.7% PET shreds considering 7 and 28 days of curing.

Moreover, for the purpose of calculating porosity a modified version of porosity Equation (3.1) was used, which was generated by (Consoli, et al., 2018a) where, porosity (η) in this equation is expressed as a function of the dry density (ρ_d), soil mass content (M_S), cement mass content (M_C), and PET shreds mass content (M_{PET}), soil cement (ρ_S), cement density ($\rho_{C'}$), and unit PET shreds density (ρ_{PET}).

$$\eta = 100 - 100\left[\left(\frac{\rho_d}{M_S + M_C + M_{PET}}\right) \times \left(\frac{M_S}{\rho_S} + \frac{M_C}{\rho_C} + \frac{M_{PET}}{\rho_{PET}}\right)\right] \qquad (3.1)$$

Also, a relationship based on the cement/porosity index (η/Civ) was generated to predict the performance of soils-cement blends (Consoli et al., 2016), this relationship can just be used for cement. But, Ekinci, et al. (2019) introduced a general index (Xiv), which can be used for each binder. Therefore, to predict the CBR and G_0 for blends this proposed index was modified, where Xiv was evaluated from the Equation (3.2), where $V = M/\rho$ is applicable for each of the employed materials.

$$X_{iv} = \frac{V_C + V_{PET}}{V} = \frac{\left(\frac{M_c}{\rho_c}\right) + \left(\frac{M_{PET}}{\rho_{PET}}\right)}{V} \tag{3.2}$$

where, X_{iv} is the modified index for this research, V_C is the cement volume and V_{PET} is the PET shreds volume, V is the specimen total volume, M_c is the cement mass content, M_{PET} is the PET shreds mass content, ρ_c is the cement density, ρ_{PET} is the PET shreds density.

The 0.32 external exponent of adjusted porosity/binder index was mentioned to be the best-fit exponent in this study and other previous studies (Hanafi. et al. 2020; Ekinci, et al., 2020; 2020). . The 0.32 choosing was based on the literature where, studies that were conducted for several kinds of soils revealed that the exponent varies between 0.28 and 0.35 (Consoli et al., 2017a; 2018).

3.4 Laboratory/Experimental Tests

3.4.1 Standard Proctor test

Compaction is the soil compressing by removing air, which demands mechanical force, and the soil compression is presented in the matter of dry density (Das, 2010). The Standard Proctor compaction tests were carried out on soil and soil mixed with PET shreds made of plastic waste bottles according to ASTM D 698, to determine the soil's MDD and OMC and soil mixed with PET shreds, therefore a comparison between them can be done and the effect of PET shreds can be studied. The soil was placed in the mold of volume of 943.69 cm^3 in three equal layers and every layer was compacted 25 blows by an automatic compactor which has a mass of 2.5 kg and a diameter of 5.08 cm, which compact the soil with a free fall of 30 cm height. The blows were being applied uniformly on the face area of each layer.

The Figure 3.28 illustrated compaction process while procedure of compaction test is presented in Figure 3.29. These steps were hold for a couple of water contents so that a curve between water content and dry density can be drawn to get the MDD and OMC. The compactor used in this study was MATEST N199 automatic compactor. The dry density can be gotten by the following formula:

$$P_d = \frac{P_b}{1 + W_c} \tag{3.3}$$

$$P_b = \frac{\text{Weight of compacted moist soil}}{\text{Volume of mold}} \tag{3.4}$$

$$W_c = \frac{\text{Weight of water}}{\text{Weight of dry soil}} \tag{3.5}$$

Where, P_d is the dry density, P_b is the bulk density, and W_c is the water content

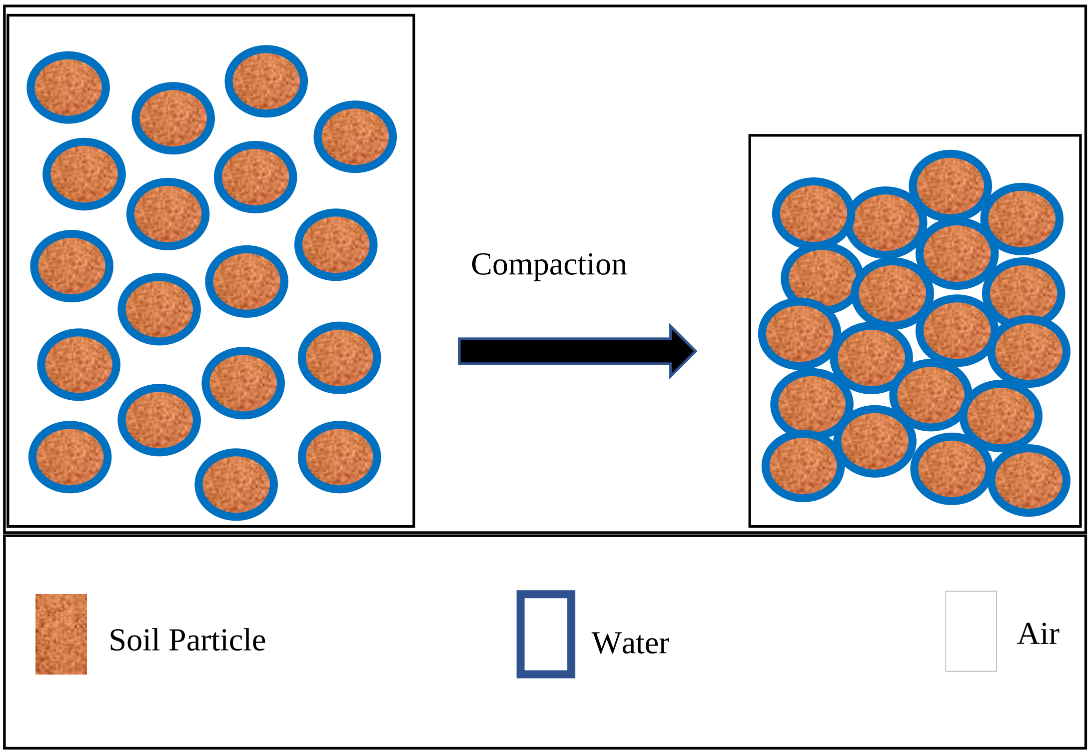


Figure 3.28: Compaction process

(a) Soil

(b) Adding water to soil

(c) Compaction mold

(d) Putting soil mix in compaction mold

(e) Compacting layers of mix

(f) Molded sample

(g) Weighing of molded sample

(g) Sample extruding

Figure 3.29: Procedure of compaction test

3.4.2 California Bearing Ratio (CBR)

This test method covers the determination of the CBR (California Bearing Ratio) of pavement subgrade, subbase, and base/course materials from laboratory compacted specimens. The objective of the test is to determine the relative strength of a soil with respect to crushed rock, which is considered an excellent coarse base material. CBR value obtained in this test forms an integral part of several flexible pavement design methods. CBR test is the calculation of the ratio of bearing of a soil in terms of relation between load and penetration, where the penetration piston is loaded into the soil sample with a rate of 1.27 mm/min. The value of CBR is indicated as a percentage of the actual load generating the 2.5 mm or 5.0 mm penetrations to the standard loads and the higher value to be utilized (O‟Flaherty, 2002). In this study, a MATEST S205N testing machine with sample size of 11.62 cm in height and 15.24 cm diameter was used for the CBR tests. The test was conducted for specimens of soil and PET shreds blends, and also for the specimens of soil, cement, and PET shreds blends. The specimens without cement were tested right after molding, while the specimens with cement were cured for 7 and 28 days, then they were tested for CBR tests. The tests were conducted as per the standard ASTM D1883-16. To get each CBR value, three CBR molds were prepared. Figure 3.30 shows that the soil sample in CBR mold and the procedure of CBR test presented in Figure 3.31. In each mold, the soil was compacted in 5 layers, but the blows were different, the first mold with 10 blows, the second mold with 25 blows and the third mold is with 56 blows. Later, by drawing the CBR of each mold with its calculated dry density in one curve, the CBR value was obtained depending on 95% of required density. The CBR of a mold at a 2.5 mm or 5 mm penetration can be calculated by the formula below:

$$CBR = \frac{Total\ load}{Standard\ load\ of\ crushed\ rock\ given\ in\ ASTM\ D1883} \times 100 \quad (3.6)$$

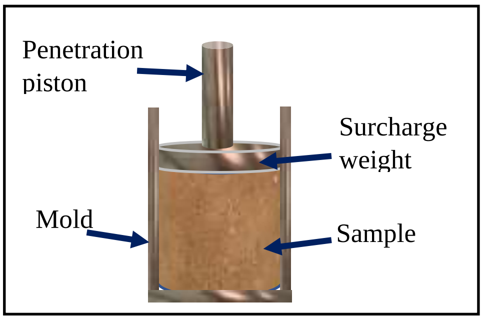


Figure 3.30: CBR test

(a) Molded sample

(b) Surcharge weight put on sample

(c) Sample under Penetration piston

(d) Sample testing

(e) Sample extruding

(f) Moisture content sample

(g) Oven drying sample

(h) Weighing sample

Figure 3.31: Procedure of CBR test

3.4.3 Ultrasonic Pulse Velocity (UPV)

Ultrasonic pulse velocity test was conducted as per ASTM D2845-08 and was used to estimate the shear modulus (G0) for the same specimens of CBR tests. After curing and before testing the samples for CBR, they were tested for UPV. The device employed was MATEST Ultrasonic Tester Model C368. Transducers were attached to the both edges of the specimens using grease as shown in Figure 3.32, where, the distance between the transducers was accurately calculated. Once the device was turned on, it sent waves and the waves travel time through the specimen was shown on the device. The procedure of UPV test is presented in Figure 3.33. The velocity was gotten substituting in the subsequent formula:

$$v = \frac{d}{t} \tag{3.7}$$

Where, v = the waves velocity from the device, d = the distance between the two transducers, and t = the waves travel time through the specimen.

The shear modulus was gotten from the subsequent formula:

$$G_0 = \rho \times v^2 \tag{3.8}$$

Where, G_0 denotes shear modulus ρ denotes the density of the specimen, and v^2 denotes waves velocity.

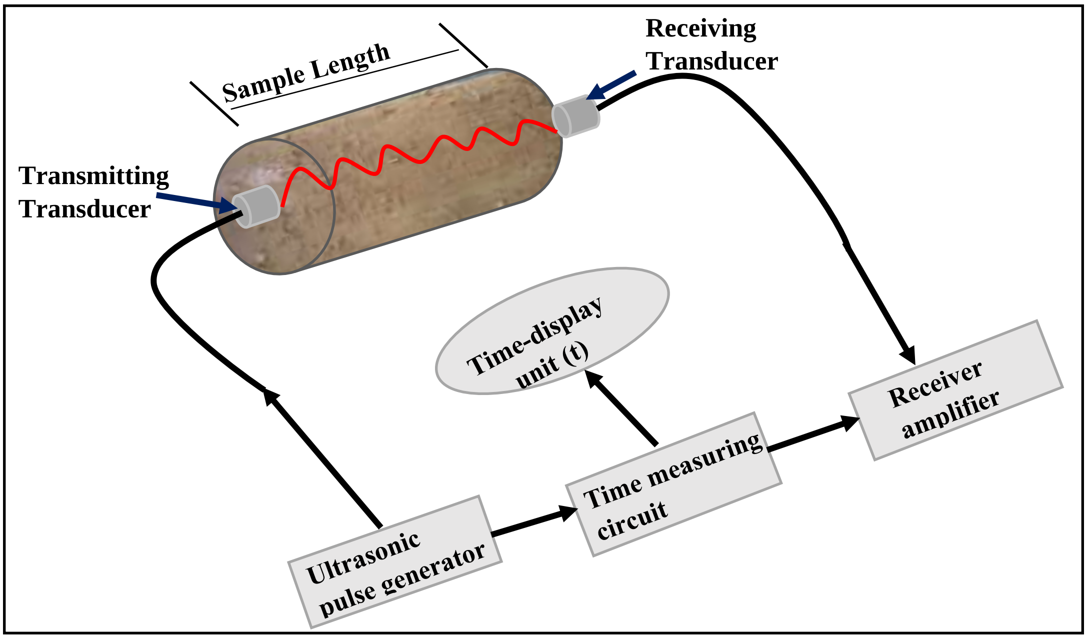


Figure 3.32: UPV sample testing

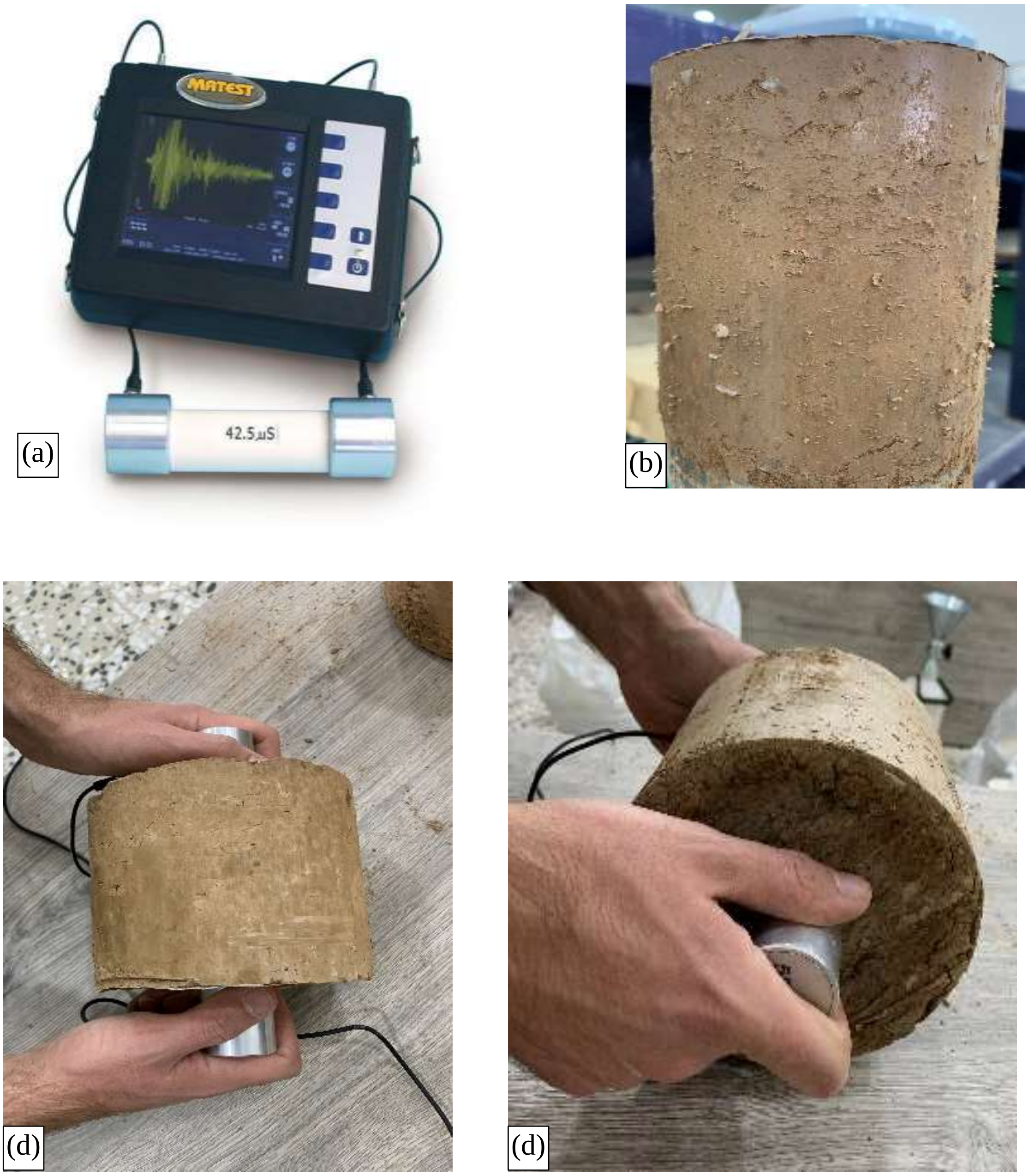


Figure 3.33: Procedure of UPV test, (a) UPV device, (b) Cured sample, (c) and (d) Sample testing

3.4.4 X-Ray Powder Diffraction (XRD)

X-ray diffraction is based on constructive interference between monochromatic X-rays and crystalline material. The X-rays are generated by a cathode ray tube, which is then filtered to produce monochromatic radiation, collimated to focus the beam, and directed towards the sample. The interaction of incoming rays with the sample creates constructive interference when Bragg's Law (n=2d sin) is fulfilled. This rule relates the wavelength of electromagnetic radiation to the diffraction angle and lattice spacing in a crystalline sample. The diffracted X-rays that have been detected, processed, and tallied are next examined. Scanning the sample across a range of 2 angles should give all possible lattice diffraction directions due to the random orientation of the powdered material. Converting diffraction peaks to d-spacings allows for mineral identification because each mineral has its own set of d-spacings. This is often done by comparing d-spacings to known reference patterns (Pathak and Lokhande, 2014).

X-ray diffraction (XRD) analysis was carried out on powder samples with Cu-closed x-ray tube (40KV, 40mA, and with Ni-filter) as shown in Figure 3.34. Intensities were measured in the range of $10° < 2\theta < 130°$. Soil mineralogy is the starting point for understanding the fundamentals of chemical stability. It also aids in detecting the types of clay minerals present in the soils under investigation so that the expansion potential of the soils may be assessed.

Figure 3.34: XRD test

3.4.5 Scanning Electron Microscope (SEM) Analysis

The Scanning Electron Microscope (SEM) is a microscope that uses electrons instead of light to form an image. The SEM uses electromagnets rather than lenses, the researcher has much more control in the degree of magnification. The scanning electron microscope has many advantages over traditional microscopes (Pathak and Lokhande, 2014).

Scanning Electron Microscope (SEM) was utilized to show the clay structure and analyze the pore space of different samples. In SEM, pictures are produced by scanning the sample with a high-energy beam of electrons. The electrons interact with the inherent electrons of the atoms. Because of this interaction, atoms of the sample produce signals. These signals contain information about the surface topography, composition and other properties.

The Scanning Electron Microscope (SEM) was carried out for the soil samples using VEGA 3 TESCAN scanning electron microscope operated at 20 KV as shown in Figure 3.35. Cube soil specimens (6 mm) were produced and dried before vacuuming. The tested soils were glued on aluminum holders to scan. The cracked surface of the soils was coated with gold instead of carbon to obtain micrographs with high quality. The micrographs were taken at a number of magnifications (100, 300, 1000, 5000, and 10000).

Figure 3.35: SEM test equipment

CHAPTER FOUR
RESULTS AND DISCUSSION

4.1 Introduction

The behaviors of the PET shreds reinforced soil and cemented soil-PET shreds waste composite was examined by focusing on the influence of percentage inclusion of PET plastic waste to the soil and cemented soil. Based on the various experiments elaborated in chapter 3, this chapter presents the test results, analysis and discussions. The tests were performed on plain soil, reinforced, stabilized with cement and cement with PET shreds. The plain soil worked as a base to investigate the PET sherds influence on utilized soil. Also, the cemented soil worked as a base to investigate the cemented soil with PET plastic influence.

4.2 Standard Compaction Test for Soil Reinforced with PET Shreds

The compaction test was carried on for plain soil and soil with both PET shreds sizes, the results are presented in Figure 4.1 and 4.2.

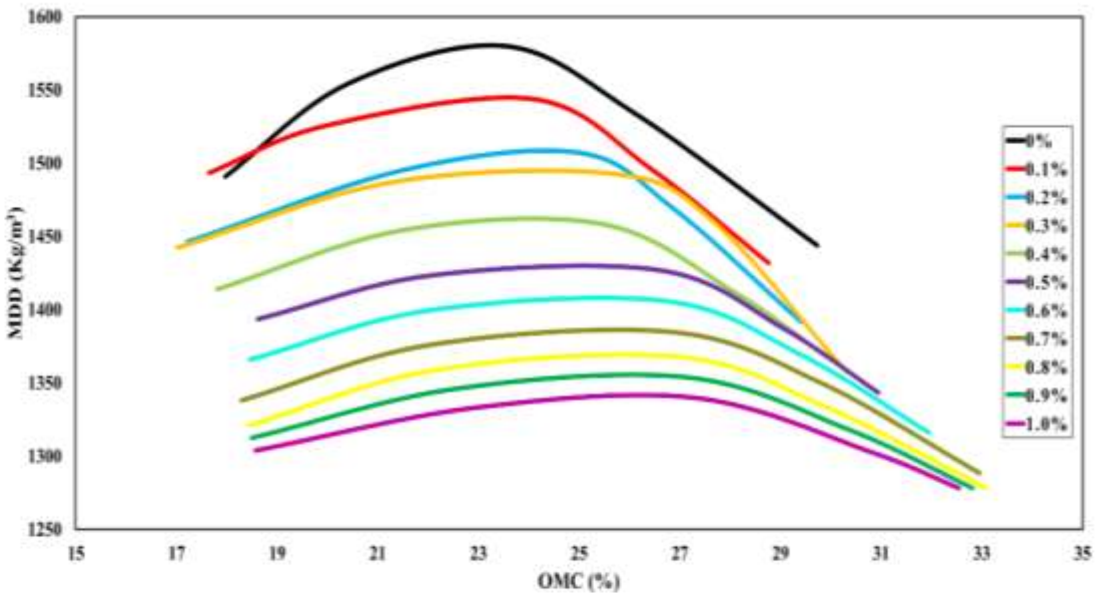


Figure 4.1: Relations between soil MDD and OMC of different PET shreds contents of size (10)

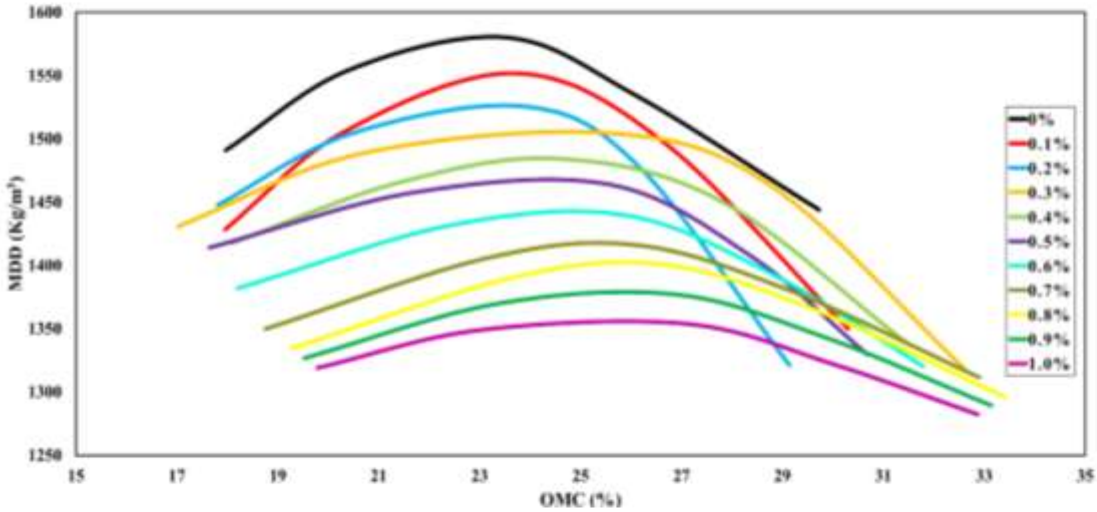


Figure 4.2: Relations between soil MDD and OMC of different PET shreds contents of size (40)

Figure 4.3 show that by PET shreds addition the moisture content was increased, the possible reason for this is probably the contact between soil and PET shreds as it requires a little more water so that PET shreds can fit in their place in the soil. Therefore adding more PET shreds results in increased OMC, these results confirm what was found by other researchers (Mai et al., 2017; Singh et al., 2017; Memon et al., 2019; Paramkusam et al., 2013; Mohammed et al., 2018; Kirubakaran et al., 2018) . Also, the size of PET had a slight effect on the optimum water content. It can be seen that size 10 PET shreds needed more water, as size 40 PET shreds were fitted in between the spaces of particles, as a result, less water was needed and their OMC was observed to be lower.

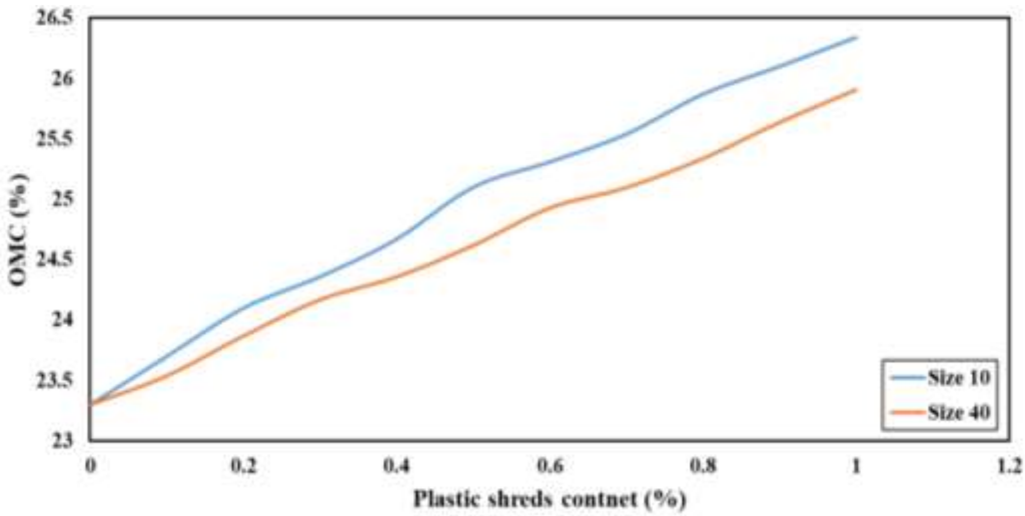


Figure 4.3: Relation between OMC and PET shreds content

Figure 4.4 show that the PET shreds affected the maximum dry density, the density got lower by PET shreds due to the lightweight of plastic materials and that is the reason why the density decreases more by adding more PET shreds. The results of other researchers confirmed this as well (Singh and Sonthwal, 2016; Memon et al., 2019; Khan and Pachghare, 2015; Laskar and Pal, 2013; Mohammed et al., 2018; Ramirez and Casagrande, 2014; Silveira et al., 2018; Louzada et al., 2019). The addition of coarser PET shreds size to soil (size 10) reduced the density more than the finer size (size 40). The possible reason is that the coarse size PET replaced the soil grains and as it has a lower density, it reduced the general dry density of the mixture. However in the case of the finer PET (size 40), the shreds were fitted in spaces between soil particles, therefore it did reduce the density but has a less effect than size 10 as it did not replace as many soil particles. The soil with PET shreds has a lower density therefore, it could be used as a suitable backfill soil in retaining walls construction.

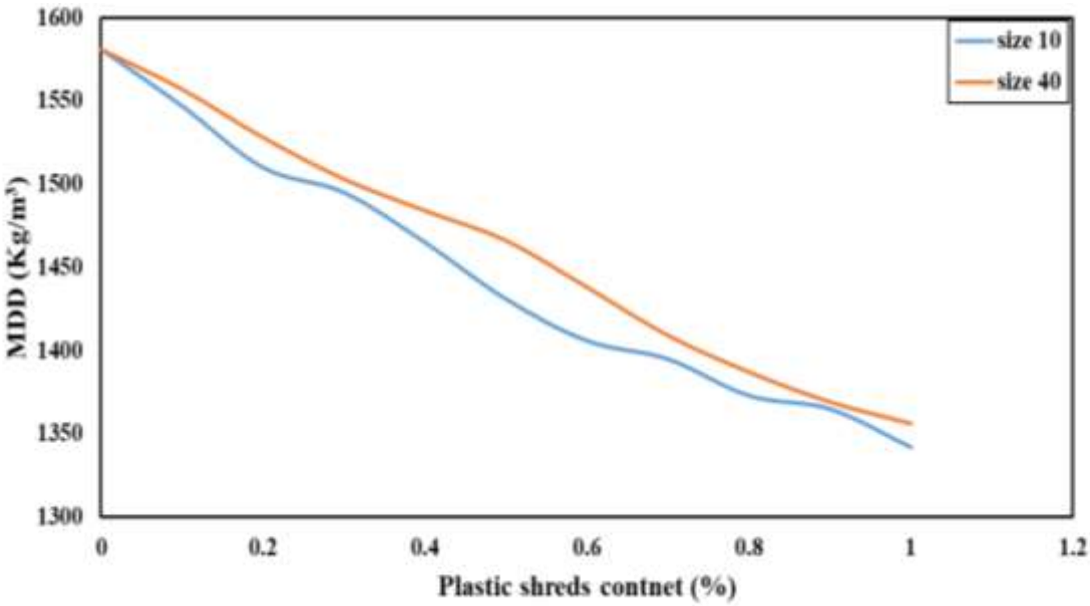
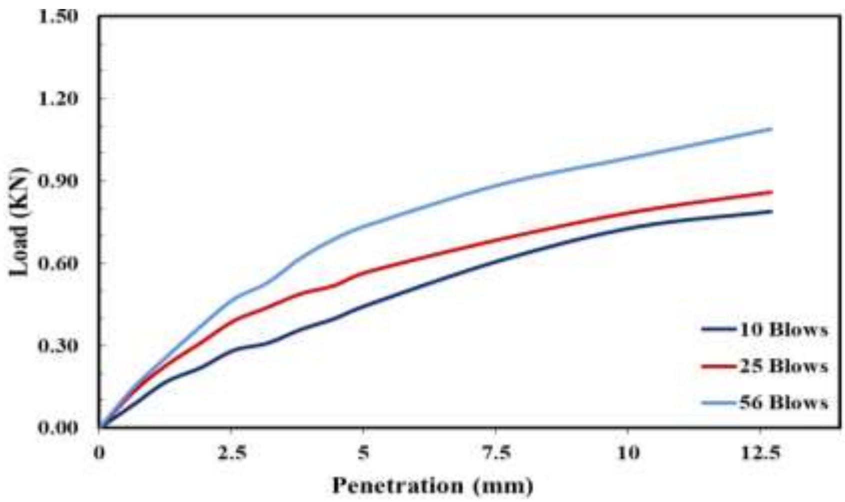


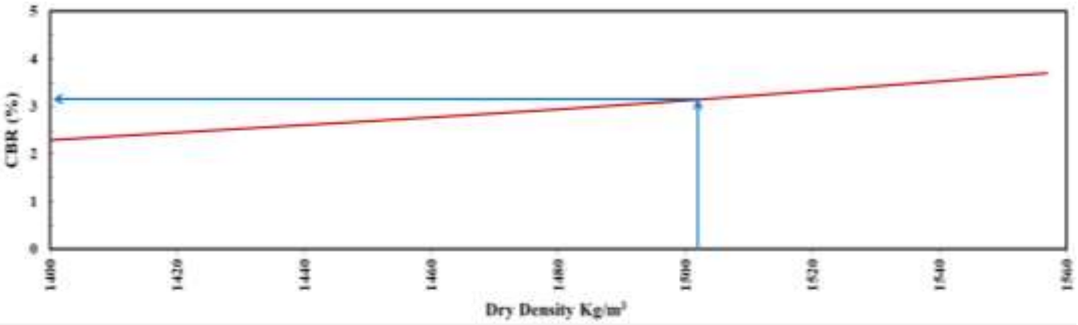
Figure 4.4: Relation between MDD and PET shreds content

4.3 Effect of PET Shreds on Strength (CBR)

A series of CBR tests were conducted to study the PET shreds influence on the CBR of soil. The tests were conducted for a set of percentages and sizes at MDD and OMC. The CBR was found by preparing three CBR molds with different blows numbers. As a result, the dry densities were different for each mold and three different CBR values were found for each mix. In order to find the best simulation of the reality and practical world, 95% of the MDD was used to be tested. As it can be seen in Figure 4.5, the curves for plain soil samples are illustrated. The other samples were tested in the same manner. As it can be seen in results the mechanical effort has an effect on the density of the samples, compacting the sample with more blows gives higher density and therefore higher CBR values.



(a)



MDD = 1581 Kg/m^3	CBR @ 95% MDD = 1501.95 Kg/m^3

CBR = 3.15 %

(b)

Figure 4.5: (a) Graphs of load versus penetration of plain soil with different blows, (b) Determination of CBR value @ 95% of the MDD

Figure 4.6 shows the results of the CBR tests. From the results it can be seen that the PET shreds enhanced the CBR of soil, an improvement can be seen with increase of percentage of PET shreds until 0.6% PET, and then the values declined for size 40, while for size 10 this value reached 0.7% and then declined. Also, it can be seen that the size 10 is more effective in enhancing the CBR than the size 40. The possible reason for that may return to the fact that PET shred size 10 have a bigger size that PET shreds size 40 this may allow more soil grains to be attached to the surface of the PET shreds and therefore the matrix integrity will be better and strength. Precisely talking, the percentage 0.7% had the best role in enhancing for size 10 with an improvement of 90.79% compared to the plain soil while the percentage 0.6% had the best role in enhancing for size 40 with an improvement of 63.49% in the CBR compared to the plain soil. As mentioned before according to (IRC37, 2012), CBR for subgrade should not be less than 3% and (SORB R5-16, 1983) as per AASTHO T180, CBR should be minimum 4% for subgrade, therefore all the treated mixtures with varying percentages satisfied the minimum requirements of the standards. But generally discussing, it can be expressed that the best performances were observed in percentage range 0.6, 0.7, and 0.8 in both sizes, and hence these percentage range is to be used in the rest stages of this research.

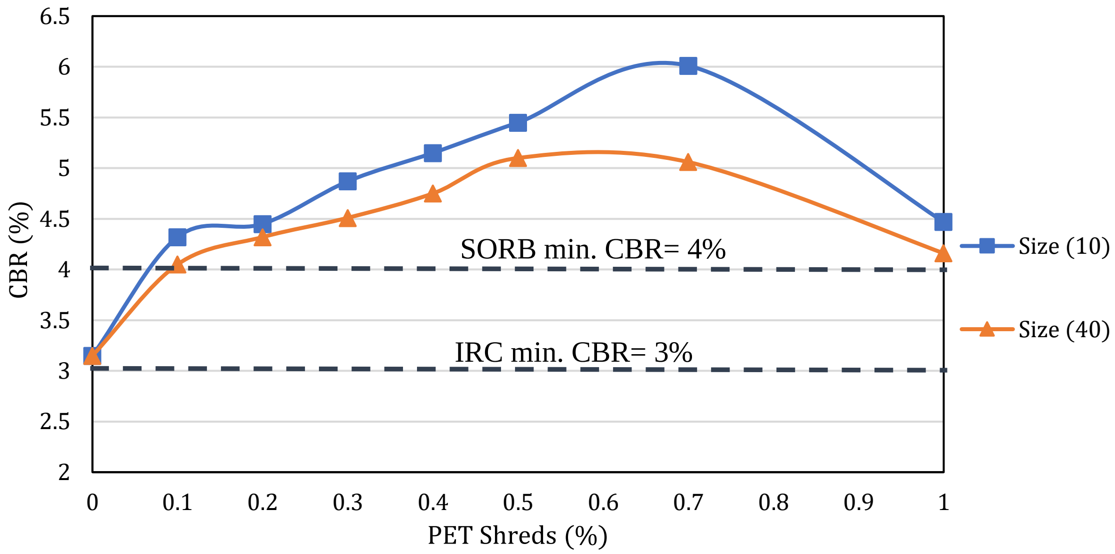


Figure 4.6: CBR Values of plain soil and soils reinforced with PET shreds

4.4 Investigation of Soil Reinforced with PET Shreds for Highways Pavements

As results showed that reinforcement of soil with PET shreds enhances the soil's CBR, therefore it should be beneficial to use as a subgrade material in functionally, economically and environmentally. This section examines the benefits of using this reinforced soil as subgrade.

4.4.1 CBR method recommended by California State of highways

The California state department of highways recommends the usage of CBR method for the design of the pavement thickness. If this method is applied for this soil sample before and after the reinforcement, the effect of this treatment could be monitored. If the heaviest traffic is considered as 55.43 kN, as it can be seen in Figure 4.7, the thickness design will be as following:

- Natural Soil, CBR = 3.15% the pavement thickness would be 550 mm.
- Soil reinforced with size 10 PET shreds with optimum percentage 0.7% the CBR was 6.01%, so that the thickness would be 380 mm.
- Soil reinforced with size 40 PET shreds with optimum percentage 0.6% the CBR was 5.25%, so that the thickness would be 400mm.

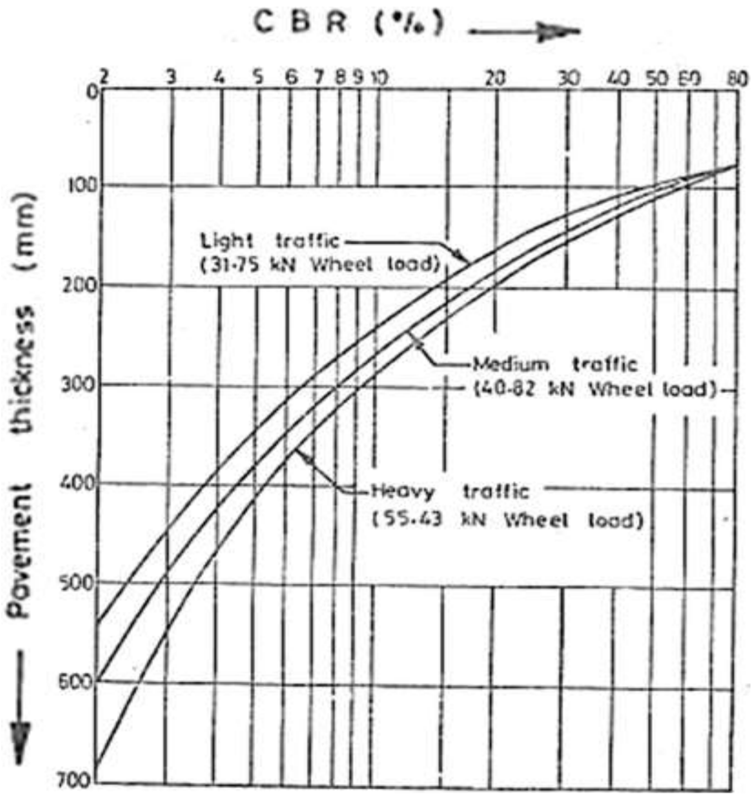


Figure 4.7: CBR versus pavement thickness curves (Hansen, 1959)

4.4.2 CBR Method Recommended by Indian Road Congress (IRC)

On the other hand, according to another CBR method which is recommended by IRC, if the worst traffic, Class G, is considered, the thickness design will be as following (Figure 4.8):

- Natural Soil, CBR = 3.15% the pavement thickness would be 680 mm.
- Soil reinforced with size 10 PET shreds with optimum percentage 0.7% the CBR was 6.01% so that the thickness would be 485 mm.
- Soil reinforced with size 40 PET shreds with optimum percentage 0.6% the CBR was 5.25% so that the thickness would be 525mm.

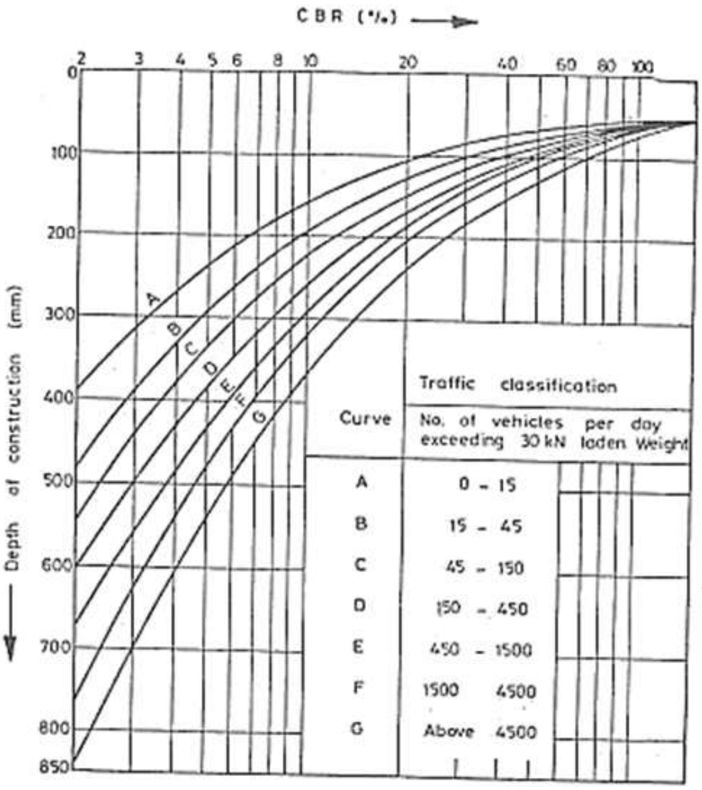


Figure 4.8: CBR versus pavement thickness curves (IRC: 37-1970 & 1984)

As it can be seen, reinforcing soil with PET shreds reduced the thickness of pavement, hence it is considered to be effective. Because functionally it has a higher CBR, environmentally it helps the nature to get rid of garbage rather than using raw materials and dragging natural earth resources. Last but not least, considering the economic effects as mentioned before, the pavement materials are expensive, in this way garbage with little to no cost will be used as a material and in turn it reduces the thickness of expensive pavement materials. Therefore, soil reinforced with PET shreds is considered functional, economical, and eco-friendly.

4.5 Cracks and integrity investigation of soil reinforced with PET shreds by visual inspection

The addition of PET shreds can help to reduce the cracking and shrinking characters of the soil by bridging between the cracks. This was witnessed when the compacted soil was extruded from the mold and left to be air-dried until it fully cracked. The cracks outlined on the surface of the molded soil and its ability to maintain its original spherical shape were compared by visual inspection. The PET shreds resulted in a very considerable reduction of cracking. Figure 4.9 shows the cracking mode of the soil for plain soil, and the soil sample reinforced with PET shreds. It can clearly be seen that the plain soil sample showed excessive cracking.

(a)

(b)

Figure 4.9: (a) CBR sample of plain soil, (b) CBR sample of soil reinforced with PET shreds

In addition, the samples were visually examined after leaving them to hit the ground, to check the integrity of samples with and without PET shreds. Figure 4.10 shows the plain soil and soil reinforced with PET shreds samples, after hitting the ground. As it can be seen, the failure in plain soil, as it already had big cracks the sample was broken and separated apart. While, adding fibers in soil, made cracks get smaller, this sample also did lose some of its parts but it did not separate apart as the plain soil did and could keep its integrity considerably. Therefore, the fibers added to cemented soil changed the brittle behavior to ductile behavior and considerably increased the integrity of the soil.

(a) (b)

Figure 4.10: Soil sample after hitting (a) plain soil, and (b) Soil reinforced with PET shreds

4.6 Effect of Cement on Strength (CBR)

In this section, the effect of cement on soil is presented as can be seen from Figure 4.11. The results show that cement stabilization increases the strength of soil regardless of the amount of cement added. With a higher cement, a higher strength was gained. The cement adding effect may be illustrated by the instant influences that it strengthens the structure of soil. Two things happen, the first one is a result of the mechanisms of flocculation and agglomeration that precipitate to a denser structure, and the other one is regarded to the pozzolanic responses among the clay minerals and the calcium hydroxide $Ca(OH)_2$ that encourages the deposit of products of cement hydration (Al-Rawas et al., 2005). Adding cement to the soil reduces plastic properties of soil and improves the bond between soil particles. This property increases the load resistance of cement-stabilized soils. Soil stabilization with cement increase CBR value of soils, cement creates strong bonding between soil particles and improves plasticity behavior. Therefore, a more extended curing duration is appropriate to the generating of the mentioned reactions as well as to the mechanisms of cement hydration. Maximum increase in CBR is obtained for 10% of cement as shown in Figures 4.12 and 4.13 As mentioned before according to (IRC37, 2012), CBR for subgrade should not be less than 3% and (SORB R5-16, 1983) as per AASTHO T180, CBR should be minimum 4% for subgrade, therefore all the percentages added satisfied the requirements of the standards.

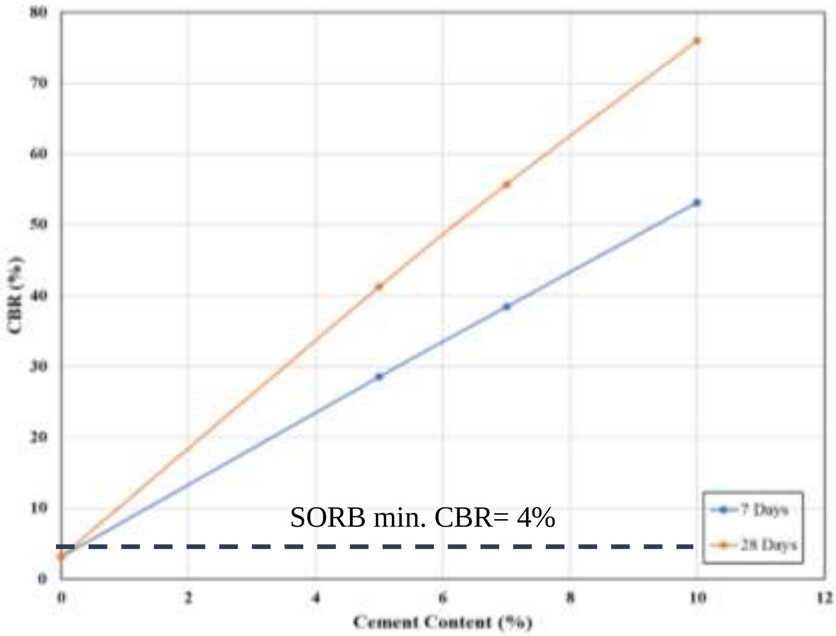


Figure 4.11: CBR value of soil and soil stabilized with cement content

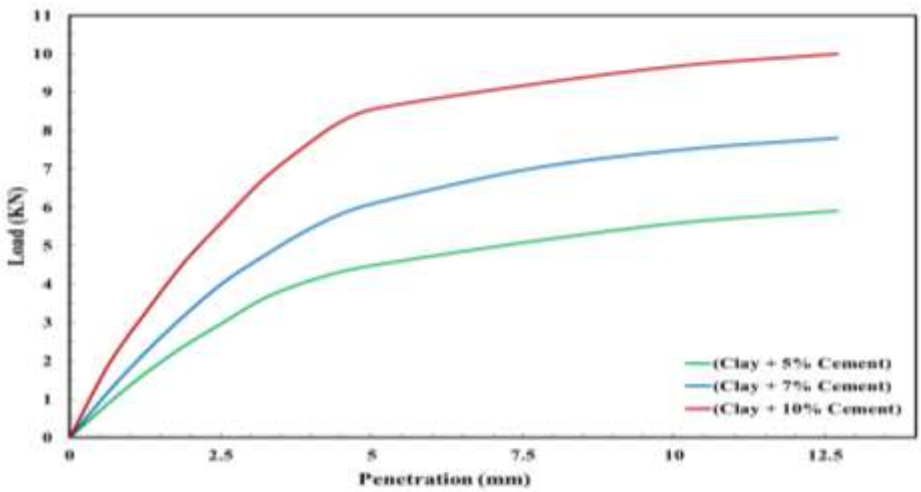


Figure 4.12: Graph of load versus penetration for mixes with cement cured for 7 days

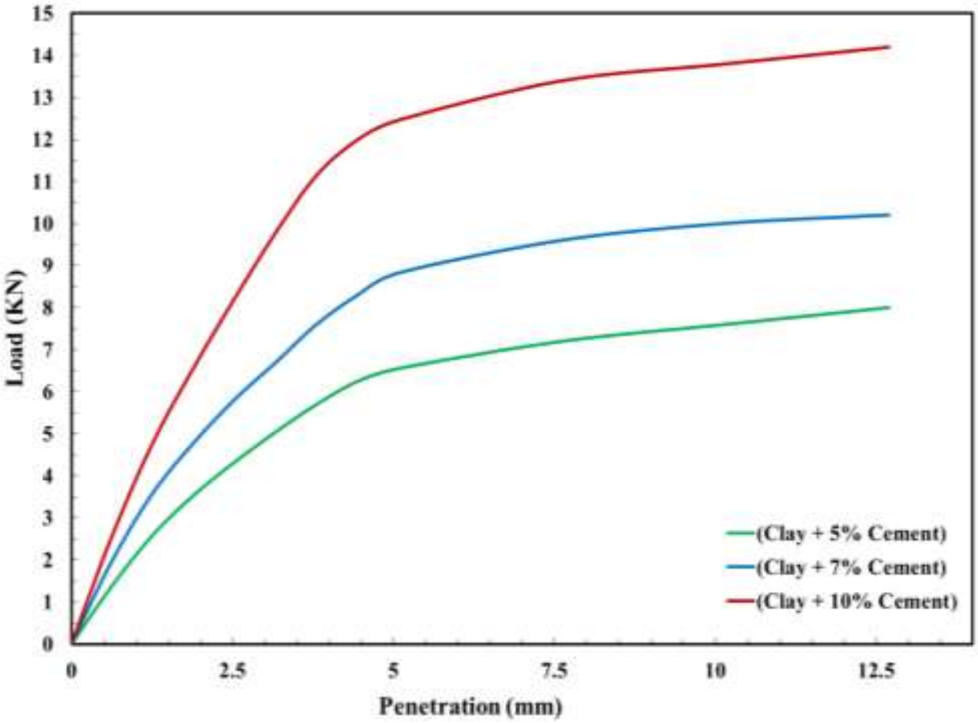


Figure 4.13: Graph of load versus penetration for mixes with cement cured for 28 days.

4.7 Effect of Cemented Soil Reinforcement with PET Shreds on Strength (CBR)

The influence of PET shreds on strength was investigated through CBR (Figure 4.14). The factors were considered cement content, PET shreds content, PET shreds size, and curing period. The results show that there is a soil strength improvement by the cement addition, where, with a higher cement a higher strength was gained. The cement adding effect may be illustrated by the instant influences of it in strengthening the structure of soil. The reason behind that is that as mentioned before flocculation and agglomeration and pozzolanic responses happen which increase the strength. A more extended curing duration is appropriate to the generation of the pozzolanic responses among the clay minerals as well as to the mechanisms of cement hydration (Figure 4.15a). Figure 4.15 demonstrates, generally, higher values of strength for longer curing periods. The increase in percentage of cement gave a less declared influence concerning the strength than the other mentioned factors, yet, higher cement percentages resulted in higher strengths. As a result, the cement content of 7% can be considered reasonable from the performance and also from the economic and environmental aspect. The addition of PET shreds, has a positive influence in the performance of the blends since the CBR was increased by the addition of PET shreds regardless the amount and size of them. This phenomenon can be explained by the reinforcement action that the PET shreds offer in the mixes. Figure 4.15b shows the effect of the PET shreds sizes. Size 10 gave better performance than size 40 of PET shreds, as the CBR values were more than CBR values of size 40 in different mixes. The percentage of the PET shreds has an effect on CBR value as well, 0.6, 0.7, and 0.8 percentages of PET shreds were added to observe this effect. For size 10 the best performance was observed at percentage of 0.7, while, for size 40 best performance was observed at percentage of 0.6% as can be seen in Figure 4.15c. The percentages and sizes added to the mixture, has satisfied the minimum CBR values of the required by above mentioned standards. Also, according to (SORB R5-16, 1983) there are three classes of A, B, and C, based on CBR value of base and subbase layer. A class does not allow less than 45%, B not less than 35%, and in class C not less than 30% is permitted. It can be seen addition of cement and PET shreds to clay make it usable as base and subbase. Stabilizing soil with PET shreds and cement together made clay satisfy the requirements of all the three classes. Furthermore, an equation was established to predict the CBR value from the different factors (equation 4.1) as shown in Figure 4.15(d):

$$CBR\ (\%) = 1.38073 + 6.38932 * Cement\ Content\ (\%) - 6.35833 * Additive\ \% - 0.264648 * Size\ No. + 0.900185 * Curing\ (Days) \tag{4.1}$$

The graphs of loads against penetrations of all mixes are presented in Figures (4.16-4.21).

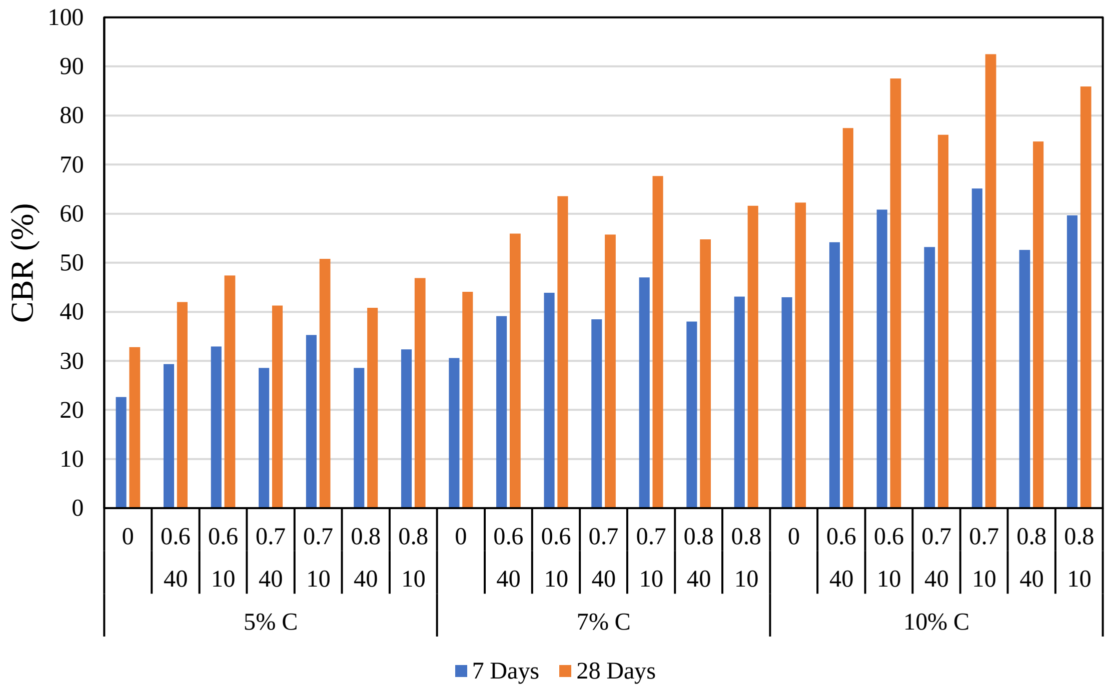


Figure 4.14: CBR Value for all mixes for curing periods of 7 and 28 days

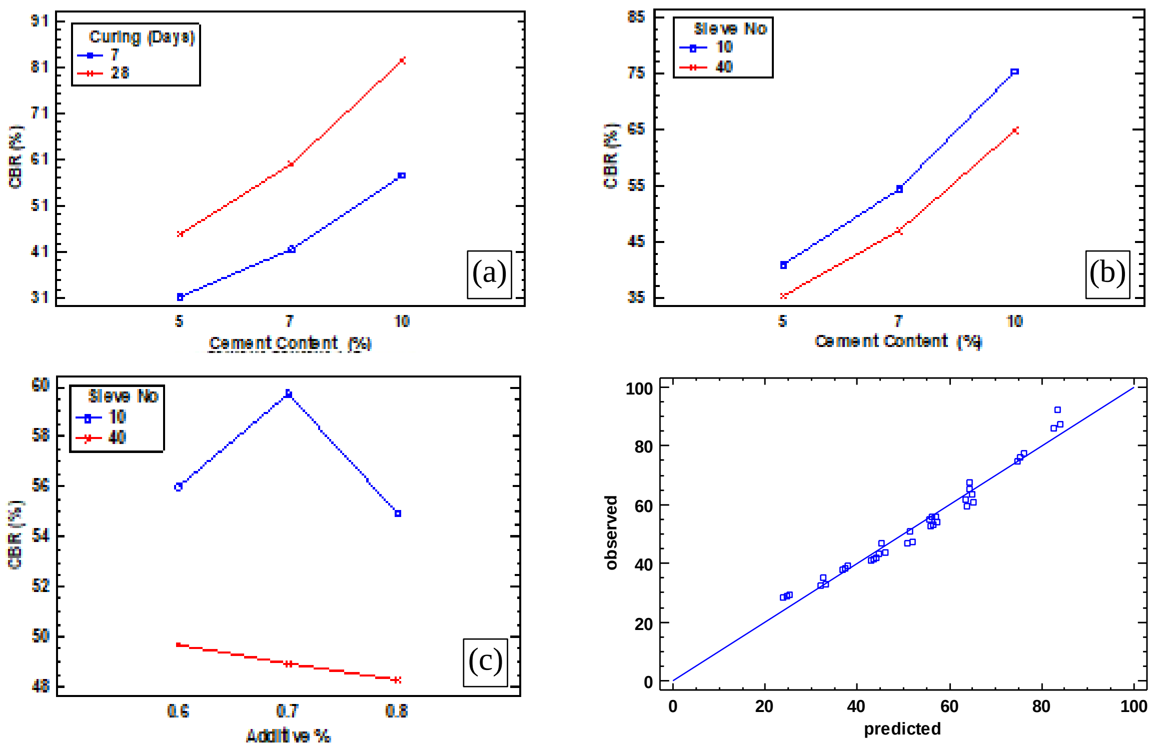


Figure 4.15: Main Effects Plot for CBR values: (a) Effect of Curing period, (b) Effect of PET shreds size, (c) Effect of PET shreds percentages, (d) CBR prediction from different factors

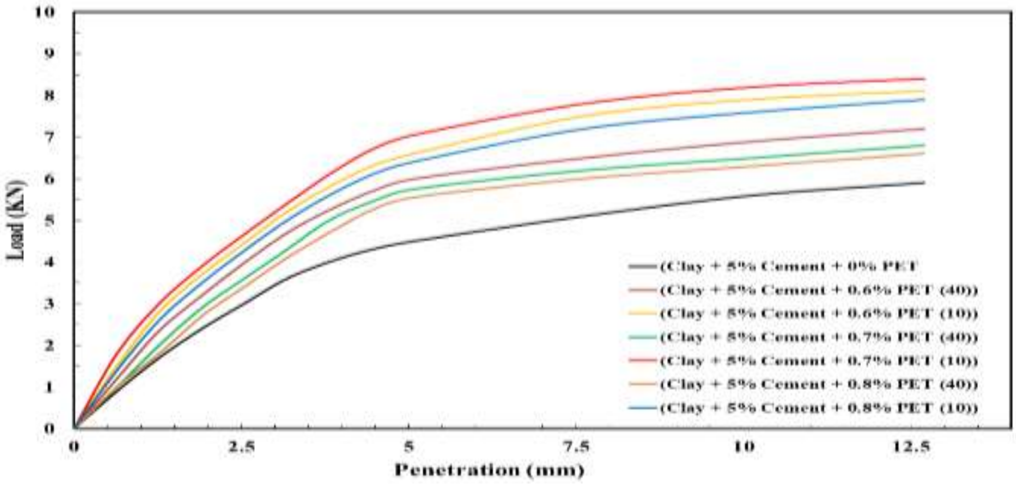


Figure 4.16: Graph of load versus penetration for mixes with 5% cement cured for 7 days

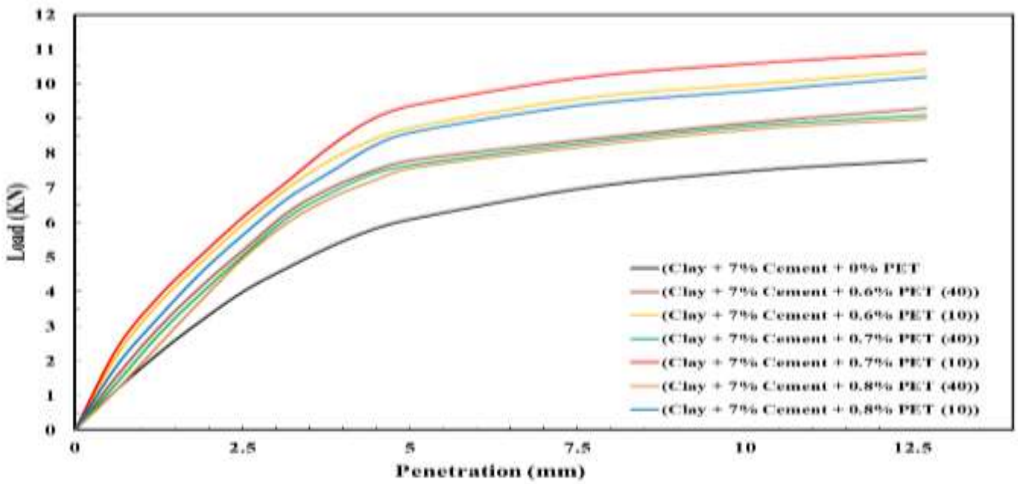


Figure 4.17: Graph of load versus penetration for mixes with 7% cement cured for 7 days

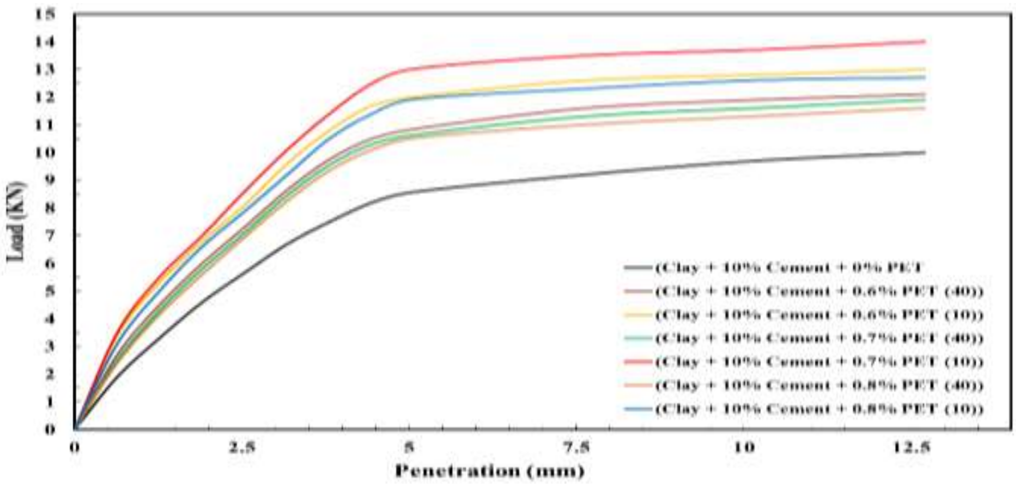


Figure 4.18: Graph of load versus penetration for mixes with 10% cement cured for 7 days

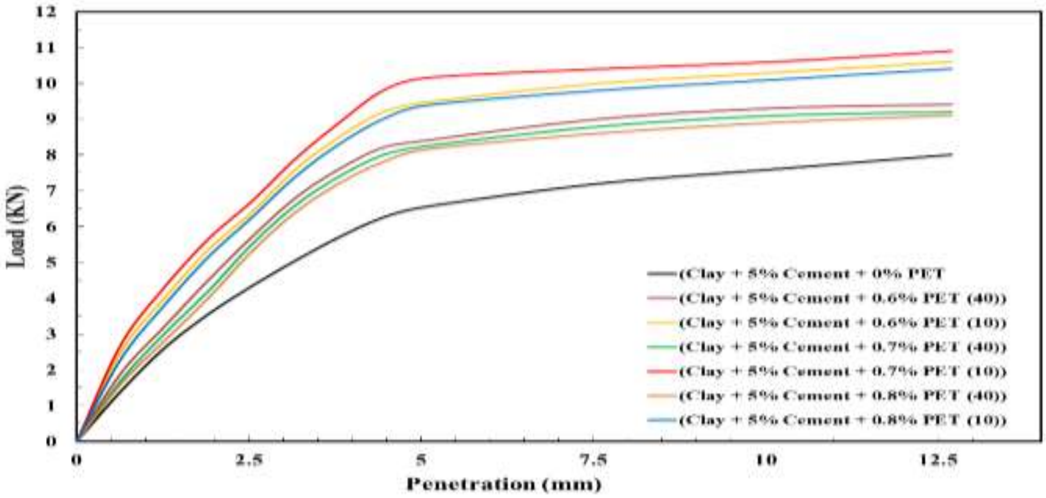


Figure 4.19: Graph of load versus penetration for mixes with 5% cement cured for 28 days

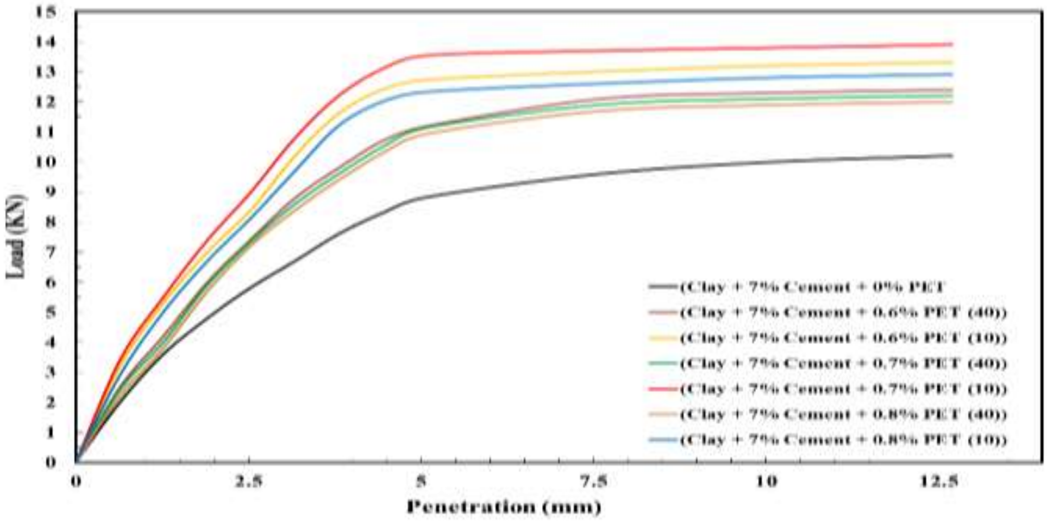


Figure 4.20: Graph of load versus penetration for mixes with 7% cement cured for 28 days

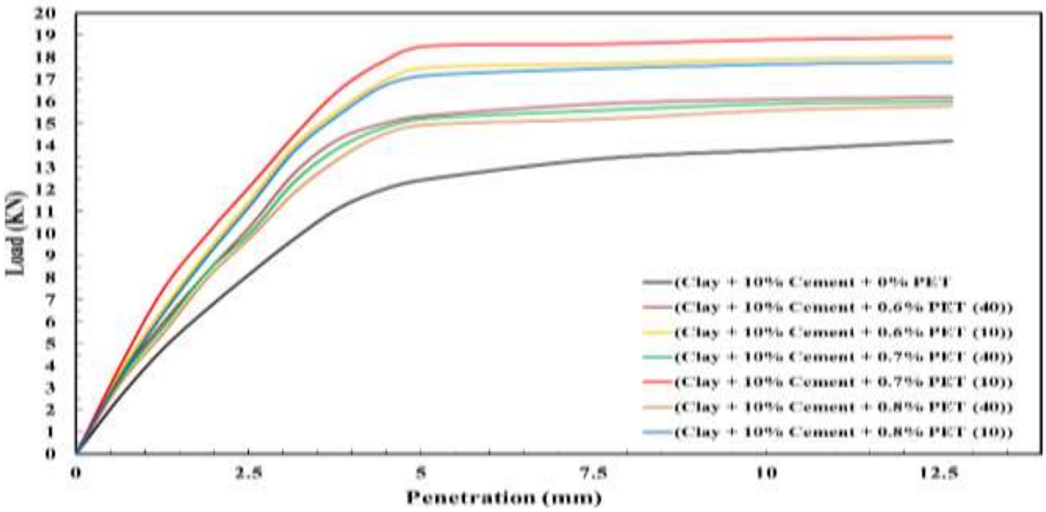


Figure 4.21: Graph of load versus penetration for mixes with 10% cement cured for 28 days

4.8 Effect of Cemented Soil Reinforcement with PET shreds on Stiffness (UPV)

The effect of PET shreds on stiffness through ultrasonic pulse velocity was studied as well (Figure 4.22 and 4.23). The results reveal that PET shreds addition decreases the stiffness of the soil regardless of the amount and size, it's because it makes the soil less brittle and more ductile, and that is due to the elastic character of PET that is in agreement with findings of previous researches (Consoli et al., 1999; 2002; 2004). As the content of PET shreds increases within the mixture, the stiffness reduces. That occurrence is expected as the amount of the elastic materials increases in the mixes. Regarding the cement content in the soil, as the cement content increases it increases the stiffness of the mix, which is due to the brittle character of the cement. The other studies confirm these results as well (Consoli et al., 2012; Jovičić et al., 2006; Puppal et al., 2006; Trhlíková et al., 2012). In Figure 4.24a it can be seen that the longer curing period gave a higher stiffness and that is due to the hydrations that occur within the cement. By time the hydrations increase which results in increasing the stiffness in the mixes, that also confirms findings of Chang and Woods, (1992). Regarding the other parameters, the size of the PET shreds, size 10 gave higher stiffness than size 40 as seen in Figure 4.24b. The percentage of the PET shreds also had an effect on the stiffness of the soil. The PET percentage of 0.6 gave the higher stiffness than percentage 0.7 and 0.8 as illustrated in Figure 4.24c. Furthermore, a reasonable equation of high coefficient of determination (R^2 = 0.96) was found which correlates the UPV to the CBR, where from this equation 4.2 by knowing the UPV of a sample the CBR can be predicted, as shown in Figure 4.25..

$$CBR\ (\%) = 0.7604 * UPV - 1243.4 \qquad (4.2)$$

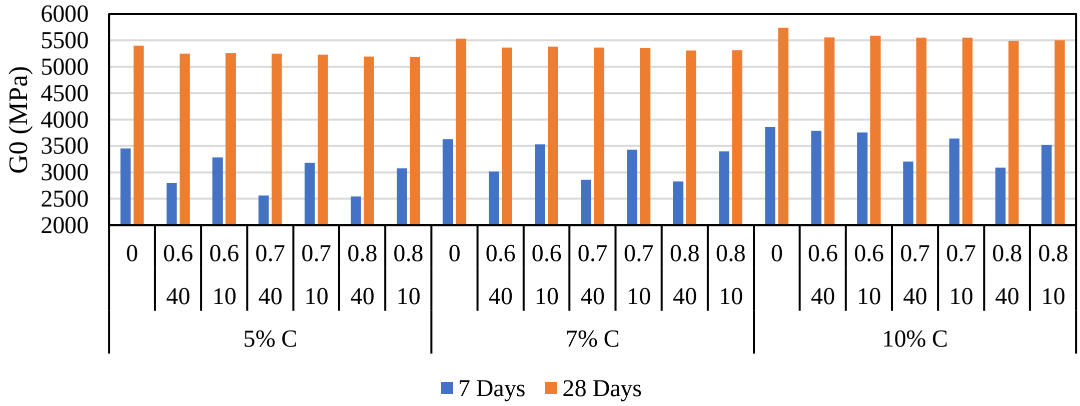


Figure 4.22: Stiffness (Shear Modulus G_0) for all mixes for curing of 7 and 28

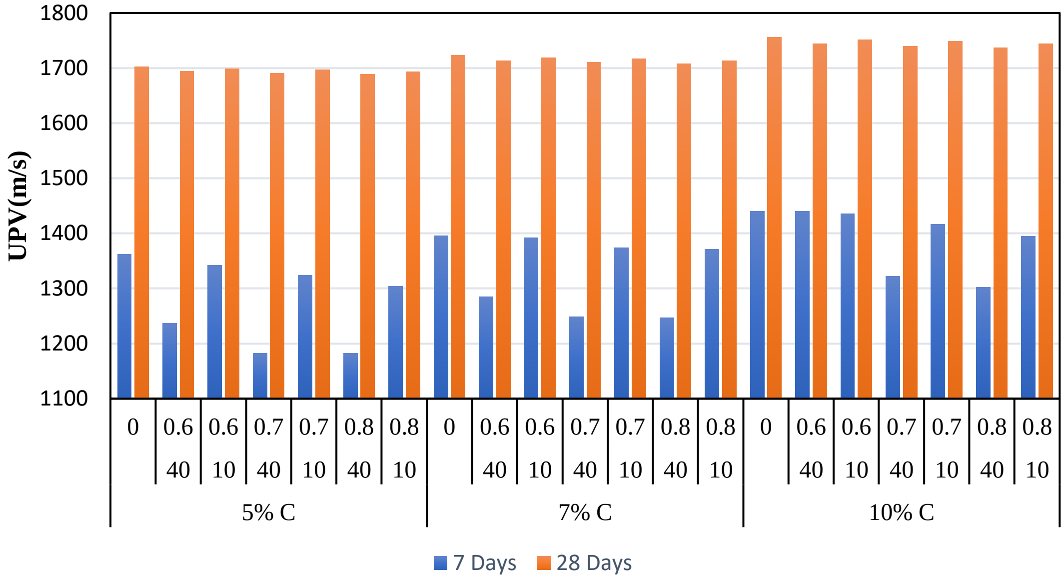


Figure 4.23: UPV for all mixes for curing of 7 and 28 days

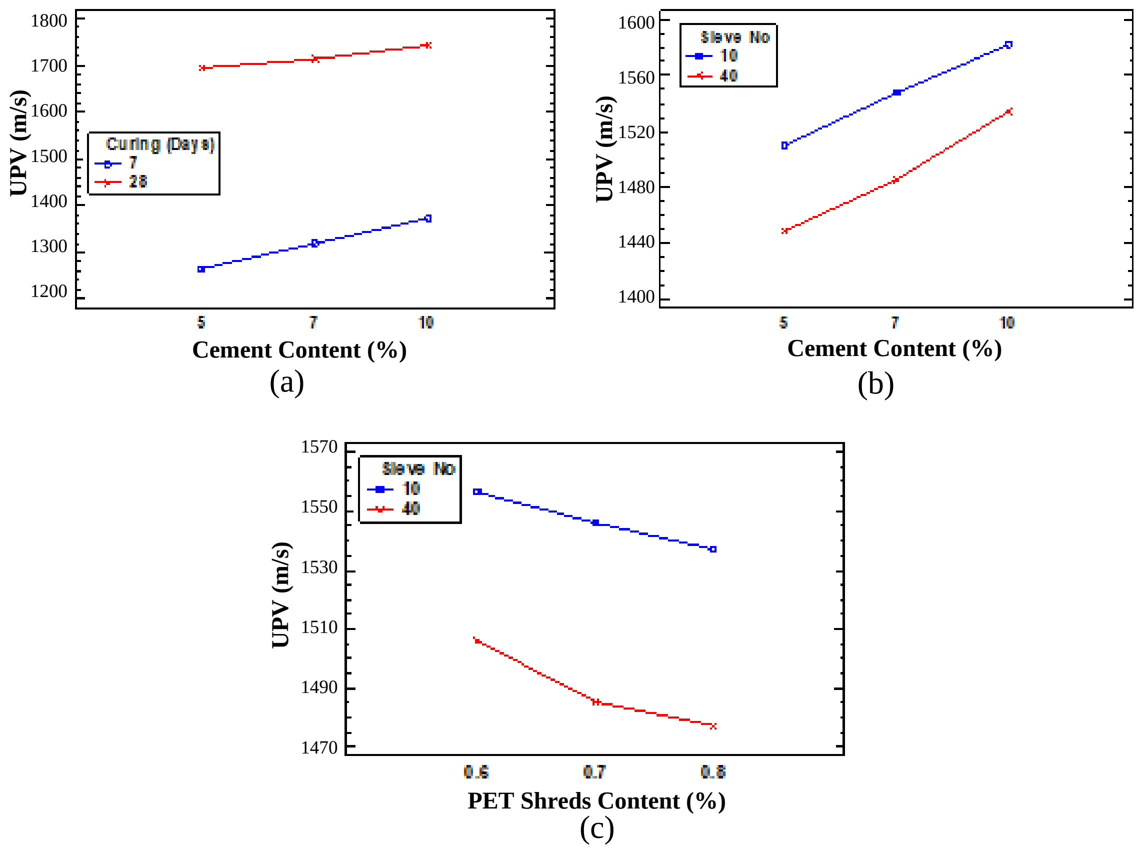


Figure 4.24: Main effects plot for UPV values: (a) Effect of curing period, (b) Effect of PET shreds

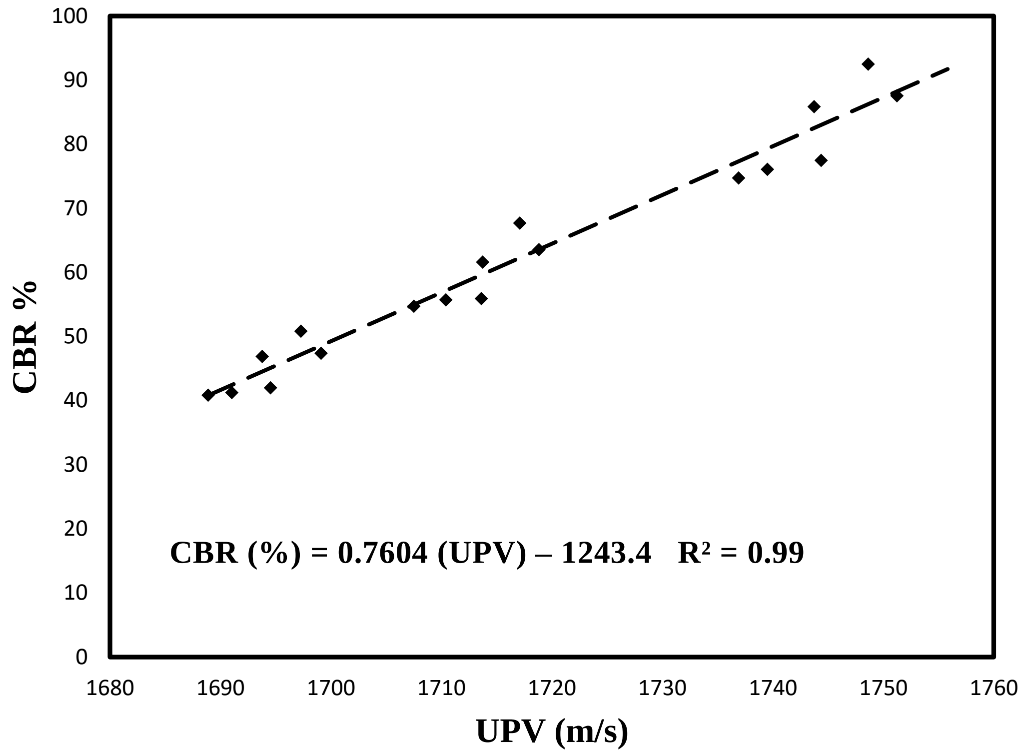


Figure 4.25: Relationship between CBR and UPV

4.9 Effect of PET Shreds on Porosity of Cemented Soil

Effect of PET addition on porosity was studied as well, the results show that the addition of PET shreds regardless of the other factors, reduce the porosity of the mixes as shown in figure 4.26. The sizes had an effect on the porosity of the mixes. Size 10 reduced the porosity more than size 40. The percentage of PET shreds also had an effect on the porosity. The higher percentage resulted in a lower porosity for size 10, while for size 40, the 0.7% had a higher porosity than 0.8% and 0.6% PET contents. Regarding the cement percentage, the higher cement content, the lower was the porosity. Likewise, the curing time had an effect on the porosity, but the effect of the curing period was not very significant. However, the longer curing period resulted in observing lower porosity.

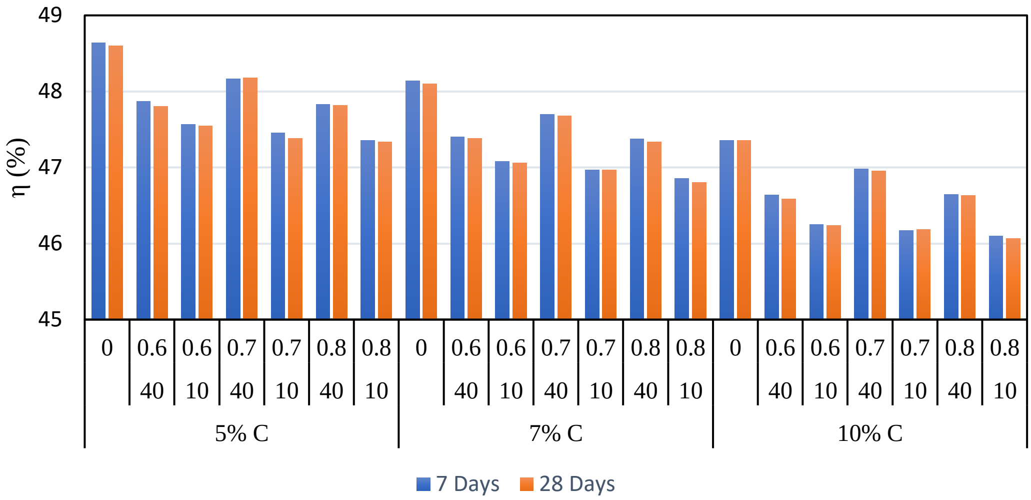


Figure 4.26: Porosity of the different blends for 7 and 28 days

4.10 Influence of Adjusted Porosity/binder index on CBR

Figures 4.27 and 4.28 displays the results for CBR of the specimens in terms of the adjusted porosity/binder index and (η/Xiv0.32). Fig. 4.27 (a) shows the results of soil with 5%, 7%, and 10% cement content, dry density of 1.4 g/cm3; and curing time of 7 and 28 days. Figures 4.27b-4.27f and Figures 4.28a and 4.28b present the results of soil stabilized with cement and PET shreds contents of 0.6, 0.7, and 0.8 and sizes of 10 and 40. All specimens were sampled with the same dry densities and cured for the same periods. As can be seen from the results, the lower the (η/Xiv0.32) the higher the strength is.

A reasonable agreement between CBR and (η/Xiv0.32) for all the mixes was found utilizing power equations. A general normalization was proposed for normalizing the results obtained for various blends and curing time, by dividing the equations by a specific value of strength and stiffness (related to a specific value of [porosity/binder] = ∇), to predict the mechanical performances (strength and stiffness) of a particular mix of sand and pozzolan (Consoli et al., 2021). Herein, that model was expanded to show results of a clay improved with cement and PET shreds, a normalizing model is illustrated in Figure 4.29 by dividing the obtained equations for every blend by a particular CBR value. In this research, samples were selected with certain CBR at (η/Xiv0.32) = ∇ = 31 for all mixes. The relation between normalized California Bearing Ratio [(CBR)/ (CBR for η/(Xiv)0.32 = 31)] and the adjusted porosity/binder index is showed in Figure 18. A total of 42 CBR results were used to obtain Equation (4.3), permitting the generalization of a relation between the CBR and the porosity/binder index. An excellent coefficient of determination (R2) of 0.99 was attained. This equation, allows the CBR for particular mixes of clay treated with cement and PET shreds cured for particular ages to be calculated using just one test.

$$\frac{CBR}{CBR_{(\frac{\eta}{(\mathrm{Xiv})^{0.32}}=31)}} = 23744 \times \left(\frac{\eta}{(\mathrm{Xiv})^{0.32}}\right)^{-2.932} \qquad (4.3)$$

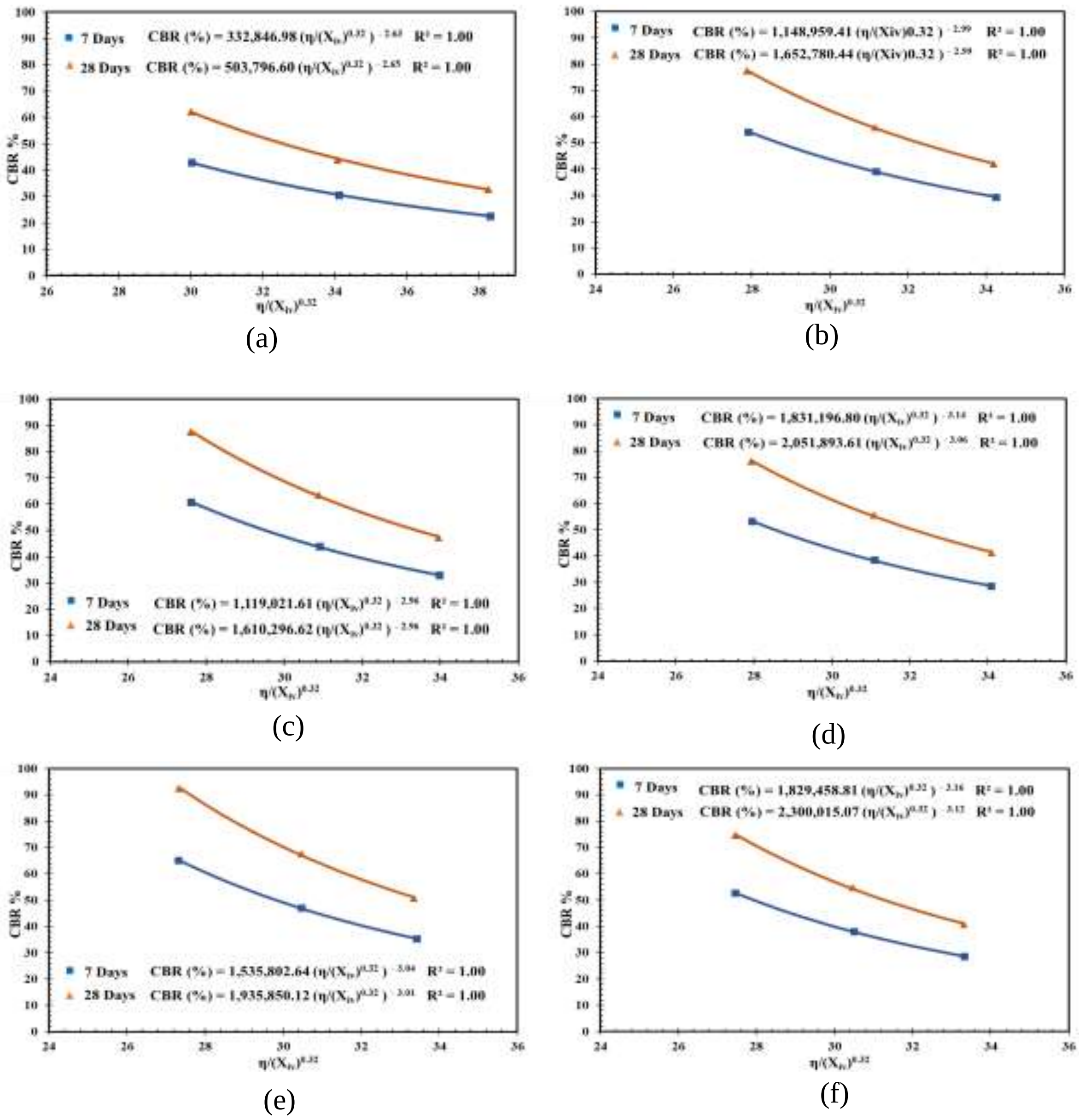
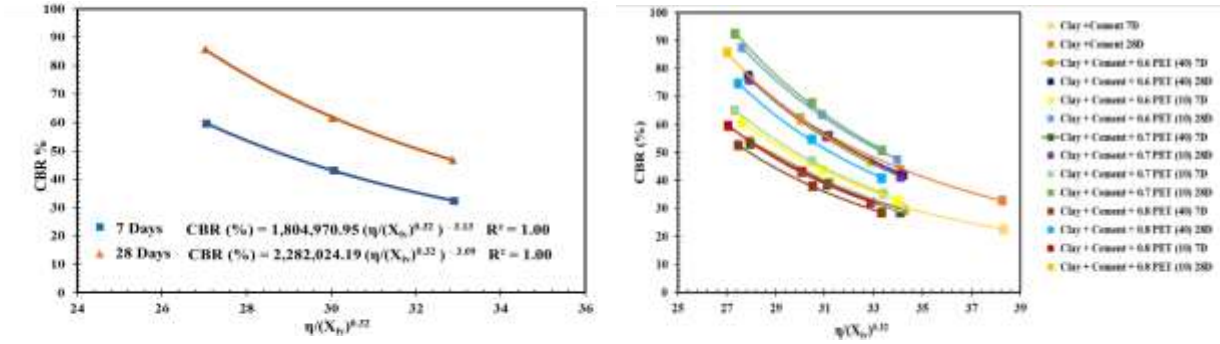


Figure 4.27: CBR vs porosity/binder index (a) Clay + Cement, (b) Clay + Cement + 0.6 PET (40), (C) Clay + Cement + 0.6 PET (10), (d) Clay + Cement + 0.7 PET (40), (e) Clay + Cement + 0.7 PET (10), (f) Clay + Cement + 0.8 PET (40)



(a) (b)

Figure 4.28: CBR vs porosity/binder index (a) Clay + Cement + 0.8 PET (10), and (b) All for all mixes.

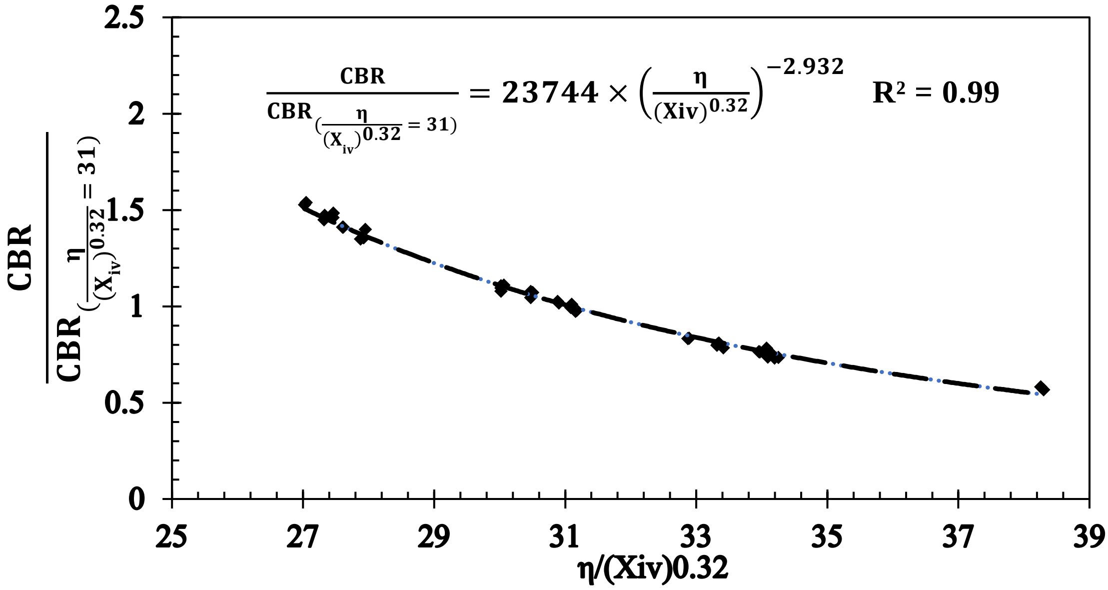


Figure 4.29: Normalized variation of California Bearing Ratio (CBR) $\frac{CBR}{CBR_{(\frac{\eta}{(Xiv)^{0.32}}=31)}}$, with adjusted porosity/binder index

4.11 Effect of adjusted porosity/binder index on stiffness (G_0)

Figures 4.30 and 4.31 show the correlation between the initial shear modulus (G_0) and the adjusted porosity/binder index (η/Xiv0.32) of the samples in this research. Fig. 4.30a shows the results of soil with 3%, 7%, and 10% cement content with dry density of 1.4 g/cm3; and curing time of 7 and 28 days. Figures 4.30b- 4.30d and Figures 4.31a-4.31d present the results of soil stabilized with cement and PET shreds contents of 0.6, 0.7, and

0.8 and sizes of 10 and 40. The results show that the G_0 gain is higher in relation to the decrease of η/(Xiv)0.32 parameter value. Therefore, as porosity decreases and binder content increases the values of G0 increases. Also, the same analysis was held for G_0 in terms of CBR, the results revealed a reasonable relation between G_0 and (η/Xiv0.32). Also, as for CBR, G_0 can be normalized by dividing the equations for every blend by a specific G_0 value. The relation between normalized G_0 [(G_0)/(G_0 for η/(Xiv)0.32 = 31)] and the adjusted porosity/binder index is presented in Figure 4.32. A collect of 42 G_0 data results were used to get Equation (4.4), permitting the generalization of a relation between the G0 and the porosity/binder adjusted index. The equation has a $R^2 = 0.70$. The attained equation, allows the G_0 for particular mixes of clay, treated with cement and PET shreds and cured for particular ages, to be obtained using just a test.

$$\frac{G_0}{G_{0\left(\frac{\eta}{(Xiv)^{0.32}}=31\right)}} = 5.42 \times \left(\frac{\eta}{(Xiv)^{0.32}}\right)^{-0.49} \qquad (4.4)$$

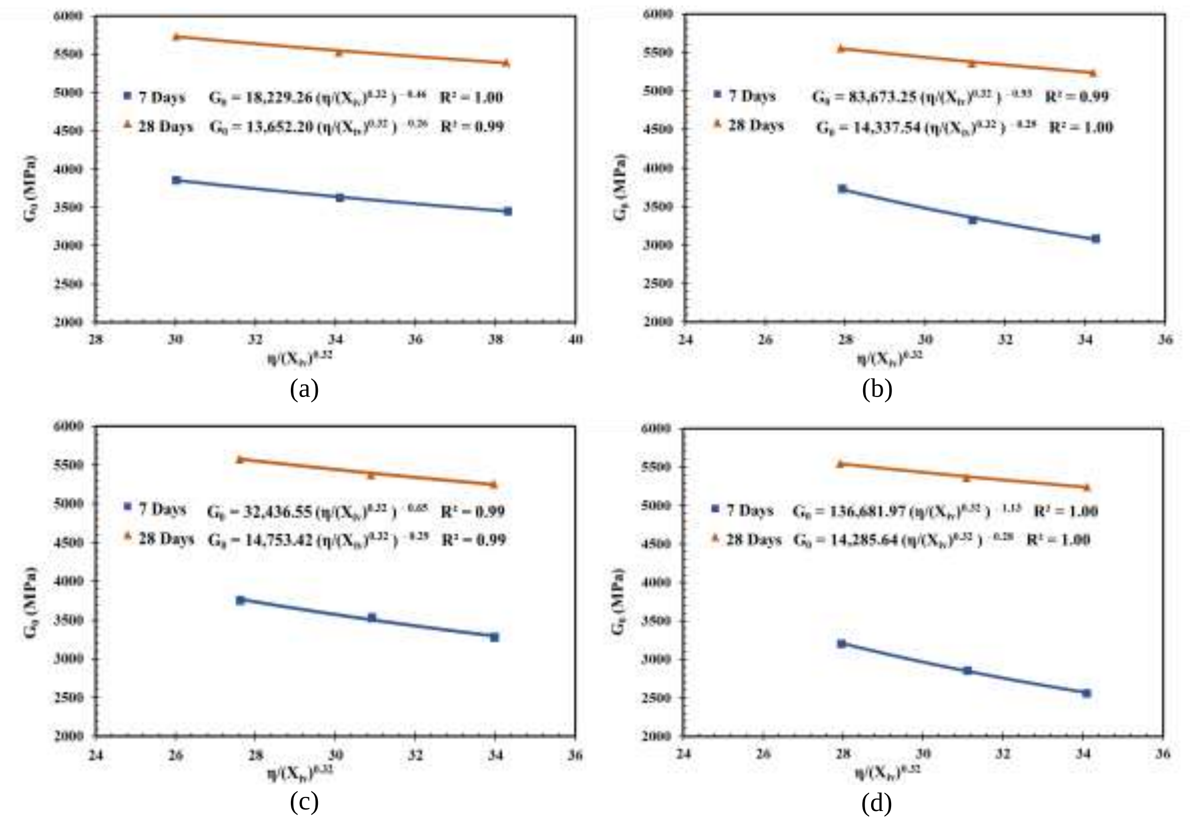


Figure 4.30: G_0 and porosity/binder index (a) Clay + Cement, (b) Clay + Cement + 0.6 PET (40), (C) Clay + Cement + 0.6 PET (10), (d) Clay + Cement + 0.7 PET (40)

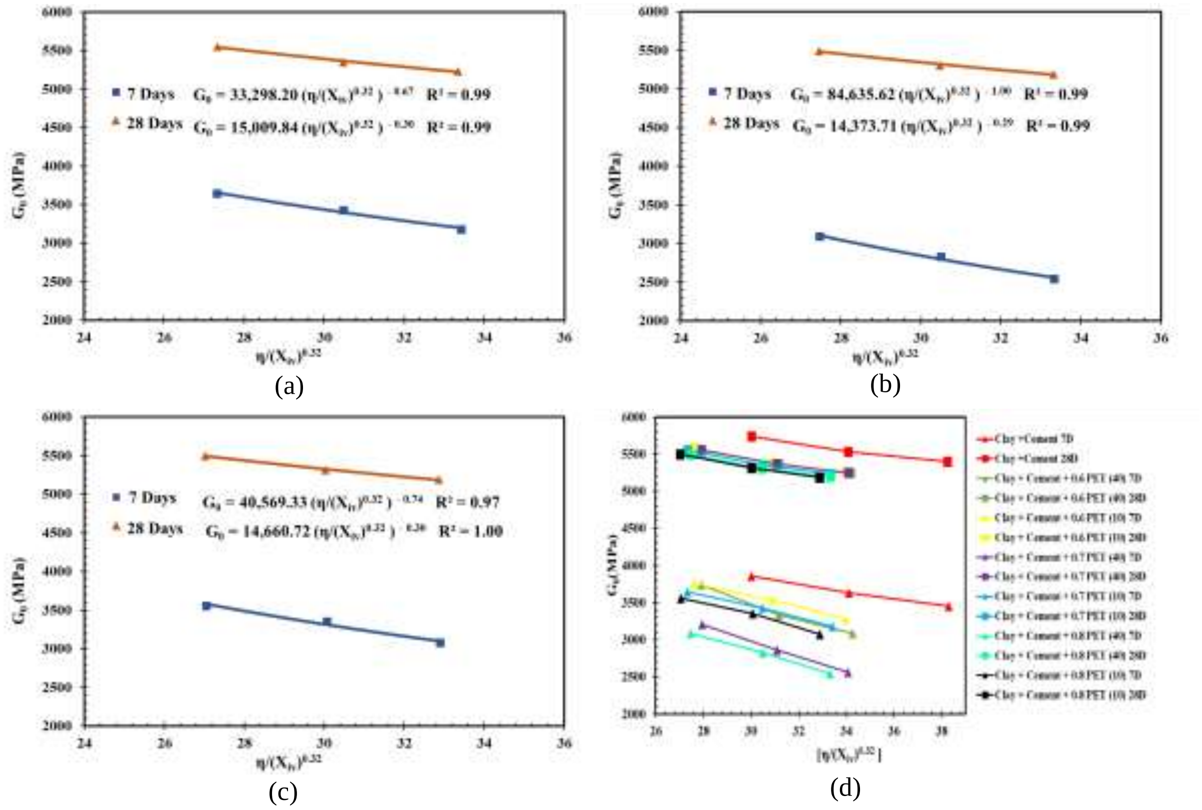


Figure 4.31: G_0 and porosity/binder index (a) Clay + Cement + 0.7 PET (10), (b) Clay + Cement + 0.8 PET (40), (c) Clay + Cement + 0.8 PET (10), and (d) All the mixes together.

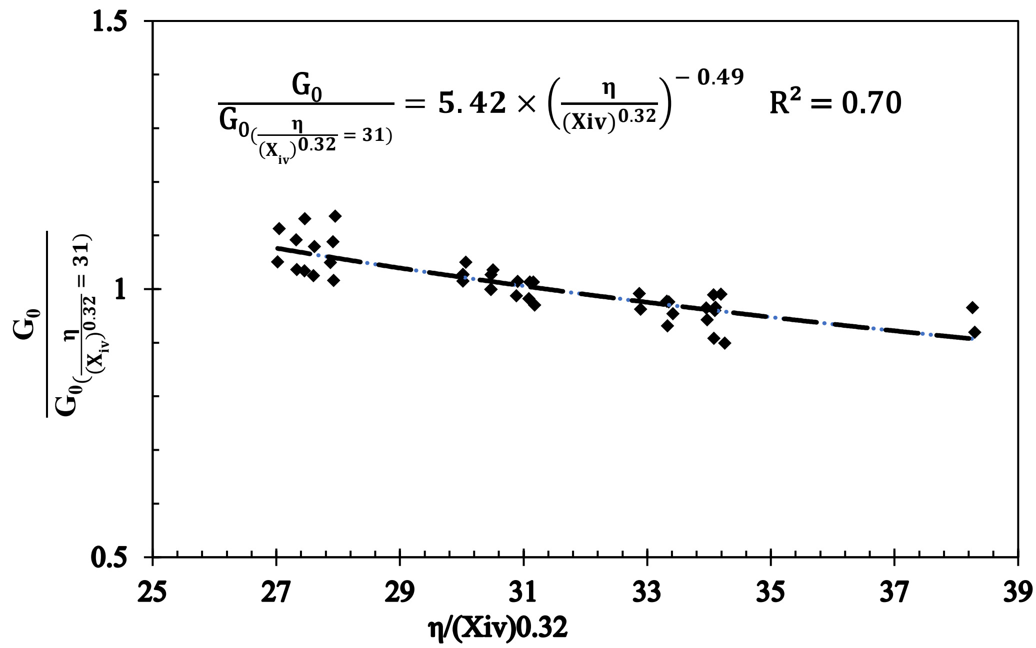


Figure 4.32: Normalized variation of G_0 $\frac{G_0}{G_{0\left(\frac{\eta}{(X_{iv})^{0.32}}=31\right)}}$, with adjusted porosity/binder index

4.12 Relationships among Initial Shear Modulus (G_0) and California Bearing Ratio (CBR)

Figures 4.33 and 4.34 show the correlation between CBR and the initial shear modulus (G_0) of the samples in this research. Figure 4.33a shows the results of soil with 3%, 7%, and 10% cement content, dry density of 1.4 g/cm3, and curing of 7 and 28 days. Figures 4.33b and 4.34a-4.34f, present the results of soil stabilized with cement and PET shreds contents of 0.6, 0.7, and 0.8, and sizes of 10 and 40. The results show that the CBR increases when G_0 increases, therefore there is a direct relationship between CBR and G_0. As a result, the higher G_0, the higher are the values of CBR.

The same analysis was held for CBR with G_0 as before, the results revealed a reasonable relation between CBR and G_0. Also, as it was normalized for porosity binder with CBR as mentioned before, CBR with G_0 can be normalized by dividing the equations for every blend by a specific CBR value. The relation between normalized CBR [(CBR)/(CBR for G_0 = 4000)] and the G_0 is presented in Figure 4.35. A collection of 42 CBR data results were used to get Equation (4.5), permitting the generalization of a relation between the CBR and G_0. The equation has an $R^2 = 0.95$. The attained equation allows the CBR for particular mixes of clay treated with cement and PET shreds and cured for particular ages, to be obtained using just a test.

$$\frac{\mathrm{CBR}}{\mathrm{CBR}_{(G_0=4000)}} = 3 \times 10^{-26} \times (G_0)^{7.187} \qquad (4.5)$$

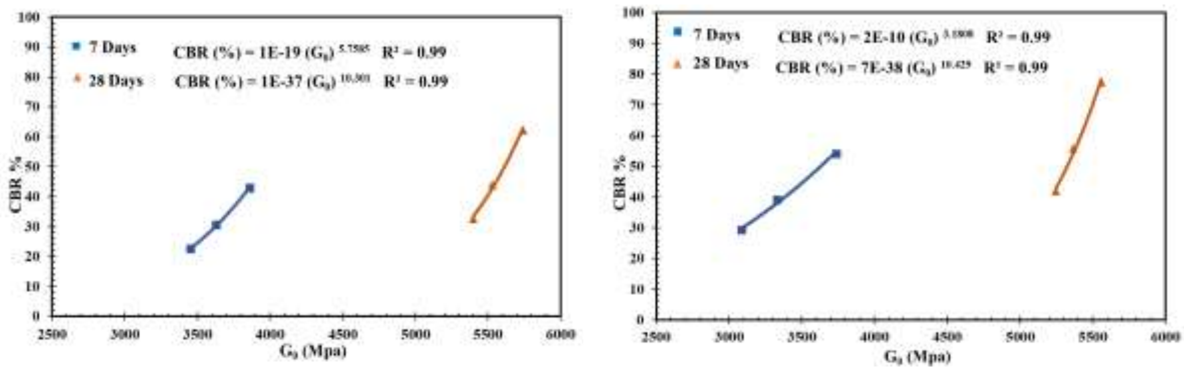


Figure 4.33: CBR vs Go (a) Clay + Cement, (b) Clay + Cement + 0.6 PET (40)

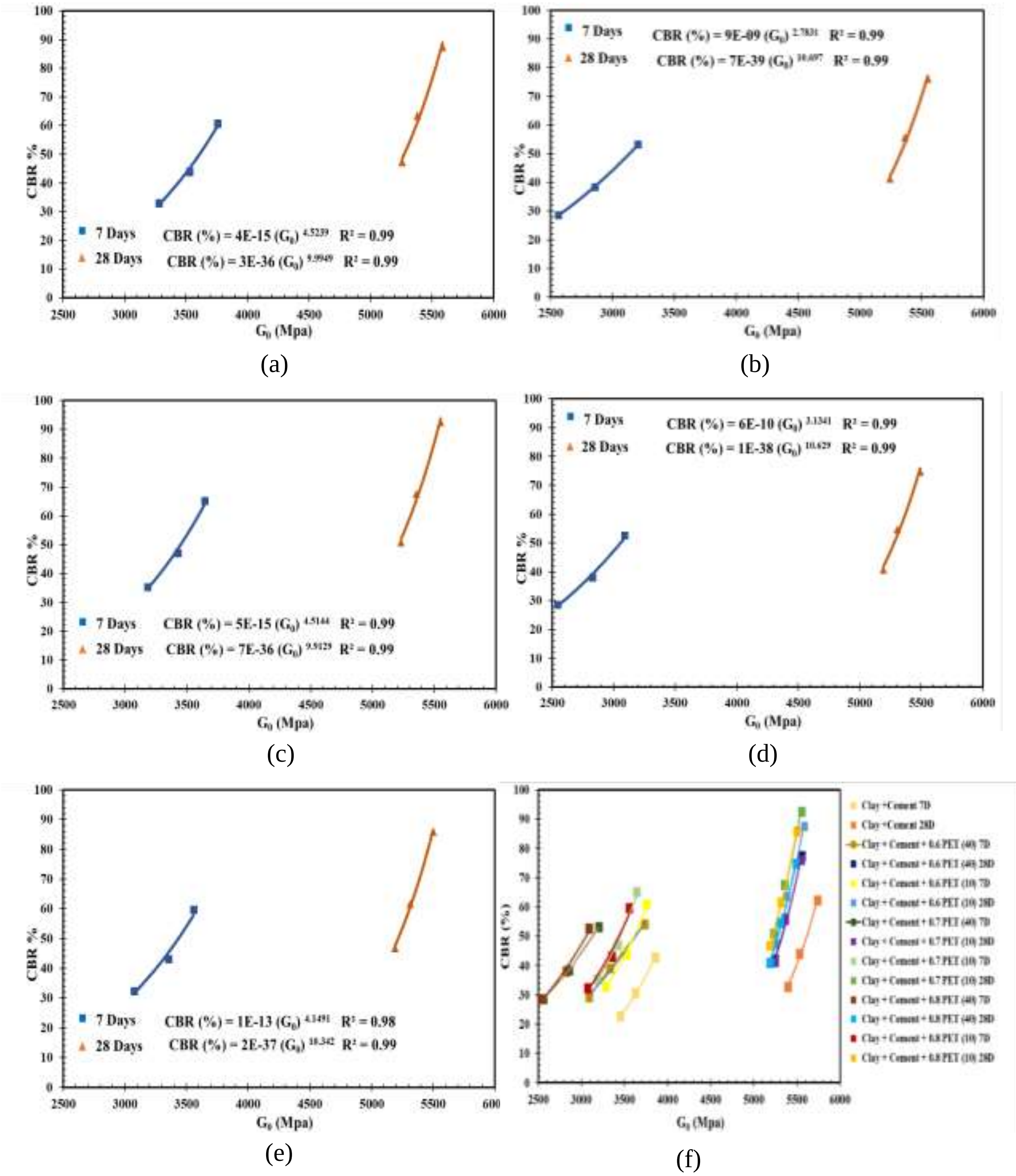


Figure 4.34: CBR vs Go, (a) Clay + Cement + 0.6 PET (10), (b) Clay + Cement + 0.7 PET (40), (c) Clay + Cement + 0.7 PET (10), (d) Clay + Cement + 0.8 PET (40), (e) Clay + Cement + 0.8 PET (10), and (f) All for all mixes

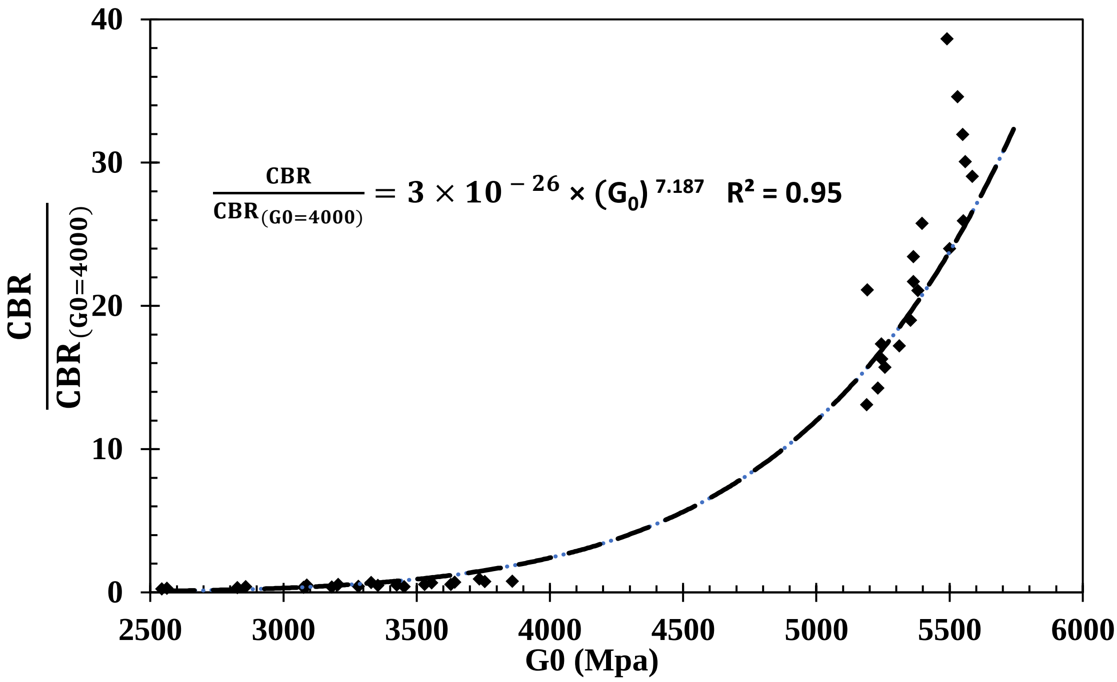


Figure 4.35: Normalized variation of CBR $\frac{CBR}{CBR_{(G0=4000)}}$, with G_0

4.13 Investigation of Soil Stabilized with Cement and PET Shreds for Highways Pavements

As it was discussed reinforcing the soil with PET shreds was found effective and as it is well-known stabilizing soil with cement increases soil strength effectively and therefore the pavement could be built thinner. In this section soil stabilized with cement and PET shreds will be carried out to find out how the beneficial it will be.

4.13.1 CBR method recommended by California state of highways

According to California state department of highways method for designing pavement thickness, considering the heaviest traffic (55.43 kN) as can be seen in Figure 4.36, the thickness design will be as following:

- Natural Soil, CBR = 3.15% the pavement thickness would be 550 mm.
- Soil stabilized with just 5% cement, cured for 28 days the CBR was 32.79%, so that the thickness would be 170 mm.
- Soil stabilized with 5% cement reinforced with size 10 PET shreds with optimum percentage 0.7%, the CBR was 50.82%, so that the thickness would be 110 mm.

- Soil stabilized with 5% cement reinforced with size 40 PET shreds with optimum percentage 0.6% the CBR was 47.41%, so that the thickness would be 120 mm.

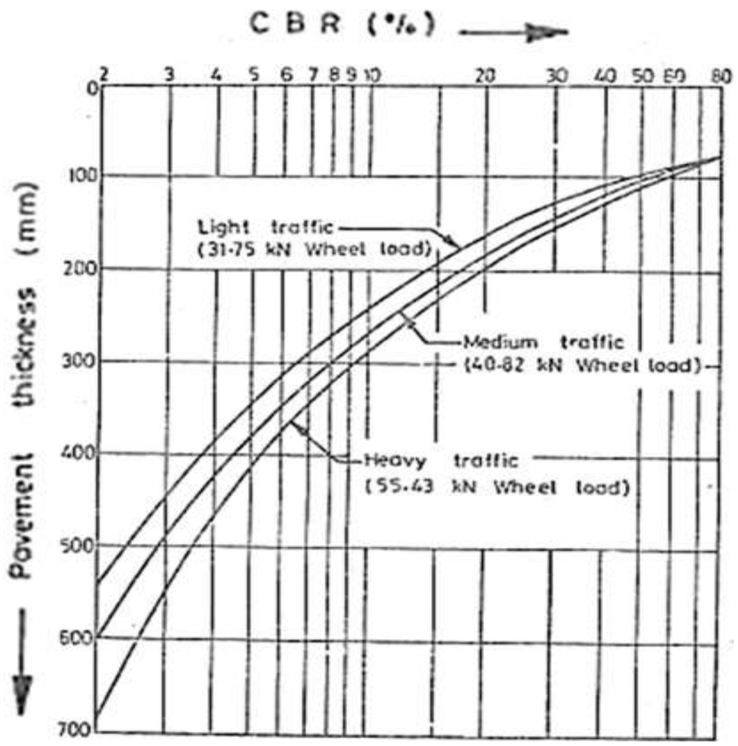


Figure 4.36: CBR versus pavement thickness curves (Hansen, 1959)

4.13.2 CBR method recommended by Indian road congress (IRC)

Also, the other CBR method is recommended by IRC, if the worst traffic (curve G) is considered, as can be seen in figure 4.37, the thickness design will be as following:

- Natural Soil, CBR = 3.15% the pavement thickness would be 680 mm.
- Soil reinforced stabilized with just 5% cement, cured for 28 days the CBR was 32.79%, so that the thickness would be 170 mm.
- Soil stabilized with 5% cement reinforced with size 10 PET shreds with optimum percentage 0.7%, the CBR was 50.82%, so that the thickness would be 120 mm.
- Soil stabilized with 5% cement reinforced with size 40 PET shreds with optimum percentage 0.6% the CBR was 47.41%, so that the thickness would be 130 mm.

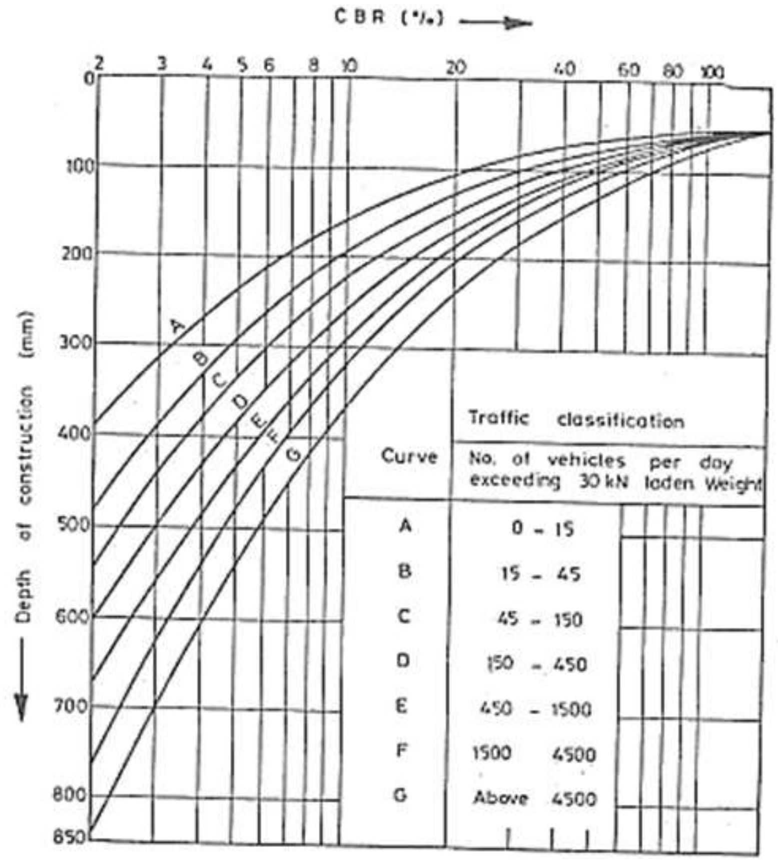


Figure 4.37: CBR versus pavement thickness curves (IRC)

As it can be seen stabilizing soil with cement and PET shreds reduced the thickness of pavement, which is considered to be cost effective. Because functionally the treated mixture has a higher CBR, environmentally it helps the nature to get rid of garbage rather than using raw materials and dragging earth resources. Meanwhile it reduces consuming cement, therefore it is accepted as a more eco-friendly solution. Last but not least, as mention before, the pavement materials are expensive, in this way free garbage will be used as a construction material so the last product will be more cost effective. Likewise it reduces the amount of cement used and therefore it is more economical. As a result, soil stabilized with cement and PET shreds is considered effective functionally, economically, and environmentally.

4.14 Investigation of soil stabilized with cement reinforced with PET shreds for airport (runway) pavements

As it was demonstrated, stabilizing soil with cement reinforced with PET shreds was beneficial for highways design and herein the suitability of using these mixes for airports pavement is checked. In this section these mixes will be studied as airports subgrade material.

Federal Aviation Administration (FAA) recommends the usage of a curve which was developed by them as illustrated in figure 4.38. If the heaviest aircraft weight is considered which is 850000 Ib and the worst annual departures is considered, the design thickness will be as following:

- Natural Soil, CBR = 3.15% the pavement thickness would be 50 in.
- Soil reinforced stabilized with just 5% cement, cured for 28 days the CBR was 32.79%, so that the thickness would be 13 in.
- Soil stabilized with 5% cement reinforced with size 10 PET shreds with optimum percentage 0.7%, the CBR was 50.82%, so that the thickness would be 9.5 in.
- Soil stabilized with 5% cement reinforced with size 40 PET shreds with optimum percentage 0.6% the CBR was 47.41%, so that the thickness would be 10 in.

Therefore, stabilizing soil with cement reinforced with PET shreds is beneficial as it reduced the runway pavement thickness. The PET shreds' role appears in increasing the CBR, reducing the thickness of pavement. It is known that the airport paving materials are expensive, therefore it will be helpful economic and environmental wise. In addition, it has a functional role in reducing the brittleness of soil and increasing its ductility which means the hit load of the aircraft tires effect on the structure of the pavement will be reduced, as it increases the ductility of soil. Therefore almost no cracks will be initiated, in addition to the reinforcing action the shreds provide. Therefore, it can be considered as a good material for runways pavements.

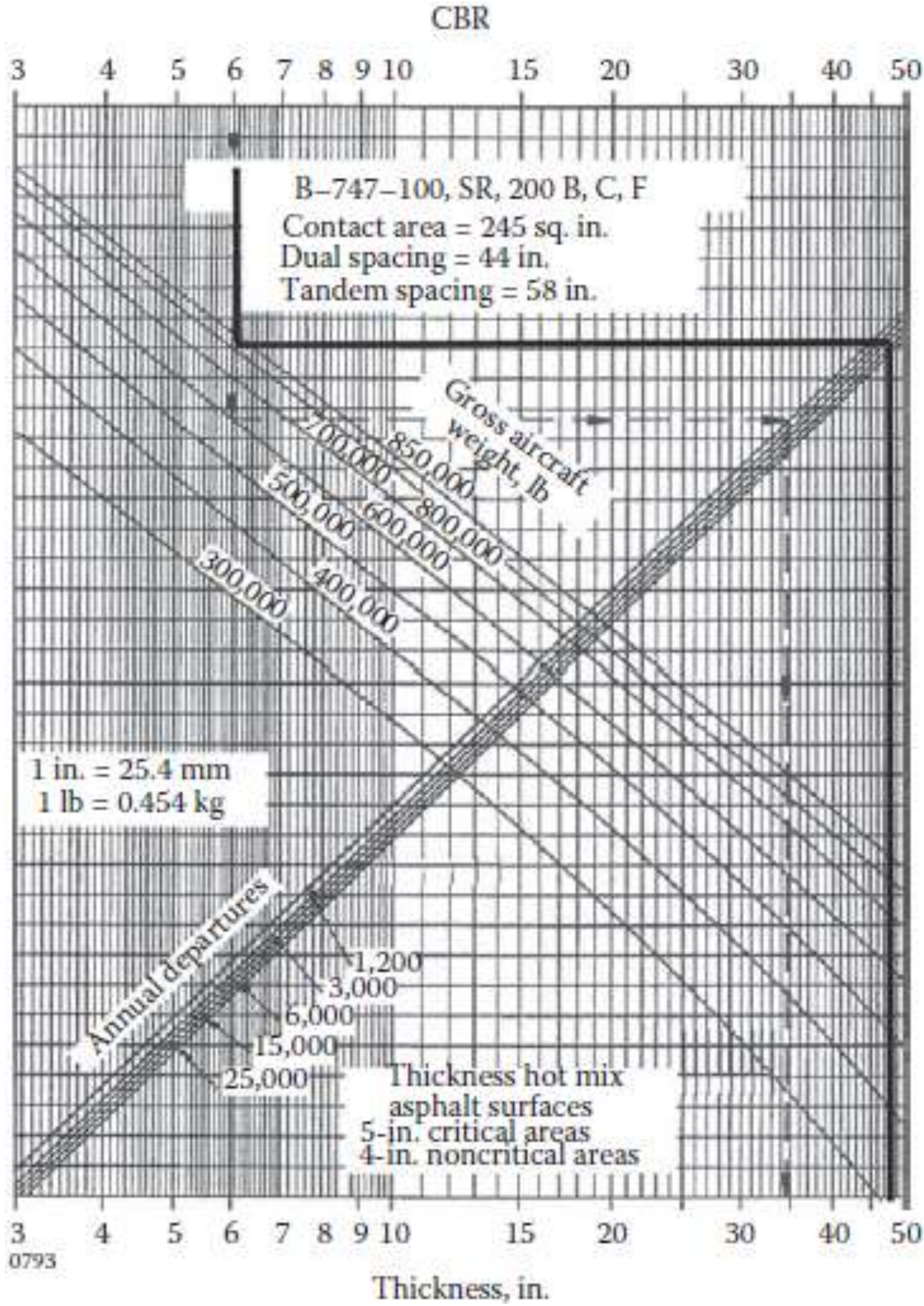


Figure 4.38: Pavement design by CBR method for Airport Runway (Adapted from FAA, 1995). (Mallik and El-Korchi, 2009)

4.15 Cracks and Integrity Investigation of Soil Stabilized with Cement and PET Shreds by Visual Inspection

It is well-known that the cemented soil is a highly brittle material which results in noticeable cracks. The cracks in cemented soil are caused by volume change and shrinkage. This shrinkage can occur for a number of reasons, such as cement hydration, temperature change, and drying. The greatest amount of shrinkage occurs in the early life of the pavement. Therefore, it is considered a problem with cemented soils as it can lead to strength loss and decline in other notable needed properties of soil. In this section, the soil stabilized with cement and PET shreds will be visually examined to find out how effective this solution is. Figure 4.39 shows the cracks initiated in cemented soil and it is compared with that one reinforced with PET shreds. As it can well be noticed, the reinforcement with PET shreds highly reduced the cracks in the cemented soil. The main reason behind it is that reduction in cement reduces the cracks in the samples. The other reason is that the PET shreds act as bridges that prevent the cracks initiation and they increase the ductility of cemented soil.

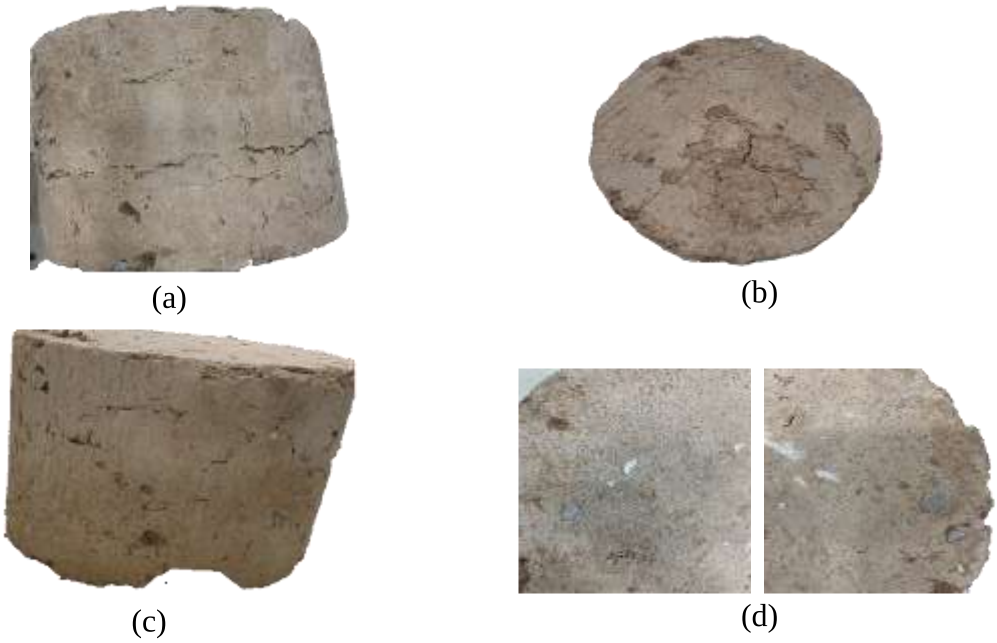


Figure 4.39: (a) Cemented soil. (b) Top view of cemented soil, (c) Fiber reinforced cemented soil has reduced cracks, and (d) Top view of Fiber reinforced cemented soil

In addition, the cemented soil samples and the reinforced ones with PET shreds were hit to the ground to compare their brittleness. Figure 4.40a illustrates the cemented soil with no reinforcement, which shows that it was separated apart and it did not protect its integrity. Hence it can be concluded that it has a high brittle behavior. The reinforcement with PET shreds of cement reduced the brittleness of cemented soil, converting it to be a more ductile material. It protected its integrity more and its parts did not separate as the cemented soil did, as can be seen in figure 4.40b.

Figure 4.40: Cemented soil sample after hitting (a) Without fiber (b) with fiber (PET) shreds

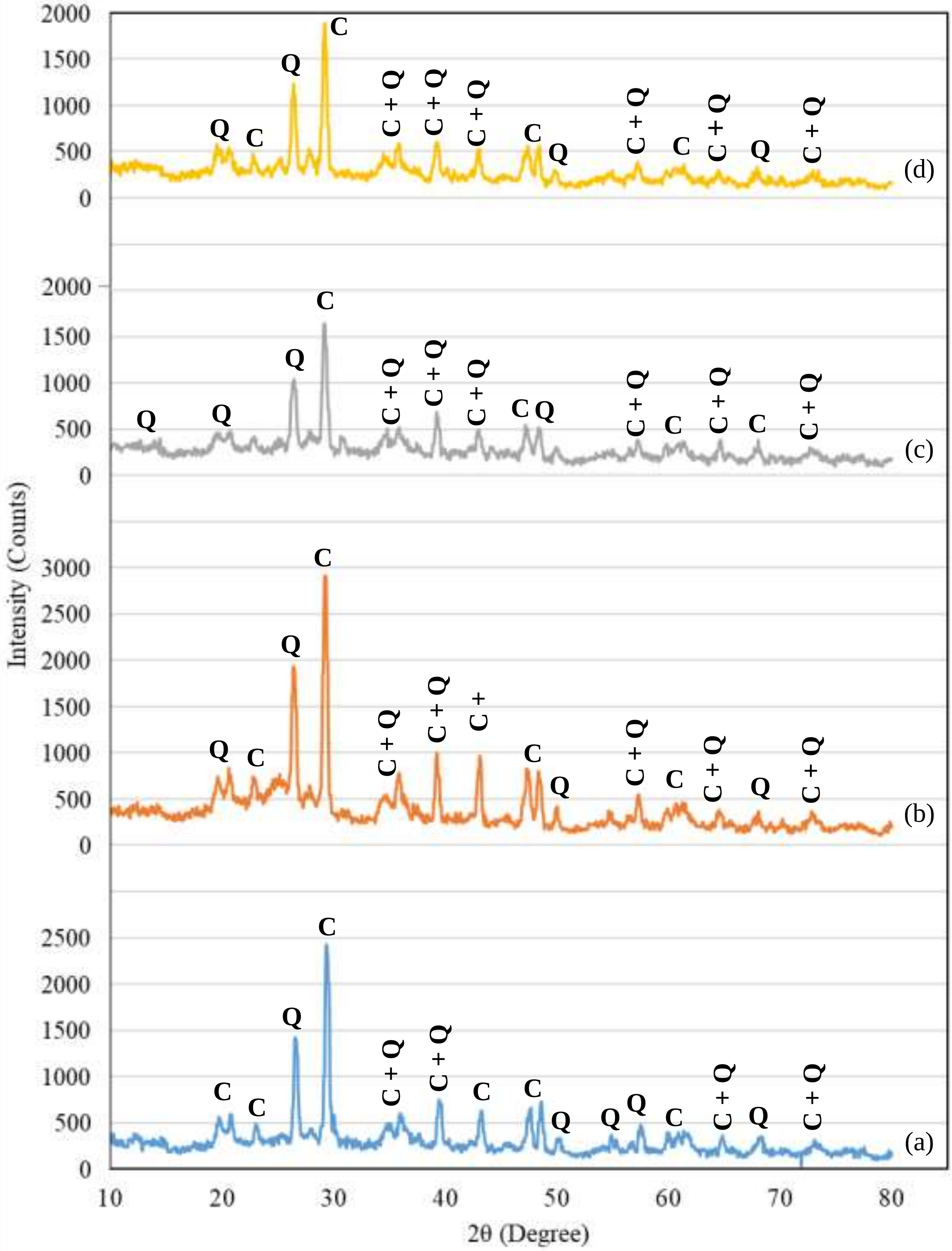
4.16 Mineralogical Analysis via X-Ray Powder Diffraction (XRD) Analysis

The X-ray powder diffraction (XRD) analysis was carried out for the mixes containing PET shreds of the size of 10 and 40, cement content of 7%, and curing ages of 7 and 28 days. The XRD pattern is presented in Figure 4.41.

The XRD test results show that the main components existing are Quartz (SiO_2) and Calcite (Calcium Carbonate, $CaCO_3$). As a comparison between size 10 and size 40, it is clear that Quartz (SiO_2) and Calcite ($CaCO_3$) are more in size 10. For size 40, it can be noticed a considerable increase in calcite ($CaCO_3$) and quartz (SiO_2) content by increasing the curing age, as in the curing age of 7 days the intensity of these components were less than the ones in age 28 days. For size 10, a high increase in calcite ($CaCO_3$) and quartz (SiO_2) content can be seen by increasing the curing age, where in curing age of 7 days the intensity of these components was less than age 28 days.

The XRD patterns reveal that there are two main picks in all the cases, the first and highest pick is Calcite ($CaCO_3$) at an angle of 29.1525 degree and the second highest pick is Quartz (SiO_2) at an angle of 26.4453 degree. The literature also shows that the clay soil is reach with Calcite ($CaCO_3$) and Quartz (SiO_2) (Kolias et al., 2005).

The increase in calcite is a result of the continuous reaction and hydration, whereas it is known, cement keeps hydrating with time and most of its hydration happens in the 28 days, therefore the calcite keeps increasing. Calcite contains hard minerals so the increase in their contents increases the strength of the soil. Calcite binds the particles with each other (Islam et al., 2020; Phang et al., 2020). That explains the higher strength that size 10 has. In addition, at curing age of 28 days, the strength is higher than the strength at age 7 days.



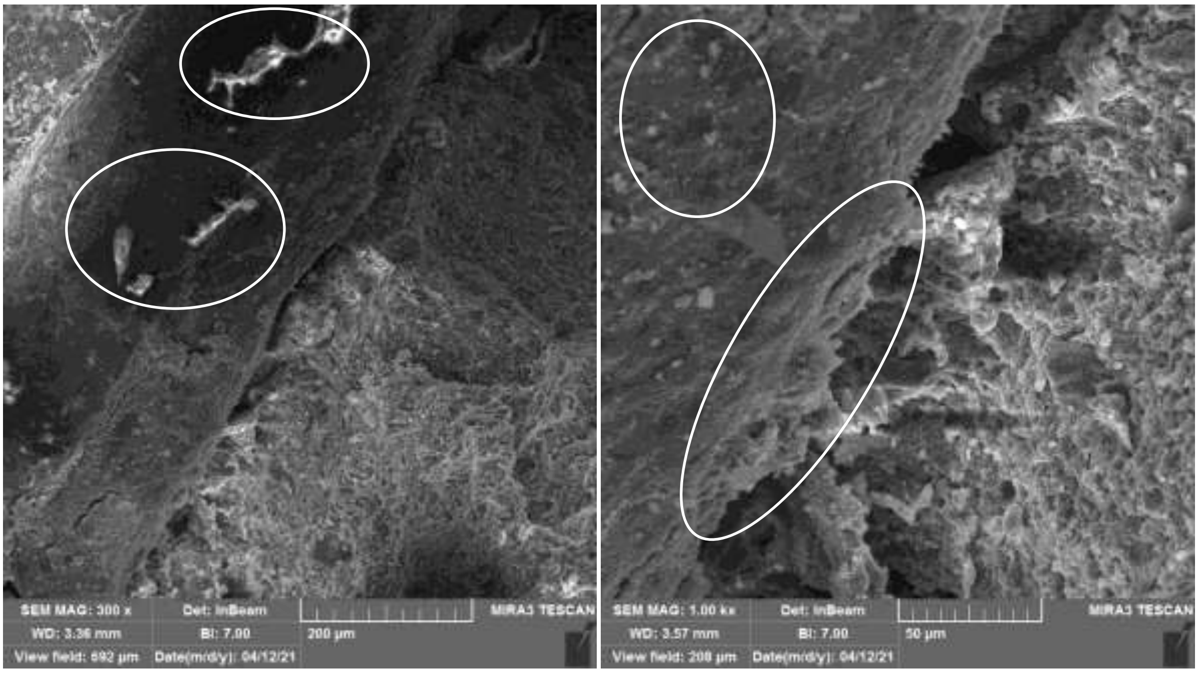
C = Calcite ($CaCO_3$) and Q = Quartz (SiO_2)

Figure 4.41: The XRD pattern of samples with 7% cement and 0.7% PET shreds for (a) PET size 10 cured for 7 days, (b) PET size 10 cured for 28 days, (c) PET size 40 cured for 7 days, (d) PET size 40 cured for 28 days,

4.17 Microstructural Analysis via Scanning Electron Microscope (SEM)

Scanning Electron Microscope (SEM) analysis was carried out for samples that contain PET shreds size 10 and 40, PET shreds the content of 0.7%, and cement content of 7% and cured for 7 days and 28 days to investigate the microstructure of these samples. After subjecting the samples to the CBR test the samples were tested for SEM to see the reactions on a microstructural level.

Figure 4.42 demonstrates that the PET shred surface is stuck by cement hydrated byproducts. The cement byproducts have high cementation and strength, which improves the interaction strength between the soil and PET shreds. Because the cement byproducts have higher cementation and strength than the grains of clay. Therefore, the interface and bonding strength of cemented soil reinforced with PET shred is much higher than that of PET shred reinforced un-cemented soil.



(a) (b)

Figure 4.42: SEM images of samples with 7% cement and 0.7% of PET shreds size 10 cured for 28 days (a) x300 and (b) x1000

The compounds of clay, alumina, and silica react with calcium and produce calcium silicate hydrate (CSH) and calcium aluminate hydrate (CAH) in pozzolanic reactions of cement hydration process. The mentioned byproducts extend and get stronger, hence enhancing the cemented clay strength through the curing time (Hanafi et al., 2020).

Figure 4.43 shows that there are pores in the mixes however these pores get lower by increasing the curing time, therefore as pores decrease the strength increases. The bonding between the soil particles is better and the reason for reducing the pores in the mixes during the curing time. The hydration byproducts fill the pores in the matrix during the curing time of 7 to 28 days, and the voids get reduced noticeably between these curing times.

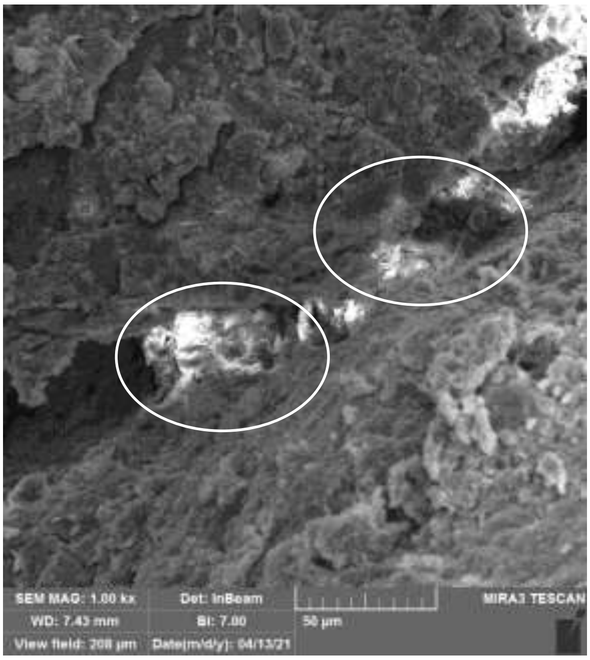
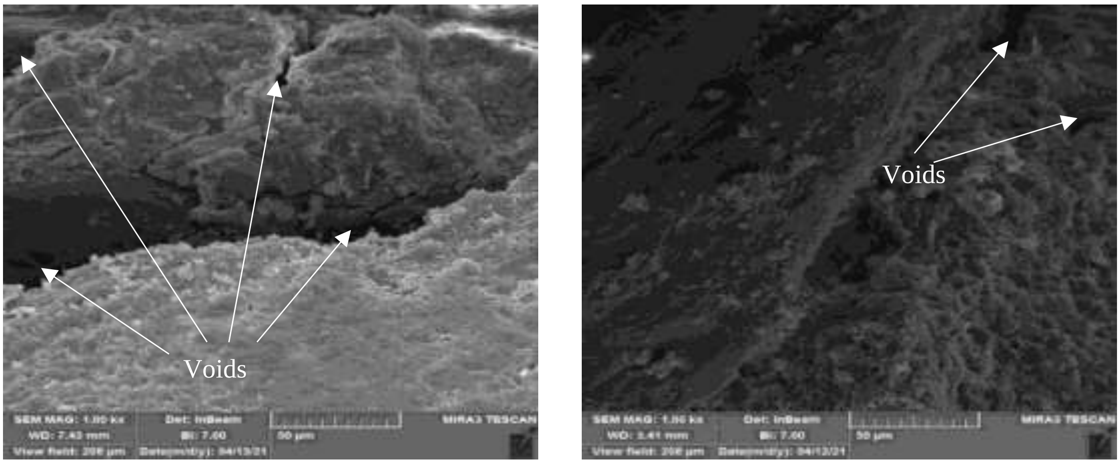


Figure 4.43: SEM images of samples with 7% cement and 0.7% of PET shreds size 40 cured for 7 days, x1000

In addition, the SEM images show that cement hydration products are existing on the surface of PET shreds and these products increase in the age of 28 days, compared to the age of 7 days due to the increase in hydration. As it is known most of the cement hydration happens in the duration of up to 28 days which results in increased strength, these products increase the interaction (bonding) strength between the PET shreds and soil matrix.

After the 28 days curing period, it is observed that the voids were filled with calcium silicate hydrate, as illustrated in Figure 4.44. Aggregation of particles is visible as a result of the reactions of cation exchange. This process decreases the double layer thickness between the particles of clay, and the attract among particles, make the particles get closer. With increasing the curing time, the voids of the samples get deceased as a result of cementation. It can be noted that 7 days is the start of curing and the cement reactions initiation. As shown in Figure 4.44, the samples voids cured for 7 days are more, and the voids get lower with curing.

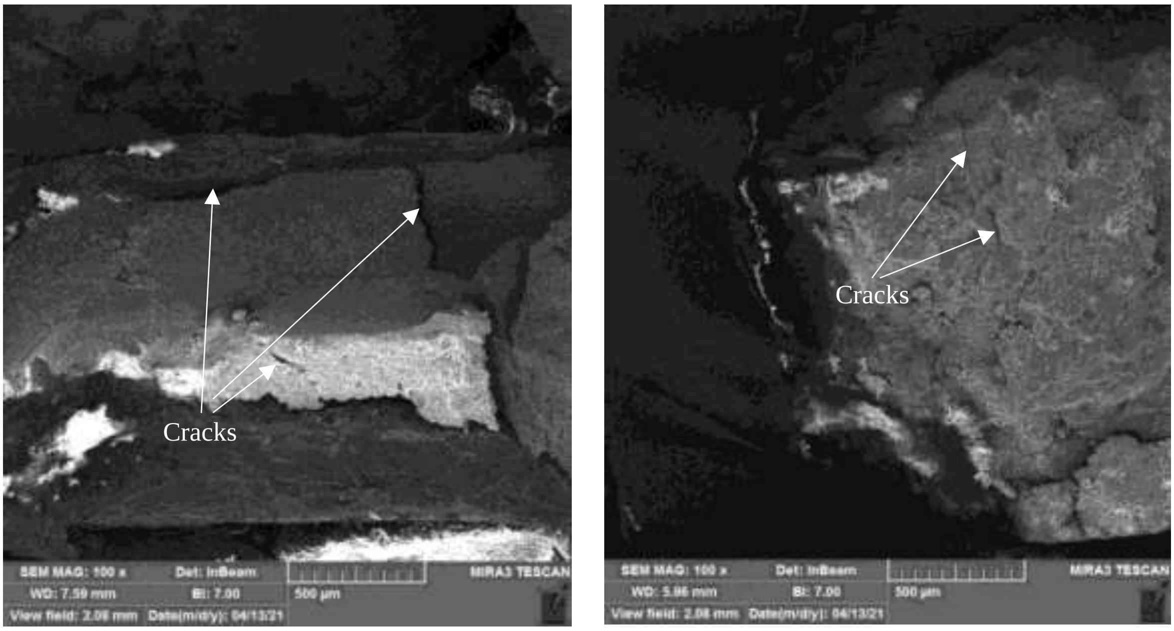
The silica and alumina reaction has happened at the parts where the property of cementing is more observable. This is a result of the development of secondary reaction after twenty-eight days, allowing reducing of voids because of the cement presence. A result of secondary calcium silicate hydrate reuse in this point of hydration as the reaction is in its early stage since the cement reacts in a longer time. This characteristic is seen in the development of strength as well. Moreover, addition of hydrated lime leads to activating pozzolanic reactions at earlier points of hydration, allowing an increase in the strength.



(a) (b)

Figure 4.44: SEM images of samples with 7% cement and 0.7% of PET shreds size 10 cured for (a) 7 days, x1000 and (b) 28 days x1000

Figure 4.45 revealed that regarding the cracks, size 10 was more active in reducing the cracks because PET shreds size 10 have bigger size. As a result, these shreds can hold more soil particles and therefore it reinforces the soil matrix more effectively. While in the case of size 40 the size is smaller so that it was not that effective to hold the cracks from initiating as the PET shreds served as bridges through the cracks.



(a) (b)

Figure 4.45: SEM images of samples with 7% cement and 0.7% of PET shreds cured for 7 days for (a) size 40, x100 and (b) size 10, x100

As a comparison between size 40 and size 10, size 40 had more pores and more cracks therefore it suffered from lower strength where the interaction between size 40 and soil matrix is lower than size 10. In addition, due to the bigger size of PET shreds, size 10 had more cement hydration products on it and therefore more interaction strength than size 40 of PET shreds. This means the interaction between the soil matrix and PET shreds is more and therefore it act like a single unit, which result in much higher strength. The higher pores in size 40 mixture is due to the lower needle-like structures initiated in this mix, while in the case of size 10 the pores are less and there are more needle-like structures filling the spaces between the soil particles. This was a significant factor effecting the unity of soil that led to higher reaction between the soil particles and PET shreds. Therefore, the strength was higher for size 10. Figure 4.46 presents the SEM images of samples with PET shred size 40 and 10.

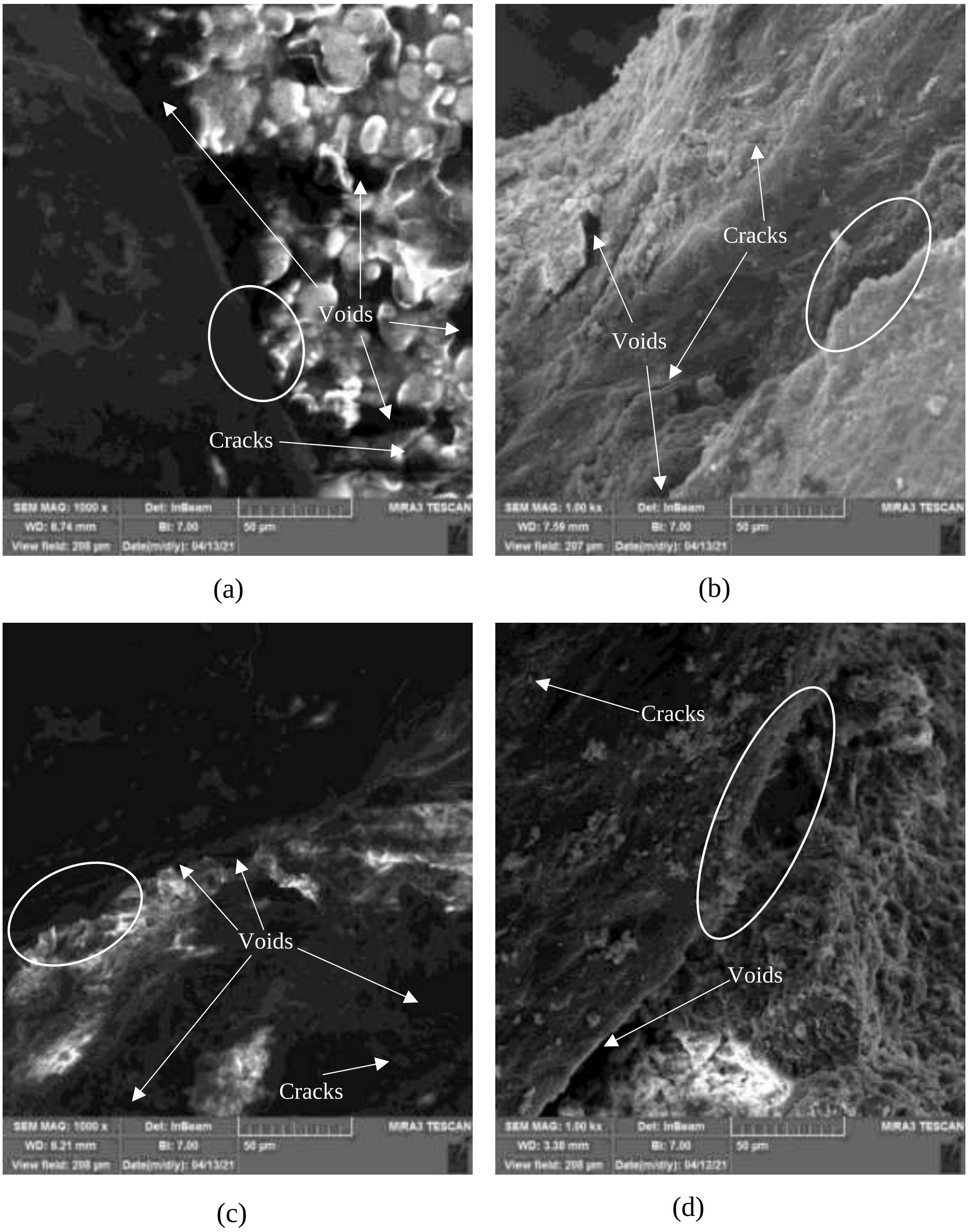


Figure 4.46: SEM images (x1000) of samples with 7% of cement and 0.7% of PET shreds (a) size 40 cured for 7 days, (b) size 40 cured for 28 days, (c) size 10 cured for 7 days, and (d) size 10 cured for 28 days

CHAPTER FIVE
CONCLUSION AND RECOMMENDATIONS

5.1 Conclusions

From the results of tests described before the following concluding remarks can be made:

- The addition of PET shreds improved the CBR of soil compared to natural soil with an improved range of 28.5to 90.7 %. It made it meet the requirements of the Iraqi standards (SORB) for CBR. It was revealed that size 10 acts better than size 40 in terms of improving CBR values of soil and the best PET shreds percentages were demonstrated to be 0.6, 0.7, and 0.8%.
- The addition of cement to soil improved the strength (CBR) of soil. With a higher cement percentage, a higher strength was gained.
- The reinforcement of cemented soil with PET shreds was found to be beneficial in terms of CBR as the PET shreds reinforcement improved the CBR of the soil compared to cemented soil, and size 10 showed better results than size 40, also the optimum percentage of PET addition was found to be 0.7%.
- The cement addition increased stiffness and brittleness of soil while the cemented soil reinforced with PET shreds presented reduced stiffness. Hence PET addition reduced the brittleness of cemented soil and made it a ductile material due to the ductile properties of PET shreds.
- The porosity/binder index is an appropriate parameter to evaluate the strength and stiffness of the mixtures studied.
- The shear modulus (stiffness) was found to be related to CBR as it can be used to determine CBR. Good determination coefficient equations were found between the parameters and there was a direct relationship between stiffness and CBR.
- The PET shreds usage alone or as a reinforcement of cemented soil helped to reduce the thickness of pavement as the PET shreds improved the CBR of both natural soil and cemented soil, therefore the reduction in design thickness would be providing a more economical and environmental solution.

- The cement percentage of 10% gave the best improvements however because the percentage of 7% gave close effects, using 7% is more economic and environmental as less cement is being used.
- The usage of cement or PET shreds or both of them together proved to be effective in solving weak soil problems as it improved the properties of soil.
- XRD patterns demonstrated that the main minerals in the soil samples were Calcite and quartz and the quantity of them was being increased over time. The mixes with PET shreds size 10 had higher calcite and quartz picks than the mixes with PET shreds size 40.
- The SEM images showed that there are soil grains and cement byproducts stock on the surface of PET shreds which improves the soil matrix-PET shreds interaction.
- The voids got reduced by time due to the initiation of ettringites which fill the voids within the soil matrix and consequently improves the strength of soil samples.
- The SEM also revealed that PET shreds size 10 did more reinforcement through the cracks than size 40, and that is the reason that size 10 was better in improving cemented soil properties.
- The PET shred's usage alone or as reinforcement of cemented soil seems to be environmental and economical, as using it alone helps to reduce waste materials amassing in nature. Also, using it as a cemented soil reinforcement reduces the amount of cement used, therefore leads to less CO_2 emission, and by that it reduces environmental hazards while being economical.

5.2 Recommendations

This research showed many interesting findings which may be beneficial in practice therefore this topic needs further future works as recommended here, to get to a better and deeper understanding of the mechanisms of the ideas presented in this study:

- Equations to predict the CBR and stiffness through (n/Xiv) were proven effective. Other studies could be performed to check the validity of these equations with other soil types.

- In this study, clay soil was used and the improvement methods in this study were found effective, therefore other soil types can be studied to study the effectiveness of the suggested methods.
- In this study, two sizes were used and were proven effective. Other sizes of PET shreds can be studied to prove if they perform better. In the case of better performance, the cement used could be reduced and therefore more benefits could be obtained.
- In this study, CBR, Stiffness (UPV), microstructure, and visual inspection of soil stabilized with cement partially replaced with PET shreds were performed. Therefore, some other tests can be conducted such as plate load tests to examine its settlement behaviors.
- In this study, the suggested equation to predict the CBR through stiffness was proven effective. Other studies could be performed to check the validity of this equation with other soil types and to prove its applicability to use in practical areas.
- Different government agencies should be aware of this possible soil stabilizing method and its uniform production should be encouraged and applied.
- Future studies can be carried out to partially replace cement with PET shreds which will allow the reduction of cement amount used and may work more beneficially.

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APPENDICES

APPENDIX 1

Plagiarism and Ethical Rules Contract Form

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