Mechanical Behaviour and Compaction Characteristics of Shredded Expanded Polystyrene Mixed Clayey Soils

By

Muhammad Haseeb

(Registration No: 00000320323)

Department of Geotechnical Engineering

NUST Institute of Civil Engineering (NICE)

School of Civil & Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST), Islamabad, Pakistan

2023

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Muhammad Haseeb

(Registration No:00000320323)

A thesis submitted to the National University of Sciences and Technology, Islamabad, in partial fulfillment of the requirements for the degree of

Master of Science in

Geotechnical Engineering

Thesis Supervisor: Dr. Zain Maqsood

NUST Institute of Civil Engineering (NICE)

School of Civil & Environmental Engineering (SCEE)

National University of Sciences and Technology (NUST)

Islamabad, Pakistan

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Signature: Zain Maqsood

Name of Supervisor Dr. Zain Maqsood

Date: 25-07-2023

Signature (HOD):

HoD Geotechnical Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

Date:

Signature (Associate Dean):

Dr. S. Muhammad Jamil
Associate Dean
NICE, SCEE, NUST

Date:

Signature (Dean/Principal)

PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

Date: 29 AUG 2023

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We hereby recommend that the dissertation prepared under our Supervision by: (Student Name): Muhammad Haseeb (Reg No): 320323

Titled : Mechanical behavior and Compaction Characteristics of Shredded Expanded Polystyrene Mixed Clayey Soils

be accepted in partial fulfillment of the requirements for the award of degree with (B+ Grade).

Examination Committee Members

1. Name: Dr Badee Alshameri — Signature:
2. Name: Dr Abbass Haider — Signature:

Supervisor's name: Dr Zain Maqsood — Signature:

Date: 26-5-2023

HoD Geotechnical Engineering
NUST Institute of Civil Engineering
School of Civil & Environmental Engineering
National University of Sciences and Technology

(Associate Dean)

COUNTERSIGNED

Date: 30 AUG 2023, 2023

Principal & Dean SCEE
PROF DR MUHAMMAD IRFAN
Principal & Dean
SCEE, NUST

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Student Name: Muhammad Haseeb
Signature:___________________________

Examination Committee:

a) GEC Member 1: Dr. Badee Alshameri
   Signature:___________________________
   (Designation & Office Address)
b) GEC Member 2: Dr. Abbas Haider
   Signature:___________________________
   (Designation & Office Address)

Supervisor Name:
Dr. Zain Maqsood Signature: _________________

Name of HOD:
Dr. Badee Alshameri Signature: _________________

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Dr. Syed Muhammad Jamil Signature: _________________

Name of Dean/Principal:
Dr. Muhammad Irfan Signature: _________________

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I, Muhammad Haseeb, hereby declare that my MS dissertation titled **"MECHANICAL BEHAVIOUR AND COMPACTION CHARACTERISTICS OF SHREDDED EXPANDED POLYSTYRENE MIXED CLAYEY SOILS"** is my original work and has never been submitted before by me for taking any degree from this University or anywhere else in the country/ world. At any time if my statement is found to be false even after I graduate, the university has the right to revoke my MS degree.

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DEDICATION

I dedicate this research to my beloved parents and teachers.

ACKNOWLEDGEMENTS

I am grateful to Almighty Allah, the most beneficent and merciful, whose abundant blessings empowered me with the determination and strength to successfully complete this research project. I am indebted with thankfulness and appreciation to all those who assisted in completing my thesis.

I want to begin by extending sincere gratitude to my supervisor, Dr. Zain Maqsood, for his instructions, patience, and persistent help during the study process. His invaluable ideas, insightful feedback, and constant encouragement were essential in helping develop and improve this work. I sincerely thank the members of my research panel, Dr. Badee Alshameri, and Dr. Abbas Haider, for their invaluable input, constructive criticism, and scholarly advice.

I want to convey my heartfelt appreciation to the laboratory staff for allowing me to utilize the laboratory facilities and research resources. The institution's supportive atmosphere enabled my intellectual development and the completion of my research. I am indebted to the volunteers who kindly gave their time and expertise for the study. Sharing willingness to share their knowledge and experiences has improved my research and allowed me to reach useful findings. I value their efforts very much.

ABSTRACT

One of the emerging problems of the modern day is the safe disposal of expanded polystyrene (EPS) waste and its successful recycling of it. The engineering properties of mixing coarse-grained non-plastic soils with various EPS waste types to create lightweight fill materials have been the focus of various studies in recent decades. However, limited research work has been done on the deformation and strength response of fine-grained clayey soils combined with EPS waste, and it is still unknown how soil plasticity affects this reaction. In this work, the experimental analysis of three different kinds of fine-grained soils mixed with shredded EPS waste, ranging from 0.5% to 3.0% shredded EPS content, was done to determine the compaction properties, strength, and consistency limits. As a result of the incorporation of shredded EPS, the maximum unit weight of all three types of clayey soils was significantly reduced, resulting in the development of lightweight fills. The findings of direct shear testing showed that as the percentage of shredded EPS increased, there was an improvement in the frictional strength and a drop in cohesiveness. Unconfined compressive strength (UCS) seemed to enhance initially as shredded EPS content increased and to decrease subsequently when shredded EPS proportion increased further. The plasticity indices of the shredded-EPS mixtures were observed to be much lower than those of the untreated clays, and the workability of the shredded-EPS mixed clayey soils also improved.

Finally, a framework based on the ideal shredded EPS content is suggested, which offers optimized strength at the lowest unit weight for the three different clayey soils.

Keywords: Shredded-EPS, compaction, shear behavior, unconfined compressive strength.

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
USCS	Unified Soil Classification System
ASTM	American Society for Testing and Materials
MDD	Maximum Dry Density
OMC	Optimum Moisture Content
UCS	Unconfined Compressive Strength
$(UCS)_n$	Normalized Unconfined Compressive Strength
EPS	Expanded Polystyrene
PI	Plasticity Index
LL	Liquid Limit
PL	Plastic Limit
LP	Low Plastic Clay
MP	Medium Plastic Clay
HP	High Plastic Clay

CHAPTER 1 INTRODUCTION

1.1 Background

Improving the engineering performance of in-situ soils is a well-established technique within the field of geotechnical engineering. For deep in-situ placements or shallow fills, mixing soils with cementitious or other pozzolanic substances like fly ash, slag, silica fume or lime is a popular practice to increase the performance of soil. A transformed soil's decreased compressibility can also enhance the structural performance of engineering fills by decreasing the settlement tendency of deposits. Geotechnical engineers have effectively used various readily available materials such as crushed glass, shredded tires, and ground granulated blast furnace glass to alter the behavior of soil [1]–[3].

Over the past thirty years, the expanded polystyrene geofoam has been utilized in various geotechnical applications for various purposes, i.e., compressible inclusions, lightweight fill, and thermal barriers. There are some situations where it would be preferable to combine EPS particles with soils instead of installing huge pieces in the subsurface. Modified soils consisting of EPS particles mixed with typical fill materials could show advantageous mechanical and physical properties.

Clayey soils are extensively and frequently used in building materials. Due to their high compressibility, poor strength, and lower drainage characteristics, these soils pose challenges. Researchers and engineers have investigated a variety of stabilization approaches by applying additives to improve the engineering characteristics of clayey soils [4]–[7].

Expanded polystyrene, also known as Styrofoam, is a lightweight, cellular plastic matter that is used in insulation and packaging. However, its disposal poses a considerable environmental challenge due to its non-biodegradable nature. Incorporating shredded EPS waste into soil materials has evolved as a solution to handle EPS waste and transform the properties of clayey soils. Expanded polystyrene (EPS), a potential additive that is produced from waste foam packaging materials, has attracted interest. EPS is lightweight, rigid, and has efficient insulating characteristics. Due to its potential to enhance soil compaction and mechanical response, researchers have investigated its capacity as a stabilizer for clayey soils.

The mechanical behavior of the shredded EPS mixed clayey soils is defined as the response of the composite material under different load cases and environmental situations [8]. The mechanical behavior of clayey soils mixed with shredded EPS is an essential aspect of this research. The impacts of various EPS proportions on the strength, stiffness, and deformation characteristics of soil have been evaluated in various research works. The mechanical properties of the soil, such as shear strength, load-bearing potential, and settlement behavior, are transformed by the addition of EPS particles. To assess the mechanical behavior of the EPS particles mixed with clayey soils, researchers have conducted laboratory studies such as direct shear testing, unconfined compression tests, and triaxial tests. These tests measure parameters such as shear strength, stress-strain relationships, and deformation properties to develop an understanding of how the incorporation of EPS affects the soil's response to external forces.

Another essential component of the study is the features of how shredded EPS mixes with clayey soils. Compaction is the process that aims to enhance soil strength, decrease voids, and improve soil density. Researchers have studied the impacts of EPS content, compaction energy, and moisture content on the compacted characteristics of the soil-EPS mixes. Compaction tests, including the standard and modified Proctor tests, have been applied in studies to assess the compaction properties of EPS-clayey soil combinations. To assess the effect of the shredded EPS on the compaction method and ensure soil improvements, these tests take measurements of variables including the maximum dry unit weight, the optimum moisture, and compaction characteristics [9], [10].

The research offers insights into the mechanical response and compaction characteristics of shredded EPS mixed with clayey soils. Understanding how EPS influences soil strength, stiffness, and deformation response is critical for assessing its feasibility as a stabilizing agent. Determining the compaction characteristics assists in predicting optimal EPS content and compaction conditions for attaining desired soil properties.

The incorporation of shredded EPS into clayey soils can have several potential benefits. The lightweight nature of EPS assists in decreasing the overall unit weight of the composite material, which can be advantageous in applications where unit weight reduction is required, such as lightweight fill material for embankments, bridge abutments, retaining walls, and slopes. The EPS particles also introduce voids within the soil structure, enhancing its drainage properties and minimizing the potential for pore water pressure build-up.

The research findings have significant implications for geotechnical engineering applications and construction practices. If the mechanical behavior and compaction characteristics of shredded EPS mixed with clayey soils are favorable, it might provide an environmentally friendly and cost-effective solution for enhancing the engineering characteristics of clayey soils. Additionally, utilizing EPS waste materials as a stabilizing agent aligns with sustainable waste management practices and contributes to environmental sustainability.

1.2 Significance of Research

Since the enlightenment, man has brought a tremendous revolution in the field of science that improved the living standards of people worldwide. Though it brought the man to new heights of success regarding industrialization, it caused damage to the environment and several habitats. It produced so many non-decomposing waste materials, engineering waste soil, sludge, etc. These all-waste products must be dumped somewhere, and it wastes a lot of land. This situation becomes intense when land is scarce due to urbanization and the rising population, and there is not enough space to stack all the waste material [11]. The annual dredging amount is more than one billion m^3 in China alone [12]. Therefore, waste materials ought to be utilized in more effective ways by fulfilling the demands without compromising economic and environmental needs.

In recent times, the usage of lightweight materials in construction and geotechnical applications has gained importance worldwide [13], [14] Because of the inherent engineering characteristics of the material and the unavailability of landfill areas, low-quality and recycled materials are acceptable in construction markets. The development of improved engineering materials with optimized properties has the potential to improve the sustainability of multiple projects [15].

Expanded polystyrene (EPS) is a lightweight matter generally used as a packing and transporting material for consumer and electronic appliances. It is excessively used in the market due to low price and convenience in handling which is in turn increasing the amount of EPS waste product [16]. EPS in a nonbiodegradable or decomposable material [8]. It is a lightweight material that requires a substantial amount of land for its stacking and therefore it consumes immense landfill area [17]. The European Union has thus banned its dumping and made its recycling mandatory. There are several recycling approaches like compression and thermal procedures but contamination of products while transportation and restricted availability of recycling equipment render consumers to find an innovative option for bulk utilization of EPS waste products.

The study of mechanical behavior and compaction characteristics of shredded expanded polystyrene (EPS) mixed with clayey soils is important for various engineering applications. It includes assessing the impacts of incorporating shredded EPS, which is a lightweight material, into clayey soils, which are generally cohesive. The composition of these two materials can have considerable impacts on the mechanical properties and compaction response. By analyzing the correlations between the percentage of EPS, compaction characteristics, and resulting mechanical properties, optimization of the mixture is done to attain the desired engineering performance. This knowledge enables effective design and construction approaches, resulting in cost-effective and optimized project outcomes.

The effective utilization of shredded EPS in clayey soils can have environmental gains. EPS is a recyclable matter and using it in soil decreases its need for conventional fill materials like gravel or sand [18]. This assists in the conservation of finite natural resources and reduces the requirements for energy-extensive activities such as excavation and transportation, which can have a high amount of carbon footprint. Furthermore, reusing EPS waste in this way can assist in handling the disposal of EPS materials and preventing them from ending up in landfills.

1.3 Problem Statement

Clayey soils are generally famous for their poor engineering characteristics, such as low volume change, low shear strength, and excessive settlement. These characteristics make unsuitable poor clayey soils challenging to utilize effectively in various construction projects, including building foundations, road embankments, and slope stabilization. In recent years, researchers have investigated different techniques to increase the engineering characteristics of clayey soils.

One such practice is to use effectively, EPS a lightweight and thermoplastic material, in clayey soils. EPS material is generally known for its low density, thermal insulation properties, and high compressive strength, and is generally used in the packaging industry. The problem statement emphasizes the mechanical and compaction responses of clayey soils when mixed with shredded Expanded Polystyrene (EPS). Considering its possibility of being utilized in several areas of civil engineering, the incorporation of EPS with clayey soils has attracted substantial attention in geotechnical engineering. Developing sustainable methods of construction necessitates an understanding of the mechanical and compaction behavior of this combination.

Studying the mechanical and compaction behavior of shredded EPS mixed with clayey soils is the primary purpose of this work. Following are the specific study questions that must be answered:

1. How do the mechanical properties of clayey soils vary when shredded EPS is added?

2. Considering the research outcomes of the extensive laboratory research program, what percentage of shredded EPS is optimum for enhancing mechanical behavior?

3. How do the compaction properties of clayey soils affect when shredded EPS is present?

4. Can the stability and bearing capacity of clayey soils be improved by the addition of shredded EPS?

5. Do shredded EPS-improved soils show variations in engineering soil properties that would be beneficial in specific design frameworks?

6. What effects does utilizing shredded EPS in clayey soil mixtures have on the environment?

The concept of effectively using shredded EPS to improve soils is generated from the demand to develop composite soil mix that gives enhanced engineering performance. Enhanced engineering performance is referred to in this research study as manifesting decreased unit weight without considerable loss of material strength and stiffness.

The plasticity index is the most important factor in the strength characteristics and classification of soil. Soil with a higher plasticity index becomes problematic due to the high potential of volume changes and reduction in strength characteristics. Previous researchers evaluated the impact of EPS beads and Geofoam on specific types of clayey soils, but field conditions witness soils with variable plasticity. The effect of shredded EPS on soils of different plasticity indices and corresponding variation in engineering properties of soil is yet to be explored. This contributes to further research on the impacts of shredded EPS on the engineering characteristics of different plasticity soils. Such an approach will help the stakeholders to overcome the environmental issues related to the adverse effects of solid waste management, as illustrated in Fig. 1.1.

Figure 1.1 Conventional Solid Waste Management [19]

1.4 Aims and Objectives

The key purpose is to understand how the incorporation of shredded EPS transforms the mechanical properties of clayey soils. This includes evaluating various parameters such as unit weight, moisture content, strength, stiffness, deformation, and shear resistance. By evaluating these parameters, the potential benefits of using EPS as a soil stabilizer have been concluded. The characterization of engineering parameters for the altered soils was quantified by conducting classification, shear strength, compression, and compaction tests.

One of the objectives is to evaluate the optimum limit at which the incorporation of EPS can increase the engineering characteristics of clayey soils. EPS is known for its lightweight and insulating characteristics and incorporating it into the soil can potentially reduce settlement, improve bearing capacity, and increase overall stability. This study aims to quantify these improvements and provide concepts related to the mechanisms behind them.

The goals also incorporate the sustainability and environmental implications of adding shredded EPS into the clayey soils. EPS is a non-biodegradable material, and its disposal poses environmental challenges. By reusing the EPS in the soil improvement technique, researchers aim to explore a potentially sustainable and cost-effective solution for mitigating waste and environmental impact.

The study seeks to assess the feasibility and practicality of using shredded EPS in geotechnical engineering applications. This includes evaluating the compatibility of shredded EPS with clayey soil and assessing the performance of composite material. The goal is to provide guidance and recommendations for engineers and practitioners considering the application of shredded EPS in soil improvement construction projects.

The following are the main objectives of the research study:

- To evaluate the compaction behavior of shredded EPS mixed clays of different plasticity.
- To determine the deformation and strength parameters of different proportions of shredded EPS mixed in clays.

- To discuss the role of plasticity in shredded EPS mixed clayey soils by proposing correlations between PI and different mechanical properties
- To provide recommendations for the effective use of shredded EPS mixed clayey soils as lightweight engineering fill for geotechnical applications.

The goals and objectives of studying the mechanical behavior and compaction characteristics of shredded EPS mixed with clayey soils incorporate understanding the potential benefits, limitations, and practical considerations of utilizing this composite material in geotechnical engineering applications.

1.5 Research Scope

Expanded polystyrene (EPS) plays a critical role in the stability of various constructions. They can be utilized in road embankments over soft soils, backfill of retaining walls, reduction of subgrade settlement, and slope stabilization. The scope of the study for this experimental investigation is to optimize the weight and strength of the soil by adding shredded EPS. The desired value of strength and unit weight will be opted in the field as per requirements.

EPS waste is produced in large quantities throughout the world. This waste can be used effectively as a lightweight engineered fill instead of polluting the environment by burning the waste, as this practice of burning a waste product is followed in many rural areas of Pakistan. Moreover, this research will also fulfill the Sustainable Development Goals as the waste will be utilized in the preparation of lightweight engineered fill which shall meet the engineering goals.

Pakistan is in the race to accomplish the sustainable development goals to have a place in the league of upper-middle-class countries by the end of 2030. One of the goals envisaged is reducing waste generation through prevention, recycling, or reusing techniques. Current research is to reuse the EPS waste in the shredded form to make lightweight soil which will help in waste utilization and fulfilling the geotechnical applications altogether. Most of the near-surface soils in Pakistan, especially in the Islamabad region, are clayey soils. Therefore, the impact of shredded EPS on the mechanical properties of various clays having different plasticity indices is considered in the research work.

In short, the scope of the study for the mechanical response and compaction characteristics of shredded EPS mixed clayey soils includes assessing the characteristics, mixing and compaction practices, mechanical response analysis, stabilization effects, and environmental considerations of the composite materials. The findings of such a study can give invaluable concepts related to the feasibility and performance of using shredded EPS as a soil stabilization practice, with potential applications in construction, geotechnical engineering, and sustainable waste management.

1.6 Areas of Application:

Geotechnical engineers need to understand the mechanical behavior and compaction characteristics of clayey soils incorporated with shredded expanded polystyrene (EPS). This knowledge is useful in determining the strength, stability, and settlement of soil structures such as embankments, slopes, dams, and foundations [20]. It enables engineers to make decisions on the design and construction of these buildings with knowledge, providing their stability and safety. In building projects, the use of shredded EPS blended with clayey soils may be advantageous. The selection and application of these composite materials help in optimizing various applications, such as lightweight fill, backfill matter, and a replacement for traditional soil materials, by understanding mechanical behavior and compaction characteristics. Knowing how these mixes behave helps to guarantee that construction projects are economical, effective, and environmentally friendly [21]. After being initially used, shredded EPS is frequently dumped as garbage. Shredded EPS may be used as a building material by mixing it with clayey soils, lowering the quantity of waste dumped in landfills. Reusing waste materials, implementing sustainable waste management strategies, and supporting the circular economy are made easier by having a proper comprehension of the mechanical response and compaction properties of these mixes [22]. Different applications of EPS are illustrated in Fig. 1.2.

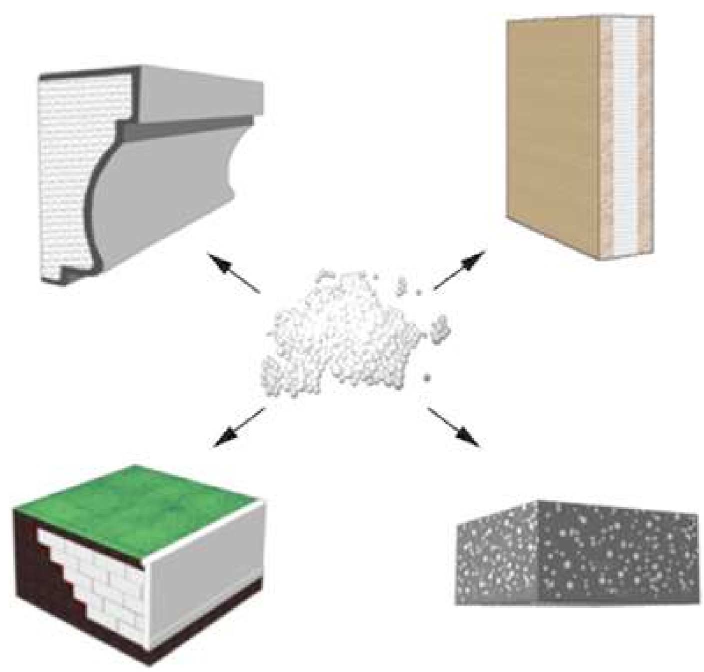

Figure 1.2 Uses of Expanded Polystyrene (EPS) [23]

Clayey soil often exhibits poor engineering properties, such as poor strength and high compressibility. By incorporating shredded EPS into clayey soils, their mechanical behavior can be improved. Understanding compaction characteristics makes it easier to choose the best combination ratios and compaction techniques to increase the stability and strength of the soil. This can be utilized to improve road subgrades, embankments, and other earthen retaining structures. The use of shredded EPS mixed with clayey soils can have environmental benefits. The usage of shredded EPS combined with clayey soils can be advantageous for the environment. It minimizes the requirement for disposal in landfills and reduces the demand for natural resources by incorporating waste materials into the soil. Additionally, the lightweight characteristics of EPS could reduce the soil's overall weight, which may benefit transportation, energy use, and carbon emissions related to building projects [18], [24].

1.7 Research Approach

The research approach adopted to comprehensively examine the compaction behavior and strength characteristics of Shredded-EPS mixed clayey soils is illustrated in Figure 1.3. The overall approach has been split into three different sections, and the first stages of the present studies involve the selection of appropriate materials, including three types of clays having different plasticity and Shredded-EPS. By mixing Shredded-EPS at different proportions with different clays, three different types of lightweight shredded-EPS mixed clayey soils were prepared.

In Phase-II, the Shredded-EPS mixed clayey soils were first subjected to standard proctor tests, and the results with compared with those of the respective untreated soils to evaluate the effects of PI and Shredded-EPS content on the compaction behavior of such lightweight mixtures. A similar approach has also been adopted to assess the strength characteristics of these shredded-EPS mixed clayey soils using unconfined compression tests and direct shear tests.

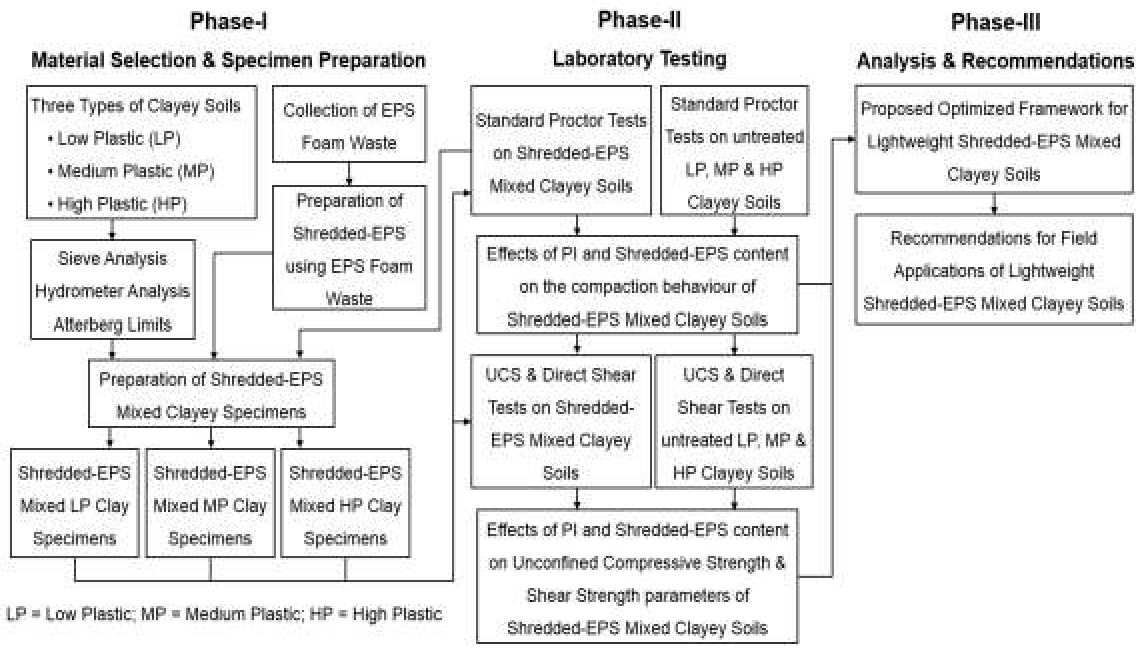

Figure 1.3 Research Framework of the present study.

An optimized framework has been suggested taking into consideration the relationship between strengths, unit weights, and the amount of shredded EPS present in shredded EPS mixed clayey soils based on the outcomes from the second phase of this work. Finally, suggestions for the field uses of mixed clayey soils with shredded EPS have been made. Table 1.1 lists all the tests that were performed for this study. Complete compliance with the applicable ASTM standards was ensured at all stages.

Table 1.1 Summary of Laboratory Tests

Sr. No.	Test	Standards	Parameters determined
1	Sieve Analysis	ASTM D 421	Gravel content [%] Sand content [%] Fines content [%]
2	Hydrometer Analysis	ASTM D 7928	Clay content, C [%] Silt content, M [%]

3	Atterberg Limits	ASTM D 4318	Liquid Limit, LL [%] Plastic Limit, PL [%] Plasticity Index, PI [%]
4	Standard Proctor	ASTM D 698	Maximum dry density, MDD [g/cm^3] Optimum moisture content, OMC [%]
5	Unconfined Compression	ASTM D 2166	Unconfined compression strength, UCS [kPa] Undrained shear strength, s_u [kPa]
6	Direct Shear	ASTM D 3080	Cohesion, c [kPa] Friction angle, φ [°]

1.9 Thesis Layout

The research dissertation has been organized into five chapters.

Chapter 1 **Introduction** discusses the context and significance of the research topic. This chapter illustrates the research objectives and research questions related to the research study. This chapter also incorporates the significance of the research study. This also demonstrates the areas of applications and research scope in the geotechnical domain. The overview of the thesis layout has been presented at the end of this chapter.

Chapter 2 **Literature Review** discusses a review of previous research works on clayey soils and their mechanical behavior. This includes the review of studies related to the usage of shredded expanded polystyrene (EPS) in soil improvement. This also incorporates the applications of EPS in the geotechnical engineering and construction industry. This also includes the discussion of relevant literature related to soil mechanics and compaction characteristics

Chapter 3 **Experimental Details** includes the details of the experimental setup and testing procedures. This also explains the selection criteria for soil samples and EPS material. This includes details of laboratory tests conducted, including compaction tests, shear strength tests, and other relevant tests.

Chapter 4 **Results and Discussion** includes the analysis of the results from laboratory tests. And presents the discussion of the impact of shredded EPS on the mechanical response of clayey soils, including changes in soil strength, deformation characteristics, and stress-strain response. This includes a summary of the key findings from the experimental investigations. This presents the interpretation of the results from the perspectives of the research objectives and research questions. This illustrates the implications and field applications of these findings

Chapter 5 **Conclusions and Future Recommendations** discussion of potential future research directions and recommendations for further experimentation. This includes final remarks and concluding thoughts.

CHAPTER 2 LITERATURE REVIEW

2.1 Overview of Clayey Soils

Clayey particles, which are microscopic mineral particles with diameters less than 2 micrometers, make up most of the components of clayey soils. These soils show unique characteristics due to their plasticity and fine particle size. The samples of clayey soils have been classified into three categories such as low plastic soil, medium-plastic soil, and high-plastic soil. The preparation of the soil specimens mixed with shredded EPS has been shown in Figure 2.1.

2.1.1 Low Plastic Soil

In comparison to high-plastic soils, low-plastic soils often have a wider particle size distribution. They have a smaller percentage of fine-grained particles like clay-sized or clay and a larger proportion of larger particles like silt. The presence of bigger particles affects the soil's permeability, shear strength, and compressibility, among other qualities [25].

Cohesive strength is often lower in low-plastic soils compared to high-plastic soils. The cohesive forces inside the soil matrix are lessened when there are not any fine-grained particles present, notably clay. In general, low-plastic soils are less compressible than high-plastic soils. A soil matrix is less compressible when bigger particles and less clay are present [26]. Low plasticity soils have less settlement under applied stresses, which makes them appropriate for bearing structural loads. Compared to high-plastic soils, low-plastic soils often exhibit less swelling and shrinking. Due to the availability of clay minerals in soil samples, which can vary in volume in response to variations in water content, swelling, and shrinkage phenomena happen. Low-plastic soils have less volume change with changes in moisture conditions because they contain less clay [27].

2.1.2 Medium Plastic Soil

The consistency of medium plastic soil is its defining characteristic. When damp, it maintains its form and is easily moldable. When dried, it is not very sticky or solid, though. Medium-plastic soil is suitable for many buildings and engineering applications due to its consistency. Moist soil with medium plasticity retains some moisture. It can hold onto the water without being too saturated [28]. This characteristic is crucial for keeping the soil's stability and workability in balance. Cohesion, or the soil's capacity to stick together, is moderate in medium plastic soil. The soil's clay minerals have a significant role in maintaining cohesion. The load-carrying capacity and stability of medium plastic soil are affected by its moderately cohesive characteristics. The capacity of the soil to be compressed underweight is referred to as moderate compressibility for medium plastic soil [29]. The soil's particles may reorganize and rearrange themselves under pressure, resulting in a decrease in volume [30]. When anticipating settlement and structural deformation, this feature is important in geotechnical engineering.

2.1.3 High Plastic Soil

Due to the high percentage of clay, highly plastic soil, also known as highly cohesive soil, shows unique characteristics. It is characterized by its capacity to hold onto water and experience large volume and consistency variations in response to external forces. The high clay fraction offers the soil its plastic and cohesive response. High-plasticity soils may be easily molded and shaped while wet, making them very flexible

[31]. The clay particles attract each other when the water is introduced, creating a strong cohesive mass. The tendency of high-plastic soil to experience considerable variations in volume as the moisture content changes is one of its unique characteristics [32], [33]. When the soil dries, it shrinks, reducing its volume and creating fractures in the process. On the contrary, the volume of the soil is enhanced when it absorbs moisture. This soil's tendency to shrink and swell might cause problems in construction and detrimental effects on the integrity of the structure built on such soils [34], [35].

2.2 Description of Expanded Polystyrene Foam

Due to its exceptional insulating qualities, durability, and adaptability, expanded polystyrene (EPS), a lightweight, rigid plastic foam material, is frequently utilized in a variety of applications. Styrene monomers are joined to create a long-chain polymer during a procedure known as polymerization, which is how EPS is created. Through a molding procedure, polystyrene beads comprising a blowing agent—typically pentane—are expanded to form EPS. Polystyrene pellet production is the first phase in the production of EPS. Styrene, a monomer derived from petroleum, is polymerized into a solid resin to create these pellets. The resin is subsequently extruded and granulated or crushed into tiny beads, which are used as the starting ingredient to make EPS [36].

The polystyrene beads are subjected to heat in a mold after being mixed with a blowing agent to make EPS. The expanding and vaporizing of the blowing agent enable the beads to swell and unite with one another to create a closed-cell foam shape. Pre-expansion is the term for this action. The expanded beads, or "pre-expanded" EPS, are then sent to a second-phase expansion procedure, where they are expanded further and shaped into sizeable blocks, sheets, or forms [37].

The expanded polystyrene sheets or blocks may be customized with hot wires, saws, or other cutting tools in a variety of sizes and forms. Construction, packing, insulation, and other manufacturing industries all utilize these EPS materials extensively. In the construction sector, EPS is frequently used as wall, floor, and roof insulation material. Due to its exceptional thermal insulation performance, buildings may use less energy and transmit less heat. EPS insulation is available as rigid panels, boards, or custom-molded forms that are made to meet a particular purpose [38]. Because it is lightweight, shock-absorbing, and has protective qualities, EPS is also widely utilized in packaging. It is frequently used as protective packing material for fragile goods including glassware, electronics, and appliances.

To provide the secure fit and cushioning effect needed for the safe transport and handling of products, EPS packaging may be molded into a variety of forms. Additionally, EPS finds effective utilization in the automotive sector, where it is used in the production of lightweight automobile parts including bumpers, seat cushions, and interior trim. Its lightweight ability contributes to increased fuel economy and lighter vehicles. Discussions have been had regarding EPS's effect on the environment. EPS is recyclable despite not degrading naturally [39]. Many recycling facilities accept EPS waste, which can be compressed, recycled, and made into new EPS products or other plastic materials. In addition to looking into more sustainable alternatives, efforts are being made to encourage the recycling of EPS for similar applications. In buildings, refrigeration systems, and cold storage facilities, EPS efficiently restricts heat transfer and offers efficient insulation because of its low coefficient of thermal conductivity. By contributing to maintaining a constant interior temperature, EPS insulation can lower the quantity of energy required for cooling and heating.

Despite all its benefits, EPS has certain environmental drawbacks. It is not biodegradable and can last a very long period in the environment. Pollution and litter can result from the improper disposal of EPS waste, such as indiscriminate dumping or cremation. Nevertheless, EPS is recyclable, and a lot of recycling facilities now accept EPS goods to be turned into new materials [40]. Expanded Polystyrene (EPS) is a highly recommended substance for a variety of engineering applications due to its lightweight nature, thermal insulation abilities, mechanical strength, and resistance to moisture and chemicals [41]. The shredded EPS material has been shown in Fig. 2.1.

Figure 2.1 Shredded EPS prepared in Laboratory

2.3 EPS Beads in Construction Practices

It has been found that utilizing recycled EPS beads as a substitute admixture in expansive soils reduces the risk potential of swelling and shrinkage phenomena [42], [43].

If no chemical stabilizer is used, EPS beads are added to the soil at the optimum moisture level and mixed until a homogeneous and consistent mixture is achieved to achieve maximum strength. Due to their elastic characteristics, EPS beads (shown in Fig. 2.2) can still affect swelling and shrinkage potential even after being squeezed during compaction [44]. The air inside the bead increases pressure while volume decreases during compression to maintain load equilibrium. The air void expands when the load is released. When there is the possibility of differential settlements, EPS mixes may be utilized to backfill behind retaining walls, fill at the shoulders of pavements, and fill underneath concrete slabs. This method is best suited if swelling and settlement are anticipated. EPS-bead mixtures are utilized in landfill cover systems [45]. The primary advantage of using EPS is the substantial decrease in the dry unit of the composite that is created for the same moisture content [46].

As a result, it performs effectively as a light backfill material. Additionally, because composite is expected to create less lateral stress on retaining walls, this reduction in dry density is particularly significant in retaining walls. The retaining wall can then be made thinner as a result [47], [48].

Figure 2.2 EPS Bead [49]

For embankments constructed on poor soils, the low value of the compacted dry unit weight of EPS-soil combinations may significantly improve stability. Because they have better thermal properties than other soils, recycled EPS beads may help decrease the penetration of frost. In pavements, equilibrium conditions concerning the moisture level will eventually be achieved. The pavement shoulders inevitably experience differential swelling and shrinkage because of exposure to the weather, which can be periodic. In this case, the movements can be controlled if soil mixed with EPS beads is utilized for the shoulder [43], [46], [50].

Keeping the two objectives in consideration, the disposal of polystyrene waste from a sustainability perspective and the substitution of aggregate from the perspective of the construction sector. It investigated how well polystyrene beads might be used as coarse aggregate. The behavior of the polystyrene aggregate was investigated through a comparison of strength characteristics with traditional concrete. The tensile, compressive, and shear strength of concrete decreases as the proportion of EPS beads in the mix of concrete increases. Without a specific bonding agent, all EPS concrete exhibits high workability and is simple to compact and finish. Workability improves when the EPS beads percentage rises. The usage of EPS as a replacement for other materials has demonstrated a favorable use in the construction of nonstructural elements, and it also provides an alternative way of EPS disposal [51], [52].

Sustainable building methods are in complying with the addition of EPS beads in concrete. Because EPS is recyclable, using it in construction practices decreases the requirement for conventional construction building materials, which are finite resources. Furthermore, EPS the material's small weight reduces transportation costs and resulting carbon emissions. Reviews of the literature highlight how effective utilization of EPS in construction engineering is good for the environment, making it a desirable material for green building initiatives [45], [52].

2.4 Applications of Geofoam in Geotechnical Engineering

Expanded polystyrene has already been considered a recognized application in construction engineering practices because of its excellent thermal capacity, acoustic insulation, and ability to absorb shocks and settlements. This material, known as geofoam in geotechnical engineering, is manufactured in prismatic blocks and possesses qualities that enable it to be used in a variety of applications [53].

In the geotechnical design of pavements and embankments, the issues of excessive long-term settlement and poor bearing capacity associated with extremely compressible and weak soils are extensively recognized and extensively documented in the literature [53]–[56]. Engineers adopt a range of solutions to address these problems; the common one is to replace lighter fill materials with heavier soils to decrease the weight of the construction materials. EPS geofoam is a synthetic fill matter that is now being utilized and is extremely lightweight [57].

Because of its low unit weight and larger mechanical strength, EPS geofoam has an extensive range of applications in areas such as a base and sub-base for road pavements, bridge seats, thermal insulation, and compressible inclusion to reduce pressure on walls and compressible slopes, as well as infrastructure protection and embankments (shown in figures 2.3 and 2.4). EPS is an adaptable substance that may be employed in various geotechnical projects, particularly in the construction of pavements. The intriguing mechanical characteristics of EPS geofoam make this feasible. Because of its low weight, it is a great fill material, and its poor thermal conductivity makes it a good pavement insulator in cold climates its compressibility also makes it easy to use for underground utility protection, and ultimately, its vibration-dampening properties enable it to be used as a potential vibration dampener [58], [59].

Figure 2.3 Application of Geofoam at Bridge Abutments [60]

In Salt Lake City, Utah, USA, in 2012, recycled EPS was used as an embankment for the interstate road section I-15. The aim of utilizing EPS blocks was to speed up activities related to construction over weak clay and reduce settlement. Adding on, the significance of utilizing EPS involved increasing the stability of the weak embankment [61]. In certain areas where bridges were built, there was a need for high embankments, but the computed safety factors against the failure of the base were not satisfactory. Typically, these embankments are built using geosynthetic reinforced materials and a phased construction process that takes various weeks to permit the release of excess pore pressure and the ultimate increase in shear strength. However, improved factors of safety against geotechnical instability were attained and the construction period was shortened by employing EPS blocks to build the embankments. [62].

Highway bridge structures may be sustained with EPS geofoam without a requirement for deep foundations. Further improvement in this technique will speed up construction on compressible, soft, and unstable soil. Similarly, EPS geofoam enables the swift construction of bridge foundations over these types of soils, eliminating the need for costly and time-consuming conventional foundation methods. Due to its exceptionally low weight, EPS geofoam can be utilized to prevent settlement problems at bridge approaches [63].

Controlled yielding involves incorporating a specially designed, thin, or compressible layer of material between the structure and below ground. The cases generally involve a rigid structure having direct ground contact. The primary objective of using the compressible inclusion is to allow the ground to compress fully and enable the adjacent structure to yield or move when, without the inclusion, the structure's constraints would otherwise restrict or completely block the ground movement. This displacement has the advantage of reducing the structure's susceptibility to earth forces. This can result in lower construction costs for new structures or enhanced performance for existing structures [64]. The various construction phases such as design, building, maintenance, rehabilitation, and upgrading of earth-retaining structures might be significantly and permanently changed by the application of geofoam compressible inclusions [65], [66].

The cases where the soils supported by earth-retaining structures are vulnerable to volume variations due to environmental factors, particularly variations in moisture content, is another application of geofoam compressible inclusion in geotechnical engineering [67]–[69]. Expansive soils with geofoam compressible inclusions can readily be applied as a backfill material behind earth-retaining walls or buildings in a technically accepted and financially feasible alternative [70], [71]. Additionally, an established application that also shows the validity of the basic idea is the use of compressible geofoam inclusions beneath foundation slabs to reduce vertical stress caused by the expansive soils. By applying EPS geofoam as a compressible backfill material, the lateral swelling pressure caused by swelling soil that is delivered to a retaining structure may be decreased. Distributed lateral swelling pressure reduces with increasing EPS geofoam backfill thickness [72]–[74].

The seismic resilience of structures can be improved by EPS geofoam. It reduces the likelihood of ground failure and soil liquefaction during earthquakes by reducing the strain on the underlying soil. By absorbing and dissipating seismic energy, the lightweight blocks reduce the stresses to subgrade. In seismically active areas where the long-term reliability of foundations and retaining structures is critical, this application is extremely valuable. Excellent thermal insulation qualities make EPS geofoam advantageous in geotechnical applications that require insulation [75]. It is frequently applied in frost protection systems for highways, airports, and utilities where it protects against temperature-induced ground movement and prevents frost heave. In below-grade infrastructure, EPS geofoam also functions as a thermal barrier to prevent heat loss and enhance energy efficiency. It is frequently used to fill cavities beneath the earth, including old tunnels, mines, and sinkholes. Effectively filling the gaps, EPS geofoam offers structural support and reduces the likelihood of subsiding [76], [77].

Figure 2.4 Application of Geofoam along the wall [78]

There are several domains for development and prospective study in the implementation of EPS in construction practices. They generally deal with developing new uses for the material in the construction of road pavement, improving existing ones, and creating tools to help designers during the initial design phases. This is crucial to expanding the use of EPS in construction engineering, coming up with more creative solutions to address various construction problems, and ensuring that designers are competent and confident enough to create safe designs.

2.5 Previous Studies on Engineering Properties of EPS-Soil Mixes

Lightweight soil was originally developed to reduce self-weight or applied stresses resulting in reclamation and embankment on soft ground. One strategy for stabilizing light soil is to combine it with cement, light components like air foam or Expanded Polystyrene (EPS) beads, and soil. This technique has been frequently implemented recently in Japan as a preventative measure against the rise in solid waste, such as dredging sludge from building operations. As a soil improvement technique for soft ground, one common use of the technology is the use of backfill materials to mitigate both earth pressure and its settlement [79], [80].

EPS particles may fill structures with any shape and are more compatible than EPS blocks. Because of their low unit weight, thermal insulating property, high compatibility, broad availability, and inexpensive material, EPS particles are therefore often utilized in the domain of construction engineering, particularly as the replacement for lightweight soil [81].

An innovative product called EPS granular lightweight soil is made by mixing soil with water and EPS particles. The stability of the foundation may be improved by utilizing this type of material in the filling of subgrade layers since it can lower the mass and diminish the seismic impact of roadways. However, due to its low stiffness, low strength, and high compressibility, EPS can negatively affect the mechanical characteristics of soil materials, particularly their strength and deformation parameters, when used as a lightweight aggregate [82].

The constituents and mixture ratios of EPS composite soil have a considerable impact on its geotechnical characteristics. Based on changes in ingredient amounts, a broad range of engineering characteristics has been documented [83].

Its unit weight is determined by the amount of EPS in it. Based on its constituents, this material's unit weight can range from 5 to 18 kN/m^3. EPS beads offer the composite material with the minimum dry density as compared to EPS in the form of strips [84].

Hovarth investigated how cubic EPS-geofoam specimens behaved under axial compression and found that density significantly impacted compressive strength. He developed a correlation between the unit weight and modulus of elasticity and compared different recommendations of correlations from other authors [55].

Duskov conducted compression experiments on two cylinder-shaped specimens (having a height-to-diameter ratio is approximately 2) of EPS-geofoam with unit weights of .015 g/cm^3 and 0.02 g/cm^3. Despite the material's low unit weight, the EPS strength values observed from these studies were relatively high at the defined strain value of 10%. The author also proposed a correlation between density and the initial modulus of elasticity [85].

When compared to cubic specimens, Stark noticed that specimens having a cylindrical shape tended to have a lower modulus of elasticity and yield strength. Additionally, samples of various sizes were examined, and the outcomes demonstrated that by increasing the size of the sample there was a significant increase in its modulus of elasticity. However, further investigations are still required because the outcomes were inconclusive [86].

Bueno performed compression experiments on cylinder-shaped specimens of EPS-geofoam with height/diameter ratios of 3:1. The author has concluded that the samples weren't ruptured following the conventional patterns. In this configuration, the samples exhibited lateral instability or buckling, indicating that using samples with cylinder geometries could mislead users about a material's actual compressive strength [87].

Yeo and Hsuan conducted unconfined axial compression experiments at elevated temperatures ranging from 30°C to 58°C, with 7°C intervals. They found that the strength dropped as the temperature increased and that the response was bi-linear, with an obvious change in temperature gradient at 44°C [88], [89].

The EPS unit weight, axial compressive strength, long-term creep effect, and cyclic loading impact are some of the characteristics that need to be evaluated to utilize EPS in construction projects related to geotechnical engineering, particularly for road embankments. It has been observed that even with a properly controlled production procedure, there will still be fluctuation in unit mass across blocks from the same manufacturing batch and a gradient of density inside each block. The bulk unit weight of EPS is defined by the manufacturer's specifications [90].

Horvath (2004) affirmed that because density is a governing element, the variation in density may influence the material's geotechnical design qualities. The real limits of densities at which EPS blocks may be produced globally are somewhere between 0.02 g/cm^3 and 0.04 g/cm^3. Locally, the most widely manufactured EPS blocks have a mean density of around 30 kg/m^3 [55].

Axial compressive strength is another factor that defines EPS response under various loading conditions. Testing cubes same length, depth, and width of 50 mm are experienced under a loading rate of 20 percent strain rate per minute in unconfined loading rates with 10% can be used to establish the compressive response of EPS. The shear behavior of EPS is characterized by three distinct zones. The initial linear-elastic segment of the curve was observed in several studies, to extend up to 2% strain. However, some of the researchers reported little changes in that percentage ranging from up to 5% [91]. Currently, it is widely known compressive strain of 2 to 5% constitutes elastic limit stress, where the initial modulus of elasticity is determined by the gradient of the linear-elastic section of the curve [8].

For a very long time, cement has been utilized successfully to enrich the mechanical properties of soil. To make EPS composite soil, an innovative kind of lightweight geomaterial that may be used as a replacement for mere cement, the mixture can subsequently contain EPS [92]. EPS composite soil, like cemented soil, is stronger than natural soil because it possesses intrinsic cementing properties, but it also weighs less per unit since it also includes superlight EPS. Additionally, this material's unit weight and strength may be readily controlled by using various mixing ratios that can be adjusted to the needs of the project [93]t. Additionally, to speed up building, EPS mixed soil may be created into a semi-solid state and pumped into uneven gaps on the field [94].

The unconfined compression strength enhances with enhancing cement amount at the mixing ratios and test conditions, and a well-exponential relationship may be determined. With prolonged curing times, the unconfined compression strength similarly increases, and a logarithmic relationship may be observed. The increasing amount of EPS beads will result in a lower unit weight as well as the strong performance of lightweight materials [92], [93].

Within the initial 28 days of curing, the unconfined compression strength increases significantly. The fine sand lightweight is stronger than the muddy clay lightweight, making it appropriate for varying cement amounts and the inclusion of EPS particles, varying waste soil lightweights have different strength qualities. This type of lightweight combination can function as a subgrade filler material due to its strength [95], [96].

The lightweight substance produced from the two different types of waste soil is a strain-hardening material, and when the confining pressure is increased, it becomes stronger. The mixture is stable, and the usual triaxial test may be used to measure internal friction angle and cohesion. Theoretically, this type of waste matter has an excellent tendency for recycling; still, the premise is that further supporting experiments must also be carried out [97], [98].

The ultimate mechanical response of the composites concerning the resistance characteristics was influenced by the type of soil, the amount of EPS beads, and the degree of confining stress [99]. With the addition of EPS beads, the maximum dry mass and optimal water of the clayey soil decreased, and both values decreased as the EPS proportion increased. This phenomenon can be explained by the EPS beads' low apparent density and limited moisture retention. The EPS addition changed the material's stress versus strain behavior pattern at greater initial effective stress, manifesting an elastic-plastic hardening response. [100]. At higher initial effective confining stresses for sandy soil, the incorporation of EPS beads also had an impact on the behavior of the material's stress versus deformation pattern, however at lower initial effective confining stresses, the inclusion of EPS had no impact on the sand's resistance to shearing [101], [102].

The inclusion of EPS beads did not significantly affect the rigidity, residual resistance, and maximum resistance of bentonite, regardless of the EPS content. However, when EPS beads were added, the material's stiffness decreased, but the residual and peak resistance values were sustained at higher initial effective confining stresses compared to lesser initial effective confining stresses [103], [104]. Given that one of the resistance capacities usually improved with the incorporation of EPS beads, the material's behavior remained unchanged in any of the tested mixtures of clayey, sandy, and bentonite. The outcomes expand the comprehension related to the mechanical response of soil reinforced with EPS beads and indicate the material's potential for use as soil reinforcement in earthworks subject to static loads, providing a more environmentally sustainable use for this material [105], [106].

Unconfined compressive strength rises sharply in a parabolic polynomial function with cement amount while declining in a hyperbolic function with EPS bead volumetric percentage. Because the bonding effect of cement's hydration products—which play a major role in cohesion—increases with cement concentration, cohesion is a function of cement content. Because the cohesiveness between the hydration products of cement and EPS beads is lower than that between the hydration products of sand and cement granules, the rise is less pronounced as the volumetric content of EPS beads increases. Because EPS beads have smoother surfaces than sand grains, the friction angle reduces as the volumetric quantity of EPS beads increases [107]–[109].

The researchers investigated the stress-strain response of EPS-sand for a single type of EPS bead-sand mixing regime to minimize cement costs and eventually produce a non-cementitious lightweight fill. When a significant amount of the material needs to be manufactured in the field without any supplementary materials, it is feasible to develop EPS-sand mixes [110], [111].

The studies demonstrated that the Portland cement imparted extra strength to the mix while the EPS beads presented lightweight fill cases. These mixtures are tougher than EPS-block geofoam, yet they are more lightweight than traditional fill materials due to having higher volume [112], [113].

The initial undrained elastic modulus of EPS-sand dropped in a linear function as the volumetric EPS bead content increased, and this trend depends on both the voluminous EPS bead content and the types of EPS beads available in the EPS-sand. When the volumetric EPS bead concentration was kept constant, the mixture's smaller EPS beads produced the largest deviatoric stresses and initial undrained modulus [114] At lower confining pressure, the stress-strain response of EPS-sand indicated properties like loose sand. At higher confining pressures, however, the stress-strain response of EPS-sand exhibited strain-hardening potential [115].

The findings from this research indicate that utilizing smaller-sized EPS beads produces higher stiffness characteristics. Consequently, lightweight fills may be made without substantially losing stiffness when smaller-sized EPS beads are utilized.

2.6 Knowledge Gaps and Research Needs

The impact of shredded EPS on the mechanical characteristics of clayey soils has yet to be extensively investigated. While several studies have investigated how EPS affects soil engineering characteristics, further research is required to fully understand how shredded EPS affects the mechanical behavior of clayey soils. Research needs to focus on investigating the relationship between the amount and form of shredded EPS and the resulting variations in the mechanical characteristics of clayey soils. These details are essential for establishing cost-effective and sustainable engineering applications using shredded EPS. The optimal content and size of shredded EPS for enhancing the mechanical characteristics of clayey soils are yet to be determined. Although limited research has been conducted regarding the behavior of shredded EPS when mixed with clayey soils, there hasn't been much done to determine how effectively it performs in various types of clayey soil based on plasticity.

Studying the shear strength parameters of EPS mixed soil under various load cases. To comprehend the stability and response of the mixture soil at various stress levels, it will be essential to assess the shear strength parameters, such as the angle of internal friction and cohesion.

Although limited research has been conducted regarding the behavior of shredded EPS when mixed with clayey soils, there hasn't been much done to determine how effectively it performs in various types of clayey soil based on plasticity. A complete understanding of the mechanical characteristics and compaction parameters of EPS incorporated with various soil types will help assess its suitability for use in various geotechnical engineering works.

It is well-established that compaction conditions have effects on the soil's swelling and shrinkage characteristics for compacted clayey soils. Compaction on the wet side of optimal is recommended to decrease swelling potential. Compaction on the dry side is desirable since wet side compaction causes shrinkage phenomena and enhances the risk of cracking. Compaction on the dry side is desirable since wet side compaction causes shrinkage and increases the risk of cracking. Both compaction conditions may result in undesirable behavior due to the shifting weather patterns around the globe. As a result, it's necessary to identify more favorable alternatives.

EPS composite soil can be used in various construction projects, but each application requires a unique design strategy that considers performance standards, optimum mixing ratio while making the design, and cost-benefit analysis. It is familiar that EPS composite soil can greatly lessen horizontal earth pressure. Field research is needed to investigate the precise reduction of lateral earth pressure. EPS composite soil is anticipated to become a more significant component of geotechnical engineering practice as a new lightweight geomaterial.

Therefore, analyzing the maximum dry unit weight, water content, plasticity, and compaction characteristics of clayey soils and shredded expanded polystyrene (EPS), as well as their individual physical and mechanical characteristics, is essential. This will give a baseline understanding of the individual materials and their response. Evaluating the mechanical response of mixed clayey soils incorporating shredded EPS under various loading situations, including unconfined compression and shear tests, is needed. The composite material's strength, deformation properties, and stress-strain response will be analyzed.

Standards and specifications will be developed for the design, construction, and quality assurance of shredded EPS mixed clayey soil applications based on the research findings. Recommendations and suggestions will be provided for engineers and practitioners regarding material selection, mixing procedures, compaction methods, and performance assessment. The sustainability and recyclability aspects of the shredded EPS incorporated into the clayey soils will be investigated.

CHAPTER 3 METHODOLOGY AND EXPERIMENTAL DETAILS

A series of laboratory tests and analyses were to examine the mechanical behavior and compaction properties of clayey soils incorporated with shredded expanded polystyrene (EPS). The aim is to investigate how the incorporation of shredded EPS affects the soil's mechanical characteristics and compaction behavior. To evaluate the impacts of shredded EPS on the mechanical response and compaction parameters of the clayey soils, the test outcomes are analyzed and compared. Plotting particle size distribution curves, which depict the correlation between the percentage fines and diameter of each sieve, is done using the outcomes from the sieve analysis and hydrometer analysis. Making compaction curves, which show the relationship between each mixture's dry density and moisture content, is done using the outcomes yielded from the compaction experiments. To determine any EPS-related changes, the shear strength and compressive strength parameters are computed and compared.

3.1 Collection of Soil Samples

Appropriate locations where three types of clayey soils such as low plastic, medium plastic, and high plastic soil are readily available, have been identified (shown in figures 3.1 to 3.3). Several factors such as accessibility, proximity to the laboratory, and the representative nature of the sites in terms of soil composition and geologic conditions, have been considered. The number and amount of samples required for the study have been determined while making the sample design. Testing specifications, statistical significance, precision, and accuracy played a vital role in this phase. To take into consideration the intrinsic variations in soil qualities, many samples were taken from different points around the site. Necessary equipment and tools were gathered for collecting clayey samples. The collection materials include distinct items such as labeling materials, measuring instruments, sampling bags, spades, and augers. The collection process involves four steps such as preliminary survey, digging the test pits, sample extraction, and sample handling. A preliminary survey was conducted to identify different zones with changing ground conditions and soil properties within the selected site. This was done by visually inspecting the soil profile, taking note of any visible variations, and analyzing the soil texture. Test pits at representative locations within the site were excavated. The dimensions, volume, and depth of the pits were sufficient to capture the soil layers of interest. Disturbed and partially undisturbed samples from different soil layers within the test pits were collected. Such samples were obtained from various exploration tools such as hand augers and shovels that represent a portion of the clayey samples. The desired test samples were obtained from the depth of five feet below the natural ground level making a minimum disturbance in the natural structure of the soils. Collected samples were managed carefully to reduce disturbance and maintain their water content. The collected samples were placed and wrapped in plastic, polythene bags, or other moisture-sealing materials to prevent drying, contamination, or excessive moisture loss. Labels were prepared to mark each sample with relevant information like location, collection date, and depth. These records helped in data interpretation and analysis, potential future reference, and quality control.

Three types of naturally available fine-grained soils (low-plastic, medium-plastic, and high-plastic) samples were obtained from three different sites. The low-plastic soil sample was collected from Pir Wadai Mor, Islamabad. The medium-plastic soil sample was gathered from Top City, Islamabad. The High-plastic soil sample was collected from

Nandi Pur, Gujranwala. These soils (disturbed samples) were obtained in polythene bags and transported to the geotechnical laboratory for several types of testing to achieve the desired goals.

Figure 3.1 Low Plastic Soil (LP) – Top City, Islamabad

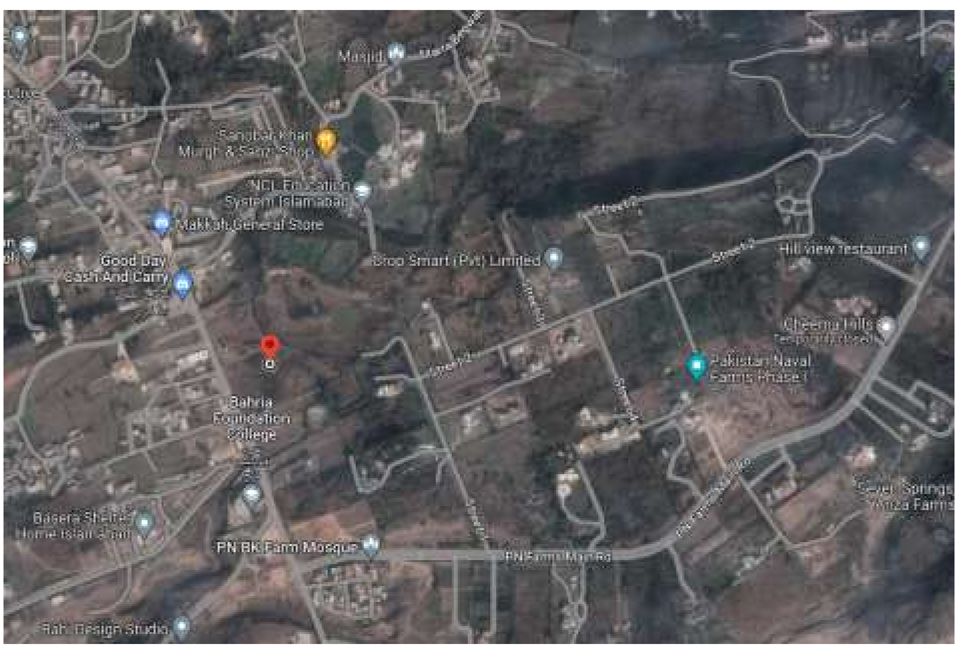

Figure 3.2 Medium Plastic Soil (MP) – PN Naval Farms, Islamabad

Figure 3.3 High Plastic Soil (HP) – Nandipur, Gujranwala

After collecting the clayey samples, they were required to go to the laboratory for further analysis. It was significant to manage the samples with care during transport to reduce disturbance and loss of properties. Proper storage conditions, such as cool, suitable temperature, and dry environments, were maintained to prevent contamination of the samples.

3.2 Classification of Soil Samples

The samples were collected from various points within the region of interest. Ensured that the samples were representative of the range of variability in the soil types that were present. A visual examination of the soil samples was performed. Texture, color, and any other visible features such as organic matter or mineral grains were observed. The valuable information related to the typical characteristics of soil was gathered through an initial visual examination.

The soil sample was mixed thoroughly and broken up into aggregates or lumps to make sure of the homogeneity of the representative sample. All the large particles or debris were removed that might have manipulated the results. The weight of the soil sample was taken accurately. The exact mass of the soil sample varied according to the expected distribution of particle sizes. A set of standard sieves with different mesh sizes was selected to incorporate the desired range of particle sizes. The sieves were placed in order of increasing mesh size from top to bottom, with the coarsest sieve at the top and the finest at the bottom. The soil sample was put on the top sieve and covered with a lid. The sieve set was shaken manually for a particular interval of time to ensure the efficient separation of particles. The shaking time was 5 to 10 minutes. After the sieving procedure, the sieve was removed from the stack and the retained sample on each sieve. The sieve was cleaned and dried before weighing the retained soil particles. The weight of the retained soil sample was assessed on each sieve and the percentage of soil passing through each sieve was determined. This was done by dividing the weight of soil passing through a particular sieve by the initial weight of the soil specimen and multiplying by one hundred.

The hydrometer test was conducted to evaluate the fine content of the soil sample, after conducting sieve analysis. A specific amount of soil sample, around forty grams, was mixed with a specified quantity of distilled water in a mixing cylinder. The mixture is vigorously stirred to ensure that the soil particles are well dispersed in the water. The hydrometer apparatus was calibrated to ensure precise measurements before initiating the actual test. This included evaluating the relationship between the hydrometer reading and the corresponding sedimentation time for known concentrations of soil particles. A table was then made to relate the hydrometer readings to particle concentrations. The sample was transferred to a sedimentation or a hydrometer cylinder once it had been properly dispersed. The proper suspension of soil particles was achieved by adding distilled water to the until it reached a predetermined volume and vigorously mixing it. The initial reading was obtained immediately after the suspension was prepared. The reading at the liquid's meniscus was taken using the hydrometer, a glass instrument with a calibrated scale, which was gently lowered into suspension. The suspension was allowed to settle for a certain amount of time 2, 4, 8, 15, 30, 60, 120, and 1440 minutes without being disturbed. It was crucial to prevent any disturbance during the settling phase. The proportion of particles finer than each corresponding size was computed using the hydrometer readings obtained at various intervals of sedimentation. This was done by referring to the table that was made during hydrometer calibration. These estimated percentages are then utilized to depict the grain size distribution. The particle size distribution curve produced from hydrometer analysis offers crucial details about the soil's engineering properties. It assists in putting the soil into different classifications following the standard classification systems, calculating its permeability, estimating its compressibility, and predicting its suitability for various engineering applications. The particle size distribution curve was drawn by making the graph of percentage passing on the ordinate and the corresponding sieve size on the abscissa. These curves offered detailed information about the grading of soil and were used to classify the soil sample as per the Unified Soil Classification System (USCS).

Table 3.1 Properties of Clayey Soils Used in This Study.

Properties	LP	MP	HP
Sand Content, S [%]	3.7	2.9	1.9
Fines Content, FC [%]	96.3	97.1	98.1
Silt Content, M [%]	75.1	67.4	53.3

Clay-sized Fraction, C [%]	21.2	29.7	44.8
Liquid Limit, LL [%]	21.7	28.2	51.2
Plastic Limit, PL [%]	14.4	15.8	23.5
Plasticity Index, PI [%]	7.3	12.4	27.7
Maximum Dry Density, MDD [g/cm^3]	1.85	1.81	1.69
Optimum Moisture Content, OMC [%]	13.7	15.8	21.6
Unconfined Compressive Strength, UCS [kPa]	214.8	170.7	159.5
Undrained Shear Strength, S_u [kPa]	107.4	85.4	79.8
Cohesion, c [kPa]	24.0	29.3	38.5
The angle of internal friction, φ [°]	29.5	21.9	13.2

3.3 Compaction Tests of Shredded EPS Mixed Soils

Effective compaction practices are considered essential parameters to achieve the desired engineering performance of the fill material. While using composite materials, it is required to optimize the proportion of the materials. Furthermore, laboratory test results are compared and simulated to the field condition to achieve desired compaction characteristics. Most of the engineering properties such as compressive strength, frictional strength, plastic limit, and liquid limit are dependent on the moisture amount. Figures 3.4 and 3.5 show the mixed EPS-clay materials prepared using different clays.

Figure 3.4 Preparation of EPS-clay sample (Medium Plastic Soil)

The Standard Proctor compaction test is an extensively applied method for evaluating the optimum moisture content and maximum dry unit weight of soils. It is essential for many engineering and construction applications, including the design of foundations, embankments, and roads. This method helps in assessing the compaction properties of soils and determining their suitability for various construction projects. The Standard Proctor Compaction test follows specific standards and procedures to make sure of precise, accurate, and consistent outcomes. The first step includes acquiring a representative soil sample from the site. The sample was collected from the above-mentioned sampling procedure, ensuring that it represents the soil being compacted. The representative sample was free from any foreign materials in the sample to ensure reliable test results. Once the sample was collected, it was required to be prepared for the compaction test. The soil was oven-dried, and any excess moisture content was removed.

It was then pulverized and sieved to break down any larger particles or lumps and obtained a homogenous soil sample with particle size distribution representative of the in-situ soil.

Figure 3.5 Preparation of samples for proctor test (High Plastic and Low Plastic Soils)

The next step was to assess the moisture-density relationship of the soil sample. This relationship was obtained by compacting the soil at different proportions of moisture contents and measuring the corresponding unit weights. The compaction is attained using a compaction hammer and compaction mold. The standard compaction mold has a volume of 944 cubic centimeters and follows predefined dimensions and specifications.

The mass of the mold was recorded before the compaction procedure. A specific quantity of the soil is then placed into the mold in layers. The compaction hammer, which normally weighs 2.5 kilograms and has a free-fall height of three hundred millimeters, was applied to compact each layer. The material is compacted into three layers, and each layer receives twenty-five blows of the compaction hammer. The number of blows per layer ensures consistent compaction energy for each test trial. Following the compaction procedure, the mold comprising compacted soil was again weighed to find its moist density. After carefully extracting the soil specimen from the mold, its moisture content was calculated by taking the mass of the soil sample both before and after it had dried in the oven. This process allowed the calculation of the dry unit weight of the compacted soil.

The Standard Proctor compaction test is performed at various moisture contents to develop the moisture-density relationship. The test outcomes are drawn on the graph with moisture content on the abscissa and unit weight on the ordinate. The graph showed a peak, manifesting the maximum dry unit weight achieved at an OMC point. The OMC showed the water content of the soil could be the most effectively compacted to achieve the maximum dry density. In the laboratory, compaction characteristics such as optimum water content and maximum dry unit weight were evaluated through the standard proctor test. A relationship had been developed between the dry unit weights and optimum water contents of the benchmark soils with and without the replacement of shredded EPS. These compaction tests aimed to analyze the variation of dry density with shredded EPS at different percentages across the different Atterberg limits and to understand the effects of shredded EPS content on the optimum moisture content and maximum dry unit weight of the mixed materials. A series of compaction tests were performed to achieve the maximum mass of the soil per unit volume corresponding to the optimum moisture content at the specified compaction energy. Similarly, additives had been added to the soil in various proportions, to change or enhance the engineering characteristics of the soil. The mixed material must be compacted to achieve maximum unit weight at optimum water content. A minimum of three samples were compacted with the variation in the starting moisture content to draw the compaction curve for each mix proportion.

3.4 Unconfined Compression Tests of Shredded EPS Mixed Material

The UCS tests aimed to evaluate the influence of EPS content on the compressive strengths of three different clays based on plasticity. Unconfined Compression testing is a general laboratory procedure for determining the mechanical properties of soils, particularly cohesive soils such as clays. It is a simple and basic test that provides valuable information about the strength and deformation characteristics of the soil. The diameter and height of the standard testing cylindrical specimen were 7 cm and 14 cm respectively, with a height-to-diameter ratio of two. The test specimens were prepared and compacted in five equal layers under specified conditions of maximum dry unit weight and optimum water content in the laboratory. The top and bottom surfaces of the testing specimens were trimmed to keep the smooth surface for the uniform distribution of loads. All the tests were conducted under unsaturated conditions.

The test includes subjecting a cylindrical specimen to axial compressive force in an unconstrained manner. The unconfined compression tests do not exert any horizontal pressure on the specimen, unlike other compression tests. This makes it suitable for testing sensitive and soft soils that are highly likely to fail or deform under confinement. The apparatus needed for performing the unconfined compression test incorporates a compression machine, load cells, a loading frame, and accessories. The soil sample is typically obtained through the above-mentioned sampling processes. To conduct the test, the soil sample was placed in a cylindrical mold with a pre-defined cross-sectional area. The height-to-diameter ratio of the specimen was kept within the range to ensure accurate test results. The specimen was carefully prepared and trimmed to ensure uniformity and remove any irregularities. Once the sample was prepared, it was positioned on the loading frame of the compression machine. The loading cell was attached to the top of the sample, and the vertical displacement was measured.

Figure 3.6 Unconfined Compression Tests for EPS mixed clayey soil

The test began by applying a vertical compressive load to the sample at a constant rate. As the load was applied, the specimen was subjected to deformation, and the corresponding load and displacement measurements were recorded. The test proceeded unit the specimen failed, by shear failure along the failure plane. The maximum load sustained by the sample was recorded as the ultimate compressive strength. Several crucial factors were assessed during the test. The UCS test performed on a sample is shown in Fig. 3.6.

The stress-strain relationship of the soil specimen was illustrated to understand its deformation response. The peak stress depicted the highest strength of the material, while the post-peak response gave concepts about the ductility of soil and strain-softening characteristics. The unconfined compression test also allowed for the evaluation of other factors, such as the elastic modulus, and the Poisson's ratio. The modulus of elasticity gave information about the stiffness of the soil. At least three samples were prepared and assessed for each mixed proportion. The strength-deformation behavior of three different plastic clays for all mixing ratios has been illustrated through stress-strain curves. The test results were discussed in terms of stiffness, ductility, Young's modulus, and peak strength response of soils with and without the addition of EPS content. The test outcomes were demonstrated in terms of shear strength and deformation response, peak shearing resistance, and the post-failure response of the soils with and without a proportion of EPS. The stress-displacement curves of each soil specimen have been developed.

3.5 Direct Shear Tests for Shredded EPS Mixed Soils

The direct shear device has been extensively used for various experimental and theoretical research purposes due to its simplicity and being an economical test. The direct shear test is a basic laboratory technique utilized to evaluate the shear strength parameters of soil, especially clayey soils. This test is used in soil mechanics and geotechnical engineering because this test provides valuable information about how soil responds to shear stresses. It enables geotechnical engineers to assess the stability and bearing capacity of structures like slopes, foundations, embankments, and retaining walls. By computing the shear strength parameters, including the angle of internal friction and cohesion, the direct shear test gives the required data for designing safe and reliable geotechnical structures. The direct shear test apparatus comprises various elements, including a circular shear box assembly, a loading pad, a proving ring, a loading frame, a dial gauge or displacement transducer, and weights.

Strain-controlled direct shear tests (Fig. 3.7) have been conducted to study the effects of EPS contents on the shear strength characteristics. The objective of these tests was to determine the angle of internal friction and cohesion of three different clays based on the plasticity at different proportions of EPS amount in the mixed soil. The diameter and height of the standard testing ring were 6cm and 2cm, respectively.

Figure 3.7 Direct Shear Apparatus used in the present study

The testing specimens with and without EPS contents were compacted in three layers through static compaction at optimum water content to achieve maximum dry unit weight and all the tests were performed in unsaturated conditions.

The sample was positioned in the shear box with a specified area and was trimmed to fit the shear box. The lower half of the shear box was attached to the base of the testing machine, while the upper half was fixed to a loading frame. The specimen was subjected to a predetermined normal load through the loading plate. The tests were conducted at different vertical loads of fifty kPa, one hundred kPa, and two hundred kPa, and the loading rate was fixed at 0.5 mm/min with a maximum horizontal displacement of 8.5 mm for all test specimens. The normal stress was computed by dividing the applied load by the cross-sectional area of the specimen. The upper half of the shear box was horizontally displaced at a constant rate. The shear displacement was recorded using a displacement gauge. As the shear displacement proceeded, the resulting shear stress was recorded using a loading cell. The shear stress was computed by dividing the recorded by the cross-sectional area of the specimen. The shear displacement was measured at the same time as the shear force. As the shear displacement enhanced, the shear force reached the maximum value defined as the peak shear strength. The soil sample undergoes shear failure at this point. The values of shear displacement and shear force were recorded at the peak shear strength. After the peak shear strength, the value of shear stress decreased, showing a reduction in shear strength. The post-peak response of the soil specimen gave insights into the deformation characteristics of soil and its potential to regain strength.

The shear strength of the geotechnical material is the linear function of normal pressure at the instant of failure, angle of internal friction, and cohesion. The test outcomes were discussed in terms of strength and deformation characteristics, peak shearing resistance, and the post-failure response of the soils with and without a proportion of EPS. The stress-displacement curves of each soil specimen have been developed.

3.6 Liquid Limit and Plastic Limit Test of Shredded EPS Mixed Soils

The liquid limit test is a fundamental process in geotechnical engineering utilized to evaluate the moisture degree at which a clayey soil transforms from a plastic to a liquid condition. It offers essential information for characterizing the engineering characteristics and response of the soil. The liquid limit test is a typical laboratory test conducted on clayey soils to evaluate their plasticity and consistency. This characteristic is critical in evaluating the engineering behavior and suitability of the soil for various construction projects. It is an important test in geotechnical engineering and is conducted according to standardized procedures, such as the ASTM D4318 or the AASHTO T89 methods. The goal of these tests was to determine the liquid limit and plastic limit of three different clays based on the plasticity at different proportions of EPS content in the mixed soil. This test incorporates the effects of shredded EPS mixed with clayey soils. It also gives information on how the moisture content changes with the incorporation of shredded EPS contents mixed with clayey soils.

The representative soil sample was obtained from the field using the above-mentioned sampling technique. The soil material was pulverized and sieved to break till sieve#40 (425 micrometers). The sample was allowed to be placed in an oven machine for 24 hours to remove the excess moisture content. A soil sample (around 100 to 150 grams) was placed in an airtight container. The sample was placed in the mixing bowl and added distilled water gradually. The water and soil particles were mixed completely using hands or a spatula to attain a uniform consistency without any formation of dry lumps. The water was added continuously in small increments and was mixed until the soil attained a plastic consistency. The liquid limit test apparatus consists of the Casagrande apparatus (Fig. 3.8) including the brass cup, brass rod, and mechanical device to evaluate the number of blows needed to close in the soil sample.

The soil sample was placed in the brass cup that was attached to the liquid limit. The apparatus was adjusted in such a way that the cup was aligned with the center of the rotating mechanism. The crank rotated at a constant speed, causing the cup to move back and forth along the groove. The number of blows needed for the halves of the soil sample to come into contact and close the groove. The test was repeated until consistent results were consistent results. Multiple trials on three soils mixing with various proportions of soil were conducted using different moisture contents of the soil sample by adding water in small increments. The graph between the percentage moisture content on abscissa and the number of blows on ordinate had been plotted. The moisture content at the groove was closed with twenty-five blows. This moisture content is known as the liquid limit of the soil.

20-25 grams of the prepared soil sample were placed on the glass plate. The soil sample was kneaded by rolling it between the palms of the hands while placing it on the glass plate. The kneading process continued until the soil formed a thread-like structure without crumbling or breaking. This indicated that the soil was in its plastic state. A small portion of the plastic soil was taken and rolled into a thread with a diameter of about 3mm. The thread of the soil was rolled and kept until the thread completely crumbled and broke apart.

Figure 3.8 Casagrande Test Apparatus used in the present study

The process of rolling and kneading was repeated with the remaining soil sample to ensure the precision and consistency of the results. The moisture content of the soil sample was at the point when the threads were broken and crumbled. The plastic limit and liquid limit were measured by taking the average moisture content values obtained from the multiple trials. It was noteworthy that the Atterberg Limit tests were performed in a controlled environment to decrease moisture loss during the testing process. The reliability of the test outcomes influences the proper handling and preparation of the soil sample, as well as the careful observation during the kneading and rolling phases.

CHAPTER 4 RESULTS AND DISCUSSIONS

4.1 Particle Size Distribution

The grain size distribution curve shows (Fig. 4.1) a balanced distribution of various particle sizes in low plastic soil. A gradual rise in the percentage of finer particles as particle size decreases is demonstrated by the graph, which is generally smooth. Clay, silt, and clay-sized particles are often present in this type of soil in different amounts.

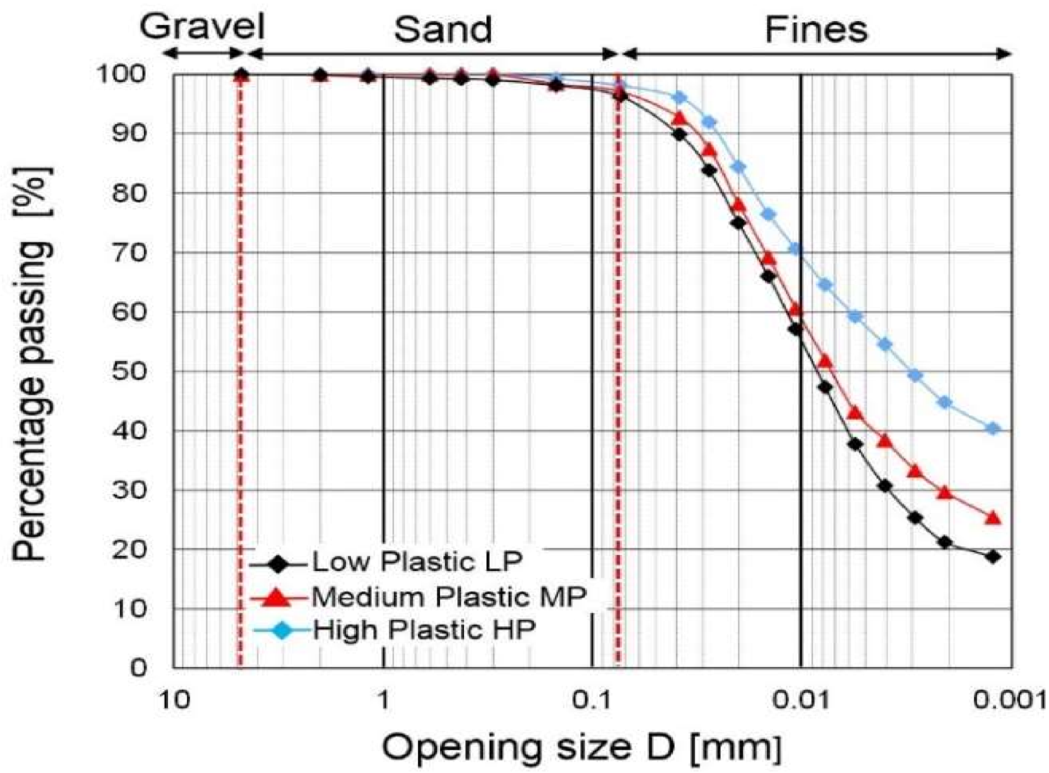

Figure 4.1 Grain Size Distribution of Low, Medium, and High Plastic Clay

In comparison to low plastic soil, the particle size distribution curve for medium plastic soil shows a more pronounced fluctuation. As the particle size decreases, the curve may first indicate a minor rise in the proportion of clay-sized particles, followed by a sharp increase in the percentage of finer particles (silt and clay). Compared to low-plastic soil, this type of soil often has greater clay percentages and comparatively lower silt particles.

High-plastic soil is classified by a significant presence of clay particles, which significantly affects its particle size distribution curve. The proportion of smaller particles (clay) is shown to sharply increase, while the percentage of silt particles is shown to significantly drop. In comparison to low and medium plastic soils, the curve often increases abruptly and peaks at a lower particle size percent.

4.1 Compaction Characteristics

Compaction curves are used to develop the relationships between the dry density and moisture content for all soil-shredded EPS mixtures. The compaction curves for six remolded soils were replaced with different proportions of shredded EPS, and are presented in Fig. 4.2.

The maximum dry density is significantly influenced by the amount of shredded EPS in the mixtures. The density of the mixture drops as the EPS proportion enhances. This is primarily attributed to the fact that EPS granules are lightweight and have a lower density than soil particles. The overall density of the mixture is reduced by the introduction of air voids through the introduction of EPS particles. The lowering in maximum dry density happens due to the lower specific gravity of EPS compared to soil particles. EPS particles consist of lightweight, small beads that are resistant to compression.

When these EPS particles are incorporated with soil, they replace specific soil particles and occupy the void space. As a result of this replacement, the volume of the mixture rises, but its weight remains largely constant, lowering its unit weight. The optimum moisture content in clayey soils may rise because of the addition of shredded

EPS. This is primarily due to the unique properties of EPS and its interaction with the clayey particles. The low weight and cellular structure of EPS particles. They act as void-forming agents when introduced into clay soils, enhancing the soil's total porosity. Clayey soils are composed of fine particles that have a high ability to retain and hold moisture content. These particles retain water even at low moisture content due to their high attraction for water molecules. When shredded EPS content is added to clayey soils, some of the void spaces previously occupied with water. As a result, the soil's overall ability to hold water declines, and the amount of water required by the clay particles to saturate them increases. More water needs to be incorporated in the soil when EPS is available, to attain the optimum moisture content. The EPS particles increase pore space, decreasing the unit weight of the soil and enhancing its porosity. A relatively larger amount of moisture content is needed because of the increased void ratio, which allows water to permeate and fill the spaces between the shredded EPS and clay particles.

Low plasticity soils have higher silt content and lower clay content. When shredded EPS is incorporated into low plastic soil, it can assist in decreasing the dry unit weight significantly. The EPS particles produce voids within the soil, decreasing its unit weight. Consequently, the dry density of the low plastic soil decreases, developing its lighter mass.

Medium plasticity soils contain a moderate amount of silt, clay, and clay-sized particles. Shredded EPS can still help to lower the dry unit weight when added to medium plastic soil, but the effect is less pronounced than compared to the low plastic soil. The clay proportion in the soil may prevent the EPS particles from completely dislodging the soil particles, leading to a relatively smaller reduction in dry unit weight.

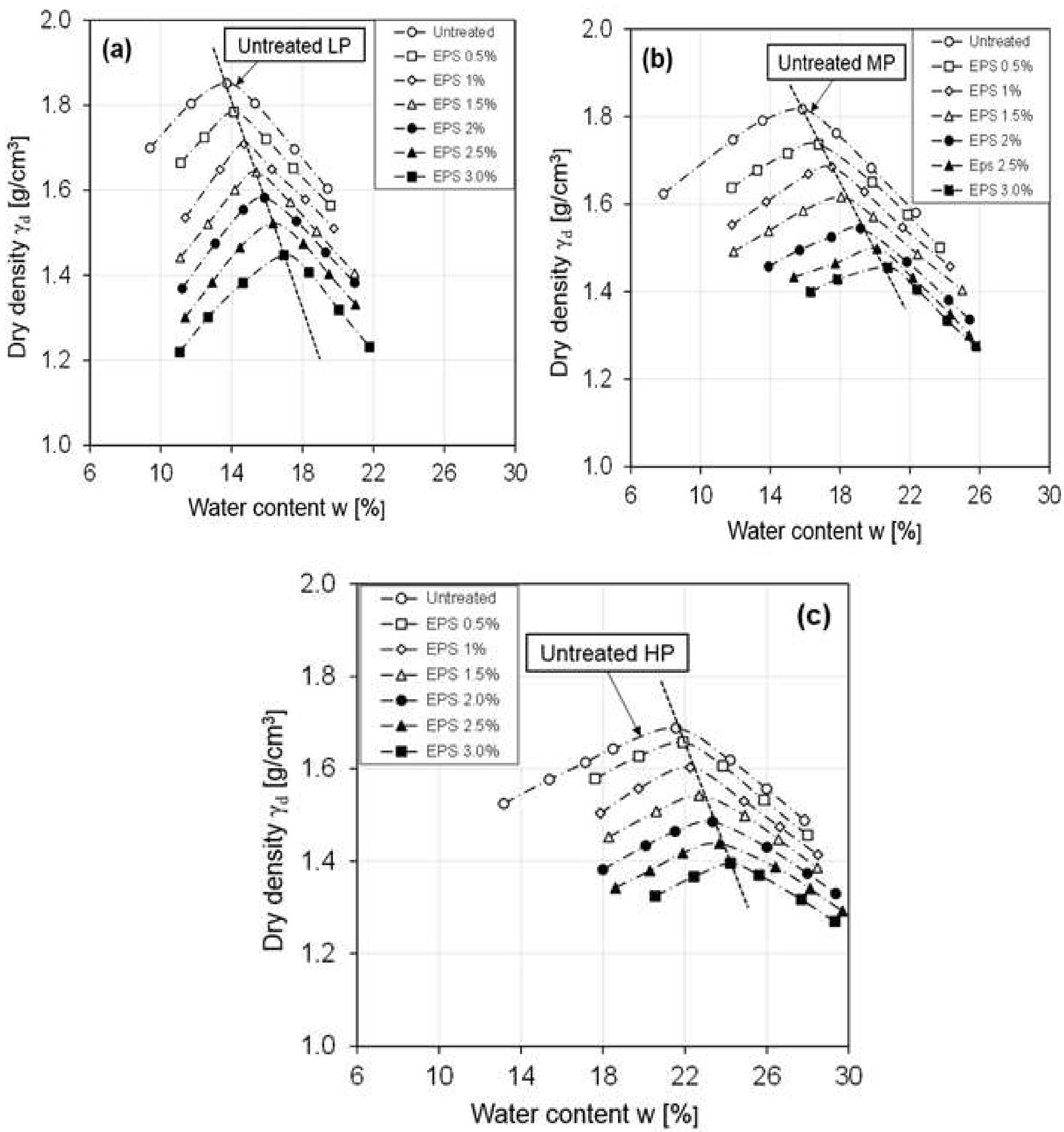

Figure 4.2 Compaction curves for shredded EPS mixed clayey soils

High-plasticity soils have very low amounts of silt particles and high clay content. The reduction in dry unit weight may be limited when shredded EPS is added to high-plastic soil. The cohesive nature of the clay particles can make it difficult for the EPS particles to replace the soil particles and create spaces. As a result, as compared to low and medium plastic soils, the impact of shredded EPS on lowering the dry unit weight of high plastic soil is slightly or negligible.

The compaction curves of Shredded-EPS mixed clayey soils having different percentages of Shredded-EPS are presented in Figure 4.2. For a rational comparison, the compaction curves of corresponding clayey soils without the addition of Shredded-EPS are also plotted in Figure 4.2. Irrespective of the plasticity of the clays, the outcomes indicate that the maximum dry densities (MDD) decrease continuously with the increase of Shredded-EPS amount for all three different types of Shredded-EPS mixed clayey soils. For instance, the value MDD for LP clay without the incorporation of Shredded-EPS was noticed to be 1.85 g/cm^3, and it reduced to 1.45 g/cm^3 with the addition of 3.0% Shredded-EPS. A similar trend can also be witnessed for Shredded-EPS mixed clays prepared by using MP and HP clays. This is attributed to the fact that Shredded-EPS replaces the clay proportion in the mixture, and Shredded-EPS has relatively lower specific gravity that eventually leads to lessening the overall dry density of the mix.

The microstructure study of EPS revealed that the incorporation of EPS causes segregation in the mix and possess excellent insulation property due to its porous nature [116]. Dry density is a function of the void ratio [117], and it is anticipated that the interaction of Shredded-EPS and soil particles resulted increase in void spaces in the overall soil-Shredded-EPS skeleton. Thus, at the given Shredded-EPS content, the specific gravity, and weight of water are assumed to be constant, and an increase in void ratio causes dry density to reduce. In contrast, the optimum moisture content (OMC) values enhance noticeably with the addition of Shredded-EPS for all three different types of Shredded-EPS mixed clays, as witnessed in Figure 4.4. Previous study has revealed that at higher EPS concentrations in the mixture, EPS-EPS interactions lead to higher pore spaces, thereby increasing the water-holding capability of mixtures. Thus, hydrophobic clay minerals absorb surplus water compared to untreated specimens [118].

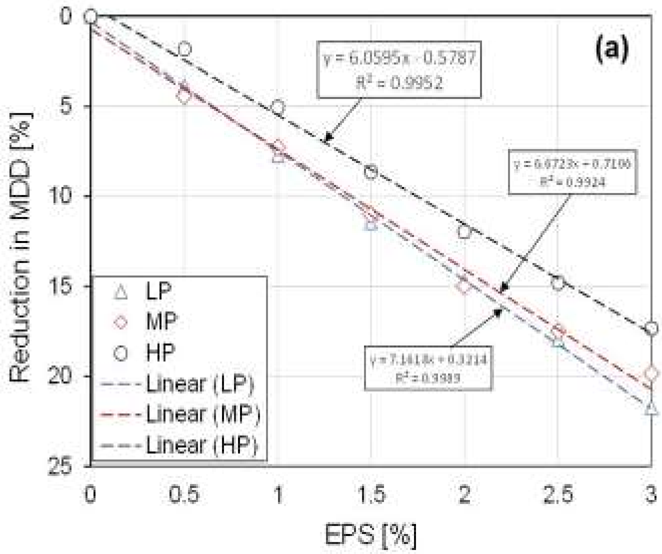

Figure 4.3 Effect of proportions of EPS on MDD of three different clayey soils

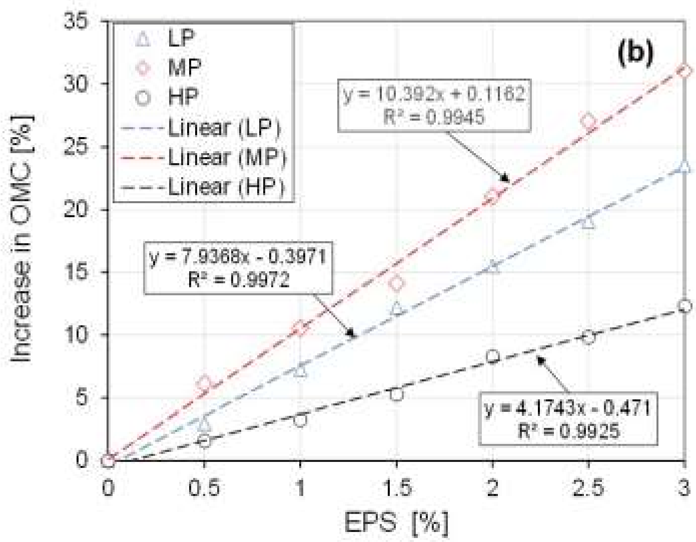

Figure 4.4 Effect of proportions of EPS on OMC of three different clayey soils

It is noteworthy that the reduction in MDD was more pronounced when LP clay was used as compared to MP and HP clays. As shown in the above figure, at the given maximum utilized EPS content (3%), MDD reduces by a maximum of up to 22% (1.45 g/cm^3) for LP as compared to untreated soil specimens. Similarly, the percentage reduction in MDD was found to be 19% and 17% for MP and HP-treated soils respectively at 3% EPS as compared to untreated specimens. The above shows the percent increase in OMC with varying EPS proportions. OMC increases by a maximum of up to 24%, 31%, and 12% for LP, MP, and HP respectively at 3% EPS content. Shredded-EPS interaction with LP produces higher voids as compared to MP and HP respectively.

The differences in the amount of reduction for shredded-EPS mixed clayey soils prepared using different clays are anticipated to be linked with the size of grains in LP, HP, and MP soils, for the noticeable reduction in MDD. Since, the size of LP clayey particles is larger than MP and HP, the interaction between Shredded-EPS and soil grains in LP results in larger pore sizes and specific areas and eventually leads to a higher percentage reduction in MDD as compared to MP and HP. Moreover, larger pore spaces caused by the interaction of LP clayey soil and Shredded-EPS require more water to bond. A similar justification has been provided by a previous study [119].

In another study, it has been demonstrated that the higher mean average size of the host specimen (soil) also increases the volume compressibility coefficient upon the inclusion of EPS [120]. Moreover, with the increase in EPS in HP soils, Shredded-EPS are anticipated to float at higher water content due to the difference in unit weight of Shredded-EPS and HP (expansive soils) and poor adhesion. This results in heaving and rebound of compaction stress and eventually less change in OMC is observed [118].

4.2 Compressive Strength

The change in unconfined compressive strength due to the inclusion of shredded EPS in clayey soils can be demonstrated by considering the characteristics and behavior of both materials. The stress-strain curves of the specimens are presented in Fig. 4.5. Initially, clayey soils' compressive strength tends to rise when shredded EPS is incorporated. This can be attributed to various factors such as dense packing of particles, water content reduction, and uniform stress distribution. The amorphous nature and irregular shape of the shredded EPS particles allow them to interlock with the clayey soil particles. The overall strength and stability are improved in the soil matrix through interlocking mechanisms. The amount of moisture in the soil is decreased by the lightweight, non-absorbent properties of EPS particles. The clay soil thus experiences less water-induced swelling potential, which enhances the compressive strength. The addition of shredded EPS granules enables a more uniform distribution of stress throughout the soil mass. This distribution of stress reduces the likelihood of localized failure and improves the overall compressive strength and load-bearing capacity of the soil.

However, as the proportion of shredded EPS enhances beyond the specific limit, the compressive strength starts to reduce. This reduction can be attributed to the following factors such as particle displacement, reduced soil cohesion, and dilution effect. At a larger proportion of shredded EPS, the particles may start to move more easily while under stress. This displacement decreases the compressive strength of soil and diminishes the overall interlocking mechanisms. Clayey soils intrinsically possess cohesive characteristics due to their fine particle size and chemical composition. The incorporation of shredded EPS can disrupt this cohesion, leading to a reduction of compressive strength. Shredded EPS is added to the soil mass, which increases its volume without significantly affecting its overall strength. This dilution effect decreases the cohesion and density of the soil, resulting in decreased compressive strength.

Therefore, while the initial inclusion of shredded EPS increases the compressive strength of clayey soils, exceeding a specific optimum limit can result in the reduction of compressive strength due to particle displacement, reduced cohesion, and the dilution effect. The limit at which the strength begins to reduce may change depending on factors such as soil composition, EPS particle size, and the percentage of EPS incorporated.

The compressive strength of low plastic soil tends to rise when shredded EPS is introduced. The EPS particles contribute to improving overall soil compaction and lowering settling by filling spaces between soil particles. The soil matrix gains additional strength from the presence of EPS, increasing the soil's compressive strength.

On the compressive strength of medium plastic soil, shredded EPS has a moderately positive impact. The EPS particles continue to fill the gaps, improving the soil's density and stability. Due to the soil's inherent plasticity, the improvement in compressive strength could not be as large as it would be in low-plastic soil. Limited impact of shredded EPS on high plastic soil's compressive strength. The soil's high degree of plasticity may make it more difficult for the EPS particles to efficiently fill spaces and increase compaction. To a lesser extent than low or medium plastic soil, EPS can slightly contribute to the increase of strength and aid in reducing settlement.

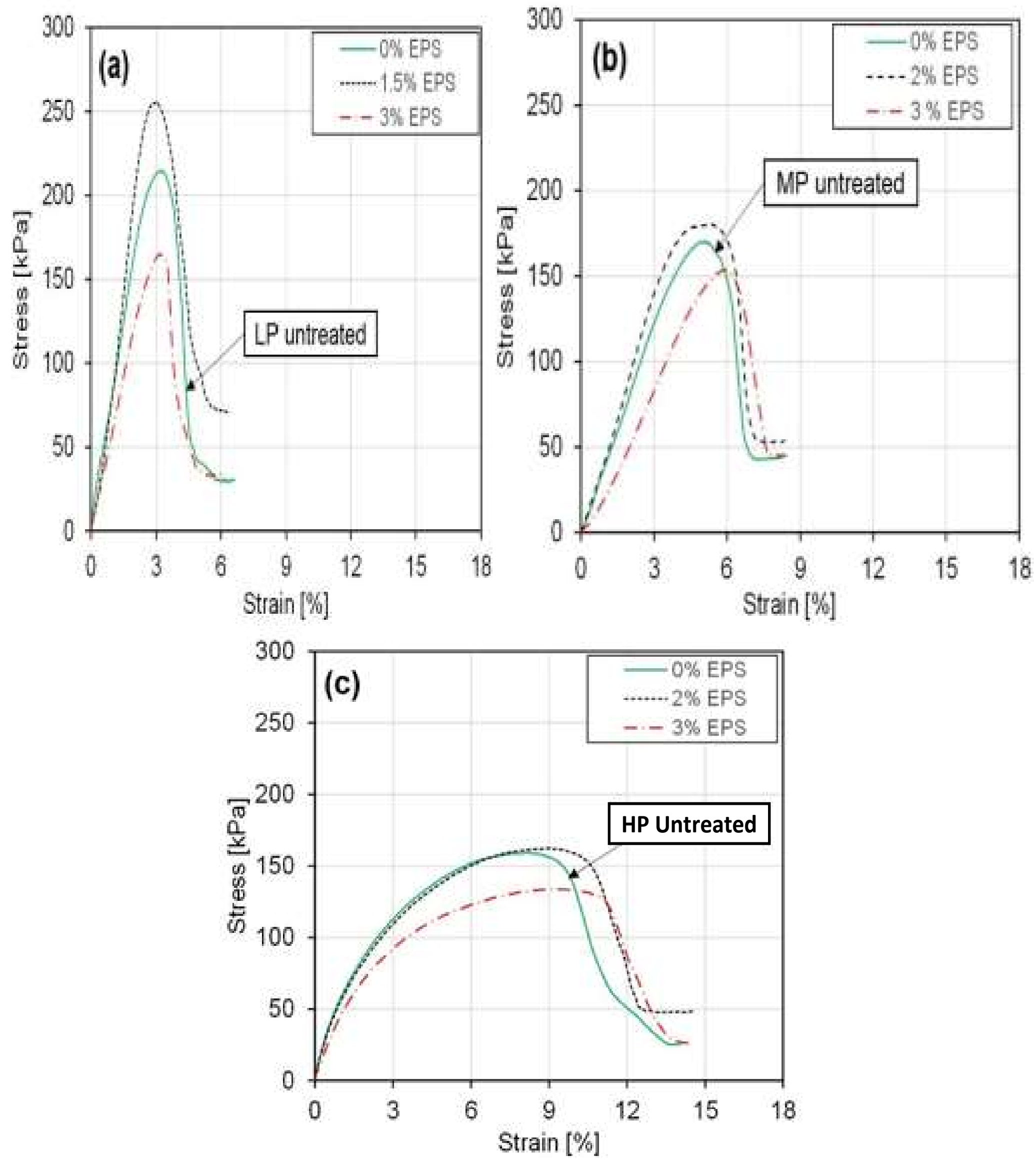

Figure 4.5 Compressive Strength Curve for Different Soil

The illustrations show the stress-strain response of Shredded-EPS treated soils and untreated soils (0% EPS). The specimens with respective optimum amounts of water and different levels of EPS were prepared and tested under a uniaxial unconfined compression state. It was witnessed that, regardless of clay type, there is an increase in Shredded-EPS content, UCS increases up to a certain limit and then reduces afterward. The maximum UCS was observed at 1.5%, 2%, and 2% EPS content in all three clayey soils respectively.

This is because the inclusion of EPS in soils up to specific limits improves the interlocking phenomenon. However, other factors such as volume of EPS beyond the optimum threshold, specimen size, and size of Shredded-EPS all had been found to vigorously effect the stress-strain behavior of EPS-treated soils [119], [121]. The EPS content corresponding to the maximum UCS is referred to as the optimum EPS content for the clay type. Here, 1.5%, 2% and 2% Shredded-EPS are regarded as optimum EPS content for LP, MP, and HP respectively. Although the increase in EPS beyond optimum content causes UCS to decline, the failure strain was found to rise with increasing EPS content and resulted in the transformation of brittle to ductile behavior in all cases. This is attributed to the fact that OMC was higher for higher EPS content, as described in section 4.1, which resulted in decreased UCS.

It is worthwhile to note that, with a gradual increase in EPS content in clayey soils, silt particles are embedded into Shredded-EPS and improves interlocking and binding effect under uniaxial compression condition up to 1.5% (for LP) and 2% EPS content (for MP and HP). However, beyond this threshold value, direct contact between Shredded-EPS and silt particles diminishes resulting in decreased UCS. Maximum strength increase resulted in low plastic soil due to a high amount of silt content as silt particles are of irregular shape and large size which paves the way for interlocking phenomenon with shredded-EPS particles. Silt content decreases in medium plastic and high plastic soils which results in poor interlocking with the EPS particles. It is also anticipated that a certain increase in shredded-EPS volume beyond the optimum level in soil specimens leads to an increase in OMC due to their water-absorbing characteristics, and results in decreased UCS. Furthermore, adding EPS beyond the optimum value could lead to segregation and workability issues [118]. In addition, at lower concentrations of EPS up to 1.5% and 2%, pore volume is anticipated to be lower causing denser microstructure [119].

4.3 Shear Strength Behavior

The angle of internal friction changed dramatically due to the incorporation of shredded EPS. The plots between shear displacement and shear stress are presented in Fig. 4.6. The angle of internal friction has been enhanced initially due to the interlocking mechanism and dilution effect. Shredded EPS particles have irregular shapes and can interlock with each other and the adjacent soil particles. The interlocking mechanism can enhance the overall shear strength of the soil mass, which at first causes the angle of internal friction to rise. The introduction of shredded EPS increases the overall volume of the soil mass without considerably contributing to the shear strength. This dilution effect decreases the proportion of clay soil particles, which generally have a lower angle of internal friction compared to the EPS particles. Because clayey soil particles normally have a smaller angle of internal friction than EPS particles do, this diluting mechanism lowers their percentage in the soil mass. The average angle of internal friction increases initially.

The angle of internal friction has been decreased beyond a certain percentage of shredded EPS mixed in clayey soils due to particle lubrication, compression and compaction, and particle breakage. Shredded EPS particles that have settled into the soil mass over time and percentage increment, may eventually function as lubricants between the clayey soil particles. This lubricating effect lowers the angle of internal friction by reducing the interparticle friction. Because EPS particles are compressible, applying weight to them can cause them to compress and compact. As a result of the compression, there is less available void space for particles to fill in the soil mass. Because there is less available void space for particles to interlock, the angle of internal friction is reduced in the compacted soil. Due to their brittle nature, the shredded EPS particles may break during loading. Smaller particles may be formed because of this rupture, which may not effectively interlock or considerably increase the shear strength of the soil. Consequently, the angle of internal friction reduces.

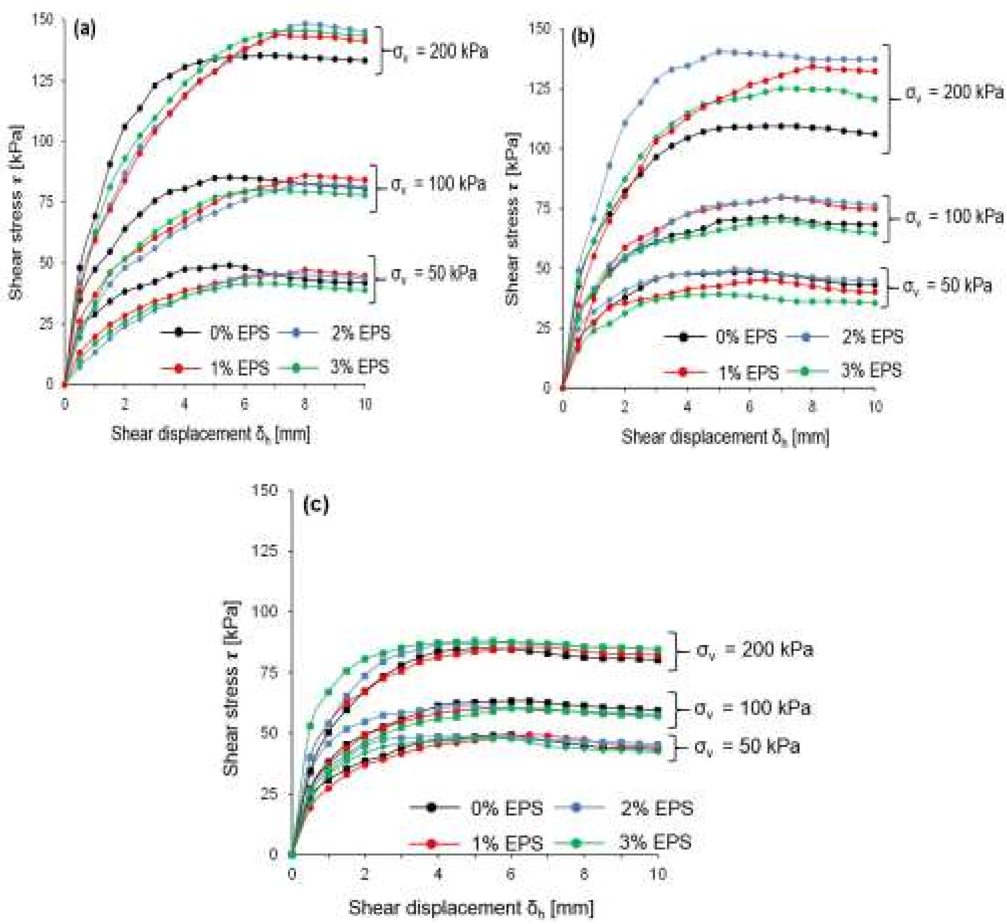

Figure 4.6 Shear Displacement vs. Shear Stress Relationship for Clayey Soils with Shredded-EPS

Figure 4.6 shows the shear stress-displacement behavior of three different Shredded-Mixed clayey soils tested under three different vertical stress stages (σ_v = 50 kPa, 100 kPa, 200 kPa) and EPS contents (EPS = 0%, 1%, 2%, 3%). It was witnessed that an increase in EPS content leads to a modest decrease in peak shear stress for LP, MP, and HP respectively. However, at 200 kPa vertical stress, some unique trends were observed in all three soils.

It was also noticed that untreated low plastic soil (0% EPS) shows higher peak shear resistance, up to 100 kPa vertical stress than the treated soils (EPS > 0%). However, peak shear resistance decreased at 200 kPa vertical stress as shown in Figure. On the other hand, subsequent increases in EPS content up to 3% caused a gradual decrease in peak shear resistance. Contrary to that, the trends were unique under 200 kPa vertical stress. In this case, an increase in EPS content up to 2% causes an increase in peak shear stress followed by a marginal decrease at 3% EPS content. Similar trends were witnessed in other soils as given in Figures (b and c).

Low-plastic soils have a low amount of clay and a larger proportion of silt particles. The stability and angle of the internal friction of low plastic soil can be improved by the addition of shredded EPS. The shear strength of the soil can be increased by the interlocking structure of the EPS particles, making it more stable.

Medium-plastic soils contain a moderate amount of clay and silt particles. The angle of internal friction can change when shredded EPS is added to medium plastic soil. It depends on various factors such as the EPS particle size, compaction, and the characteristics of the clay. The angle of internal friction may decrease in some cases because the EPS particles may create voids or weaken the interparticle bonds. However, the angle of internal friction may rise if the EPS particles successfully interlock with the soil particles.

A large percentage of clay is present in high-plastic soil, which makes it very cohesive and prone to shrink-swell behavior. Shredded EPS often decreases the angle of internal friction when added to high plastic soil. As lubricants, the EPS particles may reduce the cohesive forces between the clay particles, resulting in a reduction in shear strength.

When shredded EPS is introduced into clayey soils, it can lead to a reduction in cohesive strength due to various reasons such as reduced particle interlocking, decreased water retention, alteration of soil fabric, and increased compressibility.

Fine particles in clayey soils naturally interlock with one another, improving their cohesive properties. Shredded EPS, on the other hand, causes spaces or voids between the EPS particles and the clay particles, which disrupts the interlocking process. This weakens the overall cohesiveness and interparticle bonding. Because they can hold a lot of water, clayey soils maintain their cohesive properties. The hydrophobic property of shredded EPS causes it to repel water. The ability of the soil to hold water may be hampered when EPS is added to the soil mixture. This causes the water content of the mixture to drop, which lowers the cohesion strength of the mixture. The fabric or arrangement of the particles in the soil matrix can change with the addition of shredded EPS. The natural structure of clay particles is disturbed by the presence of EPS particles, which offer a distinct size and shape distribution. This modification may lessen interparticle interactions and hinder the mixture's cohesion. Compared to clayey soils, EPS is a lightweight material with low stiffness. Under applied stresses, EPS particles might experience compression and distortion after being integrated into the soil. The mixture may settle and consolidate because of this deformation, which will reduce the cohesion strength.

Low clay content and relatively more granular soil properties are referred to as low plastic soil. Low plastic soil may experience a minor drop in cohesive strength when shredded EPS is added. The soil becomes more compressible because of the EPS particles filling the spaces between soil particles, which lowers interparticle friction. However, the inclusion of additional fine particles or cementing chemicals may allow the low-plasticity soil to retain some of its natural cohesion.

Medium plasticity soil contains a moderate amount of clay, which contributes to its cohesive properties. When shredded EPS is mixed with medium plastic soil, the cohesive strength reduction is likely to be significant. The EPS particles act as lubricants, reducing the attractive forces between clay particles and making it easier for them to slide past each other. The soil's cohesive strength is significantly decreased as a result.

Because it contains a lot of clay, high plasticity soil is very cohesive. The cohesive strength drop is anticipated to be significant when shredded EPS is added to high-plastic soil. The clay particle bonds are broken down by the EPS particles, which also create voids in the soil matrix. As a result, the effective stress and interparticle friction are decreased, which significantly reduces the soil's cohesive strength. The highly plastic soil can change into a more granular condition with enhanced compressibility.

To fairly compare the shear behavior of all the three types of soils treated with Shredded-EPS, the shear stress responses against shear displacement were analyzed at a given vertical stress (100 kPa) and a fixed Shredded-EPS content (2%) as shown in Figure. As expected, it was observed that higher shear resistance is mobilized in low plastic clayey

(LP) soil followed by medium plastic (MP) and high plastic (HP) clayey soils (refer to the below figure). This is because of the finer particle size of HP as compared to other soils, which due to higher surface area and plasticity, leads to higher optimum moisture content and lower maximum dry density. Eventually, this leads to reduced shear resistance in HP treated with EPS. Figure 4.7 shows the failure strength envelops developed according to Mohr-Coulomb theory at the given EPS content (2%) for LP, HP, and MP. The results show that higher friction was mobilized by LP followed by MP and HP. However, cohesion was found to rise from LP to HP.

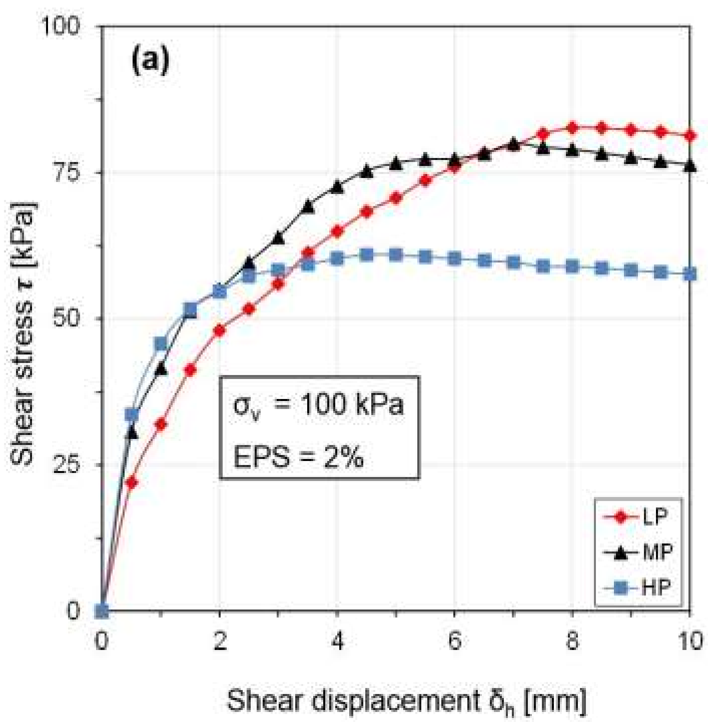

Figure 4.7 Shear behavior of LP, MP, and HP at the given displacement and EPS content

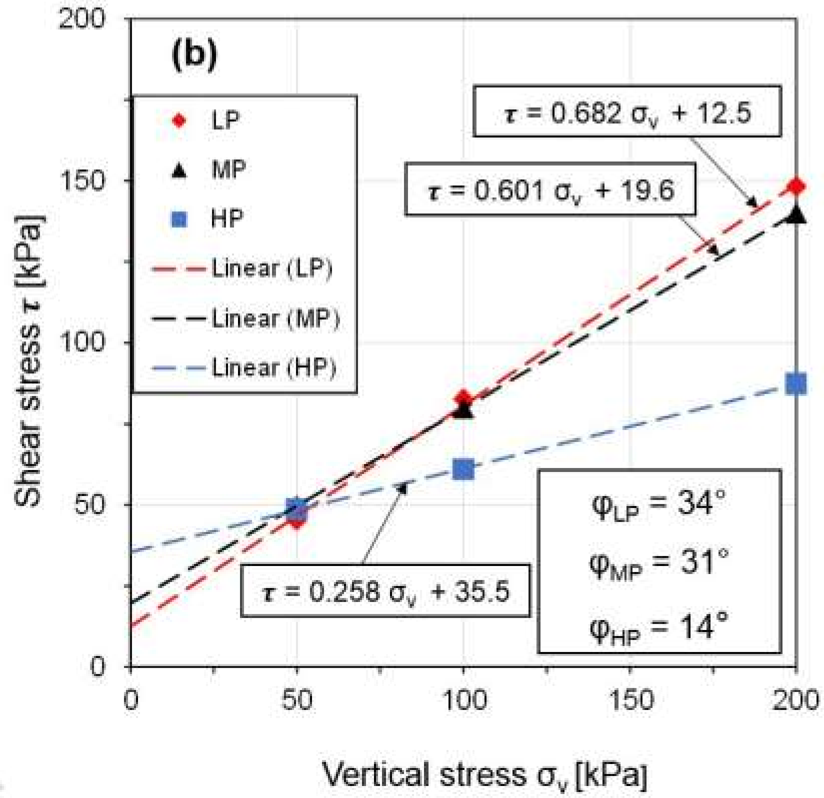

Figure 4.8 Shear behavior of LP, MP, and HP at the given vertical stress and EPS content

Figures 4.7 & 4.8 show the effect of EPS content on the shear strength parameters of LP, MP, and HP. The cohesion decreases significantly with the increase in EPS while the opposite trend was observed in the case of the angle of internal friction. The minimal difference was observed for HP soil while the variation of cohesion and friction angle was found to be more pronounced in the case of LP and MP-treated specimens. This is primarily due to the high clay fraction in HP soil. As cohesion between clay-clay particles is higher due to the absorbed double layer and high electromagnetic charge on the clay particles, it is difficult to break the bond which causes a little decrease in cohesion in HP soil. Secondly, compared to MP and HP soils, LP soil contains a greater percentage of silt particles due to which decrease is cohesion is higher in this plasticity of soil.

Shredded-EPS inclusion produces an interlocking effect with angular silt particles that tends to enhance friction angle in LP and MP soil. On the other hand, HP soil possesses a low amount of silt content and higher clay content. Clay particles are platy and possess minerals (i.e., montmorillonite) that absorb higher amounts of water leading to softening the soil skeleton upon interaction with water and reducing friction between particles. Another reason could be the lower bonding effect of clay particles with Shredded-EPS due to platy structure which causes an insignificant change in the angle of internal friction in HP soil. Overall, the effect of Shredded-EPS is more pronounced in LP and MP soils as compared to HP soils.

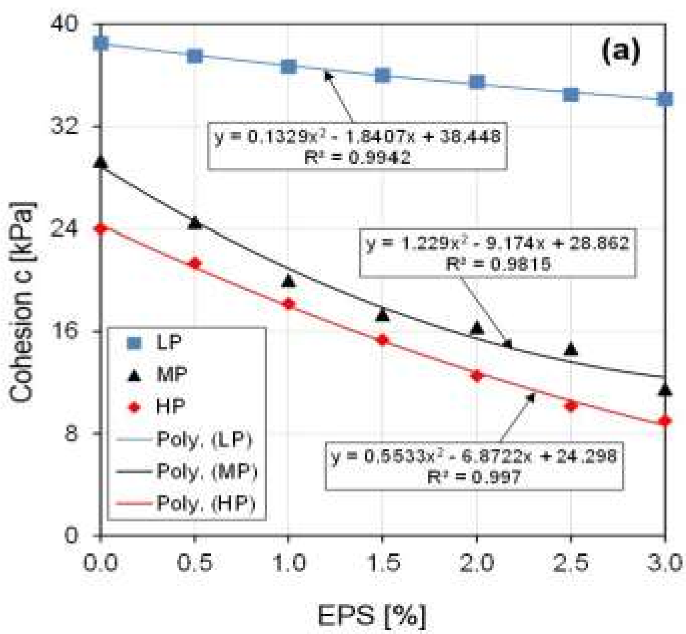

Figure 4.9 Effect of EPS on Cohesion of clayey soils

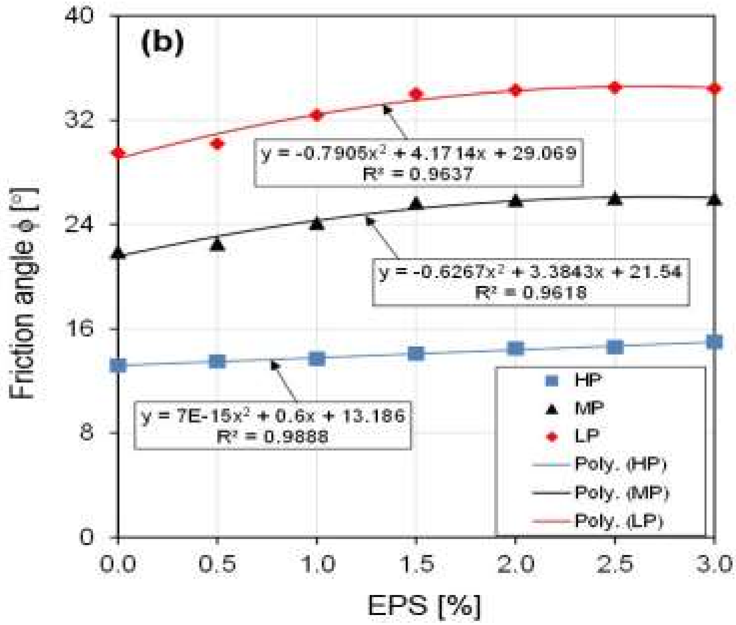

Figure 4.10 Effect of EPS on Angle of internal Friction of clayey soils

4.4 Consistency of shredded EPS mixed clays

A reduction in the soil's plastic limits, liquid limits, and plasticity indices can result from the addition of shredded EPS to clayey soils. Many factors that affect the behavior and properties of the soil are responsible for this effect such as low density and lightweight, porosity and permeability, mechanical interlocking, and reduced water content.

Shredded EPS is a low-density, lightweight material. It lowers the mixture's overall density when added to clayey soils. The soil's plasticity is influenced by the low density of EPS, which reduces the soil's weight.

EPS contains numerous interconnected void spaces or pores. When EPS is combined with clayey soils, these pore spaces add more porosity and permeability to the soil matrix. Better drainage is made possible by the greater porosity, which also lowers the soil's ability to retain water. The cellular structure of the lightweight EPS material causes voids or air pockets to form in the soil mixture. These spaces make the soil more porous, which facilitates the movement of water. As a result, the liquid limit is reduced since the soil needs less water to attain the liquid state.

Particles of Shredded EPS irregular shapes create mechanical interaction with the clayey soil particles. This interlocking lowers the soil's plasticity, and the alignment and aggregation of soil particles are effectively disturbed, which reduces plasticity. As a result of its closed-cell structure, EPS has minimal water absorption abilities. The EPS particles work as barriers when combined with clayey soils, lowering how much water the soil retains. The lower liquid limits observed in the soil mixture are a result of this reduced water retention capacity. The microstructure of clayey soils can change when EPS particles are added. Typical particle arrangement in clayey soils is plate-like or flaky, which favors the development of a dense network of interparticle interactions. The addition of EPS, meanwhile, disturbs this balance, weakening the interparticle interactions and soil cohesion. The soil's capacity for holding onto water and keeping its plasticity is consequently reduced, which lowers the liquid limit.

EPS is hydrophobic which means it repels water from adhering to it. EPS particles form a barrier that reduces the soil's ability to absorb water when mixed with clayey soils. Due to the decrease in water content, the soil is less plastic and has lower plastic limits. A lightweight, rigid material like EPS can provide the soil mixture with more mechanical stability. The shear strength and stability of the clayey soil are increased when EPS particles are dispersed throughout the soil, producing a network of reinforcement. Therefore, by strengthening the soil matrix and reducing excessive water flow, the addition of shredded EPS can lower the liquid limit.

In low-plastic soil, the incorporation of shredded EPS can have a significant effect on plasticity reduction. EPS particles act as a filler and create air pockets within the soil matrix, improving its overall porosity and reducing compaction, decreasing water retention, and improving drainage because of the enhanced porosity and reduced plasticity index. In addition to stabilizing the soil structure and avoiding excessive shrinkage or expansion, the EPS particles also contribute to soil stability.

Shredded EPS can still contribute to decreased plasticity in medium-plastic soil, although the effects could be slightly less prominent than in low-plastic soil. The EPS particles keep the soil more porous and less compact, which improves drainage and lowers water retention. The soil's total plasticity index declines, although the extent of that drop will depend on the soil's initial plasticity.

Clay content is typically high in high-plastic soils, making plasticity reduction challenging. Even though shredded EPS remains capable of assisting with plasticity reduction, its effectiveness might be limited in such types of soil. Although the high clay content may limit the ability to spread evenly throughout the soil, the EPS particles can improve soil porosity to a certain extent. As a result, the plasticity index may decrease somewhat but may not increase to the same degree as in low or medium-plastic soil.

Atterberg Limit tests (LL, PL) were performed on LP, MP, and HP soils having 0%, 1%, 2%, and 3% shredded EPS content. In the present study, it is worth noticing that liquid limit, plastic limit, and plasticity index show a considerable drop for shredded-EPS soil mixture prepared using all three types of clayey soils. The activity of shredded-EPS mix, i.e. ratio of PI and clay size fraction [122], also decreases with the increase of shredded-EPS content. Activity decreases up to 25% in high plastic soil with Plasticity Index (PI) falling from 31.5% to 23.8% as shown in Figure 4.11.

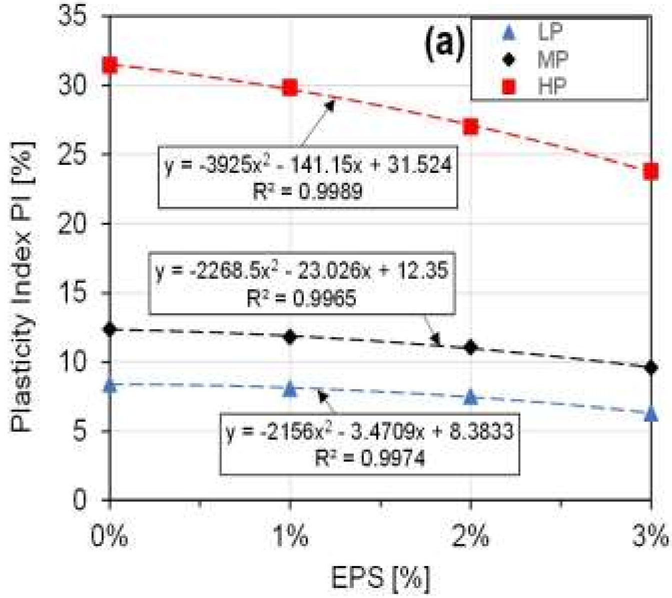

Figure 4.11 Effects of Shredded EPS on PI of the shredded-EPS mixed clayey soils.

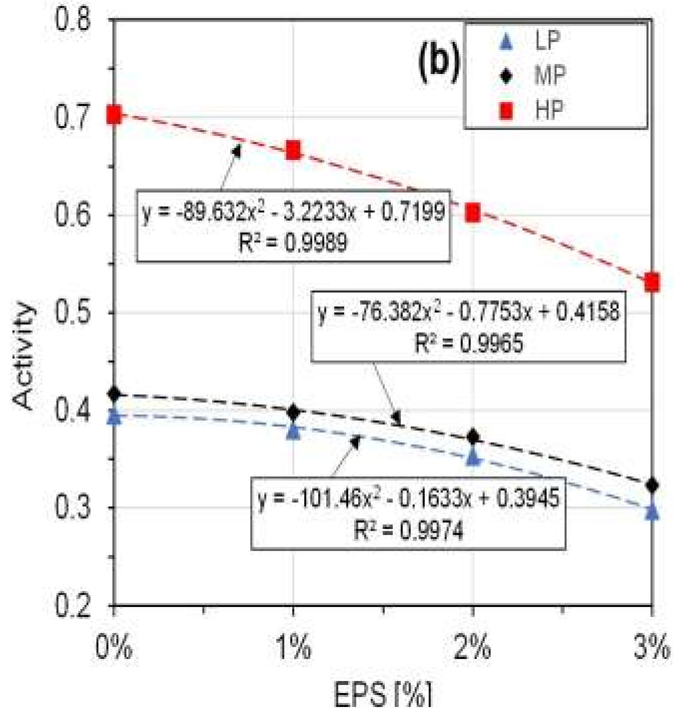

Figure 4.12 Effects of Shredded EPS on Activity of the shredded-EPS mixed clayey soils.

In clayey soils, when shredded EPS is mixed with the soils, it increases the stiffness and consistency of clayey soil. Shredded EPS creates more void space that makes the soil matrix dense and reduces compressibility potential. The incorporation of shredded EPS reduces the PI of clayey soil due to the non-plastic nature of EPS material, decreasing the clay fraction. The soil structure becomes more stable and less susceptible to shrinkage and swelling potential due to moisture variations. A similar trend is also followed for low-plastic and medium-plastic soils. As compared to shredded EPS, EPS beads' inclusion in expensive soils also causes a reduction in swelling pressure and dry unit weight. Liquid and plastic limits also decrease with an increase in the percentage of EPS. Such a significant reduction in PI and activity due to the mixing of shredded-EPS is a clear indicator that the workability of such shredded-EPS mixtures is significantly superior to those of the untreated soils, making it easier to handle.

4.5 Optimized Framework for Field Applications

Based on the findings of shredded-EPS mixed clayey soils, a framework is proposed for its potential field application as shown in Figure 4.13. Normalized UCS values for different specimens were obtained at respective normalized unit weight values. Normalized UCS refers to the ratio between a UCS of Shredded-EPS treated soil specimens to the corresponding untreated specimen as given by Eq. 1.

$$\mathrm{UCS_n} = \frac{\mathrm{UCS_t}}{\mathrm{UCS_u}} \qquad (1)$$

Where UCS_n is the normalized unconfined compressive strength value, UCS_t (KPa) is the unconfined compressive strength of treated soil, and UCS_u (KPa) is the unconfined compressive strength of untreated soil. Similarly, normalized unit weight/normalized densities can be defined as Eq. 2.

$$\gamma_n = \frac{\gamma_t}{\gamma_u} \tag{2}$$

Where γ_N is the normalized unit weight, γ_T (g/cm^3) is the unit weight of treated soil, and γ_U (g/cm^3) is the Unconfined compressive strength of untreated soil.

Three zones, namely zone A, zone B, and zone C, are proposed considering the relationship between normalized UCS and shredded-EPS content, as shown in Figure 4.13. The zone of normalized UCS values equal and greater than 1.0 is regarded as the most favorable zone, as the strength of Shredded-EPS mixed clayey soil specimens has a strength greater than that of the corresponding untreated clayey soils. As per the results shown in Figure 4.13, zone B is the most favorable zone for all three clayey soils with values of $UCS_n \geq 1$ corresponding to γ_n values between 0.86 to 0.95. Other zones A and C are relatively less favorable due to lower normalized strength values.

Based on this approach, authors propose the use of shredded-EPS content ranging from 1% to 2.5% for the potential field applications to respective clayey soil types. The intended goal of the current study is to propose a lightweight fill mixture of respective clayey soils with sufficient strength, i.e. higher than that of the corresponding untreated clayey soils. Thus, zone B provides not only reasonable strength but also a considerable lightweight mixture of clayey soils.

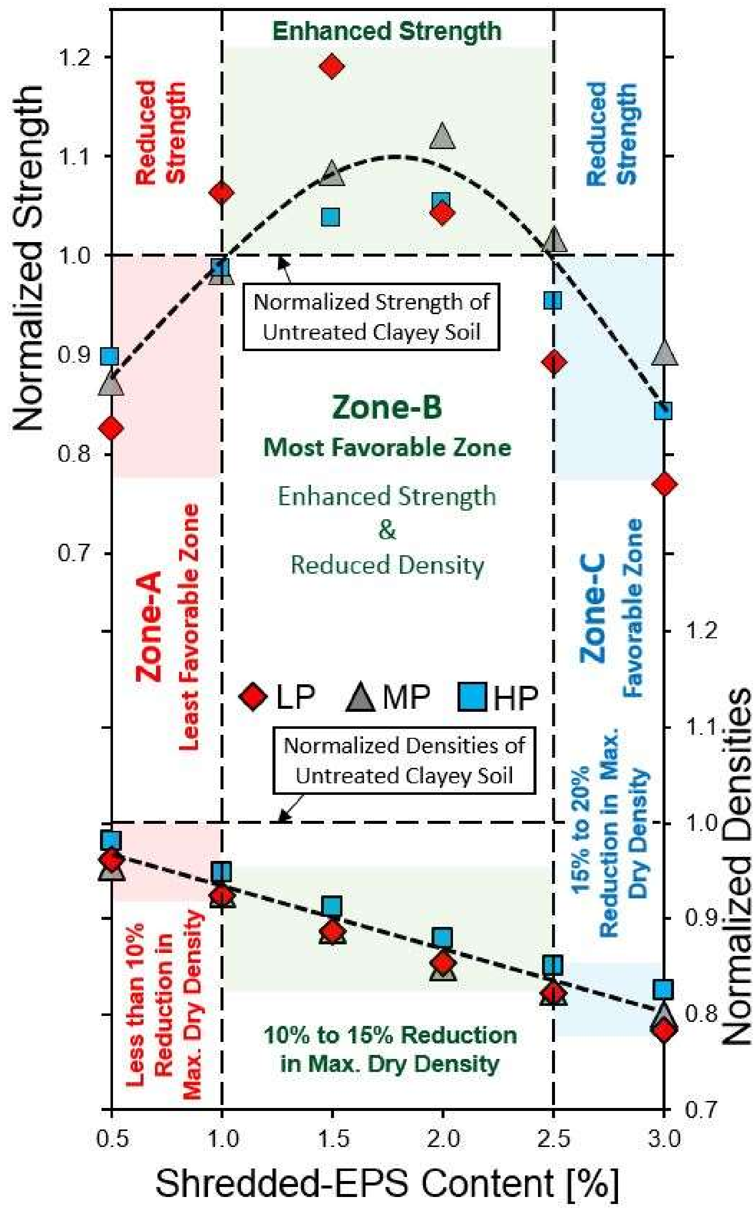

Figure 4.13 The proposed framework for different soils mixed with shredded-EPS content for potential field application.

Clayey soils are abundantly present on sites specifically in Pakistan, and generally all over the world. Shredded-EPS can be utilized in different plasticity clays as per weight and strength requirements. In this study, Zone B is advised as the most favorable zone due to its high strength and considerable reduction in unit weight for all three types of soils.

The percentage of shredded EPS for clayey soils in the zone ranges from 1% to 2.5%. Zone B criterion can be applied to projects where lightweight soil with improved bearing capacity /strength is required i.e., structure of weak soils, slope stability, and embankments. Zones B and C can help in achieving the criteria of lightweight fill with slightly compromised strength i.e., behind a retaining wall where minimal weight of soil is required to reduce lateral earth pressure, replacement with weak soil layers with high densities to reduce load underneath.

EPS beads and Shredded-EPS have their distinctive properties. Shredded-EPS shows considerable gain in UCS in LP and MP soils at 1.5% and 2% respectively. Whereas the addition of EPS beads causes a reduction in UCS in clay samples. The studies have revealed that fine beads tend to decrease UCS in clayey soils as compared to coarser beads [123].

Similarly, shear strength parameters are significantly affected by the addition of EPS beads and Shredded-EPS. Replacing clayey particles with smooth and spherical beads tends to decrease the angle of internal friction. However, the inclusion of Shredded-EPS angular and rough particles in fine-grained soils causes an interlocking effect with soil silt particles which maintain and increase the angle of internal friction. The cohesion of clay-clay particles is greater than the cohesion of clay-EPS particles [31]. In both beads and Shredded-EPS cases, cohesion decreases with an increase in EPS content.

4.5 Field Applications of Shredded EPS Mixed Soils

Engineered materials called composites combine two or more different components to produce a material with enhanced engineering qualities. One such use for composite materials is the addition of shredded Expanded Polystyrene (EPS) to clayey soils. The process, often referred to as EPS soil stabilization or EPS geotechnical engineering, has several benefits and is used in a variety of real-world applications.

Soil Stabilization

Due to their high plasticity and poor strength, clayey soils can pose challenges in construction projects. The composite material increases the soil's overall stability and strength by mixing shredded EPS with clayey soils. The soil matrix is reinforced with EPS, increasing the soil's capacity to support loads, and minimizing settling. This approach makes it possible to build strong foundations for structures like roads, buildings, and other infrastructure in places with weak or expansive soil.

Lightweight Fill

Due to its lightweight, EPS is frequently utilized as filler in several building applications. The composite material that results from mixing shredded EPS with clayey soils is designed to be lighter, lowering the fill's overall weight. This is particularly useful when the structure's weight needs to be kept to a minimum, like when building embankments, green roofs, or lightweight backfill for retaining walls. Additionally, less load exerts less stress on the earth below, minimizing excessive settlement.

Drainage Improvement

Poor drainage qualities of clayey soils can result in waterlogging and other problems. The composite material improves these soils' drainage capacities by incorporating shredded EPS into them. The EPS particles act as channels, facilitating the movement of water through the soil and reducing the accumulation of excess moisture. Stormwater management systems, sports grounds, landscaping, and other situations all benefit from its use

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusive Remarks

Shredded EPS has substantially enhanced mechanical characteristics, including shear strength, compressibility, and bearing capacity, in clayey soils. This improvement is due to the special mechanical and physical characteristics of EPS, which improve soil cohesion and lessen the susceptibility of the soil to deformation under stress. The study shows that the proportion of shredded EPS added affects the mechanical characteristics of the mixed soil. Excessive EPS content may result in a deterioration in stability due to increased lightweight and void content beyond a recommended range of EPS content.

5.2 Research Findings

In the present investigation, clayey soils (LP, MP, and HP) were experimentally tested for the development of lightweight fill using clayey soils treated with shredded EPS. The compaction, shear, and uniaxial compression behavior of EPS-treated incorporated clayey soils were analyzed. The current study's main findings include the following:

- The clay mixes comprising Shredded-EPS provide a mixture of significant lightweight fill material. All types of clays of varying plasticity indices showed a weight reduction that was notable at increasing EPS concentrations.
- For LP, the maximum dry density (MDD) decreases by as much as 22% (1.45 g/cm^3). Similar results were reported for MP and HP mixed soils, where the percentage reduction in MDD was determined to be 19% and 17%, respectively, at the highest utilized EPS content (3%).

- The incorporation of Shredded-EPS leads the friction angle of the LP, MP, and HP to increase while the cohesion between the clay-EPS particles gradually decreases. Reduced soil-soil contact caused a decrease in cohesiveness, whereas increased silt-EPS grain contact increased the friction angle.
- Mixing shredded EPS with clayey soils results in a sufficiently strong fill despite being light. By applying Shredded-EPS up to 1.5% in LP soil and 2% in MP and HP soils, the greatest UCS was observed. As a result, for a given range of shredded-EPS percentages, the lightweight combinations might produce better strength in addition to having low density.
- A framework has been suggested for the selection of the appropriate shredded-EPS content considering the requirements of the projects in terms of strength and density requirements. This framework may be easily utilized in the field for the usage of Shredded-EPS combined with LP, MP, and HP.

5.3 Future Suggestions

These are the following suggestions for the future research work:

- To assess the mechanical behavior and compaction properties of clayey soils mixed with shredded expanded polystyrene (EPS) under various environmental circumstances, carry out long-term performance experiments. This will give important information about the designed soil mixtures' stability and durability over time.
- To employ life cycle assessments and carbon footprint calculations, investigate how incorporating shredded EPS in clayey soils may affect the environment. Compared to conventional techniques, assess the advantages and disadvantages of this sustainable soil improvement approach.

- To examine the effects of adding chemical additives on the compaction and mechanical properties of clayey soils when incorporated into shredded EPS. Investigate the methods by which different additives can improve the soil mixture's cohesiveness and stability.
- To investigate the shredded EPS mixed with the thermal conductivity and insulation qualities of the soil. Examine how these mixtures might help infrastructures and buildings use less energy.
- To verify laboratory results and evaluate the usefulness of shredded EPS mixed clayey soils in practical applications, conduct field-scale tests. Keep track of the long-term behavior and performance of designed soil mixtures in real-world loading and environmental scenarios.
- Under various slope angles and rainfall conditions, assess the slope stability of slopes strengthened with shredded EPS mixed with clayey soils. This study will aid in evaluating how these mixes might be used in geotechnical engineering applications.

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