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Civil Engineering Department

**Assessing the Effectiveness of Hybrid Stabilization Methods
for Sustainable Subgrade Soil Improvement in Pavement
Construction**

A Thesis Submitted to the Council of the College of the Engineering/
University of Kerbala in Partial Fulfillment of the Requirements for the
Master Degree of Science in Civil/ Infrastructure Engineering

By:

Asraa Salah Hashem

Supervised by:

Assistant Professor Dr. Alaa M Shaban

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Muharram 1447

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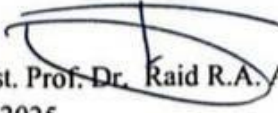
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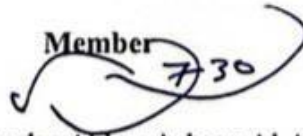
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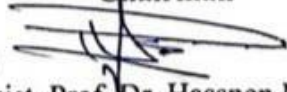
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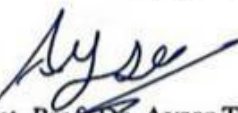
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Signature: 
Name: Assist. Prof. Dr. Aysar Tuama Al-Awadi
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Date: / / 2025

Signature: 
Name: Prof. Dr. Haider Nadhom Azziz Al Joda
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Date: 4/8/2025

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Dedication

I dedicate this work to my dear father for his constant support and assistance, to my supervisor for providing information and advice throughout this period, and to all my colleagues who helped and supported me.

Signature:

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Asraa Salah Hashem

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Abstract

Roads are vital components of infrastructure, playing a crucial role in traffic flow and providing efficient transportation. One of the significant aspects of roads is the subgrade, which serves as the foundation. However, due to the heavy traffic loads it endures, even soils with strong engineering properties can fail, leading to complete road collapse. Consequently, researchers have sought to enhance subgrade properties through mechanical and chemical stabilization techniques that are widely employed. This research aimed to assess the effectiveness of a sustainable hybrid stabilization method for stabilizing weak sandy soils using recycled concrete aggregate and asphalt emulsion. The sandy soil was stabilized using four different grades of recycled concrete aggregate (RCA), divided into four grades (with gradations ranging from 19 mm to 0.0075 mm). Each grade comprised four percentages: 5%, 10%, 15%, and 20% of the dry soil weight. Asphalt emulsion (EA) was added at four ratios: 2.5%, 5%, 7.5%, and 10% as a chemical additive. A testing program was implemented to evaluate the properties of natural and stabilized soils in three stages: The first stage included a modified Proctor test and a California Bearing Ratio (CBR) test. The laboratory testing results showed that soil strength and bearing capacity improved significantly after the addition of RCA. The addition of RCA generally improves the maximum dry density, with a noticeable increase in density when 15% RCA is added, especially in zones 3 and 4, where the percentage increases were 6.15% and 4.62%, respectively.

Increasing the percentage of RCA in the natural soil mixture significantly enhances the CBR value in all four grades, determining the optimum 15% RCA ratio. The percentage increase in CBR values ranged from 30% to 125%. The second stage involved a CBR test of soil mixtures stabilized with RCA and supplemented with EA, revealing that the CBR values decreased as EA ratios

increased. The third stage involved conducting three in-situ tests: the sand replacement method (SCM), lightweight deflectometer (LWD), and dynamic cone penetration test (DCP). All soil mixtures were stabilized with RCA and EA, and the results showed significant improvements in DCPI, surface deflection, dynamic modulus, and dry density due to the use of RCA and EA. The laboratory results served as input parameters in a theoretical model implemented in the KENPAVE program to assess the performance of natural and stabilized soils. Utilizing RCA increases compressive stress and N_d , while decreasing compressive strain and the damage rate.

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List of Abbreviations

Abbreviation	Description
AASHTO	American Association of State Highway and Transportation Officials
ASTM	American Society for Testing and Materials
BS	British Standard
CBR	California Bearing Ratio
Cc	Curvature Coefficient
CKD	Cement Kiln Dust
Cu	Uniformity Coefficient
DCP	Dynamic Cone Penetration Test
DCPI	Dynamic Cone Penetration index
FDD	Field Dry Density
LWD	Light weight Deflectometer
MDD	Maximum Dry Density
NS	Natural Soil
OMC	Optimum Moisture Content
PLT	Plate Load Test
RCA	Recycled Concrete Aggregate
SEM	Scan Electronic Microscopy
SP	Sandy Soil
SCM	Sand Cone Method
TSS	Total Soluble Salt
USCS	Unified Soil Classification System
G	Grade Number of RCA

List of Symbols

SO_3	Sulfur Trioxide
C_3A	Tricalcium Aluminates
D_c	Degree Modulus
E_d	Dynamic Modulus
MgO	Magnesium Oxide
N_d	Allowable Number of Load Repetitions
q	Bearing Capacity
S_d	Deflection of the Subgrade Layer
δ	Surface deflection
a	Radius of the Loading Plate
f	Plate Rigidity Factor
ν	Poisson's Ratio
γ_{dry}	Dry Density
γ_{wet}	Wet Density

Chapter One:
Introduction

Chapter One: Introduction

1.1 Background

The subgrade is that part of the pavement system that represents the natural soil layer on which the surface course and unbound pavement layers are built. The subgrade provides support for the rest of the paving system. The subgrade's quality greatly impacts the pavement's design and the actual service life of the constructed pavement. When this layer is weak in terms of strength and cohesion, it is also weak in terms of bearing traffic loads, which leads to the failure of the rest of the road layers (Sudas, 2013). To improve its properties, stabilization techniques are typically utilized to enhance certain soil properties. The simplest methods are compaction and drainage. Other methods may include blending soils to achieve a desired gradation or mixing in additives that can alter the gradation, texture, or plasticity, or act as a binder for the cementation of the soils (Kollaros & Athanasopoulou, 2017).

The stabilization methods fall into two broad categories, namely, mechanical stabilization and chemical stabilization. Chemical stabilization is adding chemically active substances to the soil, like fly ash, Portland cement, and lime, or injecting it with viscoelastic substances, like asphalt emulsion (Zalih, 2013). The mechanisms involved in stabilizing soil with a bitumen emulsion material differ greatly from those engaged with cement or lime. For coarse-grained, non-plastic soils, the main function of the bitumen emulsion is to add cohesive strength. Thus, the stabilization emphasis with granular soils such as sand and sandy soils is on thoroughly admixing an optimum amount of binder so that the particles are thinly coated with binder and held together without losing particle interlock (Bidin, 2017).

Mechanical stabilization depends on the resistance interaction between soil particles when external forces are applied. It occurs when soil particles are strong and distributed in a certain way, so the soil structure is stronger and more

stable. This stabilization is done through mechanical effects such as friction between particles, which increases the density and strength of the soil. The quality of the original soil materials, the size and shape of the particles, and the water content in the soil are factors affecting the mechanical stabilization process of the soil. The physical stabilization process is one of the important processes in civil engineering, as it plays a vital role in improving the properties of the soil (Afrin, 2017).

Soil stabilization methods can be implemented sustainably using recycled and waste by-product materials, providing significant environmental benefits. Old concrete can be recycled into coarse or fine aggregates, or it can be used again in its original form. Recycled Concrete Aggregates (RCA) can be reintroduced into concrete production as a natural aggregate substitute or used as backfill material in quarries, foundations, and other construction sites after sorting and processing (Hossain et al., 2016). Additionally, RCA can be used as a base or subgrade for road works. Using recycled concrete aggregates (RCA) may lessen the massive environmental impact of concrete, which accounted for more than 4% of all greenhouse gas emissions during the previous ten years. In terms of reducing waste production and the depletion of natural mineral resources, replacing natural aggregates with recycled ones may be crucial. Moreover, recovering demolished concrete leads to considerable cost advantages for contractors by eliminating charges for waste disposal (Oikonomou, 2005).

1.2 Research Problem

To ensure a durable and strong subgrade, the pavement system must be carefully designed. Weak subgrade soils present a significant challenge in road construction due to their limited capacity to support heavy traffic loads. This deficiency often results in structural deformations and reduced cohesion within the soil matrix. Consequently, roads built on such subgrades require frequent maintenance and, in severe cases. One of the common methods for treating

weak subgrade in Karbala city is to replace the soil with more suitable materials, such as well-graded granular soil, to increase the ability of the subgrade to bear high traffic loads and improve soil properties, but this method is often expensive and leads to the depletion of natural mineral resources. Therefore, geotechnical engineers often employ alternative techniques to improve the properties of weak soil. This is accomplished through soil stabilization technology, which is defined as enhancing or maintaining soil stability by improving its engineering properties.

1.3 Aims and Objectives

1.3.1 Aims

This research aims to assess the effectiveness of utilizing a hybrid stabilization technique to stabilize loose-sand soils. Two strategies are applied to achieve the hybrid stabilization technique: the use of recycled concrete aggregate (RCA) as a mechanical stabilization method and the use of asphalt emulsion (EA) as a chemical stabilization.

1.3.2 Objectives

The purpose of this study is to investigate the effectiveness of RCA and EA in enhancing sandy soil and promoting sustainability in road construction. The findings of the study will guide engineering practices and decision-making in the improvement of sandy soil for road infrastructure. To achieve this goal, the following objectives were pursued:

1. Selecting a typical sandy soil which represents the most common soil type available in Karbala city, evaluating the physical properties of the subgrade soils through a range of laboratory tests, such as sieve analysis, specific gravity, modified Proctor, and California bearing ratio (CBR)...etc.
2. Preparing a recycled concrete aggregate (RCA) with four different grain-size distributions. Then, develop and optimize the soil mixtures with four percentages of RCA through a series of controlled experiments.

3. Stabilizing the sand-RCA mixtures with different dosages of asphalt to evaluate its effect on soil strength.
4. Conducting large-scale laboratory tests to evaluate the performance of the stabilized soils under the effect of dynamic in-situ tests.
5. Based on the obtained results from laboratory testing of the stabilized subgrade soils, a theoretical analysis was conducted to evaluate the structural performance of the pavement section.

1.4 Thesis Scope

This research study was conducted under a wide range of conditions, materials, test methods, and design methods under the following scope:

1. One type of subgrade classified as poorly graded sand soil was chosen, which was obtained from a road project in the city of Karbala.
2. In the laboratory, basic physical and mechanical properties as well as laboratory testing techniques for the chosen soil type were evaluated.
3. A model was locally manufactured to conduct field tests to simulate field circumstances.
4. Quantities of recycled concrete aggregate (RCA) rubble were collected, crushed using heavy equipment, and classified into four groups with different grades.

1.5 Thesis Outline

This thesis consists of six chapters, which demonstrate the study work outcomes as listed below:

- **Chapter One:** Introduces the background of the thesis, its problem statement, aims and objectives, and finally, the thesis structure.
- **Chapter Two:** Reviews the effect of weak subgrade in pavement systems, soil stabilization techniques, emulsion as a stabilizing agent, recycled concrete aggregate, and summary.

- **Chapter Three:** It describes the research methodology, the type and location of soil used in this research, the physical properties of the specific type of soil, and the testing procedures for California bearing ratio testing, sand cone method, lightweight deflectometer, and dynamic cone penetration to achieve the research objective.
- **Chapter Four:** It shows the results of a sandy soil stabilization study with RCA and EA and presents a comprehensive analysis and discussion of this study.
- **Chapter Five:** It explains the theoretical analysis of the results, and this is done by using the KENPAVE program.
- **Chapter Six:** explain the main conclusions and recommendations for future work.

Chapter Two:
Literature Review

Chapter Two: Literature Review

2.1. Introduction

The subgrade is part of the pavement system and refers to the layer of natural soil on top of which the surface course and unbound pavement layers are built. Subgrade soil supports the rest of the pavement system; good subgrade quality significantly impacts pavement design and the actual useful life of the constructed pavement. It is impossible to overstate the importance of a high-quality subgrade to the pavement's long-term life (Sudas, 2013). So, it is known that the strength and rigidity of the subgrade layer are essential in creating a road that can withstand the loads generated by heavy vehicles and is durable by ensuring road safety and structural integrity. Since the stresses generated by the compounds are transferred to the subgrade, the subgrade must be built strong enough to withstand greater loads before it deforms to a bad degree. Sometimes, the soil on a site lacks the strength and hardness needed for a strong subgrade (Shaban et al., 2021).

Weak soils, including loose and unstable sands, soft clays, and organics, are inadequate for highway construction projects. These weak soils do not possess valuable physical properties for construction applications. The usual methods for remediation of this weak subgrade, such as removing the soil and replacing it with new one, are typically expensive (Fauzi et al., 2013). Therefore, the identification and treatment of weak subgrade soils is an essential objective. Replacement is one of the standard solutions. However, it is very costly and impractical in highway projects due to the huge volume of these projects. Improving weak soils by using lime, Portland cement, and other chemicals, which are an effective solution. However, using these admixtures adds supplementary cost. In the previous 20 years, soil stabilization using by-product chemical binders

and waste materials has increased rapidly worldwide. To improve the properties of weak soils, this technique has been used, mainly when the soils show a low shear strength and high compressibility to support in safe conditions the loads applied by several works, such as foundations of buildings, pavements, and barriers, among others. The main constraint of this technique is the low tensile strength of stabilized soil, which prevents its use in projects requiring high tensile strength, such as in structures subject to vibration (Tinoco & Correia, 2021).

2.2 Soil Stabilization Techniques

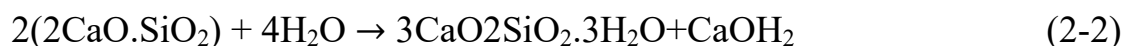
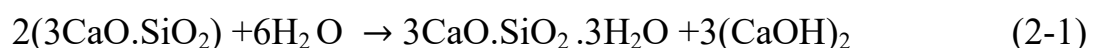
The change or preservation of one or more soil properties to enhance its performance and engineering qualities is known as soil stabilization. In a broad sense, stabilization refers to the different techniques used to alter the characteristics of the soil to enhance its engineering performance. Improving one or more of the natural properties of the soil by adding specific soil, cement, or other chemical materials is known as "soil stabilization." Stabilization can be accomplished in two ways: either by adding stabilizing material to an undisturbed soil deposit and allowing it to permeate through soil voids to create an interaction, or by mechanically mixing the natural soil and stabilizing material together to create a homogenous mixture (Afrin, 2017). Two methods to stabilize soil are summarized in the following subsections:

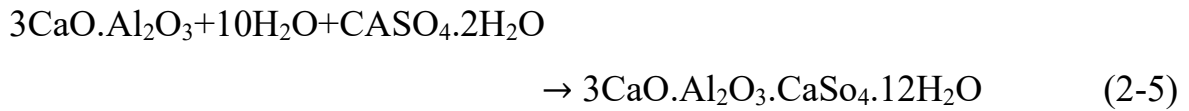
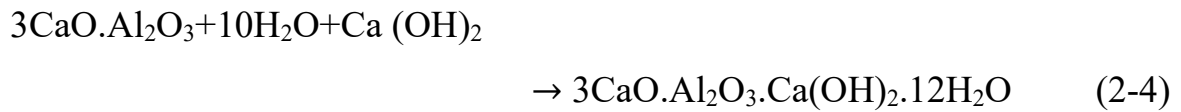
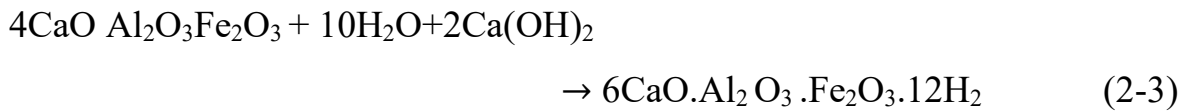
2.2.1 Chemical Methods

The most frequently utilized method of treating soil is chemical stabilization. The goal of chemical stabilization is to increase the soil material's interaction and cementation to improve stability. This process involves introducing specific chemical compounds into the soil and includes both traditional and non-traditional methods:

2.2.1.1 Traditional Stabilizers (Chemical Additives)

- Cement stabilization:** Being a hydraulic binder, Portland cement hardens and undergoes chemical reactions when water is added. It has been stated that creating soil cement by mixing soil material with cement was a common method used in chemical stabilization. A mixture of soil, water, and estimated amounts of Portland cement compacted to the desired density is called cemented soil. The purpose of Portland cement is to improve and change the properties of soil material, turning it into a cemented mass with increased strength and resilience to shear (Sherwood, 1993). This method is considered more suitable because the amount of material added to the soil is small and initiates chemical reactions such as agglomeration, cation exchange, and pozzolanic activity, which enhance the properties of the subgrade soil. Small additions of Portland cement to the soil mixture are among the most widely used chemical stabilization techniques by many researchers (Ali, Shaban, & Almuhan, 2024). Cementitious compounds occur after the hydration of Portland cement with water. Cementitious compounds consist of calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H), and the discharge of excess calcium hydroxide (CaOH), which starts to form in amounts of about 31% by weight 12 minutes after the cement meets water, as shown in the Figure (2-1). The C-S-H crystals form after a few hours and strengthen the soil's matrix by cementitious bonding with it. Crystals will continue to form if there are unreacted cement particles and free water in the mixture (Firoozi et al., 2017) (Marik et al., 2022). The equations below show these reactions (Umesha, Dinesh and Sivapullaiah, 2009):





The pozzolanic reaction is the secondary process by which calcium hydroxide combines with silica and alumina present in the soil and cement mixture. These slow, long-term pozzolanic reactions improve the engineering properties of the soil, as shown in the equation (Dunster, Parsonage & Thomas, 1993)(Marik *et al.*, 2022):

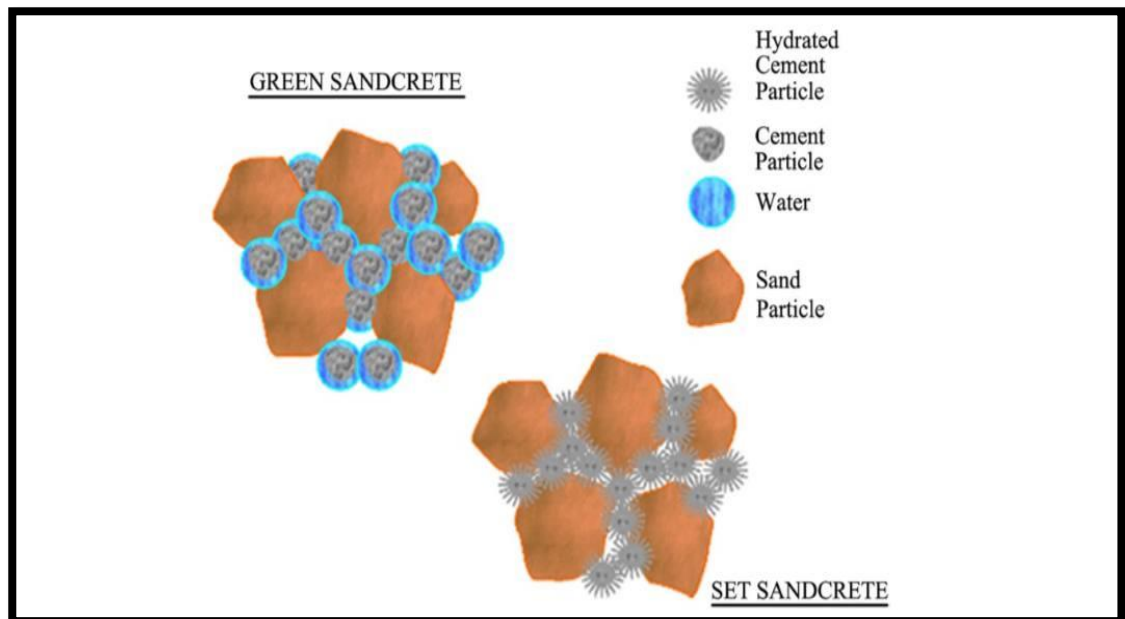
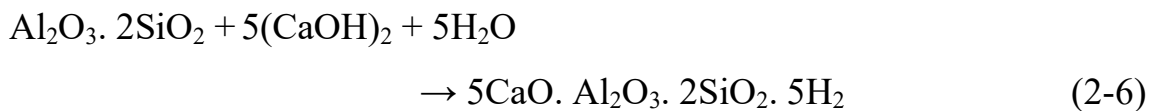


Figure (2-1): Method by which particles of cement and sand are bound together(Firoozi *et al.*, 2017).

- **Lime Stabilization:** The lime stabilization technology is the most used method of the soil stabilization process, usually used in fine-grained soil. This includes the encapsulation of pollutants, stability of slopes, and enhanced performance of foundations utilizing lime aggregate particles,

as in Figure (2-2). It refers to the pozzolanic reaction, in which the presence of water causes the lime components to react by producing cement compounds. Quicklime (CaO) or hydrated lime Ca(OH)₂ could have an impact(Kézdi, 2016). Quicklime (CaO) is more commonly used due to the following advantages:

- There is more free lime per unit mass.
- Greater density than that of hydrated lime.
- As shown in the equation below, it produces heat that significantly lowers moisture content and increases strength.



Figure (2-2): Application of Lime Stabilization(Mr. Mukherjee , 2014).

The hydrated lime (Ca (OH)₂) created when lime is added to soil in the presence of water causes the soil particles to flocculate. When iron fluctuations cause the clay particles to aggregate. This phase, referred to as flocculation, is a concentration. These reactions alter the physical properties of the soil right away, leading to a decrease in plasticity and an increase in compressibility, but they do not increase strength(Afrin, 2017). As such, it yields the subsequent benefits:

- For road construction, decrease the thickness of the unbound pavement layers due to the rising CBR value.

- Boosting unconfined compressive strength, CBR values, workability, and shear and tensile strength.
- **Fly ash:** Fly ash stabilization is increasingly popular due to its wide availability. In geotechnical applications, fly ash has been used effectively. Fly ash is a by-product of coal combustion during power generation. Compared to lime and cement, fly ash has poor stabilizing properties. Therefore, soil stabilization with fly ash has some limitations:
 1. When stabilizing soil with fly ash, it should have a lower moisture content, so drying may be required.
 2. Fly ash and soil mixtures that are improved below zero and then soaked in water cause significant erosion and loss of strength.
 3. Fly ash contains sulfur, which forms expansive minerals in the soil mixture, reducing its strength and durability in the long term(Afrin, 2017).

2.2.1.2 Non-Traditional Stabilizers (Chemical Additives)

- **Cement Kiln dust (CKD):** The production process produces large quantities of cement kiln dust (CKD). For many years, studies have been conducted on using cement kiln dust as a soil stabilizer. Its chemical composition consists of calcium oxide, calcium hydroxide, silica, alumina, and iron oxides. Its physical composition is a fine powder that can react with water to form solids, so it has a pozzolanic activity that enhances the soil properties (Toshpulatov, 2022).
- **Polymers:** Nontraditional additives include a variety of liquid or powdered substances, like polymers. Many of these materials can be created naturally, or they often occur naturally. It can be applied as a liquefaction-reducing agent or as a supplement to improve soil. Most engineers are hesitant to use these

unconventional additives in practice despite their clear potential benefits. Several factors, including a lack of independently published research to support the performance improvements claimed by additive manufacturers, a lack of standard laboratory testing procedures and methodologies for assessing field performance, and inadequate information provided by manufacturers regarding an additive's hidden active constituents, which may give rise to environmental issues in a certain situation (Latifi et al., 2017).

- **Gypsum:** "Gypsum" usually refers to a mixture of gypsum, hemihydrate, and anhydrite. An alternative to cement for ground improvement is gypsum in its natural form as a mineral, as recycled and industrial waste, or as a by-product of the phosphate industry and thermal power plants. Consequently, employing gypsum as a binder helps minimize and recycle the waste and byproducts from various industries and lowers the quantity of cement and lime needed for ground improvement techniques. Nevertheless, anhydrite, the related anhydrous mineral, expands and changes volume when exposed to water, while gypsum is only slightly soluble in water. The strength limit and service limit designs of both gypseous soils—soils that naturally contain gypsum—and soils treated with gypsum should consider strength loss from dissolution and swelling from wetting. These difficulties are most likely one of the reasons that gypsum has not gotten much attention lately for ground improvement applications utilizing cement. Given their efficiency in enhancing the mechanical characteristics of soils and their numerous sustainability benefits, it appears vital to comprehend the advantages and drawbacks of this technique and to pinpoint the

further study required to fully benefit from it (Abdolvand & Sadeghiamirshahidi, 2024).

2.2.2 Mechanical Methods

The method of increasing the soil's qualities by altering its gradation is known as mechanical stabilization. Mechanical stabilization is also carried out using a variety of rollers, rammers, and vibration techniques, and mechanical energy is applied to the soil for compaction and densification. To maintain soil stability, this approach relies on the intrinsic qualities of the soil material. We combine two or more types of natural soil to create a composite material that surpasses any of its constituent parts. Soils of two or more grades are mixed or blended to achieve mechanical stability and produce a material that satisfies the necessary specifications (Afrin, 2017). This process includes both traditional and non-traditional methods:

2.2.2.1 Traditional Mechanical Methods

- **Compaction:** The primary goal of soil compaction is to produce soil material that satisfies these three essential needs: [1] a reduction of the ensuing soil material settlement under active loads, [2] a decrease in permeability stops a rise in water stresses that would cause problems with liquefaction and water content in earth dams, and [3] raise the soil material's bearing limit and shear resistance. Furthermore, the influence of compaction on soil qualities is typically contingent upon the soil's achieved structure throughout the compaction process (Fondjo & Theron, 2021).
- **Soil replacement:** One of the most widely used mechanical soil stabilization techniques is soil replacement. The active zone depth, soil profile, regular procedures, and construction requirements all impact the soil depth that needs to be changed. Materials used for backfilling should

be non-expansive and impermeable. Additionally, backfill materials, particularly remolded in situ soil, should be replenished and compacted according to the proper compaction guidelines. Substituting porous soil material like gravel or coarse sand transfers surface moisture to the expanding clay layer, resulting in surface-equivalent differential displacement. You cannot substitute sand and gravel for soil components. The best course of action is to replace problematic soil with a substance that can withstand loads better. Finally, an effective stabilization strategy may be part of the cost-effective improvement procedure due to the greater replacement expenses of some undesirable soils, such as swelling soils (Hamzah et al., 2015).

2.2.2.2 Non-Traditional Mechanical Methods

- **Wetting-Drying Cycles:** It is uncommon to refer to the wetting-drying cycle as a standardized stabilization technique. Nonetheless, in a particular building project, the method may be utilized to lessen the swelling potential of expansive soils (ES). A few investigations on the impact of the wetting-drying cycle technique on ES have been conducted (Ahmadi et al., 2012). The results of these investigations suggest that a repeated technique could cause the expansion potential to increase or decrease. By varying the drying-wetting cycle on stabilized soil material, wetting-drying cycles are also used to examine the durability of chemical additives used in soil stabilization and to understand the time-dependent performance of such chemicals under field settings. Previous studies demonstrate that by repeating the wetting-drying process, the plastic deformation—that is, the difference between shrinkage and swelling potential due to a specific cycle—tends to diminish or attain a constant value.

- **Soil Reinforcement:** The soil reinforcement technique aims to improve the characteristics of soils by adding natural or synthetic additives. One way to stabilize the soil is to add materials with greater tensile strength, such as fiber, to improve the soil's ability to withstand shear. Fibrous materials like geosynthetics (geotextile, geogrid, geonet, geocomposite, and geo-cell) or randomly distributed fibers from natural or synthetic sources are used to reinforce weak soils(Hejazi *et al.*, 2012). Numerous parameters, such as the fiber's length, kind, aspect ratio (length/diameter), fiber content, soil qualities, and orientation, affect how well fiber can improve engineered soil properties. The incorporation of fiber into a soil mass will improve the soil's cohesiveness and angle of friction. As a result, the quality of the soil will improve(Tingle, Santoni & Webster, 2002). The following are the primary benefits of using fiber for soil reinforcement:
 - Its affordability, accessibility, locality, and environmental friendliness make it a popular choice.
 - It can reduce shrinkage and swelling qualities while increasing the soil's strength. Additionally, it can stop the spread of tensile cracks and alter the failure process once they have formed.
 - In contrast to chemical stabilizing methods such as cement and lime, fiber is not greatly impacted by weather conditions(Rizana, 2015).

Table (2-1) lists the many types and configurations of natural and synthetic fibers used for soil reinforcing.

Table (2-1): Summary of various natural/synthetic fibers used for soil reinforcement(Md Zahri and Zainorabidin, 2019).

Fiber source	Fiber type	Optimal content (%)	Optimal length (mm)
Natural	Coir fiber	0.2-1	>4.75
	Sisal fiber	0.25-1	10-25
	Palm fiber	0-1	20-40
	Jute fiber	0.3-0.9	6-18
Synthetic	Polypropylene fiber	0.5-1.5	10-30
	Waste rubber fiber	0-10	<15
	Polyester fiber	0-2	3-12
	Glass fiber	0.25-1	10-30

2.3 Emulsion as Stabilizing Agent

After processing crude oil, a byproduct known as bitumen remains, the stability of asphalt emulsions, which are intricate fluids, is dependent on the intermolecular forces that result from the equilibrium between repellent and attractive forces. A little droplet of one liquid dispersed in another is called an emulsion. Any two immiscible liquids can combine to form an emulsion; water usually makes up one of the phases. Waterproofing is a fundamental process for bitumen stability in fine-grained soils. Asphalt coatings on soil aggregates can prevent or reduce water penetration, which would otherwise cause the soil's strength to decline. Additionally, strengthening the soil's resistance to water's damaging impacts can increase soil stability. Two fundamental processes are at work when bitumen is used to stabilize soil adhesion and waterproofing. The Asphalt becomes a binder that improves both cohesion and shear strength when the aggregate particles stick to it, as shown in Figure (2-3) (Mutter, 2019).

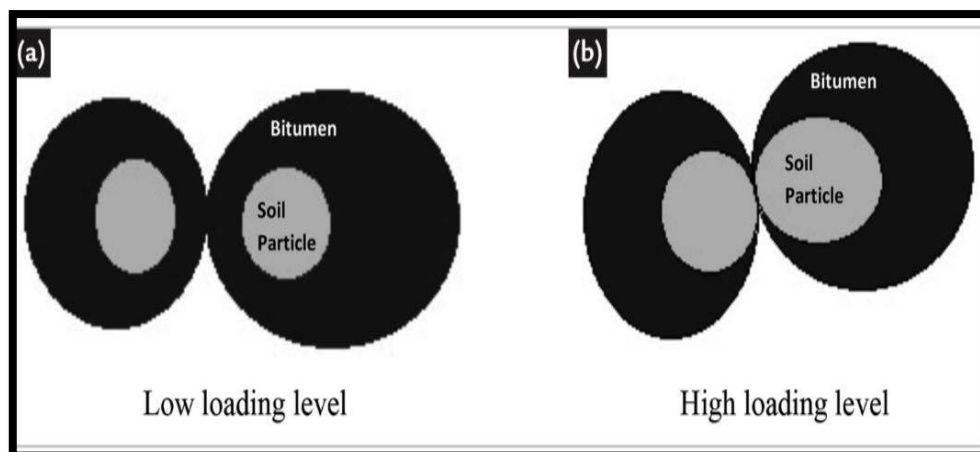


Figure (2-3): Interaction between emulsion bitumen and the soil particles(Neto, Pereira and Abreu, 2020).

Table (2-2) provides a summary of previous studies that illustrate the effect of using asphalt emulsion to stabilize soil for different types.

Table (2-2): Previous studies about asphalt emulsion for stabilizing soils.

Authors	Soil type	Asphalt emulsion content by weight (%)	Findings
Simarprect,2016	Silty sand	2 to 7	Laboratory tests revealed that soil with 6% bitumen emulsion has 65% more shear strength, increasing internal friction angle but reducing cohesiveness compared to soil without emulsion
Kadhim, A.J., 2014.	Gypseous soil	6 to 8	The study reveals that cut-back asphalt enhances gypseous soil properties by eliminating gypsum dissolution, increasing soil strength and stability, and reducing collapse potential, with the best percentage of 6-8%.

Table (2-2): Previous studies about asphalt emulsion for stabilizing soils(continued).

Oluyem,2019	Lateritic soil	2 to 8	According to the test results, depending on the plasticity of the soil, a soil-asphalt emulsion mixes of between 6 and 8 % worked best for the tested soil samples.
Bunga <i>et al.</i>, 2011	Sandy clay	1.5,3.0,4.5	The study indicates that stabilizing agents for emulsified asphalt can improve the mechanical, chemical, and features of sandy clay loam, increasing its plasticity and shear strength.
Kumar, 2017	Sandy soil	2 to 18	The study examined soil samples' unconfined compressive strength (UCS) and CBR values. Maximum strength was achieved at 12% cutback content, while increased cutback led to decreased UCS and density. Sand CBR increased with bitumen content, but further increase reversed the trend.

2.4 Recycled Concrete Aggregates-RCA

Recycled concrete aggregate, or RCA, is made from recycled concrete waste from construction and demolition. To make RCA, leftover concrete is crushed, processed, and then screened and removed impurities like gypsum, paper, wood, and plastics, as in Figure (2-4), converted into aggregates that can be used to make new concrete or to stabilize the soil. RCA comes from various sources, including construction and demolition waste, and is a sustainable alternative to natural aggregates(Oikonomou, 2005).

RCA properties depend on factors like original concrete properties and the amount of reclaimed mortar. Higher reclaimed mortar results in higher

absorption, lower specific gravity, and lower particle strength. RCA must meet the same requirements as virgin aggregate for the target application and, with proper care, can meet standard aggregate quality and grading requirements. Table (2-3) presents and compares the typical properties of natural aggregate and RCA(Snyder & Center, 2018).



Figure (2-4): RCA material after (a) primary and (b) secondary crushing(Radonjanin, 2010).

Table (2-3): Some common characteristics of both natural and recycled concrete aggregate(Snyder and Center, 2018).

Property	Natural Aggregate	RCA
Absorption Capacity (%)	0.8-3.7	3.7-8.7
Specific Gravity	2.4-2.9	2.1-2.4
Sodium Sulfate Soundness Test Mass Loss (%)	7-21	18-59
Magnesium Sulfate Soundness Test Mass Loss (%)	4-7	1-9
Chloride Content (lb./yd ³)	0-2	1-12

For sustainable soil stabilization projects, recycled concrete aggregates are a great alternative to traditional aggregate. Mixing in recycled concrete aggregates enhances the compressive and shear strengths of soil. Adding recycled concrete aggregate to the soil reduces settling and deformability. One possible use for this plentiful material, nevertheless, is subgrade soil stabilization. To define the fundamental characteristics, such as shear strength parameters, resilient modulus, and permanent deformation, (Arulrajah *et al.*, 2013) studied five recycled building and demolition materials. The study demonstrated that RCA's geotechnical qualities were on par with or even better than standard quarry subbase materials. (Poon & Chan, 2006) demonstrated that using RCA improved the optimum moisture content (OMC) and maximum dry density (MDD) of subgrade materials.

Subbase materials made with 100% RCA have lower California Bearing Ratio (CBR) values compared to their natural counterparts. When it comes to concrete, the building material of our time, there are three main areas of environmental protection to consider (Oikonomou, 2005):

- The extensive use of aggregates in concrete production leads to the depletion and ongoing degradation of natural resources. The high energy consumption is associated with the production, delivery, and use of raw and finished materials, such as cement and concrete.
- The large-scale production of recycled concrete from construction sites (demolition waste).

The density, porosity, and water absorption of recycled concrete are mainly affected by the mortar residues bound to the aggregates. For standard applications and uses of concrete in buildings, infrastructure, and other fields, the density of concrete ranges from 2400 kg/m³ to 2600 kg/m³ (Arulrajah *et al.*, 2012). The density of recycled concrete (RCA) is typically lower (about 7-9%) than that of natural aggregate (NA) (Junak & Stevulova, 2015).

The main reasons for the increase in this volume of concrete waste are the following:

- Many old buildings and other structures have exceeded their design life for use and must be demolished.
- Some structures, even if suitable for use, are subject to demolition due to the lack of engineering requirements.
- There is construction waste resulting from natural destructive phenomena (earthquakes, storms, etc.). Figure (2-5) shows the approximate percentage of construction materials in concrete demolition waste.

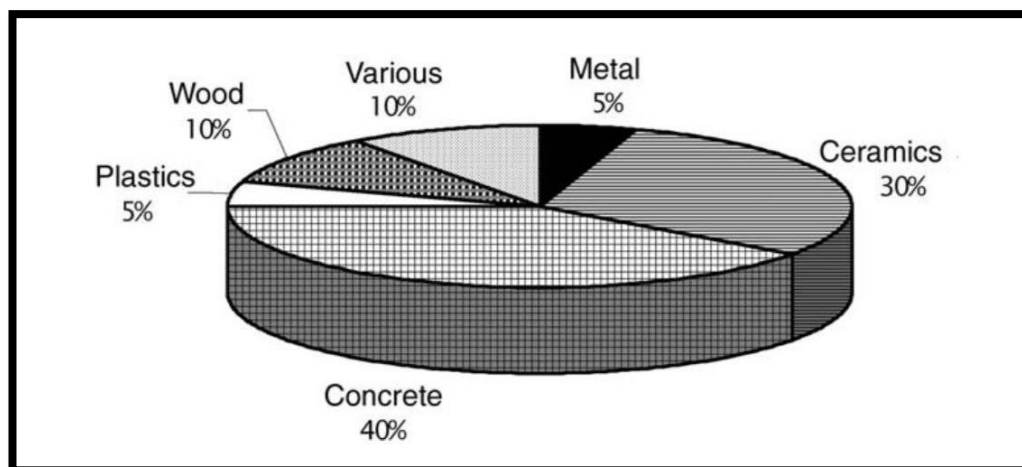


Figure (2-5): Basic composition of recycled concrete aggregates (approx.)(Oikonomou, 2005).

The most important advantages of recycled concrete aggregate are the following:

1. Using recycled concrete aggregate reduces the need for natural aggregate and conserves natural resources.
2. Producing recycled concrete aggregate is less expensive than natural aggregate, reducing construction costs.
3. Recycled concrete aggregate is as structurally reliable and durable as natural aggregate and is suitable for various construction projects.

4. The process of recycling concrete creates more job opportunities.

Disadvantages of Recycled Concrete Aggregate (RCA) (Jayakody and Kumar, 2014):

- Recycled concrete aggregate (RCA) may contain mortar, reinforcing steel, and gypsum, hurting soil stabilization.
- Recycled concrete aggregate (RCA) has a high porosity compared to natural aggregate, which leads to higher absorption.
- RCA increases the alkalinity of the soil because it contains cement, which hurts it and may cause undesirable chemical reactions that affect the stability of the soil.
- RCA is considered environmentally friendly, but it can still be a pollutant, as its production requires crushing and processing processes.
- Recycled concrete aggregate can be utilized for the following projects after processing:
 - Suitable for building pavements, gutters, and other structures.
 - Large chunks of crushed aggregate can be used to construct revetments, which help to prevent soil erosion.
 - Concrete can be made using recycled concrete rubble as coarse aggregate.
 - The soil used as the subgrade for roads is stabilized with recycled concrete aggregate (Junak & Stevulova, 2015).

As summarized in Table (2-4), a limited number of researchers have used recycled concrete aggregates with different content rates to evaluate their potential for use in soil stabilization.

Table (2-4): Summary of some experimental studies on soil stabilization with recycled concrete aggregates.

Authors	Soil type	RCA content by weight (%)	Findings
Ali and Tobeia, 2022	Loose sand	5, 10 and 15	The increase in bearing capacity is 33, 67, and 80% for RCA values of 5, 10, and 15%, respectively.
Muhmood, 2024	Clay soil	5,10,15, and 20	The study's methodologies reveal that the CBR tests from a mixture of clay soil, RCA, and plastic waste are significantly higher than those from natural materials used in the sub-base layer design.
Kianimehr et al., 2019	Clay soil	5, 10 and 15	RCA addition to clay soils enhances UCS, lowers dry density, and increases with moist curing, making it suitable for construction like road pavement sub-base/subgrade.
Hossain et al., 2016	Clay soil	0,50, and 100	Based on Proctor compaction and unconfined compressive strength test results, the methodology indicates that RCA, along with all cementitious materials except lime, enhances clay soil strength.
Paul and Cyrus, 2016	Weak soil	10,20,30,40, and 60.	The study found that using 40% waste material in kaolinitic soil stabilized pavement, reducing OMC, and increasing maximum dry density, thus shifting construction and demolition concrete aggregate from the "Waste Material" to the "Resource Material" category.
Mohd Pauzi and Mat Radhi, 2024	Clay soil	5,10, and 15	Although RCA at 15% is optimal, the value of bearing capacity increases exponentially with higher RCA percentages. Research shows that soil subgrade structures and strength are improved as RCA values rise.

2.5 Rapid Evaluations of Subgrade Soil

Laboratory testing has been the gold standard for determining the depth of subgrade soil layers for years. Because of the high costs, long processing times, and inaccurate results produced by these approaches, researchers and highway agencies have been searching for faster, less harmful alternatives. Methods

abound, including the dynamic cone penetrometer, the falling weight deflectometer, and the lightweight deflectometer (Siekmeier et al., 2009).

The Lightweight deflectometer (LWD) measures the deflection of unbound, granular, and backfilling materials to determine their bearing capacity. It is a lightweight, portable device. By measuring the force required to generate a certain deflection in millimeters for a given kind of soil, LWD can calculate its surface modulus (MPa). In addition, it quantifies compression and deformation. If you want to know how dense and rigid a material is, surface deflection is the way to go.

In contrast to the time-consuming and error-prone static plate load test, which requires a fully loaded vehicle, the LWD provides a simple, fast, and repeatable method for assessing compaction properties. Furthermore, it logs the coordinates of every testing location using its built-in GPS interface. Its portability and low weight enable it to conduct tests in tight spaces inaccessible to a conventional static plate test. It excels in testing materials such as bitumen, treated and stabilized soils, unbound mixes, hydraulically bonded mixtures, and cold recycled mixtures (Chai, van Staden, and Loo, 2015).

Since in-situ research on intact materials is more realistic, their results have always been more suggestive than those on damaged samples. Soil structures differ from those in nature, making it exceedingly difficult to produce samples that are indistinguishable from undelivered ones. Furthermore, a laboratory must collect and analyze many samples from the site for a precise evaluation of soil qualities. It is believed that this method is challenging, lengthy, and costly (Ganju et al., 2018).

Geotechnical investigations, like those using the dynamic cone penetrometer, must include in-situ tests. Many researchers have conducted

field testing and made recommendations for evaluating the mechanical properties of the subgrade and road pavement layers (Garcia et al., 2024).

The dynamic cone penetrometer is one of the best tools for determining the soil's strength at a construction site. It also helps track how granular layers and subgrade soils have changed in different parts of the pavement. Highway authorities use the DCP testing tool in areas with soft soils to identify the most effective methods. The tool can learn how the soil's strength varies with depth, which is crucial for identifying a suitable solution for unsuitable subgrade soils. It can swiftly gather data from a diverse range of sites, providing insight into the dynamic characteristics of the site's soil and facilitating the refinement of your responses (Juntasan et al., 2016).

Several studies have found varying relationships between CBR and DCP due to the challenging nature of CBR assessment in the field. This study used a DCP that adheres to ASTM standard D 6951-18.

2.6 Summary

According to the literature review, the primary function of the subgrade is to provide adequate support for the pavement. As a result, it must be stable enough to withstand demanding loading and climatic conditions. An inadequate subgrade will impede road performance and result in issues that require remediation. Stabilization is a commonly used method for treating subgrade weakness. While there are many different stabilization techniques, chemical and mechanical stabilization are the most widely used. Recycled concrete aggregate and asphalt emulsion are two of the stabilization techniques available. There are not many studies that have examined the strength characteristics of subgrade soils stabilized using RCA and asphalt emulsion.

Chapter Three
Methodology, Materials, and Testing

Chapter Three**Methodology, Materials, and Testing****3.1. Introduction**

This chapter briefly describes the research methodology, including the soil properties, location, and materials used for soil stabilization. It also summarizes the experimental tests, including the modified Proctor and California Bearing Ratio (CBR) tests. Additionally, this chapter includes field tests conducted to achieve the research objectives.

3.2. Methodology

To achieve the main purpose of this research work, a subgrade soil sample was selected from a roadway project under construction in Kerbala. The hybrid stabilization technique was used to stabilize the soil used in this research. Two strategies were applied to achieve the hybrid stabilization technique. The first was to use recycled concrete aggregate as a mechanical stabilizer for the soil, and the second was to use asphalt emulsion as a chemical stabilizer. Large test models were prepared in the laboratory and tested to simulate the natural soil conditions. The following tasks were carried out to achieve the proposed research methodology:

1. Conducting tests to determine the basic soil properties, including the sieve analysis test, specific gravity, modified Proctor test, and CBR test.
2. The recycled concrete aggregate is prepared in different grades using a sieve analysis. Each grade is then used at four different percentages (5%, 10%, 15%, and 20%), and the optimal percentage is determined through a CBR test.
3. The asphalt emulsion was also prepared in four different proportions: 2.5%, 5%, 7.5%, and 10%. After determining the optimal asphalt emulsion (EA) ratio, it was added to the mixture of soil and recycled concrete aggregate (RCA), with each different grade of RCA.

4. The stabilized subgrade layer was evaluated through a series of laboratory and in-situ tests to determine its engineering properties and performance characteristics.

Figure 3.1 illustrates the research methodology followed to achieve the research objectives.

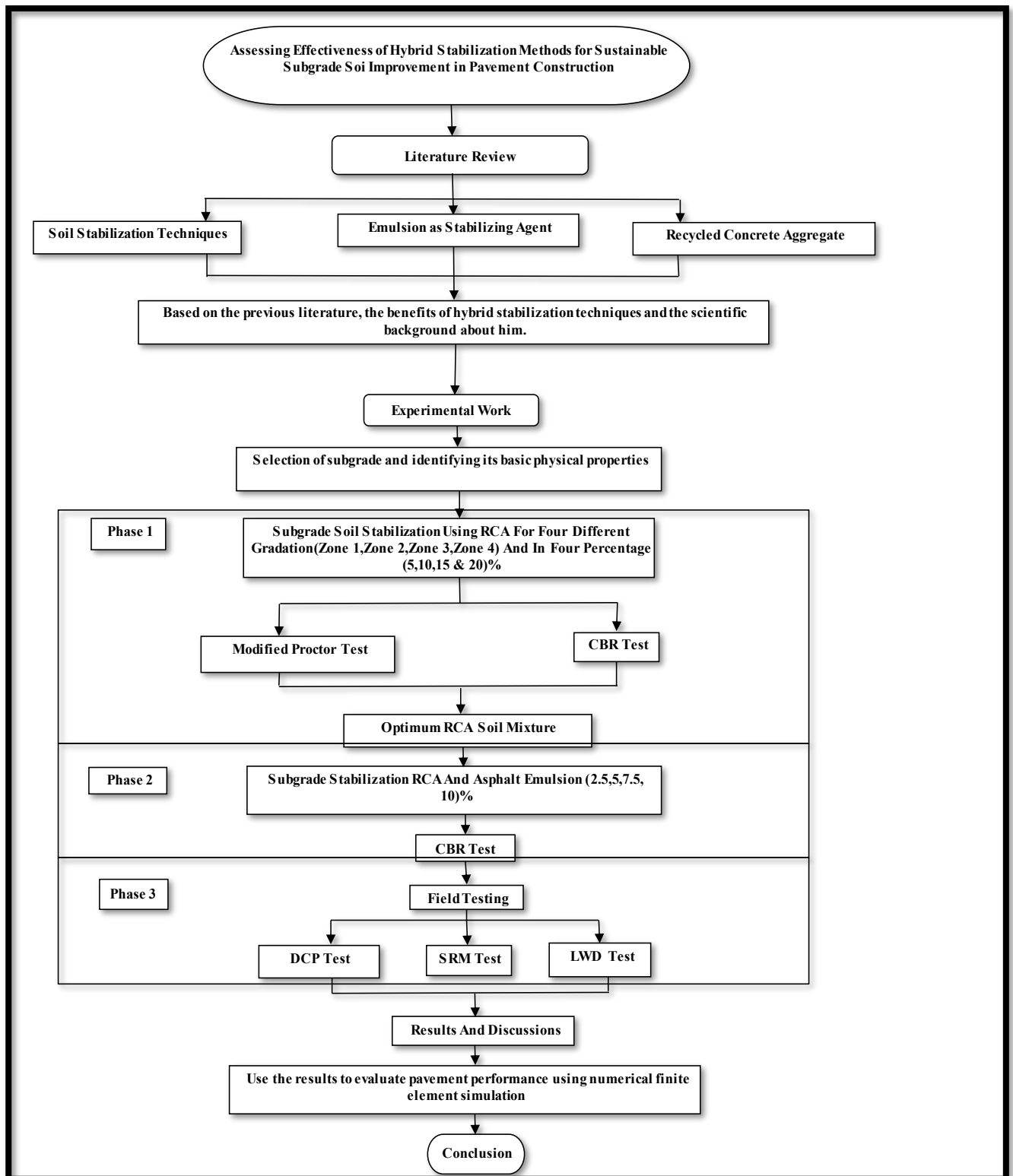


Figure (3-1): Flow Chart.

3.3. Materials and Properties

3.3.1. Natural Soil

The type of sand used in this study was from a site in Karbala (32° 33' 23" N and 44° 02' 44" E). An aerial photograph of the site from which the soil was collected is shown in Figure (3-2).

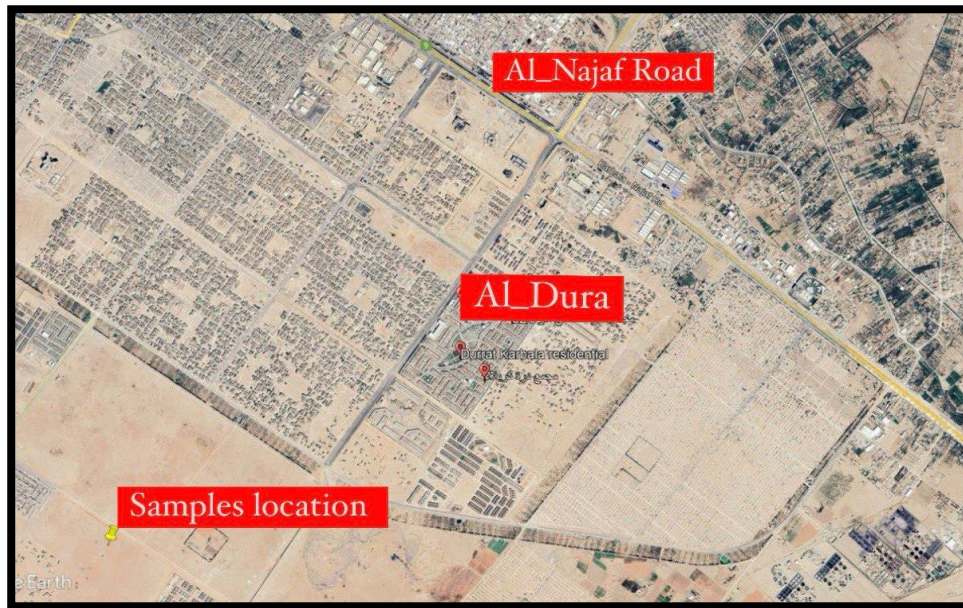


Figure (3-2): An aerial photograph of the site where the soil was collected.

A series of laboratory tests were conducted to determine the soil classification and characteristics, as listed in Table 3-1. It was found that the soil classification was A-3 according to the specifications of the American Association of State Highway and Transportation Officials (AASHTO) and that it was a poorly graded sandy soil (SP), according to the Unified System for Classification (USCS). The grain size distribution curve is displayed in Figure 3-3.

Table 3-1: Basic Chemical and Physical Characteristics of the Subgrade.

Property	Test Results	Specifications
Soil Classification	A-3	AASHTO M 145
	(SP)	ASTM D 2487
O.M.C	12.4%	ASTM D 1557
Max Dry Density	1.95 gm/cm ³	
Uniformity Coefficient (C _u)	5.09	ASTM D 2487
Curvature Coefficient (C _c)	1.097	
Specific Gravity (G _s)	2.64	ASTM D 854
CBR	27.5%	ASTM D 1883
Sand Fraction	85.6%	ASTM D 4318
Fine content	6.5%	ASTMD 2487
Total Soluble Salts (TSS)	7.3	
Gypsum Content	10.7 %	BS 1377
SO ₃	5 %	

Figure (3-3) illustrates the relationship between dry density and moisture content percentage that is used to determine the maximum dry density (MDD) and optimal moisture content (OMC) in accordance with ASTM D 1557.

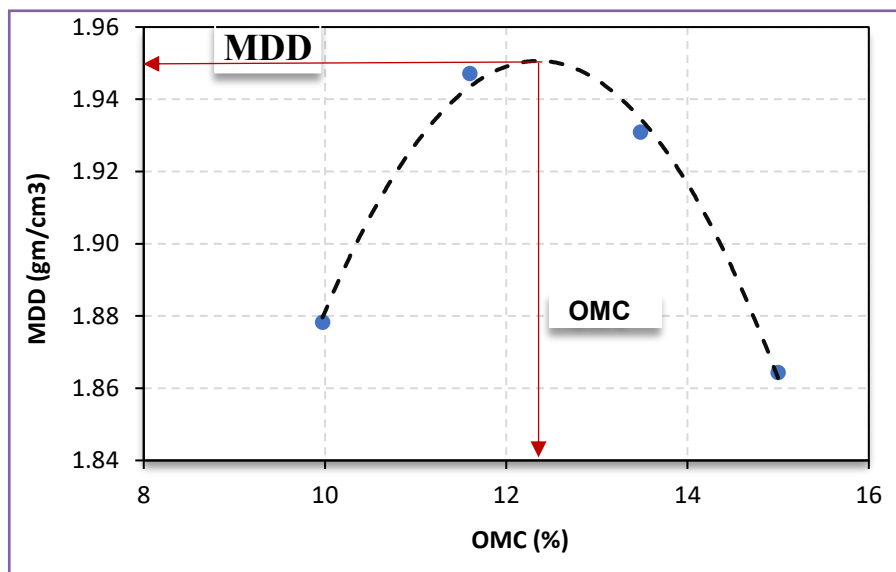


Figure (3-3): Moisture Content Curve – Dry Density

3.3.2. Recycled Concrete Aggregate

Recycled Concrete Aggregate (RCA) refers to aggregate derived from processed concrete waste, typically originating from the demolition of old structures, surplus material from construction activities, and discarded specimens from laboratory testing, such as concrete cubes and cylinders. The

use of RCA presents both environmental and economic advantages by reducing the demand for natural aggregates and minimizing construction waste (Dewanda, 2023).

In this research, RCA was sourced from local demolition debris and concrete cubes. Initial crushing was conducted on-site using heavy machinery, followed by manual refinement in the laboratory, where a steel hammer was used to achieve the desired particle size distribution. Recycled concrete aggregate has lower crushing strength and greater resistance and absorption than natural aggregate. This study utilized recycled concrete after it was crushed into various sizes. Sieve analysis of the RCA was performed, which divided the material into four zones with different grades: Grade 1: passing through a 19 mm sieve and retaining on a 9.5 mm sieve; Grade 2: passing through a 9.5 mm sieve and retaining on a 4.75 mm sieve; Grade 3: passing through a 4.75 mm sieve and retained on a 0.075 mm sieve; and Grade 4: a combination of Grades 1, 2, and 3, as shown in Figure 3-6.

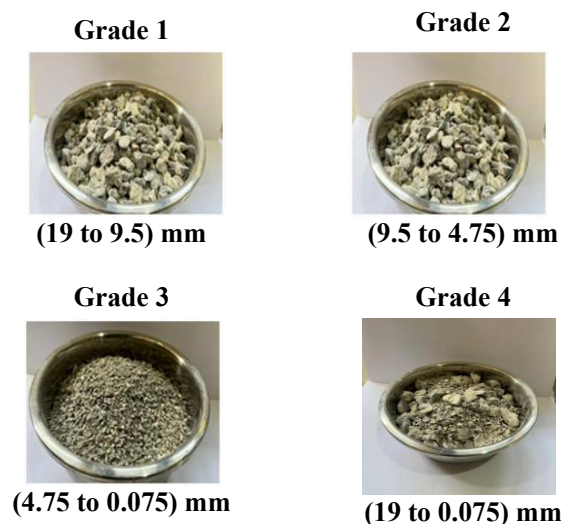


Figure (3-4): RCA was Obtained in Different Grades.

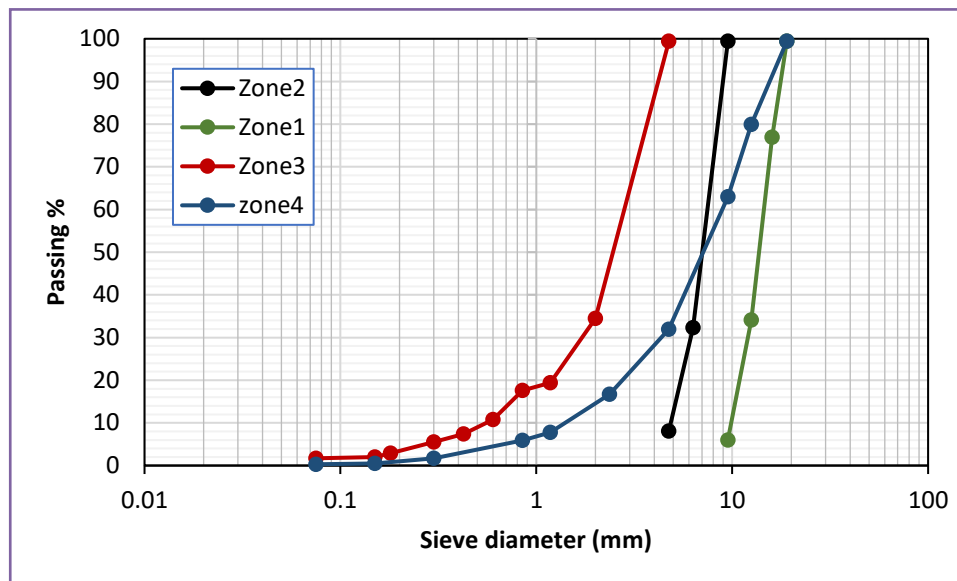


Figure (3-5): Grain sieve of RCA.

3.3.3. Asphalt Emulsion

Asphalt emulsion (ASTM-D 2397/D6997) is a dispersed system consisting of asphalt particles suspended in water, aided by an emulsifying agent. It offers a practical and environmentally friendly alternative to traditional asphalt applications, as it can be applied at lower temperatures and with reduced energy consumption. Due to its versatility and ease of handling, asphalt emulsion is widely used in road construction, surface treatments, and maintenance works. One of the emerging and valuable applications of asphalt emulsion is in soil stabilization, where it functions as a chemical stabilizer. When added to weak or granular soils, the emulsion binds soil particles together, reduces permeability, and enhances strength and durability. This process improves the engineering properties of subgrade materials, making them more resistant to water infiltration and deformation under loads (Martínez-Silva et al., 2020).

Its ability to provide both flexibility and water resistance makes asphalt emulsion a reliable and efficient solution in pavement subgrade preparation and various geotechnical applications. Asphalt emulsions typically have a specific gravity of 1.07 and a solid content of 55%. In most cases, asphalt emulsion can

be used as is without the need for heat. It also offers flexibility in application, offering the user a range of properties not found in other paving and maintenance materials. Furthermore, it is environmentally friendly, producing minimal to no hydrocarbon emissions when in use. Figure (3-6) shows the asphalt emulsion used.



Figure (3-6): The Asphalt Emulsion used.

3.4. Soil Preparation and Stabilization of Soils with RCA and EA

The soil stabilization process in this study included two stages. First, recycled concrete aggregate was added to the soil at 5%, 10%, 15%, and 20% of the dry soil weight. After that, the optimal mixture of sand and recycled concrete aggregate was treated by adding asphalt emulsion. The emulsion was added at a rate of 2.5%, 5%, 7.5%, and 10% as an additive to the mixture. The required amount of water (optimum moisture content) was added, and then the mixture was mixed well with soil and recycled concrete aggregate. Next, the samples were compacted using the modified Proctor test. After the optimum soil mixture was stabilized using RCA, it was then treated with EA to improve the adhesive properties of the RCA granular soil. Table (3-2) summarizes the percentages of RCA and EA used in the soil stabilization methods.

Table (3-2): Summary of the Soil Mixtures.

Soil Mixture	Content (% by weight)		
	Sand	RCA	EA
NS	100	0	0
NS+5%RCA	95	5	0
NS+10%RCA	90	10	0
NS+15%RCA	85	15	0
NS+20%RCA	80	20	0
NS+15%RCA+2.5% EA	85	15	2.5
NS+15%RCA+5% EA	85	15	5
NS+15%RCA+7.5% EA	85	15	7.5
NS+15%RCA+10% EA	85	15	10

3.5. Experimental Testing Methods

3.5.1. Laboratory Tests

All samples of stabilized mixtures, including subgrade, sand with recycled concrete aggregate (RCA), and sand with recycled concrete aggregate (RCA) and asphalt emulsion, were subjected to two standard laboratory tests for characterization purposes:

3.5.1.1. Modified Procter Test

The modified Proctor test (**ASTM D1557**) was used to determine the maximum dry density and optimum moisture content of the soil mixtures. Soil was compacted in a standardized mold in five layers, each receiving 25 blows from a standard weight dropped from a fixed height. After compaction, the dry density was calculated by subtracting the mold's weight from the total mass of the compacted sample.

Moisture content was determined following a standard oven-drying method. A clean, dry container was first weighed (W_1), then filled with a moist soil sample and weighed again (W_2). The container was placed in an oven at a

constant temperature for 24 hours. After cooling, the final weight was recorded (W3). Moisture content was calculated using the formula:

$$\text{Moisture content} = \left[\frac{W_2 - W_3}{W_3 - W_1} \right] \times 100 \quad 3-1$$

Once the researcher determined the moisture content, she could calculate the dry density of the soil. Calculate using the following equations (3-2) and (3-3).

$$\gamma_{wet} = \frac{\text{weight of compacted soil}}{\text{volume of compaction mold}} \quad 3-2$$

$$\gamma_{dry} = \frac{\gamma_{wet}}{1 + \text{water content}} \quad 3-3$$

3.5.1.2. California Bearing Ratio Test -CBR

The California bearing ratio (CBR) test typically determines the strengths of subgrade soil, subbase, and base course material from laboratory compacted specimens. Roads, airfields, and other massive infrastructure projects rely on accurately assessing the load-bearing capacities of the material, which this tool provides. In a controlled environment, a plunger measures the resistance of the sample as it pushes through it. One of the most used standards for doing the CBR test is **ASTM D1883**. The CBR test was carried out on all the mixtures specified in Table 3-2 that were packed into a cylindrical mold at the optimal moisture content and maximum dry density for this research. To replicate fully saturated conditions, the researcher immersed the sample in water for around three days (96 hours). After the soaking time was over, the researcher put the sample in the CBR apparatus and slowly lowered a plunger into the surface of the mixture, making sure to penetrate it thoroughly. The testing and preparation processes are illustrated in Figure 3-7.



Figure (3-7): Preparation of Test Specimens of the Treated Soil Mixtures for CBR Test.

3.6. Model Soil Preparation

This study conducted static and dynamic in situ tests on natural and stabilized subgrade soils, including dynamic cone penetration (DCP), sand cone method, and light weight deflectometer (LWD), to identify the strength and stiffness characteristics. To achieve this objective, the soil mixtures presented in Table 3-2 were prepared based on the optimal moisture content identified through the modified Proctor test. The mixing was done with an electric mixer with a capacity of 0.25 m³. Figure (3-7) illustrates the procedure for preparing the treated soil mixtures. Each mixture was compacted into a large cylindrical steel mold designed and manufactured with dimensions (diameter = 70 cm and height = 100 cm) to simulate in-situ subgrade conditions. The desired height of the compacted soil inside the cylindrical steel mold is 60 cm, whereas the thickness of each soil layer is 20 cm in Figure 3-9. Each layer contains approximately 140 kg of mixture. This quantity was divided into three

approximately equal parts, where every part was added to the mold and compacted to obtain the required dry density.



Figure (3-8): Steps to Prepare a Sample of Soil.

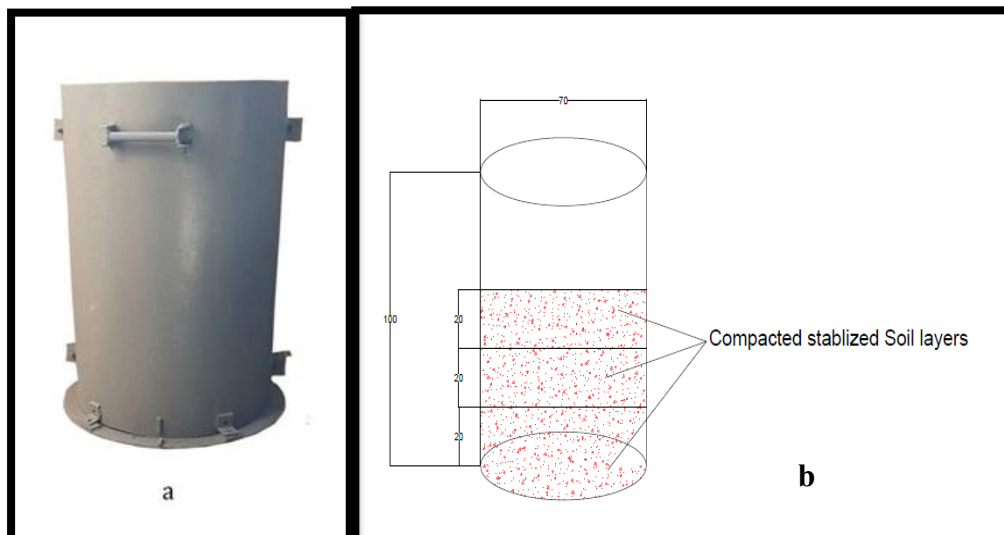


Figure 3-9: (a) Cylindrical Mold. (b) Sketch of the Cylindrical Mold Shows the Thickness of the Compacted Layers.

3.7. Dynamic Cone Penetration Test- DCP

Based on **ASTM D6951**, the dynamic cone penetration (DCP) is a tool for assessing the soil strength of the site. Additionally, it facilitates long-term monitoring of pavement granular layers of the section and subgrade soils. The DCP is a lightweight, portable device. The DCP device consists of three components: an 8 kg standard weight hammer that drops from the top of the rod against an anvil to advance the tip into the ground, a hardened conical tip, and a standard diameter steel rod, as shown in Figure 3-10. The test procedure is described as follows:

1. The initial reading of the equipment is recorded once the instrument is adjusted. This is accomplished by placing the DCP on a soil surface, confirming its verticality, and then recording the initial reading on the sample at the appropriate location.
2. Lift the device vertically and carefully raise the weight to the handle. It is not permitted for the weight to meet the handle. The operator did not use his hands to reduce the drop; instead, the operator should have allowed it to fall freely.
3. Taking a scale reading after a certain number of blows is usually simpler. As a result, it is crucial to adjust the number of blows between readings based on the penetration strength of the layer. Readings after every five or ten blows are usually satisfactory for granular bases of the right quality; however, readings after every one or two blows may be appropriate for weaker sub-base layers and sub-grades.
4. Once the test is finished, DCP is removed using a gentle lifting of the weight and directing it towards the handle.

The data recorded by the control unit of the DCP test were analyzed to determine three parameters: the dynamic cone penetration index (DCPI), in-situ CBR, and bearing capacity (q). The DCP penetration index (DCPI)

measures the DCP penetration distance per drop. The California bearing ratio (CBR) was determined according to the equation below:

$$CBR(\%) = \frac{292}{(DCPI)^{1.12}} \quad (3-4)$$

Where:

DCPI: dynamic cone penetration index in (mm/ blow).

Over time, researchers have discovered several correlations for bearing strength measures of different types of soil. We solved the following equation (PCA, 1955) using the correlations to find the bearing capacity:

$$q = (3.794 \times CBR^{0.664}) \times 144 \quad (3-5)$$

Where:

q : bearing capacity in (kPa).

CBR: california bearing ratio in (%).

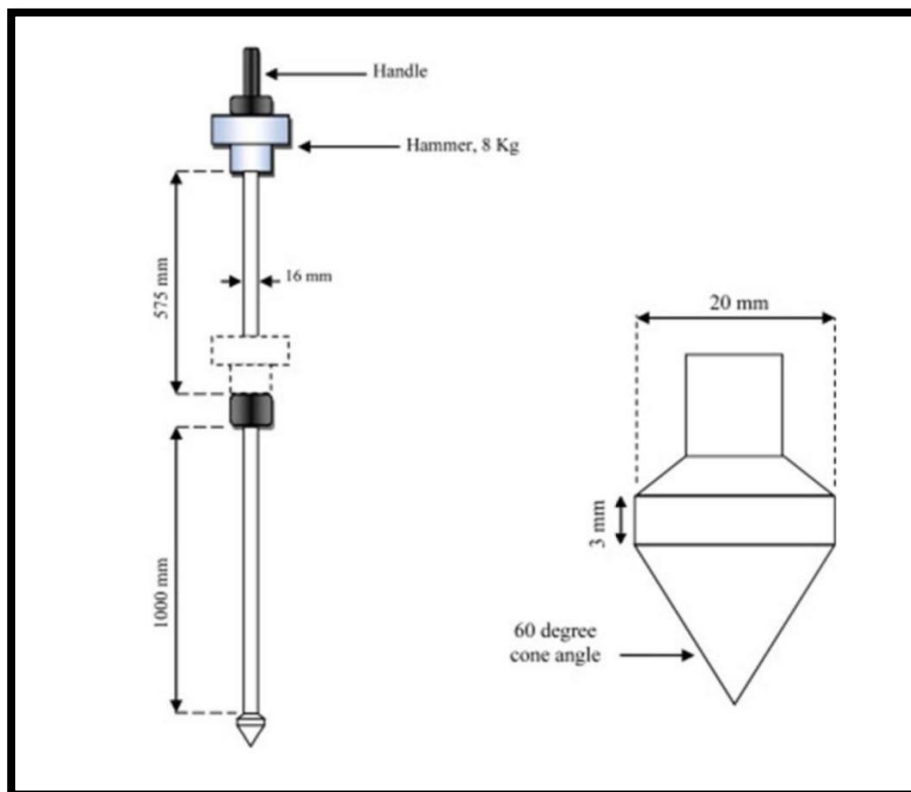


Figure (3-10): Dynamic Cone Penetrometer (DCP) Vakili et al., (2021).

3.8 Sand Cone Method- SCM

As per ASTM D 1556-15 (2015), the actual moisture content and density of the compacted soil can be determined using SRM as shown in Figure 3-10. The researcher uses SRM in soils that contain no more than 1.5 inches (38 mm) of coarse material or rock fragments. Still, it also performs well in saturated, relatively plastic, or natural soils that underwent compacting or deformation during test hole drilling. The researcher conducted the test using the following procedures:

1. For sand calibration, the researcher first filled the plastic (container + funnel) precisely with 6000 gm of known-dry-density sand. Next, we recorded the total weight (W1).
2. The ground firmly embeds the (30*30 cm) plate with the central hole.
3. The researcher excavates the test area to a minimum of 15 cm.
4. To keep the soil's moisture from evaporating, remove it and weigh it into a nylon bag (W2).
5. The researcher prepared the moisture cans and recorded their weight (W3). The researcher then filled each can with a portion of the extracted soil sample and recorded its weight (W4). The researcher dried the cans in an oven for 24 hours, recorded their weight (W5), and determined the moisture content.
6. After flipping the funnel and container and closing the valve, insert them into the plate's center hole.
7. When the valve is released, sand may fall into the hole.
8. The valve closes when the hole fills and the sand flow stops, recording the weight of the plastic container, the funnel, and the residual sand inside the container (W6).
9. By precisely adding sand to the plastic container with the funnel, one can calculate the weight of sand required to fill the funnel (W funnel). the

researcher records the weighted total as W_7 . The valve opens, allowing sand to flow from the container into the funnel until it reaches its full capacity, at which point it closes.

10. determines the volume of the soil, wet unit weight, and dry unit weight.



Figure (3-11): Sand Replacement Test.

3.9. Light Weight Deflectometer-LWD

This test method determines the surface deflections caused by the application of an impulse load. The researcher can measure the resulting deflections at different distances from the load, as well as at the center of the applied load. Deflections can be used to determine the in-situ material properties of the pavement layers or to establish a direct connection with pavement performance. A variety of purposes can be served using the data, including determining the required thickness for roadway and airport pavements, structural evaluation of load-carrying capacity, and quality control and assurance of compacted layers. This work employed the LWD model Zorn 3 to ascertain the dynamic soil properties of subgrade soils. Figure (3-12) shows the main components of LWDZFG3.

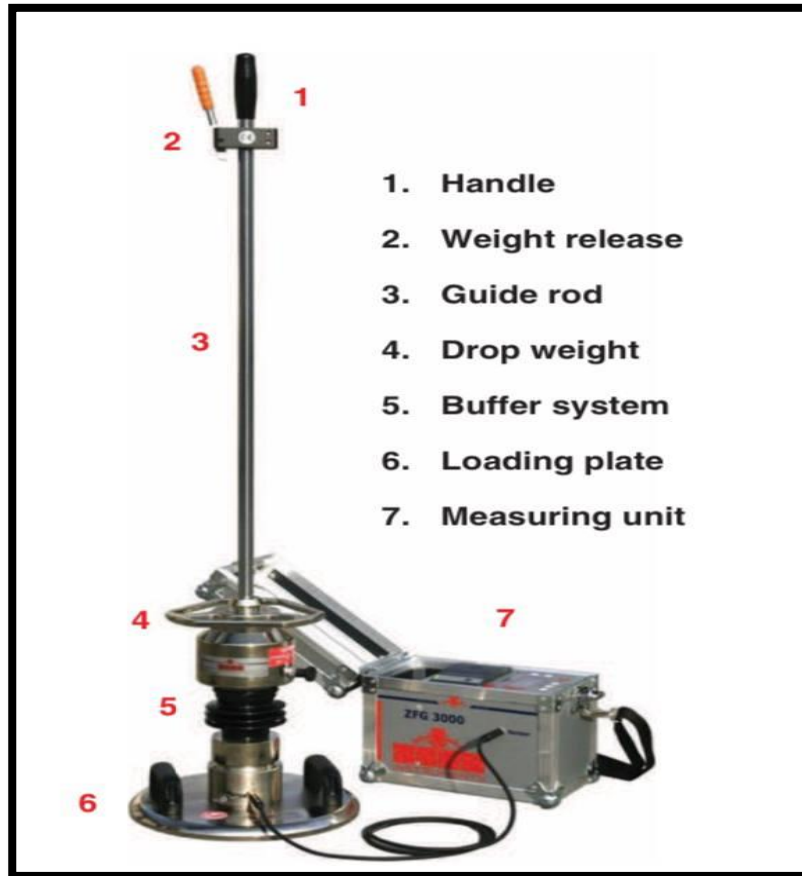


Figure (3-12): LWD Device Shaban and Cosentino (2016)

The overall LWD test procedure was carried out by the standard test approach described in ASTM E2583:

1. Preparation: the first step is to clear the test area surface of any debris and ensure that it is level and stable.
2. Placing the circular plate: place a circular plate with a diameter of about 300 mm on the soil's surface under test.
3. Level the plate: Lift a known mass weight to a specific height, then release it onto the LWD device's plate.
4. Applying the weight: When the weight falls onto the plate, it generates a dynamic impulse load on the soil surface, leading to a deflection. Three drops were performed at each testing point to reduce the impact of loose soil particles that could cause adverse plastic deformations.

5. Measuring the deflection: An attached sensor measures the deviation of the plate. Typically, the deviation was measured in millimeters.

Several characteristics, such as surface deflection (S_d), dynamic modulus (E_d), are determined by measuring the resultant plate deflection. To get surface deflection (S_d), the acceleration data related to the pulse wave times are double-integrated. An accelerometer is placed within the loading plate to record acceleration data. Soil stiffness, under dynamic loading conditions, measures the resistance of the soil to deformation under traffic loads, and it is computed by using the deflection data acquired from the LWD test. It is stated as follows:

$$E_d = \frac{(1-\nu^2)\sigma_0 a}{s_d} f \quad (3-6)$$

Where:

ν : Poisson's ratio

σ_0 : The LWD contact pressure (MPa)

a : The radius of the loading plate (mm)

f : The plate rigidity factor

S_d : Deflection of the subgrade layer (mm)

3.10. Summary

This chapter shows the practical side of the research, where the physical and chemical properties of the soil and the materials used in stabilization were identified. In this study, laboratory tests were conducted on soil mixtures stabilized with RCA and EA. Also, field tests of LWD, DCP, and SCM were carried out to establish a relationship between them and laboratory tests, which provides a more efficient opportunity to evaluate the soil before and after the stabilization process.

Chapter Four:
Results and Discussion

Chapter Four: Results and Discussion

4.1. Introduction

This chapter presents the results obtained from testing natural and stabilized subgrade soils. The results are summarized in two phases: [1] Laboratory test results, including the modified Proctor test and the California bearing ratio (CBR) test; and [2] Field test results, including the dynamic cone penetration (DCP) test, sand replacement method (SRM), and light weight deflectometer (LWD) test.

4.2. Laboratory Testing Results

4.2.1. Modified Proctor Test Results

The modified Proctor test was performed for natural and stabilized soils to determine the maximum dry density (MDD) and optimum moisture content (OMC). The MDDs of natural and stabilized soils are summarized in Table 4.1. The results of natural soil showed that the MDD was 1.95 gm/cm³.

Table 4-1: Results of Maximum Dry Density (MDD).

Type of Soil Mixtures	Maximum Dry Density, MDD (gm/cm ³)			
	Grade 1	Grade2	Grade3	Grade4
Natural Soil, NS	1.95			
NS+ 5%RCA	1.96	1.99	2.03	2.00
NS+ 10% RCA	1.97	2.01	2.04	2.02
NS + 15% RCA	2.02	2.03	2.05	2.03
NS + 20% RCA	2.05	2.06	2.07	2.04

■ NS: Natural Subgrade Soil
 ■ RCA: Recycled Concrete Aggregate

As shown in Figure 4.1, the results indicate an improvement in MDD with increasing RCA content. The nature of RCA particles, which have a higher density than sandy soil, is responsible for this improvement. As RCA-grade1 stabilizes the soil at four different percentages, including 5%, 10%, 15%, and 20%, the MDD value increases from 1.95 gm/cm³ to (1.96, 1.97, 2.02, and

2.05) gm/cm³, respectively. In Grade 2, the MDD increased to (1.99, 2.01, 2.03, and 2.06) gm/cm³, while the results in Grade 3 were (2.03, 2.04, 2.05, and 2.07) gm/cm³. Grade 4 showed a clear improvement in the MDD, making it the best grade regarding MDD values: (2.00, 2.02, 2.03, 2.04) gm/cm³. These results are consistent with those obtained from a previous study conducted by (Muhmood, 2024).

This improvement is attributed to the nature of RCA particles, which have sharp corners and are irregular; this leads to increased interlocking between soil particles due to the shape of the crushed RCA, which leads to increased shear strength and friction between the particles. The interaction and interlocking resulting from mixing RCA with the soil lead to filling all the soil voids, improving the soil density. The maximum improvement was achieved when the soil was stabilized with a 20% RCA replacement content. The results show that the percentage increase in MDD was 5.13%, 5.64%, 6.15%, and 4.62% for the soil stabilized in RC-Grade 1, Grade 2, Grade 3, and Grade 4, respectively. The above results showed that zone 3 provides the optimal maximum dry density values.

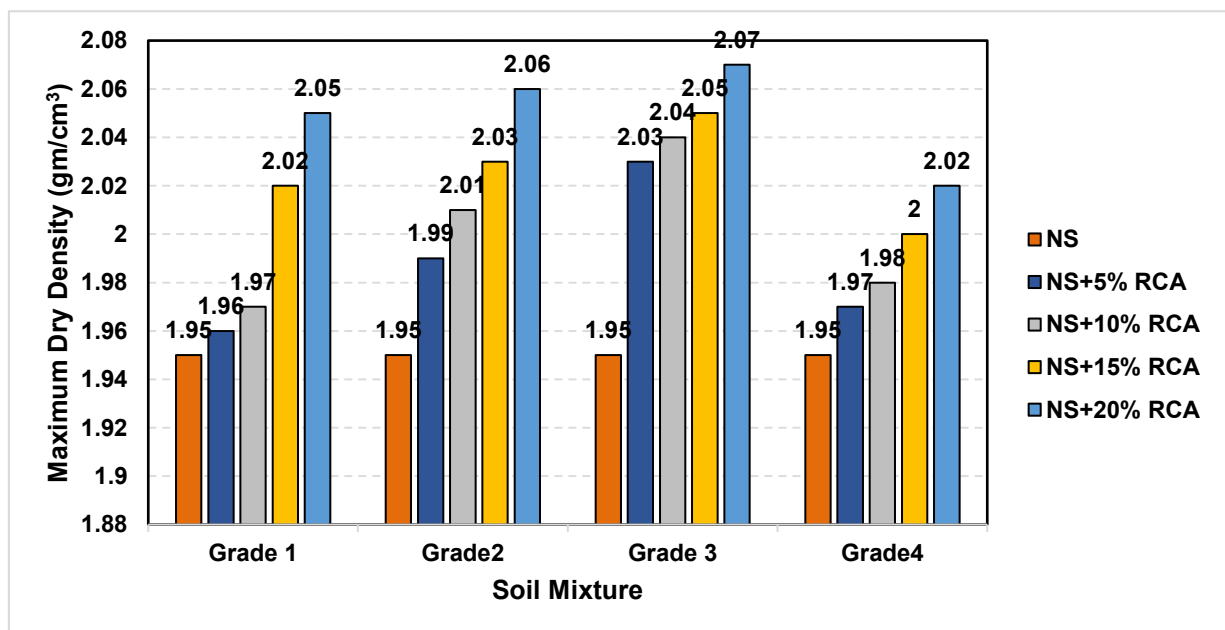


Figure 4-1: Results of MDD for Soil Mixtures.

Table 4-2: Result of Optimum Moisture Content (OMC).

Type of Soil Mixtures	Optimum Moisture Content, OMC (%)			
	Grade1	Grade2	Grade3	Grade4
Natural soil NS	12			
NS+ 5%RCA	11.58	11.17	10.30	12.0
NS+ 10% RCA	11.75	10.66	12.50	11.0
NS + 15% RCA	11.0	10.50	11.30	11.2
NS + 20% RCA	11.0	10.75	11.45	11.1

■ NS: Natural Subgrade Soil
 ■ RCA: Recycled Concrete Aggregate

Table (4-2) presents the values of the OMC of natural and stabilized soils. The OMC of natural soil is equal to 12 %. Generally, the results showed that increasing the percentage of RCA added to the soil decreased the OMC because RCA particles are solid blocks that bind soil particles together. The soil becomes denser, and the number of voids is reduced, which decreases the moisture percentage required to fill these voids and achieve maximum density (Al-Mashhadani & Sadiq ,2013).

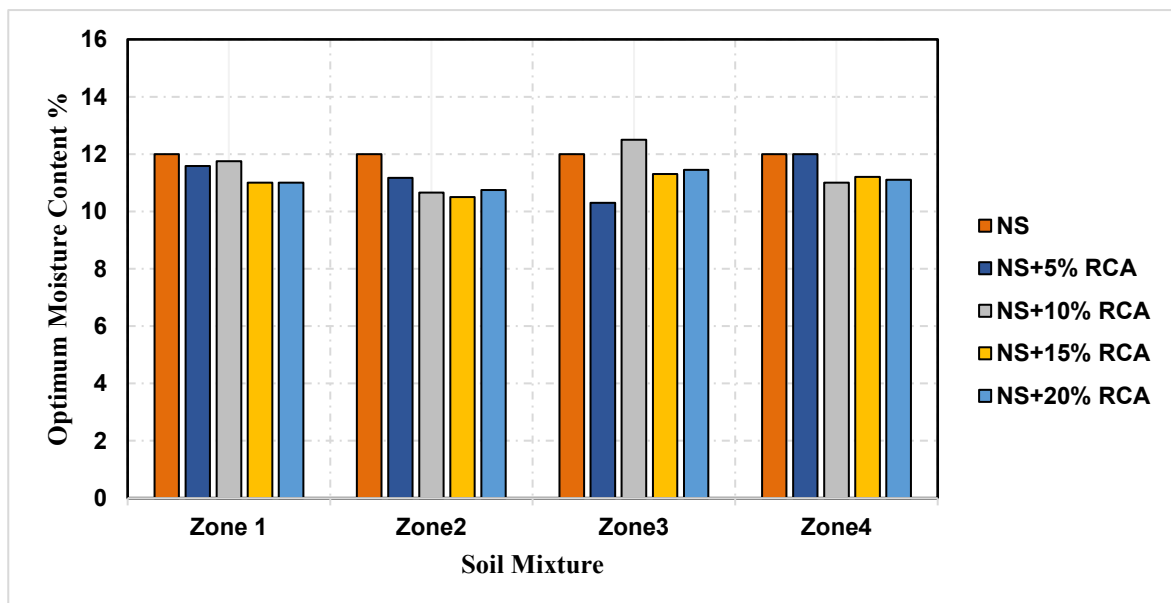


Figure 4-2: Results of OMC for Soil Mixtures.

4.2.2. California Bearing Ratio Test Results

The California bearing ratio (CBR) value was determined according to the standard testing procedure specified by the American Society for Testing and Materials (ASTM D1883). The CBR test was implemented on the subgrade soil to identify its bearing capacity. Thirty-three CBR tests were carried out as part of the experimental study program. These tests were divided into 1 test on natural subgrade soil, 16 on subgrade soil stabilized with RCA, and 17 on subgrade soil stabilized with the asphalt emulsion. Figure (4.3) shows the CBR value of natural sand soil, which is equal to 27.5 % at 95% of MDD.

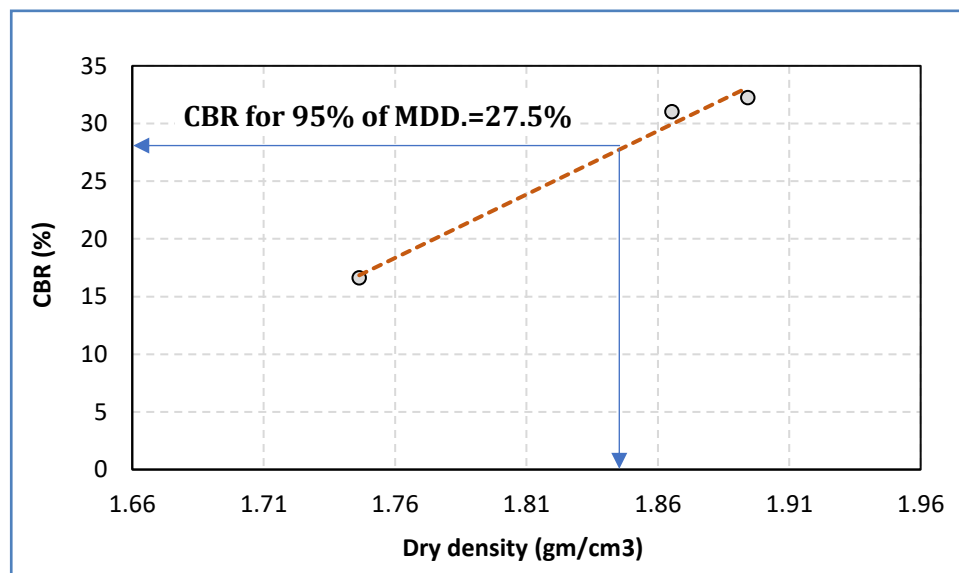


Figure 4-3: Determining CBR of Natural Subgrade Soil.

4.2.2.1. Results of CBR Test for Soil Treated by RCA

The CBR values for the soil stabilized using RCA are summarized in Table (4-3). The results of soil mixtures with RCA showed that soil-bearing resistance increases with higher RCA content.

Table 4-3: Summary of CBR Test Results for RCA-Soil Mixtures.

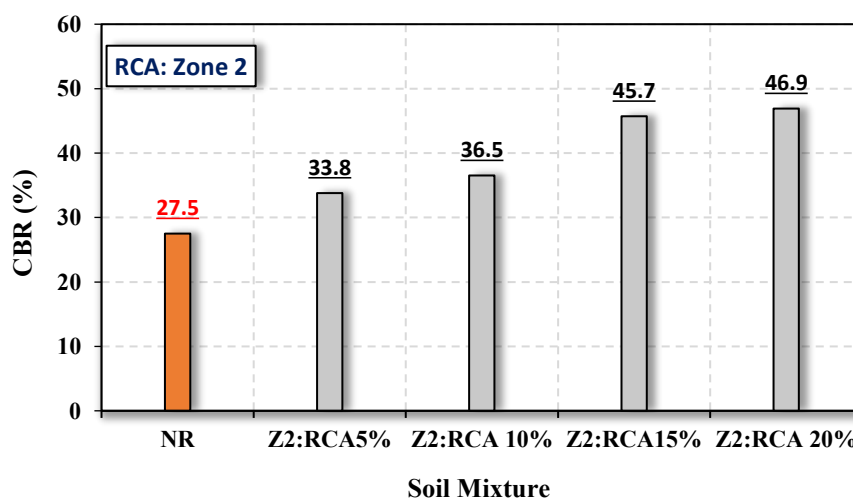
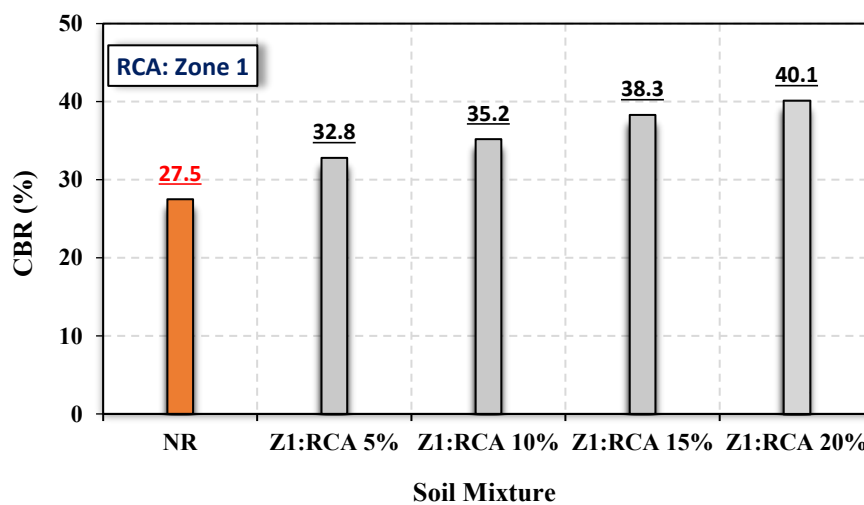
Type of Soil Mixtures	California Bearing Ratio, CBR (%)			
	Grade1	Grade2	Grade3	Grade4
Natural Soil	27.5			
NS+ 5% RCA	32.8	33.8	48.7	48.9
NS+ 10 % RCA	35.2	36.5	50.9	56.3
NS+ 15% RCA	38.3	45.7	51.3	61.9
NS + 20% RCA	40.1	46.9	54.2	67.4
<ul style="list-style-type: none"> ▪ NS: Natural Subgrade Soil ▪ RCA: Recycled Concrete Aggregate 				

For the soil stabilized with RCA-Grade 1, the CBR values were (32.8%, 35.2%, 38.3%, and 40.1%) for (5%, 10%, 15%, and 20%) RCA replacement, respectively. For the soil stabilized with RCA-Grade 2, the CBR values were (33.8%, 36.5%, 45.7%, and 46.9%) for (5%, 10%, 15%, and 20%) RCA replacement, respectively. These values were (48.7%, 50.9%, 51.3%, and 54%) for (5%, 10%, 15%, and 20%) RCA-Grade 3 replacements, respectively. For the soil stabilized with RCA-Grade 4, the CBR values were (48.9%, 56.3%, 61.9%, and 67.4%) for (5%, 10%, 15%, and 20%) RCA replacement, respectively.

Figure (4.4) shows CBR results for all stabilized soil mixtures. The CBR value increases with the increase in the RCA percentage of the soil, and for all Grades, this means that the higher the RCA replacement of the stabilized soil, the higher the soil's ability to bear and its strength. The results also showed an increase in the CBR values when the RCA added to the soil has a lower gradation, as in Grade 3. These results are consistent with this study (Ali & Tobeia, 2022). RCA is characterized by sharp angles and irregular edges, leading to increased shear strength and friction between particles. The interaction and entanglement resulting from mixing RCA with soil may increase bearing capacity, which depends largely on the angle of internal

friction. The optimal RCA content for stabilizing soil is 15%, as this percentage yielded the optimal improvement. This is because adding 15% RCA to sandy soil contributes to improving its granular gradation and enhances the ability of the soil to distribute loads, thus improving the structural properties of the soil.

In addition to increasing the bearing capacity, which is only dependent on the angle of internal friction, the mechanism of action of RCA, as previously explained, involves enhancing the friction between molecules, thereby increasing the bearing capacity factor.



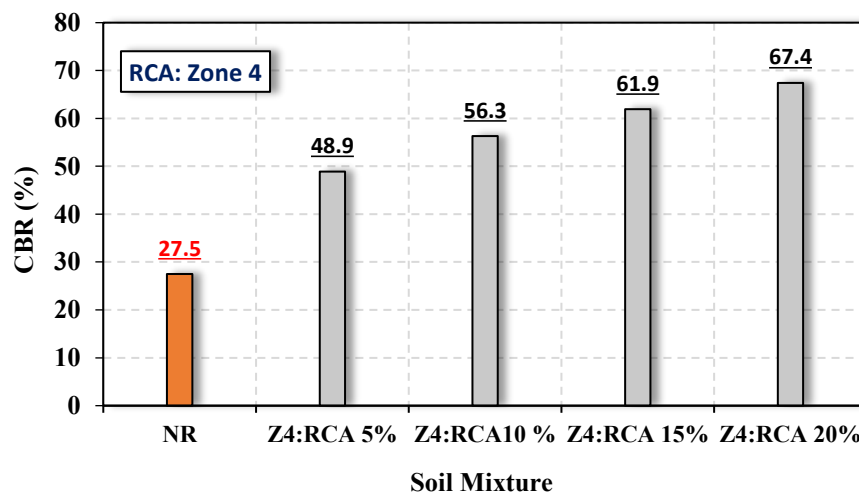
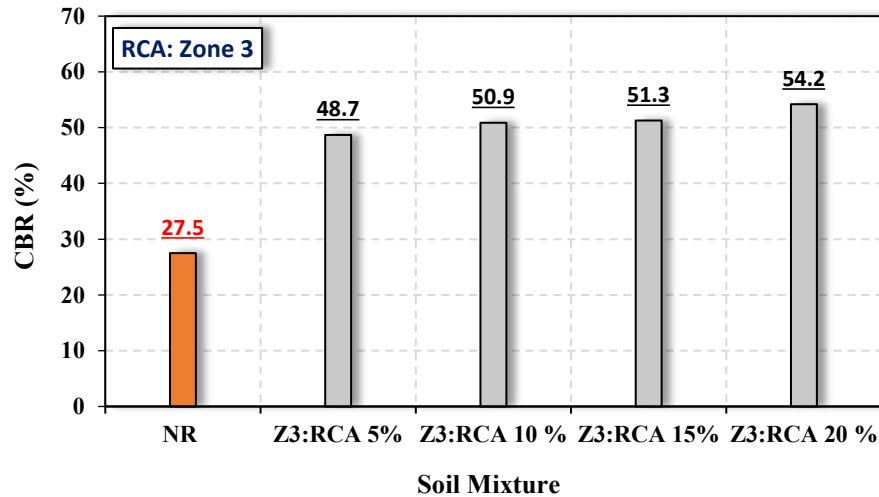


Figure 4-4: The CBR Results of Soil Mixtures Treated with RCA.

4.2.2.2. Results of CBR Test for Soil Treated by RCA and EA

The optimal RCA-soil mixtures (15% RCA replacement content) were treated with asphalt emulsion (EA) to improve the adhesion characteristics of the stabilized soil mixtures. Table (4-4) shows the CBR results for soils stabilized with RCA and EA.

Table 4-4: Results of CBR Test for Soils Stabilized by RCA and EA.

Types of Soil Mixture	California Bearing Ratio, CBR (%)			
	Grade1	Grade2	Grade3	Grade4
NS+ 15% RCA+ 0% EA	38.3	45.7	51.3	61.9
NS+15%RCA+2.5% EA	42.2	48.28	53.8	41.78
NS+15%RCA+5% EA	46.7	46.9	56.14	45.69
NS+15%RCA+7.5% EA	48.5	40.16	40.11	49.75
NS+15%RCA+10% EA	30.2	37	36.96	33.82
<ul style="list-style-type: none"> ▪ NS: Natural Subgrade Soil ▪ RCA: Recycled Concrete Aggregate ▪ EA: Asphalt Emulsion 				

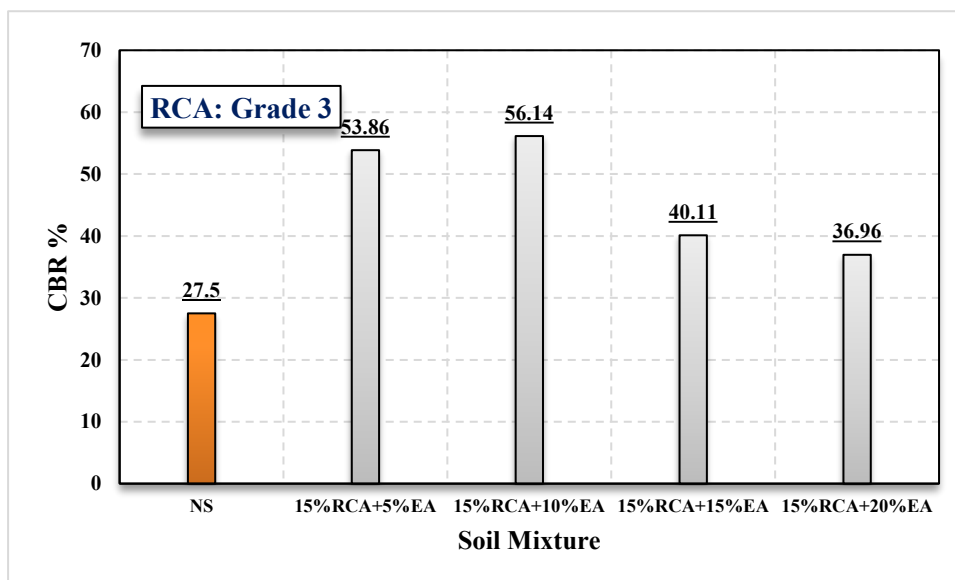
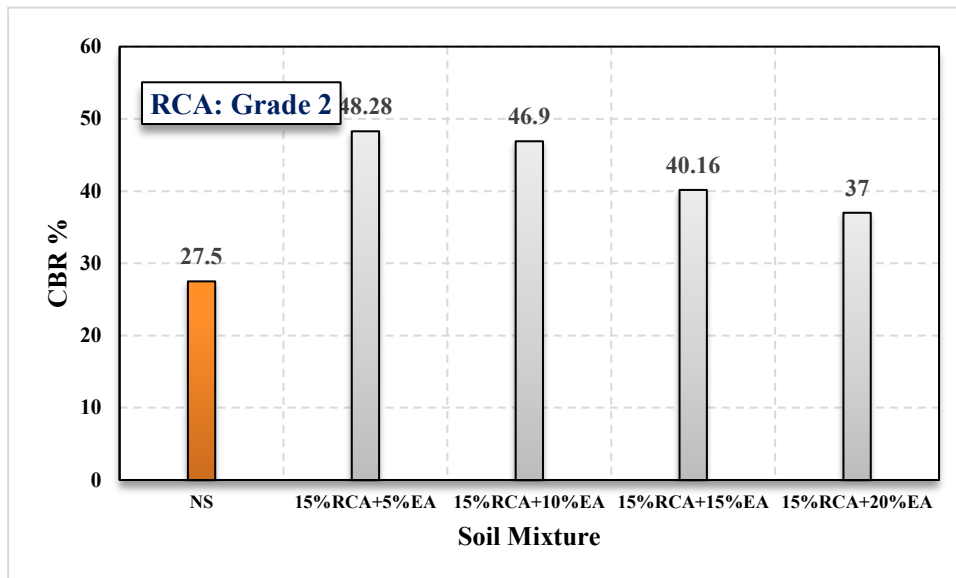
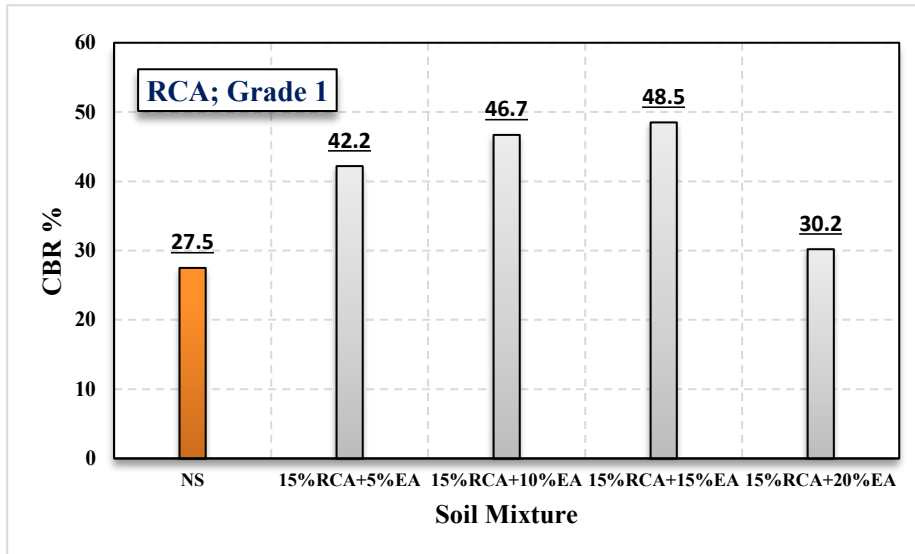
Figure (4-5) showed that when the asphalt emulsion was added to the stabilized soil with 15% RCA, it was noticed different changes in the CBR values were noticed. For the soil stabilized with EA-Grade 1, the CBR values were (42.2%, 46.7%, 48.5%, and 30.2%) for (2.5%, 5%, 7.5%, and 10%) EA and 15% RCA replacement, respectively. The improvement in CBR value may be attributed to many factors, primarily the capacity of EA to function as a binder, improving the compaction and cohesion of the soil particles. Adding EA into the soil occupies the gaps between soil particles and RCA, resulting in enhanced density and strength.

For the soil stabilized with EA-Grade 2, the CBR values were (48.28%, 46.9%, 40.16%, and 37%) for (2.5%, 5%, 7.5%, and 10%) EA and 15% RCA replacement, respectively. These percentages were (53.8%, 56.14%, 40.11%, and 36.96%) for (2.5%, 5%, 7.5%, and 10%) EA and 15% RCA-Grade 3 replacements, respectively. For the soil stabilized with EA and 15% RCA-Grade 4, the CBR values were (41.78%, 45.69%, 49.75%, and 33.82%) for (2.5%, 5%, 7.5%, and 10%) RCA replacement, respectively. These results are consistent with those obtained from a previous study (Pala, Imran, & Sabina, 2008).

The results also showed that with the use of 10% EA, CBR values are relatively decreased in all zones; with increasing the percentage of bitumen emulsion, the soil reaches the saturation point where its properties could deteriorate due to the increase in the percentage of asphalt emulsion, which then leads to a reduction in the friction between soil particles. CBR values for all zones relatively increased when the values of EA and 15% RCA replacement increased to stabilize the soil. This reduction shows an increasing effect of the asphalt emulsion ratio in the soil, demonstrating that a proportion of EA increases the interconnection of soil particles, and 15% RCA fills voids in the soil.

However, asphalt emulsion acts as an agent or adhesive that increases the bonding between soil particles and recycled concrete aggregate, improving stability and cohesion. It also acts as a protective layer that prevents water from reducing soil cohesion, thus increasing the soil's ability to bear the loads imposed on it. However, the results indicate an improvement in soil properties using recycled concrete aggregate with asphalt emulsion, where adding 15% of RCA with 2.5% EA to all grades was the optimal added percentage to the soil, and grade 4 was optimal.

In addition, the different gradients of RCA have a clear effect on the CBR results, as they contribute significantly to improving the properties of sandy soil. As for adding asphalt emulsion to the soil stabilized with recycled concrete aggregate, its effect is effective up to a specific percentage; it can have an effect. It can have a negative impact, so the asphalt emulsion ratios must be determined carefully to avoid saturating the soil, which reduces its properties.



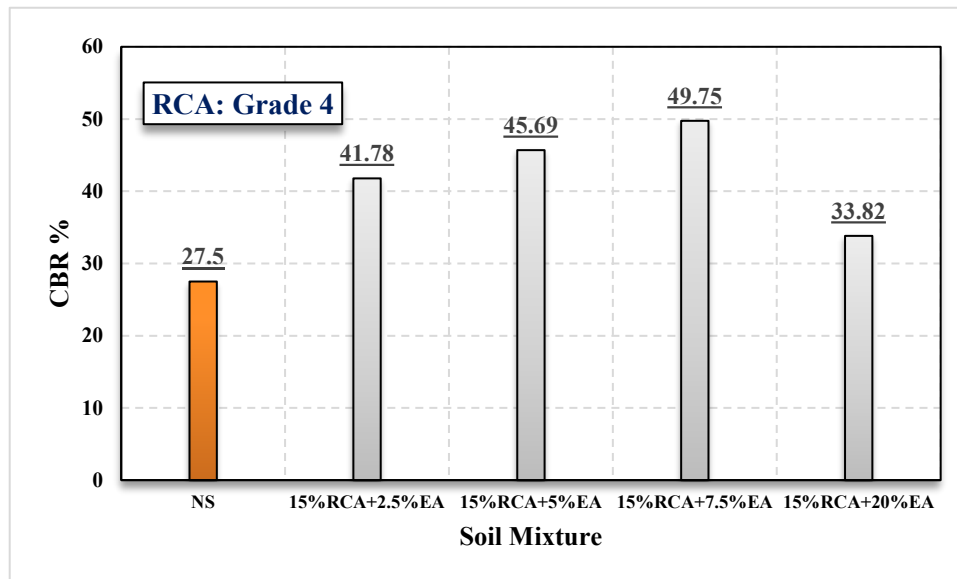


Figure 4-5: The CBR Test Results for Soil Stabilized with RCA and EA.

4.3. Field Testing Results

A representative subsoil, consisting of 3 layers of 20 cm thickness each, was constructed in a large cylindrical mold with a dimension of 70 cm in diameter and 100 cm in height. The maximum dry density and moisture content of each soil layer were specified based on the results of the modified Proctor test. Upon completing the preparation of the test model, the following tests were conducted: DCP, SRM, and LWD. The results of these tests are discussed as follows:

4.3.1. Results of Dynamic Cone Penetration Test

The Dynamic Cone Penetration Index (DCPI) is a common parameter for assessing subgrade soil strength, derived from the Dynamic Cone Penetrometer (DCP) test. The dynamic cone penetrometer (DCP) test results are summarized in Table 4.5.

Table 4.5: Results of DCP Test for Soil Mixtures.

Soil Mixture	DCPI (mm/below)	CBR (%)	Bearing Capacity (kPa)
Natural Soil, NS	9	24.75	216
NS +G1 15%RCA	7.3	41.3	287
NS + G2 15%RCA	5.6	44.7	286
NS + G3 15%RCA	5.5	48.1	301
NS + G4 15%RCA	5.4	53.6	325
NS+G1 15%RCA+2.5% EA	5.1	49.1	327
NS+G2 15%RCA+2.5% EA	4.7	51.7	311
NS+G3 15%RC+2.5% EA	4.5	55	375
NS+G4 15%RCA+2.5% EA	4.3	56	381
<ul style="list-style-type: none"> ▪ NS: Natural Soil ▪ EA: Asphalt Emulsion ▪ G: Grade Number of RCA ▪ RCA: Recycled Concrete Aggregate 			

Figure 4.6 shows that the DCPI value of natural soil is (9) mm/blow. However, when adding recycled concrete aggregate (RCA) at 15% and for four grades of dry soil weight, the DCPI values decreased to (7.3, 5.6, 5.5, and 5.4) mm/blow for RCA-Grades 1, 2, 3, and 4, respectively. This finding indicates that adding RCA leads to decreased DCPI values compared to natural soil. This decrease can be attributed to the fact that RCA fills the voids, which enhances internal friction, making the soil more rigid and less susceptible to penetration.

The study also investigated the effect of adding asphalt emulsion to the soil stabilized with 15% RCA, as shown in Figure 4.7. The results showed that when 2.5% asphalt emulsion EA was added to soil stabilized with RCA, the DCPI values were (5.1, 4.7, 4.5, and 4.3) mm/blow, respectively.

The results showed that adding asphalt emulsion EA led to a decrease in DCPI values for grade 4 compared to DCPI values for soil with RCA, indicating an increase in soil strength.

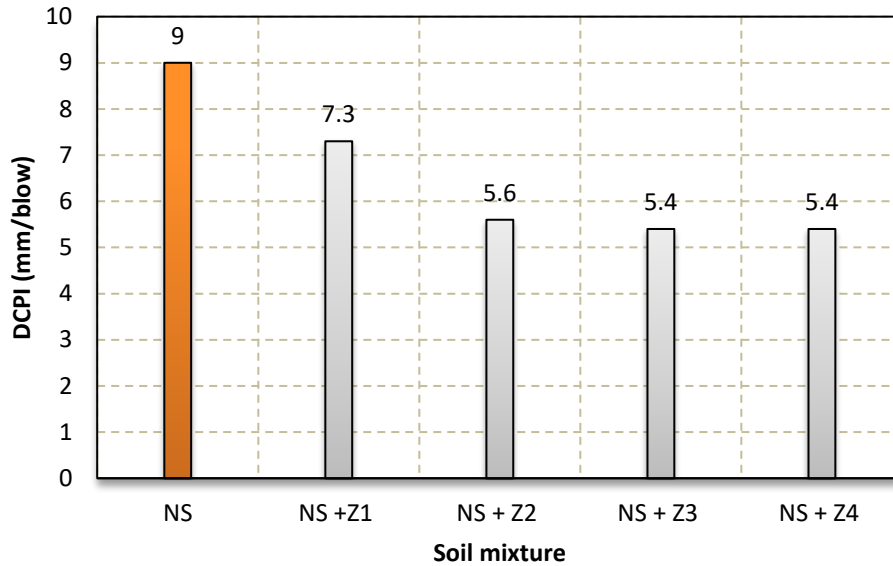


Figure 4-6: The results of DCPI for Soil Mixtures with RCA.

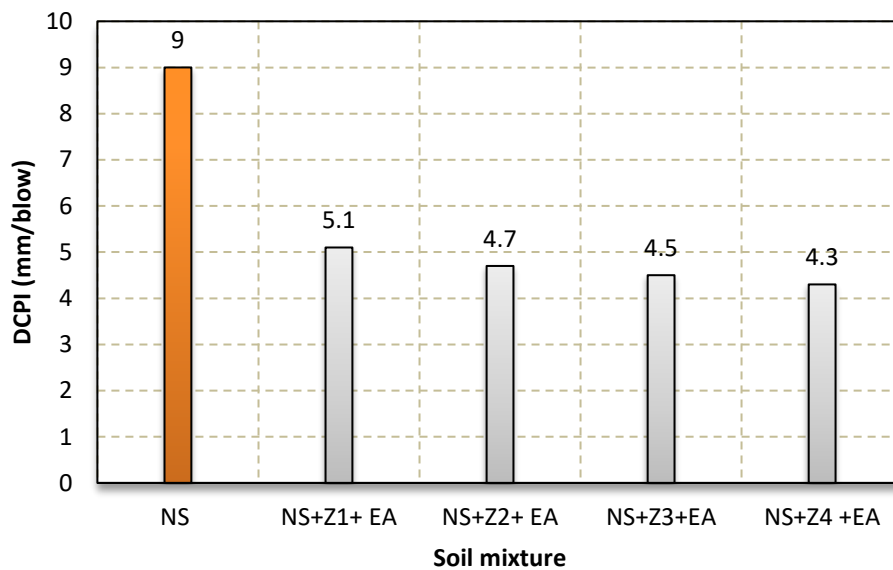


Figure 4-7: The results of DCPI for Soil Mixtures with RCA and EA.

The study also found parameters CBR and soil-bearing capacity from DCPI results. Figures (4.8) and (4.9) presented that the CBR value of natural soil was 14%, while the bearing capacity was 216 kPa. After stabilizing the soil with 15% RCA of grade1 of dry soil weight, the CBR value increased from

24.27 to 41.3%, and the bearing capacity increased from 216 to 287 kPa. The CBR value of Grade 2 was 44.7%, and the bearing capacity was 286 kPa. While the CBR value of Grade 3 was 48.1%, the bearing capacity was 301 kPa. The CBR value of Grade 4 was 53.6%, and the bearing capacity was 325 kPa.

The results showed increased CBR values and bearing capacity due to the interlocking and interaction from mixing RCA with the soil. This can also explain the increase in the soil bearing capacity coefficient, which depends on the angle of internal friction. As mentioned earlier, the mechanism of action of RCA is to increase the friction between the particles, which in turn leads to an increase in the soil bearing capacity.

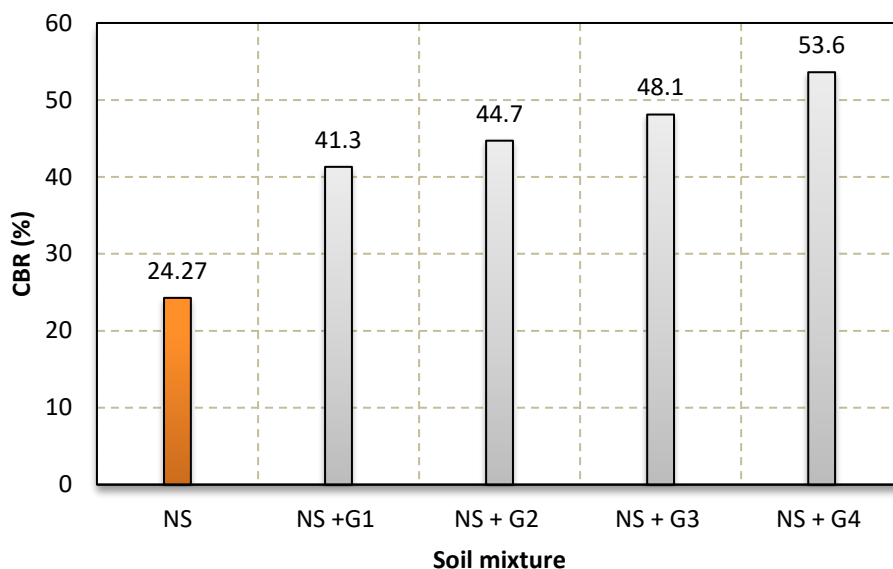


Figure 4-8: The results for CBR Value to Soil Mixtures with RCA.

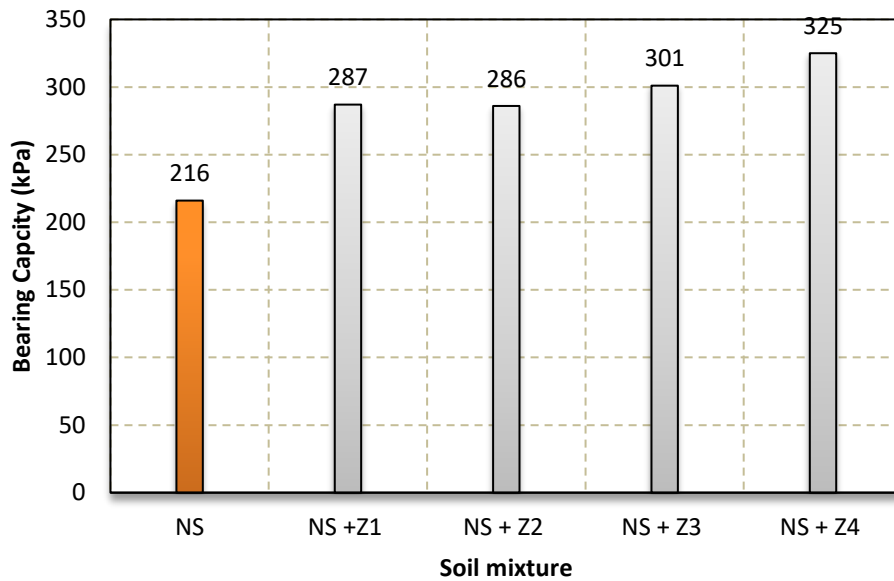


Figure 4-9: The Results for Bearing Capacity to Soil Mixtures with RCA.

Figures 4.10 and 4.11 show that after adding asphalt emulsion to soil stabilized with RCA at a rate of 2.5%, the CBR values for Grade 1 were 49.1%, and the bearing capacity was 327 kPa. The CBR value of Grade 2 was 51.7%, and the bearing capacity was 311 kPa. The CBR values for Grade 3 were 55%, with a bearing capacity of 375 kPa. The CBR value of Grade 4 was 56%, and the bearing capacity was 381 kPa. The results reveal that adding asphalt emulsion to soil stabilized with RCA improves cohesion and bonding, increasing the soil's bearing capacity and strength.

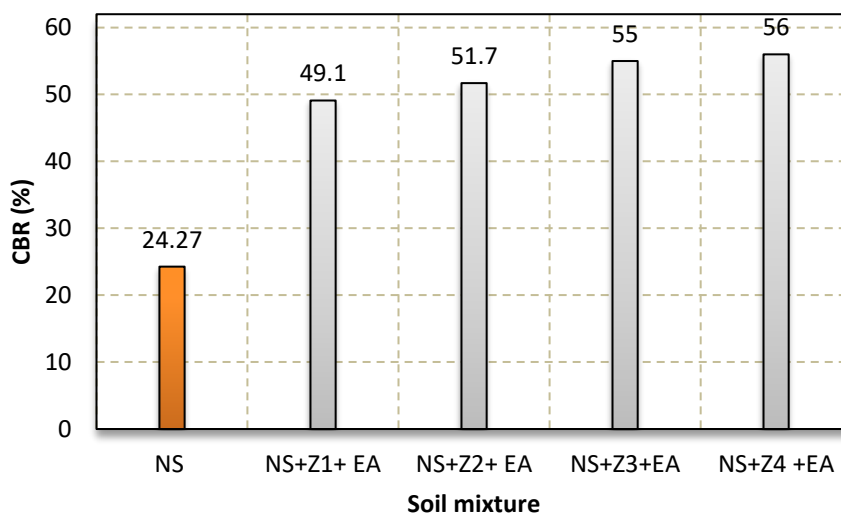


Figure 4 10: The results for CBR value to soil mixtures with RCA and EA.

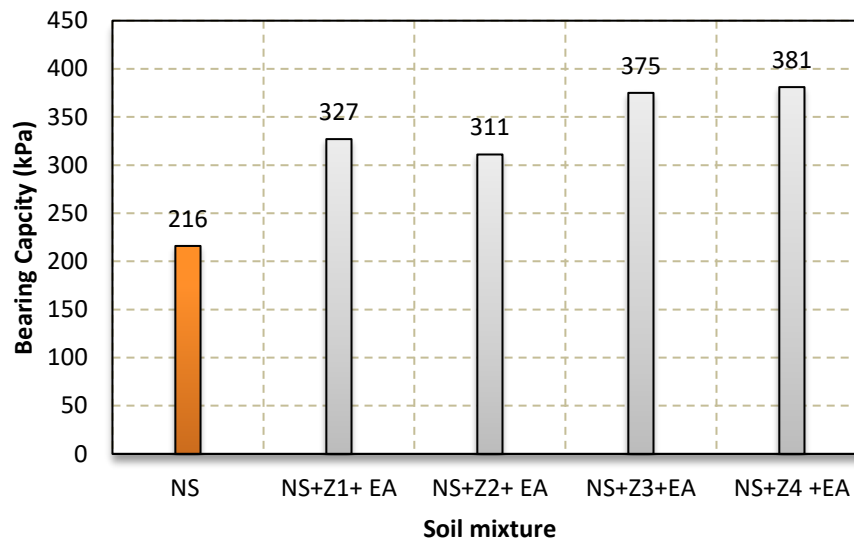


Figure 4 -11: The bearing capacity results for soil mixtures with RCA and EA.

4.3.2. Results of Sand Cone Method

The study used the sand replacement testing method (SRM) to determine the density of stabilized soil layers in the large testing mold. The results are summarized in Table 4.6.

Table 4-6: Summary of Sand Replacement Test Results.

Soil Mixtures	Dry Density (gm/cm ³)	MC (%)
NS	2.06	11.81
NS +G1 15%RCA	2.15	11.78
NS +G2 15%RCA	2.17	11.56
NS +G3 15%RCA	2.19	11.35
NS +G4 15%RCA	2.21	11.01
NS+G1 15%RCA+2.5% EA	2.18	11.15
NS+G2 15%RCA+2.5% EA	2.20	11.12
NS+G3 15%RCA+2.5% EA	2.20	11.06
NS+G4 15%RCA+2.5% EA	2.22	11.20

- NS: Natural Soil
- EA: Asphalt Emulsion
- G: Grade Number of RCA
- RCA: Recycled Concrete Aggregate

The field dry density value for natural sandy soil is $(2.06) \text{ gm/cm}^3$, as shown in Table 4.6. For the soil stabilized with recycled concrete aggregate (RCA grades 1 and 2) at 15% of soil weight, the wet density ranged between 2.15 and 2.17 gm/cm^3 . These results showed a clear increase in the density values, which can be explained by the fact that recycled concrete aggregate contributes to filling the voids between sandy soil particles. Also, the gradation of RCA for grades 1 and 2 contributed to reducing voids and increasing cohesion and bonding between particles, so the soil structure improved significantly. For the soil stabilized with (RCA grades 3 and 4) at 15% of soil weight, the wet density was 2.19 and 2.21 gm/cm^3 , respectively, as shown in Figure (4.12). These results display that grades 3 and 4 have a granular gradient that balances void filling and good cohesion but is less efficient than grades 1 and 2.

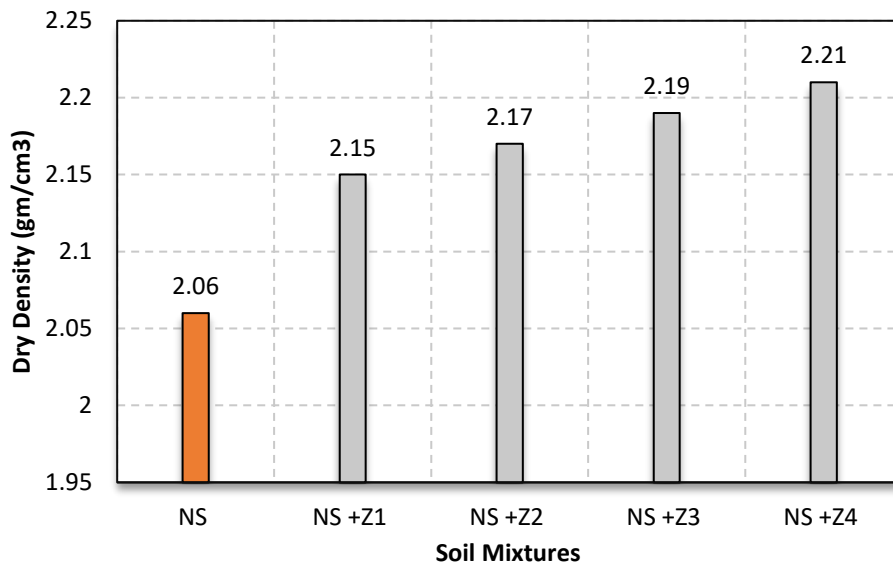


Figure 4-12: The Differences in Dry Density for Soil Mixtures with RCA.

For the soil stabilized with RCA and asphalt emulsion 2.5% for grades 1 and 2, the dry density ranged between 2.18 and 2.20 gm/cm^3 . The asphalt emulsion acts as a binder between the soil and the recycled concrete aggregate (RCA), increasing the cohesion and bonding between the particles, which improves the wet density. The EA reduces the permeability between the

particles, which helps in increasing the density. But in grades 3 and 4, the dry density was (2.20 and 2.22) gm/cm³, as shown in Figure (4.13). Additionally, a slight increase in the dry density values was noticed, which means that the asphalt emulsion EA helps stabilize the soil and increase its cohesion. From the above results, using RCA and EA improves soil properties significantly, which shows that the gradation of larger RCA gives a better distribution of particles, which helps increase dry density. The results also showed that the soil mixture with 15% RCA and 2.5% EA has the highest dry density, 2.22 (gm/cm³).

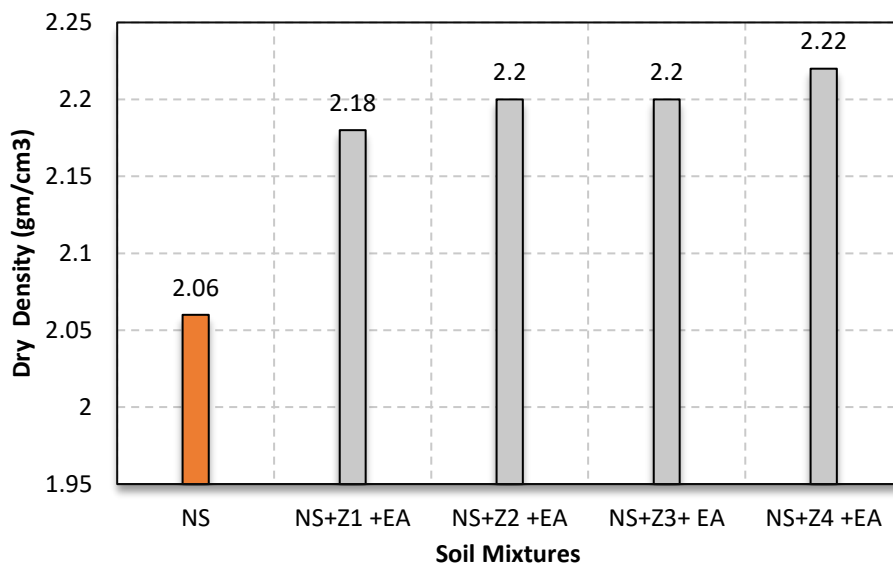


Figure 4-13: The Results in Dry Density for Soil Mixtures with RCA and EA.

As shown in Figure 4-14, the natural soil's moisture content was 11.82%. The addition of 15% recycled concrete aggregate (RCA) gradually reduced the MC to 11.78% in grade 1 and 11.01% in grade 4. This decrease indicates that RCA reduces the void spaces between soil particles due to their different shapes and sizes, achieving the maximum dry density.

As illustrated in Figure 4-15, adding 2.5% asphalt emulsion to the stabilized soil 15% RCA resulted in a decrease in the MC from 11.20% to 11.06%. The effect of EA, which increases the ability of the soil mixture to retain moisture, is responsible for this relative decrease. The interaction

between the soil EA, RCA, and soil water forms compacted masses, enhancing the cohesion of soil particles. This results in a higher soil density with fewer voids, reducing the moisture content needed to reach the maximum soil density.

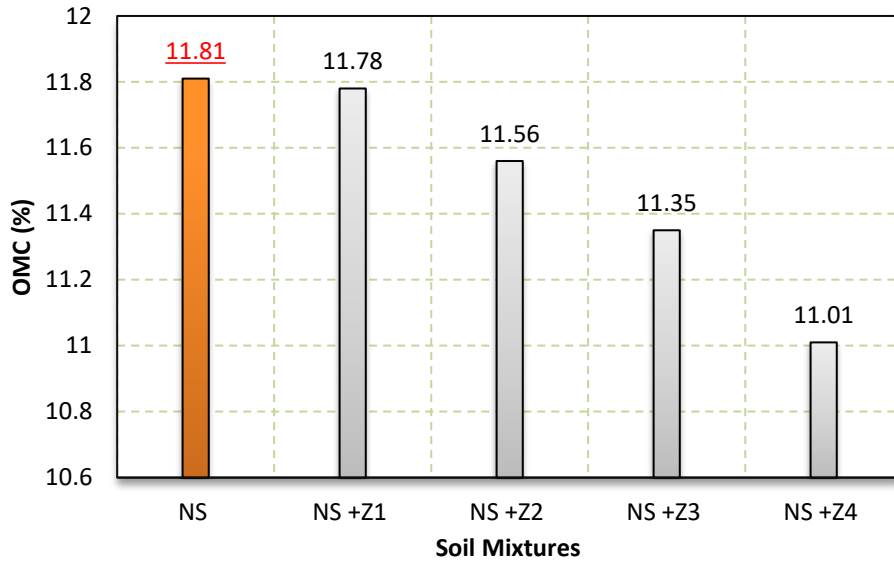


Figure 4-14: The Results in Moisture Content Values for Soil Mixtures with RCA.

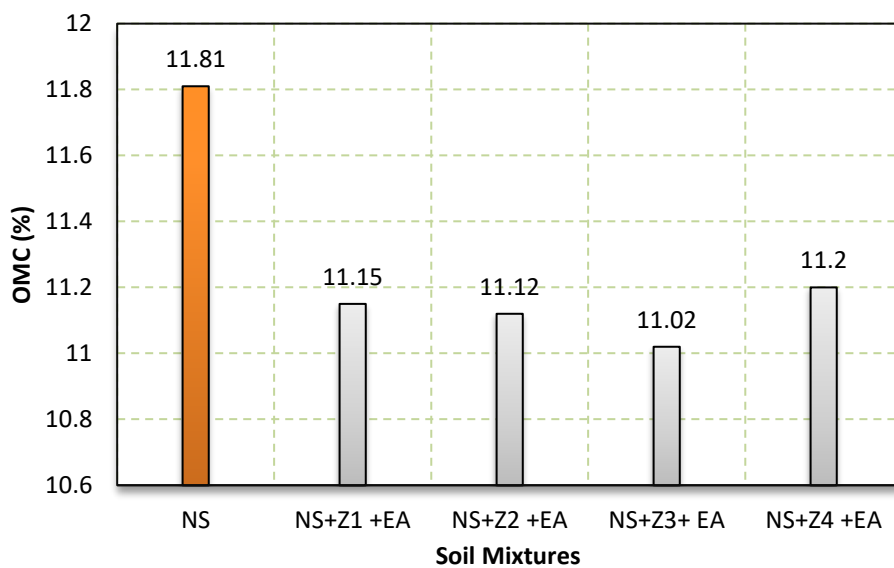


Figure 4-15: The Results in Moisture Content Values for Soil Mixtures with RCA and EA.

4.3.3. Results of Light Weight Deflectometer

The light weight deflectometer test was performed on the subgrade soil to determine the dynamic properties of the stabilized soil mixtures. The dynamic

properties include several parameters, including dynamic modulus E_d (MPa), surface deflection S_d (mm), and degree of compatibility D_c (ms). The results of the LWD test are summarized in Table 4.7.

Table 4.7: Results of LWD test for Soil Mixtures.

Soil Mixtures	Surface deflection(mm)				Dc (ms)	Ed (MPa)
	δ_1	δ_2	δ_3	δ mean.		
NS	0.631	0.615	0.591	0.612	3.859	36.76
NS +G1 15%RCA	0.586	0.552	0.563	0.570	4.305	39.47
NS +G2 15%RCA	0.563	0.547	0.535	0.548	4.543	41.06
NS +G3 15%RCA	0.543	0.535	0.527	0.535	3.809	42.51
NS +G4 15%RCA	0.519	0.503	0.502	0.508	3.79	44.29
NS+G1 15%RCA+2.5% EA	0.539	0.583	0.530	0.550	4.144	40.47
NS+G2 15%RCA+2.5% EA	0.494	0.478	0.466	0.479	3.801	42.97
NS+G3 15%RCA+2.5% EA	0.503	0.502	0.517	0.507	3.926	44.38
NS+G4 15%RCA+2.5% EA	0.463	0.498	0.491	0.484	4.143	46.49
<ul style="list-style-type: none"> ▪ NS: Natural Soil ▪ EA: Asphalt Emulsion ▪ G: Grade Number of RCA ▪ RCA: Recycled Concrete Aggregate 						

Figure 4.16 shows that the deflection and degree of compatibility for natural soil were (0.612) mm and (3.859) ms, respectively. The deflection value for the soil stabilized using RCA grades 1 and 2 decreased to (0.570, 0.548) mm compared to natural soil, indicating an improvement in soil densification due to the presence of the RCA. The decrease in the value of surface deflection is attributed to the effect of the 15% RCA added to the soil. When RCA is added, it enhances internal friction and increases mechanical resistance, and this decrease is an indication of the ability of the soil to resist deformation when subjected to loads.

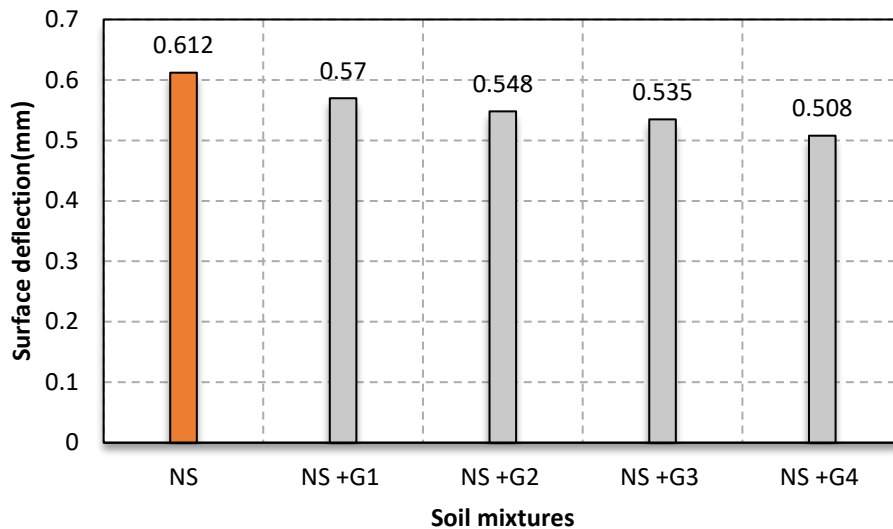


Figure 4-16: The Results of Sd for Soil with RCA.

The deflection in grade 3 decreased to (0.535) mm; the effect of adding RCA to the natural soil is responsible for reducing surface deflection. RCA increases the internal friction in the soil, which enhances its structure. Consequently, the soil strength increases with a reduction in the surface deflection, which indicates the ability of the soil to resist deformation when subjected to a load. Grade 4, which was (0.508) mm, showed a decrease in deflection, suggesting a higher level of stiffness. The gradation of this zone significantly improves internal friction and reduces voids.

The addition of 2.5% asphalt emulsion with contents of 15% RCA by weight of the dry soil decreased values of surface deflection (0.550, 0.479, 0.507, and 0.484) mm for all zones. The decrease in surface deflection can be attributed to the effect of EA on stabilization with 15% RCA. This reduction can be due to the increased stiffness of the soil and bearing capacity. However, adding 15% RCA and 2.5% EA to the soil leads to a decrease in the surface deviation values, which indicates an improvement in the mechanical and structural properties of the stabilized soil, as shown in Figures 4-17. RCA enhances the internal friction among soil particles and increases density, improving the soil's stability and strength under load.

Adding EA helps increase cohesion between soil particles and RCA and reduces permeability. These results show that adding EA and RCA to the soil enhances the ability of the soil to resist deflection from traffic loads. This decreases surface changes and improves the quality of the stabilized soil for different engineering projects.

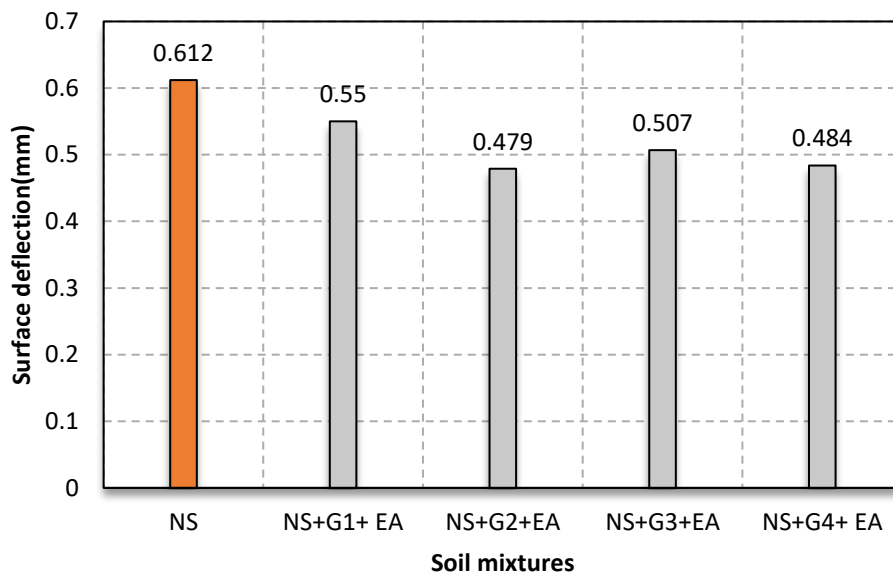


Figure 4-17: The Results of Sd for Soil Mixtures with EA.

As shown in Figure 4-18, the dynamic modulus E_d of natural soil is (36.76) MPa, and when the soil was stabilized by 15% RCA for all grades, the E_d values increased to (39.47, 41.06, 42.51, and 44.29) MPa. It was noticed that adding RCA to the soil improves the internal friction between soil particles, which contributes to increasing the hardness of the soil and thus increasing the E_d values. This increase is also attributed to the nature of the RCA particles, as their gradation plays a major role in filling the spaces between soil particles and increasing their hardness. From the results, as shown in Figure 4-19, adding 2.5% asphalt emulsion to the soil mixture and 15% RCA had a significant effect on E_d , as the E_d values increased for all grades (40.47, 42.97, 44.38, and 46.49) MPa, respectively. According to the results, it was found that adding EA to the soil mixture and RCA can provide increased reinforcement and interlocking within the soil and RCA structure, leading to a

stronger and more rigid material. In addition, this increase in the dynamic modulus indicates that the mixture has a higher resistance to failure when exposed to dynamic loading conditions.

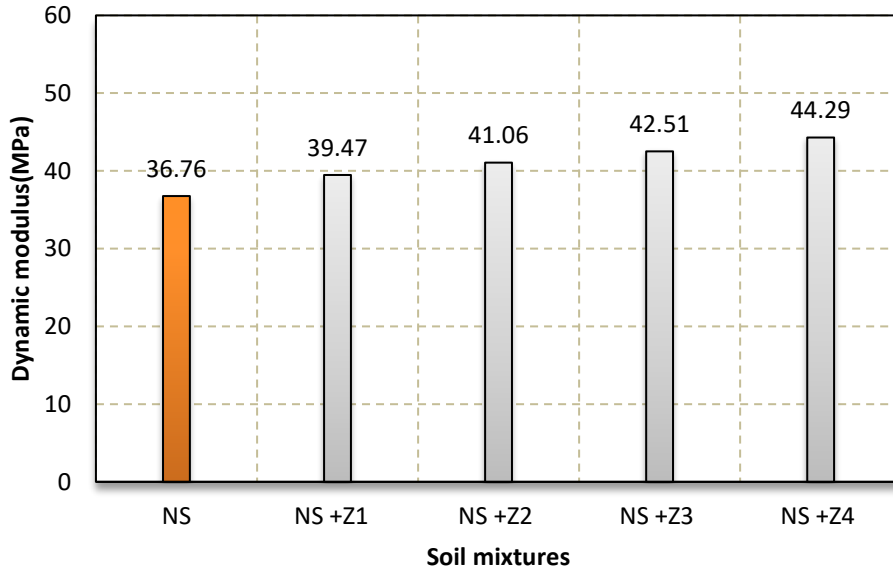


Figure 4-18: The Results of Ed for Soil with RCA.

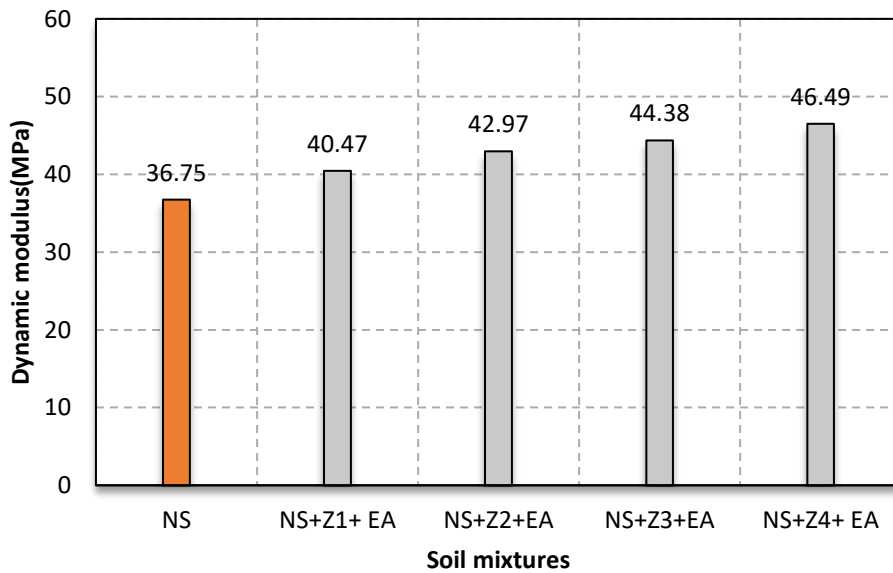


Figure 4-19: The Results of Ed for Soil Mixtures with EA.

4.4. Summary

The results of laboratory and field tests conducted on natural subgrade soil and stabilized soil with 15% recycled concrete aggregate (RCA) and 2.5% asphalt emulsion can be summarized as follows: Laboratory test results from modified Proctor compression and CBR tests showed that the inclusion of RCA in natural sand soil increased dry density and CBR values, at the same time. Field test results obtained from dynamic cone penetration (DCP), sand replacement method (SCM), and lightweight deflectometer (LWD) showed that the inclusion of RCA in natural sand soil increased in-situ CBR values, bearing capacity (q), and dynamic elastic modulus (E_d). At the same time, there was a decrease in dynamic cone penetration index (DCPI), surface deflection (S_d), and degree of compatibility (D_c). The results showed that adding asphalt emulsion EA in the sand and RCA mixtures resulted in a gradual increase in dry density, CBR, and dynamic modulus of elasticity (E_d). The results indicate that the basic soil properties were significantly improved when stabilized by the addition of RCA and asphalt emulsion EA.

Chapter Five:
Theoretical Analysis

Chapter Five: Theoretical Analysis

5.1. Introduction

This chapter details the various methods used within the KENPAVE software package to conduct structural evaluations of stabilized and unstabilized pavement sections (Huang, 1993).

KENPAVE analysis is a prevalent finite element software in pavement engineering. This computer-based modeling and simulation tool enables engineers to assess pavement systems' structural performance and behavior under various loads and environmental conditions. KENPAVE analysis is used in this theoretical research to evaluate the effect of subgrade soil stabilization on the structural performance of the pavement system under standard traffic loads (Rind et al., 2019).

When using KENPAVE, users can precisely assess the stresses, strains, and displacements inside various pavement layers by inputting design parameters and traffic load data. This program can save researchers much time compared to traditional study techniques. It allows them to compare several road design possibilities, evaluate them, and choose the best one. The program is compatible with SI and English units.

Two sections of the KENPAVE program are dedicated to the assessment and design requirements of various pavement kinds. The first section, "Asphalt," is concerned with the evaluation and planning of flexible pavements. Figure (5.1) shows the several modules that make up this component; they help with analysis and design jobs involving flexible pavements, such as LAYERINP, KENLAYER, LGRAPH, and others.

However, "Concrete," the second section of the program, is all about rigid pavements and how to evaluate and design them. Included in this part are modules like SLABSINP, KENSLABS, SGRAPH, and others (also shown in Figure 5.1). To properly study and build stiff pavements, these modules provide researchers and designers with the resources and functionality they need.

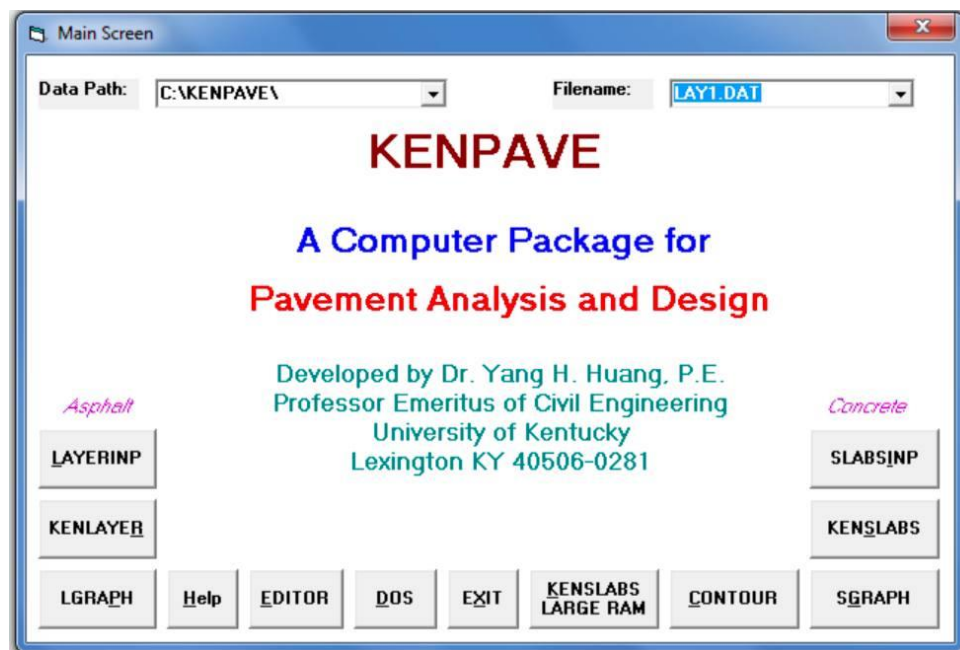


Figure 5-1: The Main Screen Capture of KENPAVE.

Dividing KENPAVE into these two components ensures that the program effectively addresses the unique needs and factors relevant to flexible and rigid pavement analysis. This program provides researchers and designers with many capabilities and features that enhance their projects, resulting in more efficient and precise pavement assessments and designs. The primary menu of LARERINP facilitates the creation and modification of data files. The data include material types, damage assessments, annual period counts, layer quantities, load classifications, and more.

KENLAYER is the primary software for pavement analysis. It can only be performed after a data file has been created. The software retrieves the information in the data file and begins the execution process.

5.2. Structural Analysis

5.2.1. Geometry Configuration of Pavement Sections

A real model of a road established in the Province of Karbala is used in the analysis of the findings. The section of the southern ring road, which is depicted in Figure 5.2, is being constructed by the Karbala Governorate.



Figure 5.2: Aerial Views of The Southern Ring Road.

A specific section of the Southern Ring Road in Karbala Governorate was analyzed to obtain optimal results. This section contains surface, base, subbase, and subgrade courses. The KENPAVE software examined these strata according to their unique properties. Subgrade layers stabilized with recycled concrete aggregate with or without asphalt emulsion were also analyzed using the same software on the same segment. The outcomes were subsequently contrasted to evaluate the impact of the stabilizing procedure. Figure (5.3) in

the research illustrates a standard cross-section of the pavement system chosen for examination.

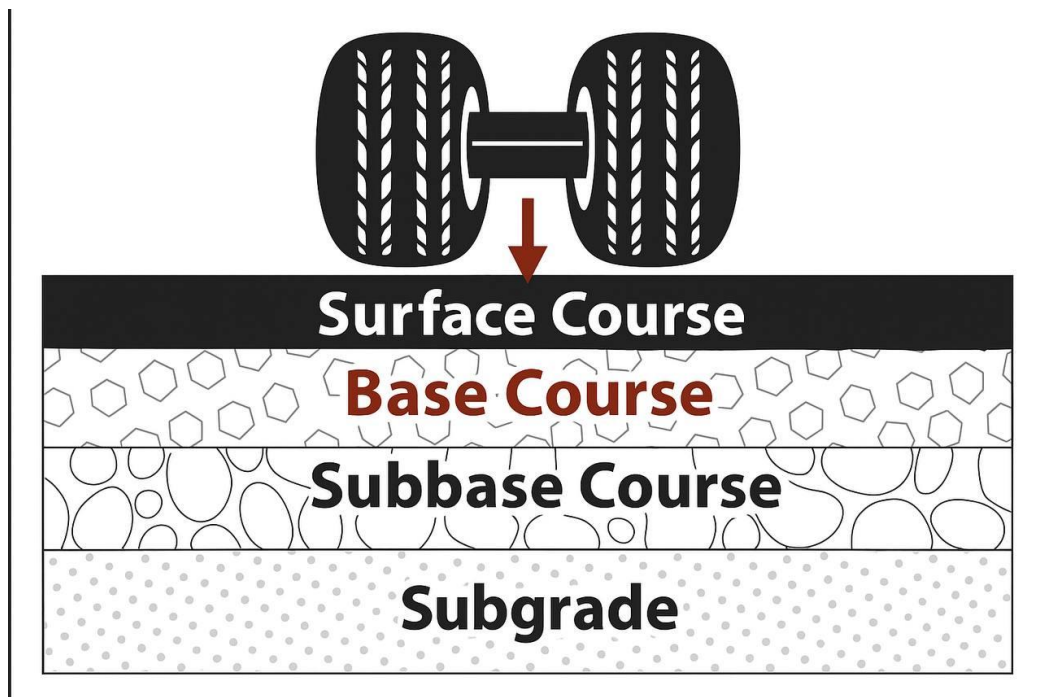


Figure 5-3: Typical Pavement System Selected in this Work.

5.2.2. Loading and Boundary Conditions

The KENPAVE software was used to carry out the structural design of the flexible pavement system. The necessary inputs were inputted according to the defined parameters for each pavement layer. Table 5.1 summarizes the characteristics of the standard pavement system used in the analysis.

Table 5-1: Summary of Input Data for Control Section Structural Design.

Layer	Type	Thickness (mm)	Poisson's Ratio	γ (KN/cm ³)	E (kPa)
1	Binder Course	80	0.35	22.8	3750,000
2	Base Course	150	0.35	21.2	189,000
3	Subbase	250	0.35	21.2	112,000
4	Subgrade	/	0.40	17.8	76,000

The characteristics of stabilized subgrade soils, the optimal RCA-soil mixtures (15% RCA replacement content for each of the four grades) treated with 2.5% asphalt emulsion (EA) for all zones to improve the adhesion characteristics of the stabilized soil mixtures, were utilized as input values to define the attributes of stabilized subgrade soil.

The response of the pavement layers to different axle loads was evaluated using the following loading conditions:

1. Traffic load: single axle (dual tires).
2. Contact pressure: 500 kPa.
3. Contact radius: 115 mm.
4. Axle loading: To study how the pavement layers react to various loads, it was adjusted to 60 kN, 120 kN, 180 kN, 240 kN, and 300 kN.
5. Design life: specified as 20 years for this study.

The characteristics of stabilized subgrade soils stabilized with 15% RCA in zones 1, 2, 3, and 4 during the first stage were analyzed. The RCA-soil mixture was then further stabilized in these four zones by adding 2.5% asphalt emulsion, which was utilized as input values to define the characteristics of the stabilized subgrade soils in the software.

5.2.3. Analysis Parameters for Pavement Evaluation

The study and comparison procedure included the following three major parameters:

1. Allowable number of load repetitions (N_d) is the maximum number of load repetitions that should be permitted to avoid rutting. The relationship between this variable and the subgrade's vertical compressive strain (ϵ_c) is as follows:

$$N_d = f_4 \times \varepsilon_c^{-f_5} \quad (5-1)$$

Where:

N_d : represents the allowable number of load repetitions.

ε_c : denotes the vertical compressive strain experienced on the top of the subgrade layer.

f_4 and f_5 : specific values, values equal to 1.05×10^{-7} and 4, respectively, (Huang (2004)).

2. Damage ratio: is calculated using the following equation:

$$\text{Damage ratio} = \frac{1}{N_d} \quad (5-2)$$

3. Rutting life: is determined by the following formula:

$$\text{Rutting life} = \frac{\text{design life}}{\text{damage ratio}} \quad (5-3)$$

Table (5.2) displays the results of the study, which included sampling and evaluating the natural subgrade soil for the control section and each type of stabilized soil section. To compare the results and demonstrate how using recycled concrete aggregate, either with or without asphalt emulsion, enhances the properties of the stabilized subgrade soil, the axle load was limited to 60 kN.

Table 5-2: Output Data Summary for Control Section Structural Design.

Subgrade soil	Axle Load	Comp. stress (Kpa)	Comp. Strain mm	N _d	Damage Ratio %	Rutting Life
NS	60	23.57	1.51E-04	2.02E+08	4.95E-09	4.04E+09
	120	47.14	3.02E-04	1.26E+07	7.92E-08	2.52E+08
	180	70.71	4.53E-04	2.49E+06	4.01E-07	4.99E+07
	240	94.28	6.04E-04	7.89E+05	1.27E-06	1.58E+07
	300	117.85	7.55E-04	3.23E+05	3.09E-06	6.46E+06
Grade1 15% RCA	60	28.92	1.48E-04	2.19E+08	4.57E-09	4.38E+09
	120	57.84	2.96E-04	1.37E+07	7.31E-08	2.74E+08
	180	86.76	4.44E-04	2.70E+06	3.70E-07	5.40E+07
	240	115.68	5.92E-04	8.55E+05	1.17E-06	1.71E+07
	300	144.6	7.40E-04	3.50E+05	2.86E-06	7.00E+06
Grade2 15% RCA	60	31.6	1.40E-04	2.73E+08	3.66E-09	5.47E+09
	120	63.2	2.80E-04	1.71E+07	5.85E-08	3.42E+08
	180	94.8	4.20E-04	3.37E+06	2.96E-07	6.75E+07
	240	126.4	5.60E-04	1.07E+06	9.37E-07	2.14E+07
	300	158	7.00E-04	4.37E+05	2.29E-06	8.75E+06
Grade3 15% RCA	60	33.29	1.38E-04	2.90E+08	3.45E-09	5.79E+09
	120	66.58	2.76E-04	1.81E+07	5.53E-08	3.62E+08
	180	99.87	4.14E-04	3.57E+06	2.80E-07	7.15E+07
	240	133.16	5.52E-04	1.13E+06	8.84E-07	2.26E+07
	300	166.45	6.90E-04	4.63E+05	2.16E-06	9.26E+06
Grade4 15% RCA	60	35.88	1.29E-04	3.79E+08	2.64E-09	7.58E+09
	120	71.76	2.58E-04	2.37E+07	4.22E-08	4.74E+08
	180	107.64	3.87E-04	4.68E+06	2.14E-07	9.36E+07
	240	143.52	5.16E-04	1.48E+06	6.75E-07	2.96E+07
	300	179.4	6.45E-04	6.07E+05	1.65E-06	1.21E+07
Grade1 15% RCA +2.5%EA	60	30.07	1.38E-04	2.90E+08	3.45E-09	5.79E+09
	120	61.4	2.76E-04	1.81E+07	5.53E-08	3.62E+08
	180	92.1	4.14E-04	3.57E+06	2.80E-07	7.15E+07
	240	122.8	5.52E-04	1.13E+06	8.84E-07	2.26E+07
	300	153.5	6.90E-04	4.63E+05	2.16E-06	9.26E+06
Grade2 15% RCA +2.5%EA	60	30.37	1.37E-04	2.98E+08	3.36E-09	5.96E+09
	120	60.74	2.74E-04	1.86E+07	5.37E-08	3.73E+08

Table 5-2: Output Data Summary for Control Section Structural Design
(Continued).

	180	91.11	4.11E-04	3.68E+06	2.72E-07	7.36E+07
	240	121.48	5.48E-04	1.16E+06	8.59E-07	2.33E+07
	300	151.85	6.85E-04	4.77E+05	2.10E-06	9.54E+06
Grade3 15% RCA+2.5%EA	60	33.97	1.31E-04	3.57E+08	2.80E-09	7.13E+09
	120	67.94	2.62E-04	2.23E+07	4.49E-08	4.46E+08
	180	101.91	3.93E-04	4.40E+06	2.27E-07	8.80E+07
	240	135.88	5.24E-04	1.39E+06	7.18E-07	2.79E+07
	300	169.85	6.55E-04	5.70E+05	1.75E-06	1.14E+07
Grade4 15% RCA +2.5%EA	60	30.27	1.41E-04	2.66E+08	3.76E-09	5.31E+09
	120	60.54	2.82E-04	1.66E+07	6.02E-08	3.32E+08
	180	90.81	4.23E-04	3.28E+06	3.05E-07	6.56E+07
	240	121.08	5.64E-04	1.04E+06	9.64E-07	2.08E+07
	300	151.35	7.05E-04	4.25E+05	2.35E-06	8.50E+06

Figures 5-4 and 5-5 illustrate that incorporating 15% recycled concrete aggregate in four different grades resulted in an increase in compressive stress from 23.57 kPa to 28.92 kPa, 31.60 kPa, 33.29 kPa, and 35.88 kPa. Simultaneously, the compressive strain decreased from 1.51E-04 mm to 1.48E-04 mm, 1.40E-04 mm, 1.38E-04 mm, and 1.29E-04 mm, respectively. This improvement can stem from the enhanced engineering properties of the soil when RCA is introduced, as it raises compressive stress while lowering compressive strain. The increase in stress can be attributed to the RCA's capacity to improve the engineering qualities of the soil. When RCA is mixed into the soil, it enhances the interlocking and cohesion among soil particles while filling the gaps between them.

This process produces a more compact and cohesive material, enhancing the strength and stiffness of the soil. Furthermore, the areas with fine gradations yield optimal results, as they promote interlocking among soil particles, thereby improving soil strength. The reduction in compressive strain is linked to increased soil stiffness resulting from adding RCA. This enhances the resistance of the soil to deformation, and incorporating RCA clearly aids in

distributing loads more effectively among soil particles. Consequently, the soil becomes less susceptible to deformation under compressive loads, leading to a decrease in compressive strain. Including RCA with fine gradations aids in establishing many of these interlocks. Consequently, this results in a greater reduction in compressive strain.

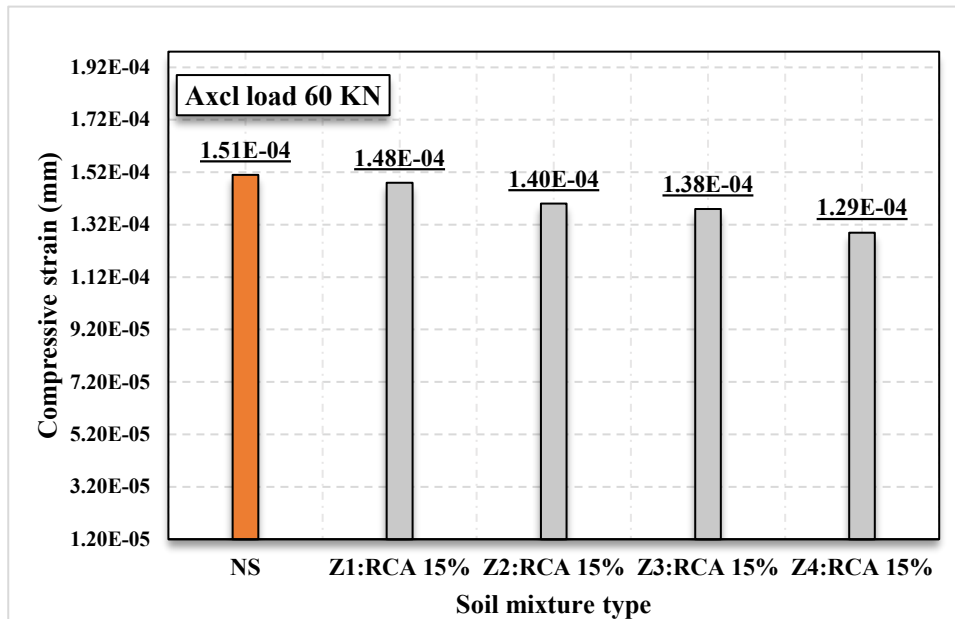


Figure 5-4: Differences in Vertical Compressive Stress for Soil Mixtures.

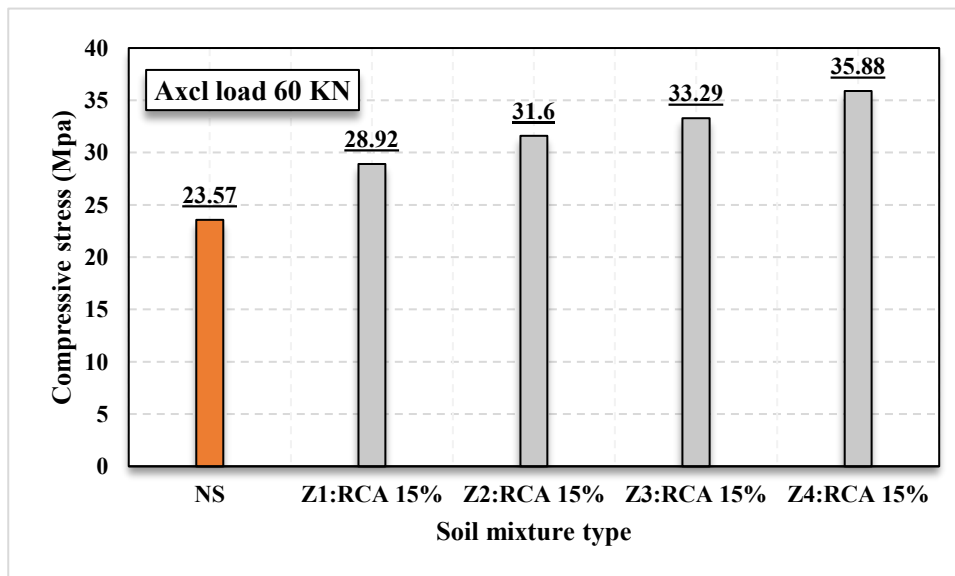


Figure 5-5: Differences in Vertical Compressive Strain for Soil Mixtures.

As shown in Figures (5-6) and (5-7), adding 2.5% asphalt emulsion to the soil mixture with 15% recycled concrete aggregate led to a gradual increase in compression stress from 23.57 kPa for a standard pavement system to 30.07, 30.37, 33.97, and 30.27 kPa, for pavement system stabilized by 15% RCA zone 1, 2, 3, 4, respectively. Meanwhile, it resulted in a gradual decrease in compression strain from 1.51E-04 mm to 1.38E-04, 1.37E-04, 1.31E-04, and 1.41E-04 mm. Asphalt emulsion to the soil mixture with RCA in four different gradations resulted in a gradual increase in compression stress and a gradual decrease in compression strain compared to those obtained for natural soils.

The increase in compression stress can be caused by the emulsion, which is usually the cause of increased soil resistance to the loads applied to it, which increases the strength of the soil. However, compared to the compression stress value of natural soil, the compression stress values for soil mixtures with asphalt emulsion for all zones are significantly higher. The decrease in compression strain may be due to adding asphalt emulsion, increasing the bonding between soil particles, and recycled concrete aggregate, which reduces soil deformation, making the soil more stable under traffic loads.

When subjected to compressive stress, the emulsion acts as a binder across cracks and stress points, limiting the spread of deformities. This crack control mechanism prevents the formation of large cracks and reduces the risk of sudden failure. Moreover, including emulsion increases the ductility of the soil mixture, allowing it to deform plastically without fracturing. As a result, the stabilized soil mixture exhibits greater resistance to compressive stress, leading to a decrease in compression strain.

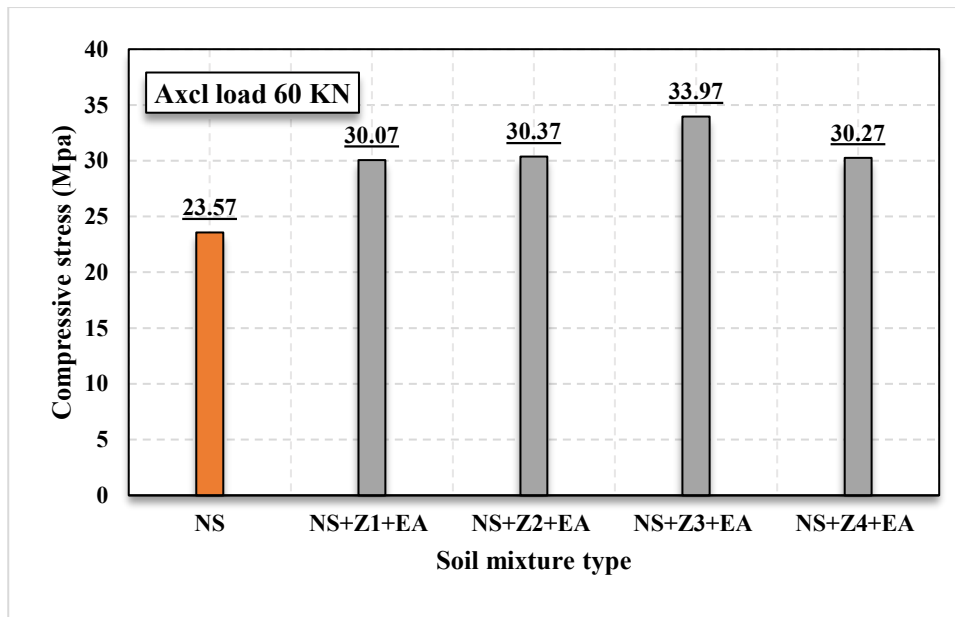


Figure 5-6: Differences in Vertical Compressive Stress for Soil Mixtures with EA.

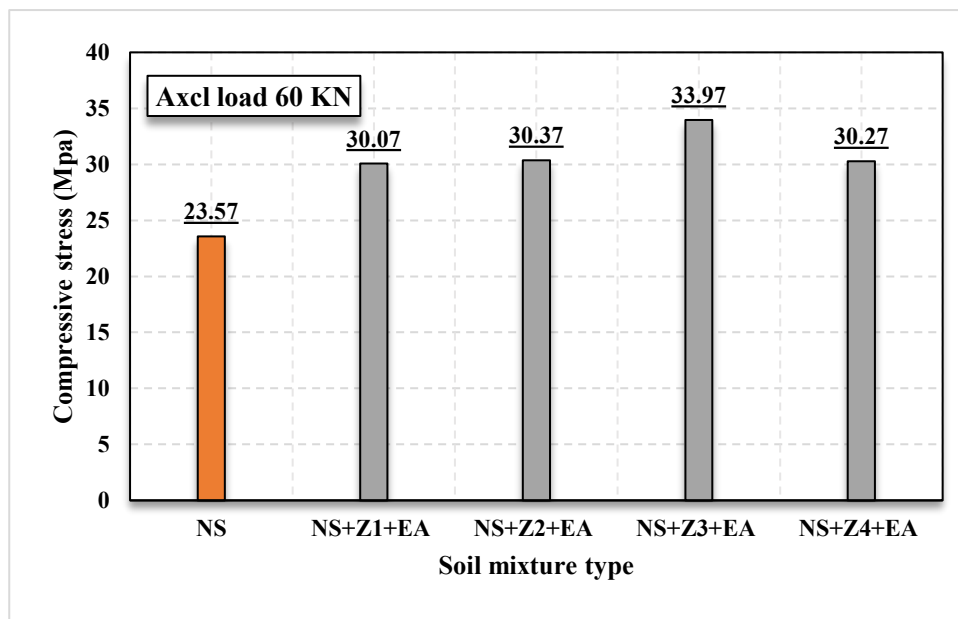


Figure 5-7: Differences in Vertical Compressive Strain for Soil Mixtures with EA.

Figure (5-8) indicates that the maximum load repetitions (N_d) for the natural subgrade sand is $2.02E+08$. This value increased to ($2.19E+08$, $2.73E+08$, $2.90E+08$, and $3.79E+08$) in four grades using 15% recycled concrete aggregate by weight of dry soil, respectively. This can be due to the different gradations of recycled concrete aggregate, which strengthen the soil structure

by increasing the density and cohesion between soil particles. It produces a more compact and stiffer matrix by filling the spaces between soil particles. Reducing the possibility of particle migration and settlement under applied loads enables the soil to endure more load repetitions.

In addition, 2.5% from asphalt emulsion to a soil mixture with 15% recycled concrete aggregate with four zones led to an increase in N_d from $2.02E+08$ to $2.90E+08$, $2.98E+08$, $3.57E+08$, and $2.66E+08$, respectively, as shown in Figure 5-9. The rise in N_d can be attributed to adding asphalt emulsion, which improves the structural load distribution. However, the N_d values for the soil mixture with 2.5% EA are significantly higher than those of natural soil. This is due to the emulsion as a binding material effect, which creates a network within the soil, enhancing its load-bearing capacity and crack control. The asphalt emulsion with recycled concrete aggregate helps distribute stresses more evenly and improves energy absorption. As a result, the presence of EA leads to improved mechanical properties, higher resistance to deformation, and enhanced performance of the material. However, when comparing the results with those of RCA and soil mixture, the researcher finds that they are higher, indicating that adding RCA improved the soil resistance, which led to an increase in N_d values. In addition, RCA improves internal friction and increases the bearing capacity of the soil under applied loads. The reason why the N_d values when adding EA are lower than the N_d values when adding RCA is that the addition of EA improves the cohesion between soil particles (RCA) but may reduce internal friction, leading to a smaller increase in N_d .

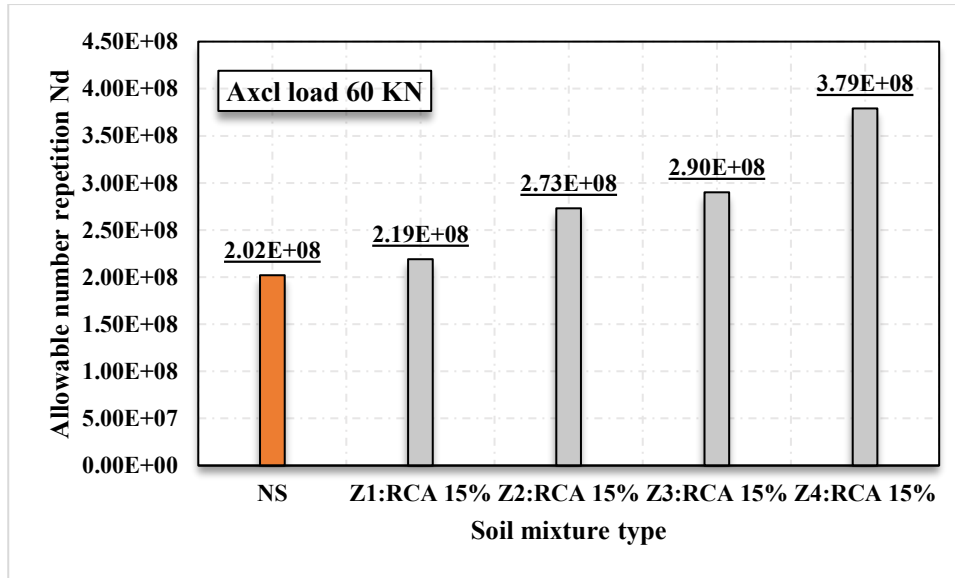


Figure 5-8: Differences in Allowable Number of Repetitions and Predictions for Soil Mixtures.

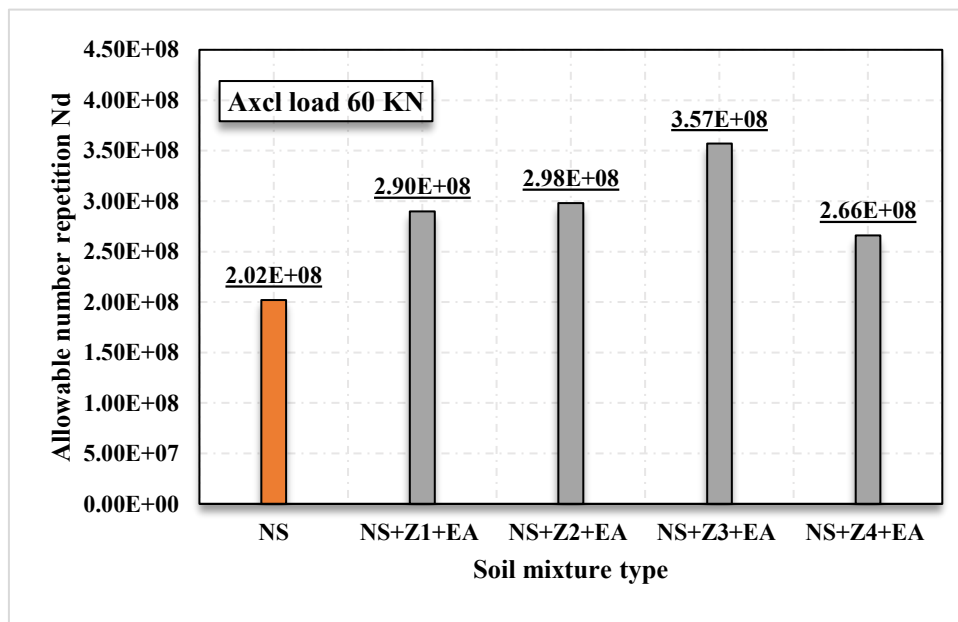


Figure 5-9: Differences in Allowable Number of Repetitions and Predictions for Soil Mixtures with EA.

Figures (5-10) and (5-11) indicate that the addition of 15% recycled concrete aggregate decreased the damage ratio from 4.95E-09 to 4.57E-09, 3.60E-09, 3.45E-09, and 2.64E-09 for each of the four grades and increased the rutting life from 4.04E+09 to 4.38E+09, 5.47E+09, 5.79E+09, and 7.58E+09,

respectively. These improvements when adding recycled concrete aggregate can be attributed to enhanced internal friction, increased load-bearing capacity, and improved stiffness of the soil mixture due to the addition of RCA.

The results also showed that adding 15% RCA to natural soil at different grades significantly improved soil properties, as a decrease in the damage ratio values and an increase in the rutting life values were observed. This decrease in the damage ratio values is attributed to the improved load distribution, as adding RCA increases soil stiffness and reduces the voids between soil particles. This leads to increased internal friction, which reduces deformations. The increase in the rutting life values after adding RCA to the soil indicates that it has become better able to withstand the loads imposed on it.

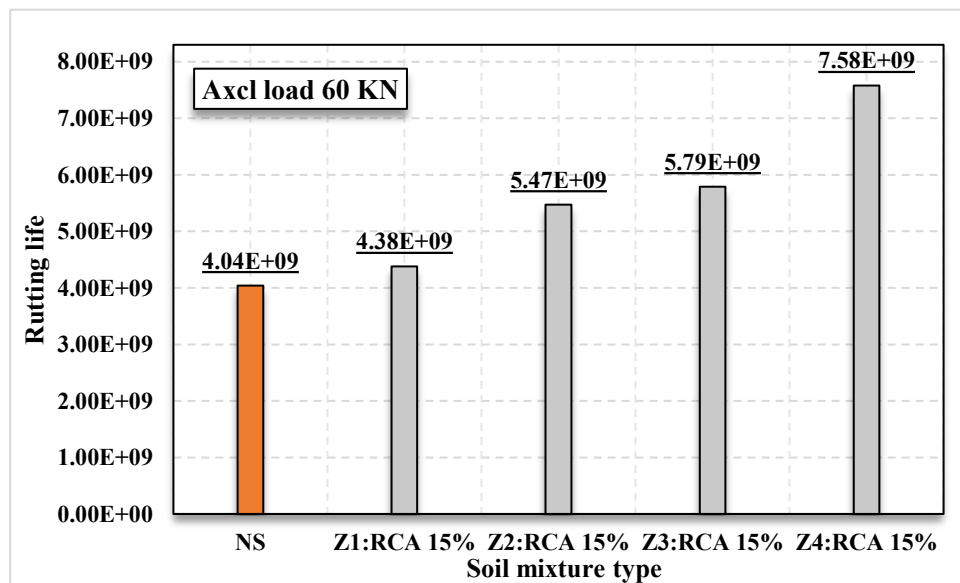


Figure 5-10: Differences in Rutting Life Predicted for Soil Mixture.

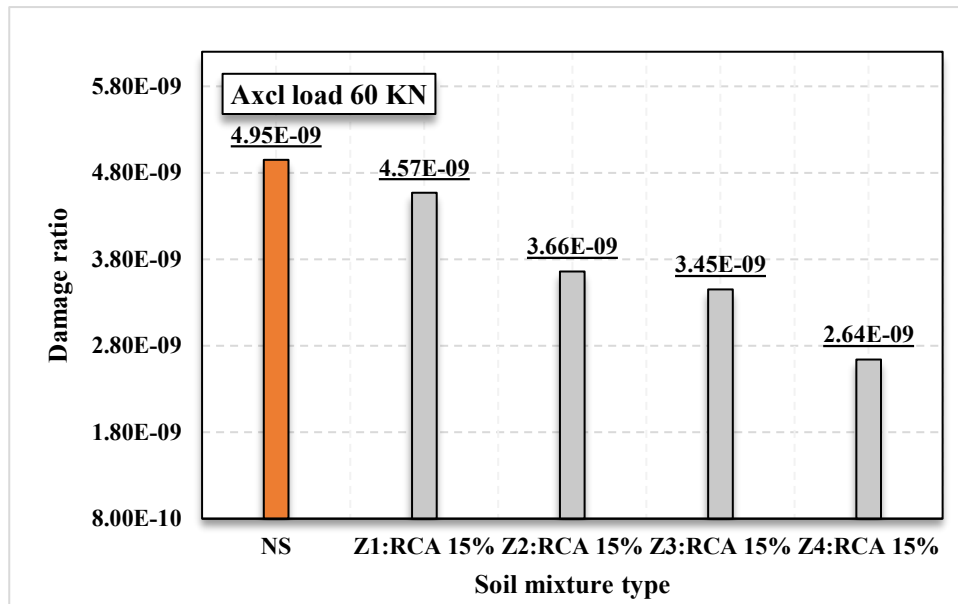


Figure 5-11: Differences in Damage Ratio Predicted for Soil Mixture.

In Figures (5-12) (5-13), when 2.5% asphalt emulsion is added to a soil mixture containing 15% recycled concrete aggregate in four grades by weight of dry sand, the damage ratio gradually decreases from 4.95E-09 to 3.45E-09, 3.66E-9, 2.80E-09, and 3.76E-09. Conversely, the rutting life increased from 4.04E+09 to 5.79E+09, 5.96E+09, 7.13E+09, and 5.31E+09. At the same time, when comparing these findings with natural soil, it becomes evident that there is a notable increase in the damage ratio values and a significant decrease in the rutting life values when incorporating 2.5% asphalt emulsion into the soil mixture with 15% RCA. This highlights the crucial role of EA in enhancing the mechanical properties of the soil.

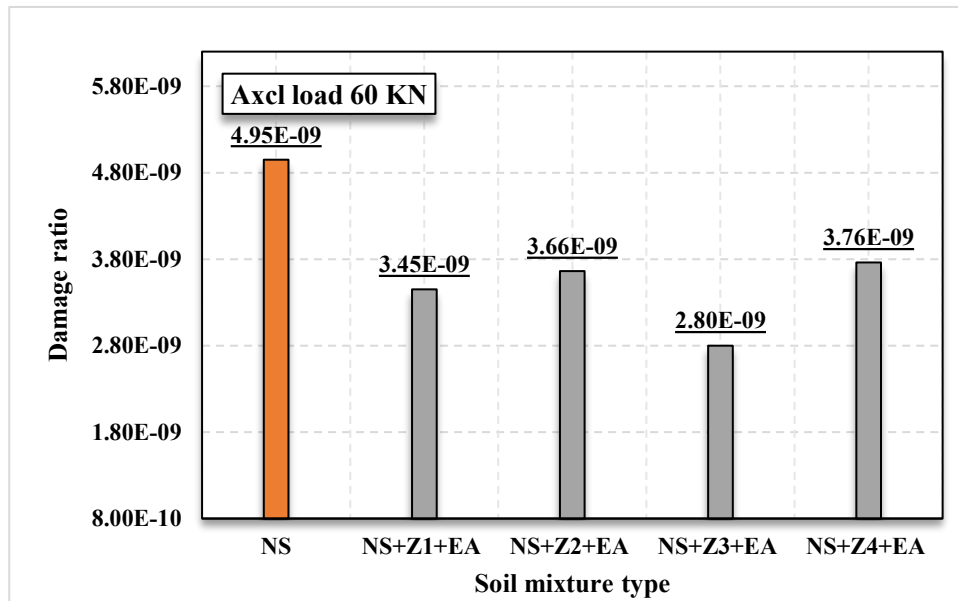


Figure 5-12: Differences in Damage Ratio Predicted for Soil Mixture with EA.

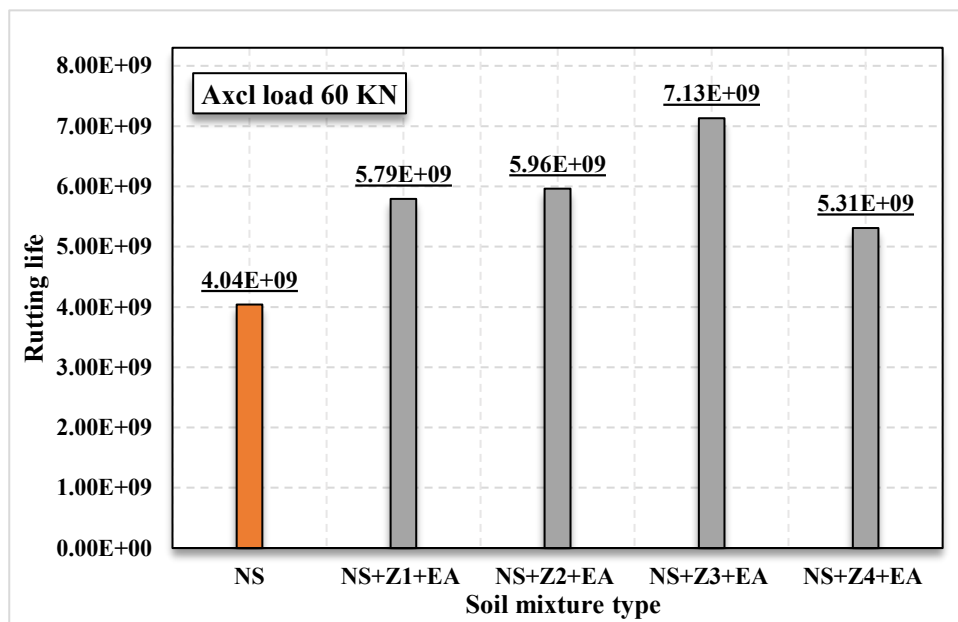


Figure 5-13: Differences in Rutting Life Predicted for Soil Mixture with EA.

5.3. Summary

In this chapter, the theoretical analysis approach was implemented to assess how stabilizing the subgrade soil using recycled concrete aggregate, with or without asphalt emulsion, affects the performance of the pavement indicators under various axle loads. It was found that adding recycled concrete aggregate

and asphalt emulsion to subgrade soil significantly increased rutting life, the allowable number of repetitions (N_d), and compressive stress while decreasing the damage ratio and compressive strain at the top of the subgrade. These enhancements demonstrate how well the stabilization process increases the pavement structure's longevity and performance.

Chapter Six:
Conclusions and Recommendations

Chapter Six**Conclusions and Recommendations****6.1. Introduction**

This study aims to evaluate the efficacy of a hybrid stabilization method for enhancing the strength and stiffness characteristics of the subgrade sands. This was accomplished through laboratory testing to assess the impact of recycled concrete aggregate and asphalt emulsion on the subgrade layer. The research aimed to establish a correlation between these laboratory tests, field tests, and theoretical analyses, which included the sand Cone method (SCM), lightweight deflectometer (LWD), and dynamic cone penetrometer (DCP).

6.2. Conclusions

According to the findings that were obtained from the experimental testing program, the following are the key conclusions:

1. Stabilizing the natural subgrade soil with 5%, 10%, 15%, and 20% RCA by weight of dry soil increased the maximum dry density percentage by approximately 5.13%, 5.63%, 6.15%, and 4.62%, respectively, while the optimum moisture content decreased by 11.0%, 10.75%, 11.45%, and 11.1%, respectively.
2. Increasing the percentage of RCA in the natural soil mixture significantly improves the California Bearing Ratio (CBR) value across all four grades, demonstrating the effectiveness of RCA in enhancing the soil-bearing resistance of the subgrade.
3. The soil-bearing resistance defined by CBR improved significantly at 15% RCA content, which represents the optimum RCA replacement content. The percentage increase in CBR values ranged from 30% to 125% compared to the CBR of natural subgrade soils. The addition of RCA improves CBR values in general, and the improvement is evident in bearing capacity when adding 15% RCA, especially in Grade 4.

4. Incorporating asphalt emulsion at rates of 2.5%, 5%, 7.5%, and 10% into an RCA sand mixture effectively fills the voids between soil particles and RCA, resulting in improved density and strength. This enhancement boosts the performance and durability of stabilized subgrade soils across various construction and pavement applications.
5. The optimal asphalt emulsion content for stabilizing the soil was found to be 2.5% EA with RCA. Beyond this point, a significant decrease in the CBR value was observed, indicating that the soil had reached its saturation point.
6. The DCPI value of the natural subgrade soil generally declines with the incorporation of recycled concrete aggregate, indicating an improvement in soil strength characteristics. Meanwhile, incorporating asphalt emulsion into the RCA-sand mixture leads to a minor decrease in soil penetration resistance.
7. The in-situ CBR value obtained from the DCP test improves by about 30% to 120% when stabilizing natural subgrade soil with 15% recycled concrete aggregate by weight of dry soil.
8. The expected bearing capacity of asphalt emulsion with RCA sand exceeds that projected for natural soil. This results in improved structural performance for diverse infrastructures that can be used in highway and building projects.
9. The natural surface deflection (S_d) values of subgrade soil obtained from LWD tests were reduced when asphalt emulsion and recycled concrete aggregate were added to the natural subgrade soils.
10. Results showed that adding 2.5% asphalt emulsion EA to soil stabilized with RCA resulted in a decrease in DCPI values for grade 4 compared to soil with RCA, indicating increased soil strength.
11. In theoretical analysis, 15% RCA improved the compressive stress by 52.2% and reduced the compressive strain by 14.57%. Adding 2.5%

asphalt emulsion increased the compressive stress by 44.1% and reduced the compressive strain by 13.25%. These results showed an improvement in the structural performance of the pavement system founded on stabilized subgrade soils.

12. The study found that adding 15% RCA to natural soil improved soil properties, reducing damage ratio values, and increasing rutting life values. This was due to improved load distribution, increased soil stiffness, and increased internal friction, reducing deformations. In addition, it reveals that incorporating 2.5% asphalt emulsion into soil mixtures with 15% RCA leads to increased damage ratio values and decreased rutting life values.

6.3. Recommendations

The study shed light on how stabilizing materials affect the strength characteristics of subgrade soil, using recycled concrete aggregate at percentages of 5%, 10%, 15%, and 20% with/without 2.5%, 5%, 7.5%, and 10% asphalt emulsion. The study focused on stabilizing sandy soils; nevertheless, it should be mentioned that the research was limited in scope due to time constraints. To ensure more effective and successful engineering projects, it is necessary to conduct more research on different kinds of soil, stabilizing agents, and different gradations of recycled concrete aggregate. These studies will help produce comprehensive standards for soil stabilization that can be utilized in designing pavement layers.

Some potential future research directions recommended by the conclusions of the study are as follows:

1. It is recommended to select more types of subgrade soils as classified according to the AASHTO classification system to stabilize them using recycled concrete aggregate in different percentages and gradations.

2. The RCA replacement rates of the study were 5%, 10%, 15%, and 20%, respectively. More combinations with varying RCA % at high replacement content should be created.
3. The present research could have concentrated on short-term performance or laboratory assessments. Conducting long-term field experiments to evaluate the durability and performance of stabilized subgrade soil under real traffic and environmental conditions would be advantageous. This would provide information on the enduring efficacy and durability of the stabilizing strategies.
4. Subsequent research can include a thorough cost-benefit analysis of various stabilizing methods. This entails evaluating the initial expenses of materials and construction alongside the long-term maintenance and performance advantages. This study would facilitate decision-making over the most economical and effective soil-stabilizing methods for engineering projects.
5. Using computational finite element modeling, the performance of unbound pavement materials is evaluated, and the stability of recycled concrete aggregate and asphalt emulsion is evaluated.

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الخلاصة:

الطرق هي مكونات اساسي للبنية التحتية، وتلعب دورًا حاسمًا في تدفق حركة المرور وتوفير وسائل نقل فعالة. أحد الجوانب المهمة للطرق هو طبقة التربة الطبيعية أسفل طبقات الطريق (Subgrade)، والتي تعمل بمثابة الأساس. ومع ذلك، نظرًا لأحمال المرور الثقيلة التي تتحملها، يمكن أن تفشل حتى التربة ذات الخصائص الهندسية القوية، مما يؤدي إلى انهيار الطريق بالكامل. ونتيجة لذلك، يسعى الباحثون إلى تحسين خصائص طبقة الأساس من خلال استخدام تقنيات التثبيت الميكانيكية والكيميائية المستخدمة على نطاق واسع. يهدف هذا البحث إلى تقييم فعالية طريقة تثبيت مستدامة وهجينة لتقوية التربة الرملية الضعيفة باستخدام ركام الخرسانة المعاد تدويره ومستحلب الأسفلت. حيث تم تثبيت التربة الرملية بأربع درجات مختلفة من ركام الخرسانة المعاد تدويرها، مقسمة إلى أربع مجاميع (بتدرجات تتراوح بين 19 ملم إلى 0.0075 ملم)، تحتوي كل منها على أربع نسب مئوية: 5% و 10% و 15% و 20% من وزن التربة الجافة. أيضاً تم إضافة مستحلب الأسفلت بأربع نسب: 2.5% و 5% و 7.5% و 10% كمادة مضافة كيميائية. تم إجراء برنامج اختبار لتقييم خصائص التربة الطبيعية والمستقرة على ثلاث مراحل: تضمنت المرحلة الأولى اختبار بروكتور المعدل واختبار نسبة تحمل كاليفورنيا (CBR) أظهرت النتائج المختبرية بأن كثافة وقوة التربة وقدرتها على التحمل قد تحسنت بشكل ملحوظ بعد إضافة بعد إضافة مادة الركام المدور، مع تحسن ملحوظ في الكثافة عند إضافة 15% RCA، وخاصة في المجموعتين 3 و 4، حيث بلغت نسبة التحسن 4.62% و 6.15% على التوالي. تؤدي زيادة نسبة RCA في خليط التربة الطبيعية إلى تحسين قيمة نسبة تحمل كاليفورنيا (CBR) بشكل كبير في جميع المجاميع الأربع، مما يحدد نسبة 15% RCA المثلى، تراوحت نسبة التحسن في قيم CBR من 30% إلى 125%. تضمنت المرحلة الثانية اختبار CBR لخلاطات التربة المستقرة مع RCA والمكملة بـ EA، وكشفت أن قيم CBR انخفضت مع زيادة نسب EA. تضمنت المرحلة الثالثة إجراء ثلاث اختبارات: اختبار استبدال الرمل (SCM) واختبار فحص الهطول الديناميكي خفيف الوزن (LWD) واختبار اختراق المخروط الديناميكي (DCP). تم تثبيت جميع خليط التربة باستخدام RCA و EA، وأظهرت النتائج تحسناً ملحوظاً في معامل الصلابة DCPI، و S_d ، ومعامل المرونة الديناميكي، والكثافة الجافة نتيجةً لاستخدام RCA و EA. وايضا استخدام النتائج المختبرية كمعاملات إدخال في نموذج نظري تم انشاؤه ضمن برنامج KENPAVE لتقييم أداء التربة الطبيعية والمستقرة. حيث اظهرت، النتائج ان استخدام RCA يزيد من الصلابة، والإجهاد الانضغاطي، ويقلل (N_d)، مع تقليل معدل التلف.



جمهورية العراق

وزارة التعليم العالي و البحث العلمي

جامعة كربلاء

كلية الهندسة

قسم الهندسة المدنية

عنوان الرسالة

تقييم فعالية طرق التثبيت الهجين لتحسين تربة الطبقة التحتية بشكل مستدام في نظام الطريق

رسالة مقدمة الى مجلس كلية الهندسة / جامعة كربلاء وهي جزء من متطلبات نيل درجة الماجستير

في علوم الهندسة المدنية

كُتبت بواسطة:

اسراء صلاح هاشم

بإشراف:

ا.م. د. علاء محمد جواد

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