In The Name of God

Stabilization of clay soil with glass powder

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I certify that all material in this dissertation which is not my own work has been identified and that any material that has previously been submitted and approved for the award of a degree by this or any other University has been acknowledged.

Abstract

Soils in construction sites are not always favourable and often their mechanical properties need to be improved by mixing the soil with other stabilizing materials. In this research, Shiraz clay soil with a specific gravity of 2.65 and an optimal moisture content of 17% was stabilized with glass powder (GP) with content ratios of 0, 5, 10, 15, 20 and 25% in order to improve the soil properties. Then Atterberg limit tests, consolidation tests, uniaxial compression tests, direct shear tests and compaction tests were performed on samples with different GP contents to evaluate the effects of the GP on the stability and strength of the clay. The results showed that, by increasing the glass powder content of the clay, the Atterberg limits decreased. A correlation was observed between adding glass powder and consolidation indexes. The soil samples without glass powder showed the highest void ratio, which decreased with increasing pressure. The inclusion of 5%, 10%, 15%, and 20% glass powder yielded a distinct void ratio pattern during consolidation tests. The highest compressive strength of the samples was observed for the soil with 15% glass powder. As the glass powder content increased up to 20%, the optimum moisture content (OMC) decreased, and the maximum dry density (MDD) increased. The results suggest a range of 15% to 20% glass powder content as optimal for enhancing the strength of stabilized clay without utilizing any alkali-activated materials. Scanning electron microscopy analysis provided visual insight into the microstructure, showcasing the interaction between glass powder and clay at varying concentrations.

Keywords: Stabilization of clay; glass powder; compressive strength; soil consolidation; uniaxial test; compaction test

Abbriviation List:

GP	Glass Powder
OMC	Optimum Moisture Content
MDD	Maximum Dry Density
SW	Well-graded Sand
GP	Gravely Sand
SP	Poorly graded Sand
GW	Well-graded Gravel
MH	Silt with a high plasticity
MC	Clay with a moderate to high plasticity
γ_{dmax}	Dry unit weight
W_{opt}	Optimum moisture content
MGP	Mixed coloured glass powder
CBR	California Bearing Ratio
CL-ML	Silty clay with low plasticity
CL	Clay with low plasticity
MFS	Microfine slag
µm	Micrometers
µS/cm	Microsiemens per centimeter
UCS	Unconfined compressive strength
ASTM	American Society for Testing and Materials
Gs	Specific gravity
ρ	Dry density
LL	Liquid limit
PL	Plastic limit
PI	Plasticity index
Cc	Compression index

Cs	Swelling index
SEM	Scanning electron microscopy
AAMs	Alkali-activated materials
XRD	X-ray diffraction
EDS	Energy-dispersive X-ray spectroscopy

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Chapter 1:Introduction

In most construction projects, the inappropriate mechanical and chemical properties of subsoil have been a serious concern of geotechnical engineers. More and larger construction projects are necessary for the development of cities and countries, which highlights the need to correct problematic soils. In most of the projects, engineers are faced with situations where it is not possible to change the project site, or replacing the soil of the project site with suitable soil is time-consuming, costly, and difficult. As a result, choosing the method of stabilizing the existing soil in the place seems to be the most reasonable method.

Soil improvement has a special place in geotechnical engineering. With the increase in population growth and the development of industries, there is a shortage of suitable land to build the desired structures. Therefore, in many cases, people inevitably turn to lands with lower quality in terms of geotechnical characteristics, to build structures. In such cases, in order to build a suitable structure, the quality of the soil should be improved in terms of geotechnical parameters so that the soil performs properly under the forces caused by the structure.

In general, soil properties should be improved for the following reasons:

- Reduction of settlement of the structure
- Improving the shear strength and bearing capacity of the soil
- Increasing the safety factor against the slope of embankments and earth dams
- Reducing the shrinkage and swelling properties of the soil

This research aims to study the behaviour, strength and stability of a clay soil stabilized using glass powder, through a programme of laboratory experiments.

1-1 Soil

Soil is a mixture of minerals, organic materials, gases, liquids and organisms that together make life possible. The earth's soil body is called biosphere. Soil consists of a solid phase consisting of minerals and a porous phase consisting of water and gas [1].

1-1-1 Soil formation

Soil formation is a multifaceted phenomenon shaped by numerous elements including the original material, environmental conditions, land features, living organisms, and the passage of time. As rocks erode over time due to weathering, they gradually disintegrate into finer particles, which, together with organic material, constitute soil. This intricate process encompasses physical, chemical, and biological interactions, ultimately giving rise to identifiable soil layers or horizons. Appreciating the mechanisms behind soil formation is pivotal for evaluating its characteristics, behaviour, and relevance to engineering endeavors.

1-1-2 Components of soil

- Hard materials:

Hard materials are composed of mineral compounds, but they may also contain some organic materials. These mineral compounds are obtained from the destruction of primary rocks or mother rocks, which are sometimes accompanied by fresh salty and colloidal materials.

- Water in the soil:

The water in the soil consists of rain and infiltrated water, absorbed water and underground water.

- Air in the soil:

In general, there is air along with water inside the pores of the soil. The amount of air in the soil depends on the amount of water in the soil [1].

1-1-3 Classification of soils

Soils are mainly divided into two categories: fine-grained and coarse-grained.

Coarse-grained soils have a larger pore volume than fine-grained soils; but the water holding capacity in them is less due to their larger particles. Fine-grained soils have fewer pores than coarse-grained soils, but their ability to hold water is greater, and the water in them is hardly lost. Therefore, coarse-grained soils have higher permeability than fine-grained soils [2].

1-2 Clay

According to the definition of the American Association of Materials and Testing, clay consists of natural agglomerated minerals including hydrous aluminum phyllosilicates, which acquire plastic properties by adding sufficient moisture and become rigid upon drying [3]. In the classification of soils, clay is placed in the fine-grained group. Clay particles are usually defined as having a size smaller than 0.002 mm. But sometimes particles with sizes of 0.002 to 0.005 mm may also be defined as clay. The particles that are placed in the clay class according to their size do not necessarily include clay minerals. In soil mechanics, clays refer to particles that, if mixed with a limited amount of water, show pasty characteristics. Pastiness is the putty-like property that clay mixed with water shows, so it is appropriate that soil particles that are classified as clays only from the point of view of size (that is, their size is smaller than 2 microns), be called clay particles instead of clay [4].

Considering that clay sources are often low-purity mixtures of clay minerals, analysis of these soils is mainly related to lower purity and/or mixed sources (common clay deposits, soils) [5].

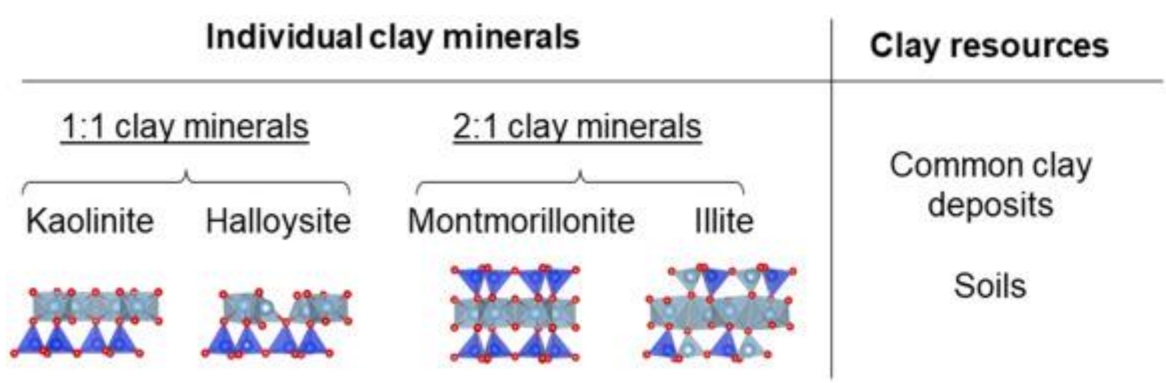

Figure 1- 1: Overview of clay resources [5]

1-3 Soil stabilization

Loose soil has always been one of the most important challenges in engineering projects. Soil stabilization is a technique that is used to change various properties of soil and increase its performance for engineering purposes. With soil stabilization, the strength and durability of soil increase and the plasticity index, permeability and swelling decrease [6]. Stabilization may also refer to the modification and improvement of the physical properties and behaviour of soil [7].

1-3-1 Classification of soil types from the point of view of stability

Stable soils: These soils serve as reliable foundations for various construction projects, offering stability and durability even amidst changing weather patterns and environmental pressures. Their consistent performance underscores their importance in engineering and land management practices, providing a solid basis for sustainable development initiatives. Examples of such soils include SW (well-graded sand), GP (gravely sand), SP (poorly graded sand), and GW (well-graded gravel). Stable soils demonstrate impressive durability against changes in the environment, staying unaffected by atmospheric elements like thawing, freezing, moisture levels, dry spells, and frost. Their ability to resist these influences means they undergo minimal changes in both volume and structural strength as time progresses [8].

Unstable soils: Unstable soils encompass a diverse array of geological compositions, notably fine-grained and stratified varieties such as MH (silt with a high plasticity) and MC (clay with a moderate to high plasticity). Additionally, soils of organic origin, characterized by their high content of decomposed organic matter, also fall within this classification. These types of soils present specific challenges because they are prone to settling, shifting, or collapsing, which can pose significant risks to construction endeavors, infrastructure integrity, and environmental conservation efforts. It is therefore crucial to comprehend their distinct characteristics and behaviours to deploy efficient measures for risk reduction and engineering interventions in regions where they are widespread [9].

1-3-2 Soil stabilization process

In soil stabilization, stabilizing materials act as glue between soil particles and strengthen its geotechnical properties, e.g., by increasing density, increasing shear strength, reducing permeability and increasing durability [6].

The stabilization process usually takes place in soft soils such as clay silt and mineral soils to achieve desirable geotechnical properties. Past experiences have shown that fine-grained soils are more ready for stabilization than coarse-grained soils, especially clay soils, which have more contact surfaces among fine-grained soils. Silty soils are very sensitive to moisture changes and are hardly stable. Organic soils also vary in their stability due to high porosity and high amount of water as well as the presence of minerals. Mineral soils have a high ion exchange capacity and can absorb the calcium ions released during the hydration process of calcium silicate and calcium aluminate cement and become hard. In these types of soils, successful stabilization is dependent on the appropriate choice of stabilizing material and the amount of added material [10, 11].

1-3-3 Stabilizers

Soil stabilizing materials can generally act as chemical stabilizers and physical stabilizers. The effectiveness of the stabilization procedure primarily relies on factors such as the dosage of the additive, the mineral composition of the soil, soil characteristics, soil pH, curing duration, freeze-thaw cycles, curing temperature, and the presence of harmful substances like organic matter and sulfates [12].

An essential aspect of soil stabilization involves incorporating binder materials that are mixed with soil to enhance its strength, durability, and water resistance. Various types of binders are frequently employed in soil stabilization such as lime, cement, fly ash, bitumen, geopolymers, calcium chloride and polymers while each offering distinct characteristics and uses [13, 14]. Waste materials can be used as binder in soil stabilization, though they are more commonly utilized as an additive or supplementary material rather than a primary binder. Binders lead to a rise in the load-bearing capacity of the subgrade. Nonetheless, it is important to note that subgrades composed of non-cohesive material experienced a lesser increase in load-bearing capacity compared to those comprising cohesive material. The Proctor compaction test findings revealed that as the quantity of binder increased, there was a corresponding rise in dry unit weight, γ_{dmax}, and, in the majority of instances, an increase in optimum moisture content, W_{opt}, except for soil-binder mixtures containing a sandy component, where some fluctuations in the results were observed [15, 16].

1-3-4 Different methods of soil stabilization

Stabilization of soils is done with a variety of methods in order to change their behavioural properties and prevent undesirable phenomena, such as liquefaction, swelling, and excessive and asymmetric settlements. These include mechanical, chemical, physical, and biological stabilization methods.

With the advancement of science and technology, there are many ways to stabilize soils. An engineer is responsible to choose the most suitable method to stabilize the soil according to all the technical issues of the conditions and limitations of the project, the economic issues of manpower and machines, the results of the tests, and most importantly, according to their engineering judgment [9]. In choosing a method for soil stabilization, an engineer should look for a method that has several features at the same time. The selected method should be suitable and applicable for the desired project. It should also be economical and reduce project costs. The time required to implement the stabilization method should not be long and preferably the desired method will cause less damage to the environment.

Among the different methods of soil stabilization, mechanical stabilization, chemical stabilization, biological stabilization, physical stabilization and electrical stabilization can be mentioned [17]. Of course, due to the interest of researchers in this field and the rapid progress of science and technology, stabilization methods are not limited to these methods and new methods are rapidly developed and used.

1-3-4-1 Chemical stabilization

In general, stabilization is a process in which natural or synthetic materials are added to the soil to improve the characteristics of the soil. Lime and cement have a special place in the chemical stabilization of the soils due to their availability, proper quality, and ease of implementation.

Soil improvement with the use of additives has been in practice for a long time in history. More than 3000 years ago, people knew and used lime mortar, lime and ash slurry. Many fire temples and buildings in the Sassanid period, whose ruins remain, were built with limestone foundations and lime mortar. Most of the great mosques of Iran, such as the Blue Mosque of Tabriz and the Jame Mosque of Isfahan, were built on the foundations of limestone shafts and lime mortar. The first stabilized cement-soil mix project was done in 1935 in Johnsville, South Carolina [18, 19].

In the chemical stabilization of the soil, stabilization takes place by adding a substance or chemicals and reacting these chemicals with minerals in the soil. Lime and cement are among the materials that have important effects on the technical characteristics of soils with the occurrence of chemical interactions. Adding stabilizing materials such as cement and lime to fine-grained soils causes several reactions including positive ion exchange reaction, aggregation reaction and pozzolanic reaction. The relative intensity of these reactions depends on the physico-chemical properties of the soil, especially the type of clay minerals, replaceable sodium ions, combinable iron, the ratio of silica to alumina, and the degree of soil weathering [17].

Past research shows that adding chemical stabilizers such as lime and cement to problematic soils improves the physicochemical properties, reduces swelling and shrinkage, changes the surface texture, and increases the strength and durability of the soil [12, 20].

Among the chemical stabilizers, sulfur, chlorine, calcium, sodium, magnesium, sodium silicate, coal ash and slag of blast furnaces can be mentioned. These materials are used alone or in combination with lime and cement to modify and improve the technical characteristics of soils [17].

1-3-4-2 Glass powder stabilization

Glass powder can be used for soil stabilization. Based on the chemical composition and additives, there are different types of glass such as brittle silica, alkaline silicates, soda-lime glass (flat glass for lamps, etc.), borosilicate glass, conductive glass, barium glass and aluminosilicate glass. Glasses are generally produced in three different colors: green, brown and colorless [21].

When glass powder (GP) is added to clay, significant changes occur at both microstructural and mechanical levels, improving the soil's overall performance. GP particles fill the voids within the clay, reducing porosity and creating a denser structure, which is reflected in the increase of maximum dry density (MDD). The addition of GP also affects the clay's Atterberg limits, increasing in plastic limit. It alters compaction behavior by lowering the optimum moisture content (OMC), making the soil less sensitive to moisture variations. On a microstructural scale, GP rearranges particles within the soil, strengthening bonds and enhancing the compressive and shear strength, particularly at optimal GP proportions. These changes lead to a more stable and durable soil matrix [22].

Reducing the size of waste glass particles increases their pozzolanic properties and leads to the production of cementitious materials during the pozzolanic reaction of cement and glass particles [23-25]. Waste crushed glass can help make the concrete more stable. Also, the random distribution of glass powder strengthens and improves soil properties [26].

Incorporating recycled glass powder, such as soda glass bottle dust, into clay soils has been shown to significantly improve various geotechnical properties. The addition of glass powder increases the soil's maximum dry density and unconfined compressive strength while decreasing the optimal moisture content, liquid limit, compression index, and swelling index. Furthermore, the soil's plastic limit increases, enhancing its workability. These improvements are attributed to pozzolanic reactions, which create additional cementitious compounds in the soil. The optimal glass powder content is around 15% by weight, which balances enhanced strength and workability. This approach not only boosts the soil's mechanical properties and durability, especially against moisture and freeze-thaw cycles, but also offers environmental benefits by diverting glass waste from landfills and reducing the carbon footprint associated with traditional stabilizers like cement or lime [26].

Also, managent of waste glass is a considerable challenge around the world due to its low recycling rate and the lack of space in material burial centers [27]. Therefore, if it is used as a mineral stabilizer in soils, in addition to its positive effects on the engineering properties of the soil, it also helps to address an environmental challenge.

In recent years the geopolymer technology has received a lot of attention due to the production of adhesives that produce less pollutants in their manufacturing process. The name geopolymer was coined in 1978 by a French scientist, Joseph Davidovich. Geopolymers are materials with a three-dimensional non-linear structure, which during the polymerization of alumina and silica, are connected by sharing their oxygen atoms and have an element or elements of alkali or alkaline earth in their structure. These materials are also known as inorganic polymers [28].

The source required for making geopolymer material is aluminosilicate source in which alumina and silica are amorphous. Natural pozzolans are found in many parts of the world, which are a source of alumina and amorphous silica. Glass powder is also full of silica and amorphous alumina. In fact, the completely amorphous structure of glass has created a great potential for its use as a supplement to raw geopolymer materials [28].

Geopolymers are a group of inorganic aluminosilicates that have been activated as alkali. The chemical structure of geopolymers is defined as follows:

$$Mn[-(SiO_2)z\text{-}AlO_2)]_n wH_2O$$

where *w* is the amount of water in the structure, *n* degree of polymerization and *z* is molar ratio of Si/Al solution [29].

1-4 Problem Statement

Today, the need to use soil to create a better life and easier transportation has expanded in cities. The increasing number of buildings, roads, highways, tunnels, railway lines, anchorages, dams, etc. are proof of this. With the rapid developments in construction projects, there is a shortage of soils with suitable conditions for constructing the foundation of structures. Therefore, there is a need to use soils with inappropriate and non-ideal geotechnical conditions for construction projects. Therefore, there is an increasing demand to improve the quality of problematic soils [30]. In order to improve the quality of problematic soils, various methods can be used, such as replacing poor quality soils with soils with more suitable characteristics, designing deep foundations, or using techniques to stabilize and improve existing soil characteristics. In such cases, stabilizing the existing soil in the place will be the best option.

One of the methods of soil stabilization is the use of chemical stabilizers. Cement is one of the most common materials for chemical soil stabilization. But the production of cement requires a lot of energy. Also, to produce 1 ton of cement, 1.5 tons of raw materials are needed, and it produces significant amounts of carbon dioxide; in total, 5 to 7 percent of the total pollution of the planet is related to the cement industry. On the other hand, a large percentage of the raw materials for the production of cement are extracted from natural sources such as gypsum, lime, silica, etc. In addition to consuming non-renewable natural resources, the extraction of these materials has many destructive effects on the environment, such as cost, time, manpower and machinery [31].

For making Portland cement, energy and non-renewable resources including limestone and clay are consumed, while these energy and resources can be used for more useful purposes. On the other hand, climate change and global warming have led to special requirements for controlling greenhouse gases [21].

As a result, researchers are always looking for suitable and environmentally friendly alternatives to cement. The term geopolymer was coined in 1970 by the French researcher Professor Joseph Davidovits. These materials are obtained by mixing geopolymer precursors with alkaline activator [32]. The characteristics of geopolymers include low density, low cost, easy synthesis, low processing temperature, excellent fire resistance, compatibility with the environment, and excellent thermal stability at high temperatures [33].

Nowadays, the use of glass and its products has become very widespread and as a result, the waste from these materials is also very large. The daily increase in the amount of glass waste will cause many problems for burial and recovery to the natural cycle. The reuse of glass waste requires a major capital spent to recirculate and produce new products. Due to the increase in the production of glass waste and its long-term decomposition by nature, the use of waste glass can improve the health of the environment. Glass shows a pozzolanic reaction in very small and soft pieces. Pozzolanic reaction refers to the formation of materials that have cementitious properties. Pozzolans, composed mainly of siliceous or siliceous-aluminous elements, lack inherent cement-like properties [34].

In general, clay soils often have problems such as high settlement, low shear strength and difficulty in compaction. Therefore, the stabilization of clays using different additives has always been of interest to researchers and engineers working in civil engineering projects and earthworks. On the other hand, the use of waste materials in soil stabilization has become common due to their economic benefits compared to the traditional additives. So, in this study, the application of glass powder, obtained from the waste of glass cutters, for stabilizion of a clay soil is investigated through a programme of experiments.

1-5 Research importance

In the past, common additives such as cement, lime, fly ash, bitumen and other materials have been used to stabilize the soil. But with the growing population and the expansion of industrialization, a large amount of waste is produced every year, which can have negative and destructive consequences on the environment and the local ecosystem. Globally, approximately 2 billion metric tons of municipal solid waste are generated each year, a figure projected to rise to 3.4 billion metric tons by 2050 if current trends continue. Industrial sectors, particularly construction, demolition, and manufacturing, contribute heavily to this waste, often including hazardous materials that pollute land, air, and water. Improper waste disposal leads to soil and water contamination, affecting local flora, fauna, and human health. Additionally, waste incineration releases harmful pollutants, contributing to air pollution and global warming. The cumulative impact on biodiversity is severe, with wildlife suffering from ingestion or entanglement in waste, disrupting natural habitats [35]. The safe disposal of household and agricultural waste is a challenging and vital concern, which has recently led to the expansion of studies on the recycling and reuse of these materials in various applications, where industrial, agricultural, domestic and civil wastes are used as valuable resources. One of the useful application of some of these wastes can be their use as soil stabilizers. For example, glass powder obtained from recycled glass in the glass industry, building glass waste and glass container waste, etc. can be used in soil stabiliztion. Glass contains various materials, including a large amount of silica, some lime and alumina, and if these materials are added to the soil, the mechanical parameters of the soil are expected to improve.

1-6 Motivation

The environmental, economic, technical concerns and the limited availability of resources of energy and primary minerals in the production of Portland cement highlight the necessity for research on substitute materials for cement in civil engineering applications. Modification and stabilization of problematic soils is one of these applications. One of the best alternatives to improve the behaviour of problematic soils is the use of geopolymers. Geopolymer is a combination of natural materials, silicate and alumina, between which a geopolymerization process has taken place, and hence it is called geopolymer. The geopolymerization process includes a chemical reaction between a solid aluminosilicate source and alkaline silicate and an activated hydroxide solution that leads to polymer Si-O-Al bonds. Although the positive effects of geopolymers in improving the mechanical properties of soils have been clearly identified, there has been very limited studies on the effects of using glass powder in soil improvement without using any alkali activator, which forms the motivation of this study. Studies demonstrate that the percentage of glass powder used can vary widely, typically ranging from 5% to 40%, depending on the specific objectives of soil improvement and the type of soil being treated. A study found that incorporating 15% glass powder by weight into clay soils was optimal for enhancing strength and workability [36]. While it was found, in another study, that higher glass powder content (40%) continued to enhance soil properties, the most substantial benefits were observed at around 30%, with further increases yielding only marginal gains [37].

1-7 Objectives

The main aim of this research is stabilization of clay with glass powder without using any alkali activator. This aim will be achieved through the following objectives:

- Design and develop a comprehensive programme of experimants, including compaction, direct shear, unconfined compressive strength and consolidation tests, to study the effects of waste glass powder on the mechanical behaviour of a clay soil.

- Evaluate the effects of different glass powder contents on the physical and mechanical properties of the stabilized clay.
- Figure out the temporal effects of glass powder content on soil properties by testing specimens at 3, 7, and 28 days, assessing how soil strength and stability develop over time with different glass powder additions.

1-8 Research implications and implementation potential.

The results of this study have important implications for both academic researchers and the construction sector. By showcasing how glass powder (GP) can effectively enhance the mechanical properties of clay, particularly in terms of compressive and shear strength, this research adds valuable insights to the growing field of sustainable soil stabilization. The use of GP, an affordable waste material, supports global sustainability efforts and the circular economy by encouraging the recycling of industrial by-products.

From a practical standpoint, incorporating GP into soil stabilization presents key advantages for infrastructure projects, especially in areas where access to high-quality construction materials is limited. GP's ability to enhance soil strength and durability makes it suitable for applications such as road construction, embankments, land reclamation, and foundations. Furthermore, using GP can reduce reliance on traditional chemical stabilizers, which often have negative environmental effects. However, before it can be widely used in engineering projects, large-scale field trials and further investigation into the long-term behavior of GP-stabilized soils are necessary. Establishing guidelines and conducting cost-benefit analyses will also be crucial for its broader adoption in the construction industry.

1-9 Research limitations

This study's findings are limited by several factors that should be addressed in future research. First, the scope of the investigation was confined to a specific type of clay soil with known properties, and the results may not be fully generalizable to other soil types or environmental conditions. The glass powder used in the study was of a single particle size (<20 μm), limiting the exploration of how different particle sizes might affect soil behavior. Additionally, while laboratory tests such as direct shear, compaction, and compressive strength were performed, no field trials were conducted to evaluate the real-world performance of glass powder-stabilized soils. The long-term effects of environmental factors, such as freeze-thaw cycles or chemical exposure, were also not explored, leaving gaps in understanding the durability of the stabilization method. Finally, the study focused solely on glass powder as an additive, without considering potential synergies with other waste materials that could further enhance soil stabilization.

Chapter 2: Literature Review

In recent years, there has been an increasing focus within geotechnical engineering on soil improvement techniques designed to enhance the physical and mechanical properties of soils to satisfy the requirements of construction and infrastructure projects. This chapter presents an extensive review of the literature on soil improvement, with special attention given to innovative methods that incorporate recycled materials. The review is organized as follows:

Section 2.1 offers an overview of various soil improvement methods, highlighting the traditional and contemporary techniques employed to modify soil properties for enhanced performance.

Section 2.2 delves into the utilization of glass powder, an environmentally sustainable by-product, as a potential material for soil stabilization. The properties of glass powder and its relevance in geotechnical applications are examined, providing a foundation for its inclusion in soil improvement practices.

Section 2.3 explores the specific application of glass powder in soil stabilization, presenting a detailed analysis of the mechanisms through which glass powder enhances soil characteristics. The design considerations for soil mixtures stabilized with glass powder are discussed in Section 2.3.1, emphasizing the optimization of mixture proportions to achieve desired outcomes in terms of strength, durability, and environmental impact.

This literature review synthesizes the existing research on these topics, identifying gaps in knowledge and potential areas for further investigation, thereby laying the groundwork for the subsequent experimental and analytical work presented in this thesis.

2-1 Soil improvement

Reclamation involves the controlled restoration of soil in place for reuse in a new geotechnical structure. Soil improvement methods are widely used in civil engineering practice. The use of these methods improves the geotechnical properties of the soil, reduces costs and increases the lifespan of the operation [38].

The use of improvement methods is divided into five main groups as follows [38]:

1) Improving the quality of the land, which includes reducing the future settlement of buildings due to loading, earthquakes, and construction in problematic soils such as loose sands, landfills, mineral waste, rammed soils and swelling soils.
2) Base treatment that includes strengthening and reconstruction of the footings.
3) Stabilization of the pit, which includes the role of a support structure, controlling and limiting the settlement of the tunnel and excavation.
4) Pollution control, which encompasses various aspects, such as addressing localized instances of pollution caused by soil, water, or gases in the soil. This may involve solidification or stabilization of contaminated soil, as well as biological decomposition of harmful substances on-site.
5) Underground water control, which includes limiting the flow of groundwater and sealing underground structures.

2-1-1 Soil improvement methods

There are many methods of soil improvement. These methods are divided into six main groups according to the type of executive operation, the mechanisms of changing the geotechnical characteristics of the soil, the type of granulation, etc. These six groups are as follows [39]:

1) Compression methods

This group includes dynamic compaction, loading, artificial drainage, vibration compaction and creation of stone columns with vibration placement.

2) Adhesion enhancement

This category involves freezing, and chemical injection (such as chemical grouts which typically consist of a mixture of water, cement, and additives such as bentonite or polymers) to improve soil adhesion.

3) Drilling and replacement methods

Implementation of mortar walls (using cement, bentonite, plastic concrete, etc.) and high pressure injection are subsets of this method.

4) Physical and chemical stabilization

Electroosmosis, limestone columns (mixing), chemical injection systems, glazing and soil mixing are also subsets of this method.

5) Soil reinforcement methods

Reinforcement methods include soil and stone anchors, stone columns with vibration replacement, stone columns with vibration displacement, vibrating concrete columns, micropiles, underground concrete load-bearing walls, nailing, geosynthetics, fissile injections and soil mixing.

6) Biological transformation methods

Biological systems or stimulating injections, root strengthening and enzyme reduction are subsets of biological transformation methods.

2-2 Glass powder

The total production of waste glass in 2007 in the world was about 4.89 million tons while it was about 27 million tons in 2018. The process of glass production in the world is increasing. According to United Nations statistics, in 2004, about 200 million tons of solid waste was produced, of which 7%, or about 14 million tons, was waste glass while the production of solid waste was 2.01 billion tons in 2023. Waste glass around the world is considered a challenge for the waste management system due to its low recycling rate, the lack of space in existing burial centers and the occupation of new burial centers [40, 41]. Figure 2-1 shows an example of glass powder used by Blayi et al. (2020) for soil consolidation [42].

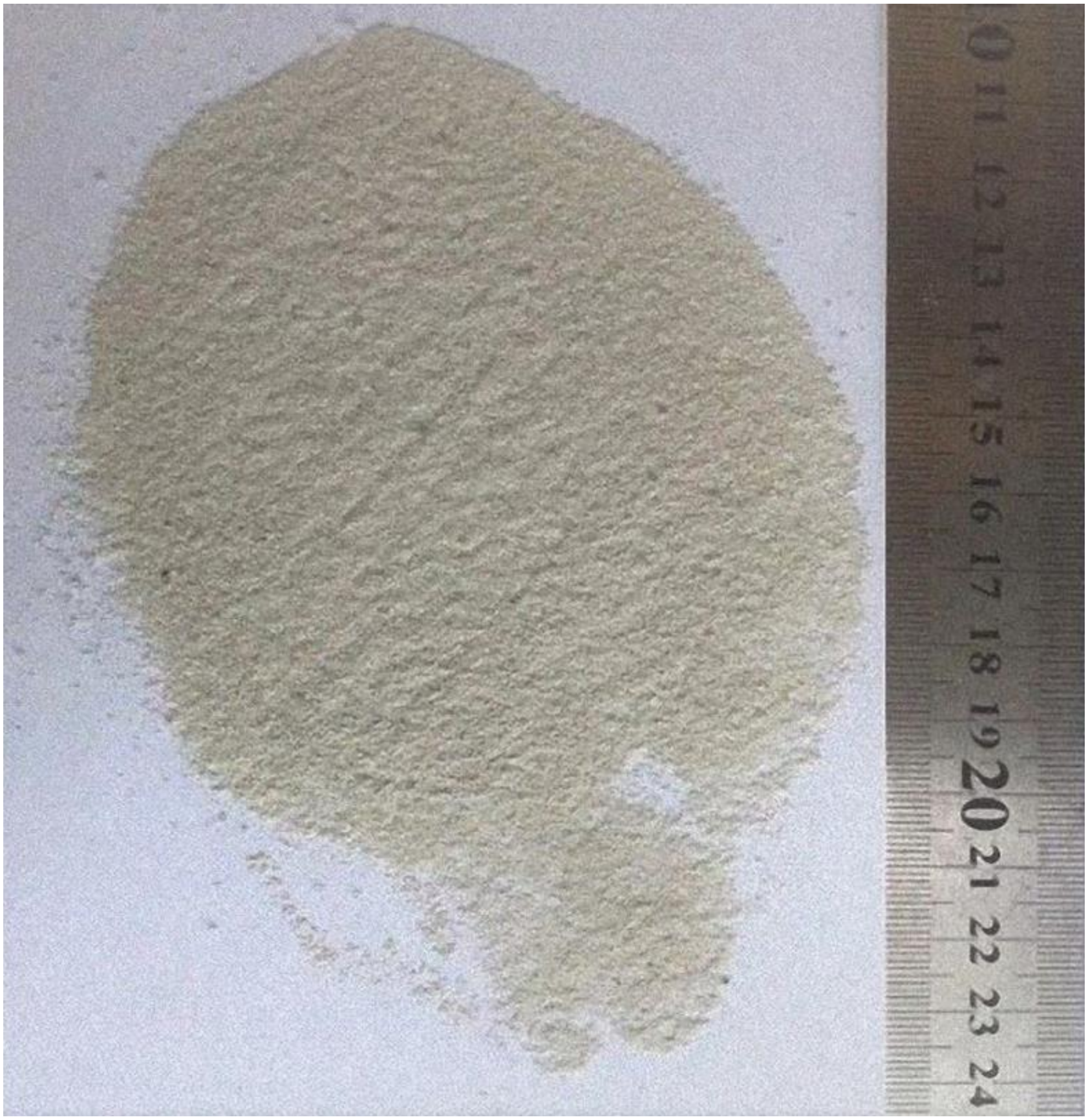

Figure 2- 1: An example of glass powder [42]

The use of glass powder with other materials has been investigated by several researchers for different types of soil. Pascual et al. [43] investigated the use of waste glass powder in the production of alkali-activated mortar. The study explores the potential of glass powder, an environmentally friendly and sustainable material, as a key component in alkali-activated binders. The research focuses on the physical and mechanical properties of the resulting mortar, assessing its suitability as a construction material. The findings indicate that waste glass powder can effectively contribute to the production of alkali-activated mortars, offering a promising alternative to traditional cement-based products, with potential benefits in terms of sustainability and performance.

The paper by Blayi, et al. [42] investigates the use of waste glass powder to improve the strength of expansive soils, which are known for their significant volume changes in response to moisture variations, posing challenges in construction. The study assesses how effectively waste glass powder can be used to improve the mechanical properties of expansive soil, with a focus on enhancing its strength and stability. The experimental findings reveal that incorporating waste glass powder markedly boosts the soil's strength, decreases its expansion potential, and thus enhances its suitability for construction. This research underscores the promise of using recycled materials such as glass powder to solve geotechnical issues, presenting a sustainable method for soil stabilization.

Benny, et al. [44] explores the impact of adding glass powder on the engineering properties of clayey soil. The study seeks to evaluate the impact of incorporating glass powder on important soil properties, including strength, compaction, and plasticity. The researchers conducted laboratory tests and discovered that adding glass powder enhances the strength and decreases the plasticity of clayey soil, thereby improving its suitability for construction purposes.

Olufowobi, et al. [22] explores the use of powdered glass for stabilizing clay soil. The study examines the impact of adding powdered glass on the mechanical properties of soil, such as its strength and stability. Experimental results reveal that the addition of powdered glass notably increases the strength and decreases the plasticity of clay soil, thus enhancing its suitability for construction use.

Ibrahim and Mawlood [45] explores the application of waste glass powder for stabilizing high-plasticity clay in Erbil, Iraq. The study evaluates how effectively waste glass powder can improve the engineering properties of this difficult soil type, with particular emphasis on its plasticity and strength. Laboratory tests revealed that adding waste glass powder considerably improves the soil's mechanical characteristics, decreasing its plasticity and boosting its strength. The results suggest that waste glass powder offers a practical and sustainable solution for stabilizing high-plasticity clay, making it more suitable for construction and engineering projects in the region.

Torres et al. [46] conducted a research on the use of glass powder in the alkaline activation production. The research demonstrates that waste glass can be effectively used as a precursor in alkaline activation, leading to the formation of stable and durable materials and highlights the potential of waste glass to serve as a sustainable alternative in construction applications, contributing to both waste management and the development of eco-friendly building materials.

Sabbagh Gol and Toufigh [28] stabilized sandy soil using glass powder and a natural pozzolan. They concluded that glass powder in very fine size can react well with the help of strong alkaline solution. They also concluded that replacing 20% of glass powder instead of natural pozzolan increases the unconfined compressive strength of sandy soil by 20%.

Bilondi et al. [29] investigated the use of glass powder and alkaline sodium hydroxide solution in improving the mechanical properties of clay soils. The study involves a series of experimental tests to assess how the addition of glass powder affects the strength, stiffness, and durability of clay soils. The results demonstrate that incorporating recycled glass powder significantly improves the mechanical behavior of the clay, making it stronger and more stable.

Marcin et al. [47] studied the effect of glass powder, as an additive, on the mechanical properties of a geopolymer based on blast furnace slag. Sodium hydroxide powder, sodium-water glass and water were used as alkaline activators. In this research, the diameter of the glass particles was once smaller than 1 mm and another time between 1 and 4 mm, with percentages of 10, 20 and 30 and without glass powder. They concluded that the use of glass powder decreases the water obserption, while the use of 20% glass powder with a size of 1 to 4 mm increases the compressive strength. This research underscores the potential of combining industrial by-products like slag and waste glass to create sustainable, high-performance building materials.

Puertas et al. [48] used glass waste as an activator in the preparation of alkali-activated slag. The study investigates how incorporating glass waste affects the mechanical strength and characteristics of the resulting paste.Their results showed that the addition of 25% glass powder and the use of sodium hydroxide activator increases the compressive strength. The findings suggest that using glass waste not only offers a sustainable solution for recycling but also enhances the quality and functionality of alkali-activated slag in construction applications.

Liu et al. [49] used glass waste as a binder in alkali-activated slag-fly ash mortars. Through a series of tests, the researchers found that waste glass can effectively enhance the properties of alkali-activated slag-fly ash mortars, providing a sustainable alternative to traditional binders. The findings demonstrate that waste glass not only contributes to improved material performance but also supports recycling efforts and promotes more sustainable construction practices.

Shao et al [50] investigated the effect of the size of waste glass particles on the properties of cement and concrete by replacing 30% of cement in the concrete mixture. The results stated that the compressive strength increases with decreasing particle size.

Sheob, et al. [51] investigates the use of a blend of cement and waste glass powder to enhance the properties of a clayey soil. The study assesses the impact of combining cement with waste glass powder on essential soil properties like strength, compaction, and durability. Laboratory tests revealed that using both materials together markedly enhances the mechanical properties of clayey soil, resulting in greater strength and improved performance for construction uses. The results indicate that this mixture provides a promising and eco-friendly method for soil stabilization, utilizing the advantages of both cement and recycled glass powder.

2-3 Soil stabilization with glass powder

According to previous studies, the addition of glass powder to clay improves the Atterberg range of the soil [52]. Adding glass powder up to a certain percentage increases the compressive strength of samples stabilized with glass powder. Mixed coloured glass powder (MGP) can serve as a pozzolan when mixed with cement, and is particularly effective when 20% of the cement is replaced with MGP. Glass powder also reduces the shrinkage limit of the sample [53].

It has been shown that the uniaxial compressive strength of samples of clay stabilized with glass powder increases with increasing the curing time [54]. Glass has a greater effect on the load ratio values of California Bearing Ratio (CBR) when the soil is unsoaked, while its impact on saturated soil samples is negligible [55].

The addition of glass waste can increase the optimum moisture content and decrease the maximum dry density [56]. It should be noted that reducing the size of waste glass particles increases their pozzolanic properties and leads to the production of cementitious materials during the pozzolanic reaction of cement and glass particles. So the glass powder is more effective when its particle size is smaller. Also, glass powder reduces the swelling potential in clay [56].

2-3-1 Design of soil mixtures stabilized with glass powder

Canakci, et al. [57] investigated the impact of incorporating glass powder into grout used for the deep mixing of marginal sand with clay. The study evaluates how the addition of glass powder influences the grout's performance and the resultant properties of the mixed soil, such as strength and stabilization. Experimental results indicate that adding glass powder to the grout significantly improves the mechanical properties of the treated soil, enhancing its strength and stability. This research demonstrates that glass powder can be an effective and sustainable additive for improving the quality and performance of deep-mixed soil in geotechnical applications.

Asl and Taherabadi [56] modified a silty clay in the condition of cold regions by using glass waste. The soil used by them was prepared from a clay mine near Qazvin (Iran) and was classified, using the unified classification system, as a silty clay with low plasticity (CL-ML). The glass waste used was obtained from Qazvin glass factory. Standard compaction tests were performed on the soil with 0, 10, 15 and 20% glass waste. Figure (2-2) shows the compaction curves (curves of dry density vs moisture content) for the soil with different percentages of glass powder. Furthermore, using cylindrical samples of soil and recycled glass, uniaxial compressive strength and tensile strength tests were performed after 0, 3, 6, 9, and 11 cycles of freezing and thawing.

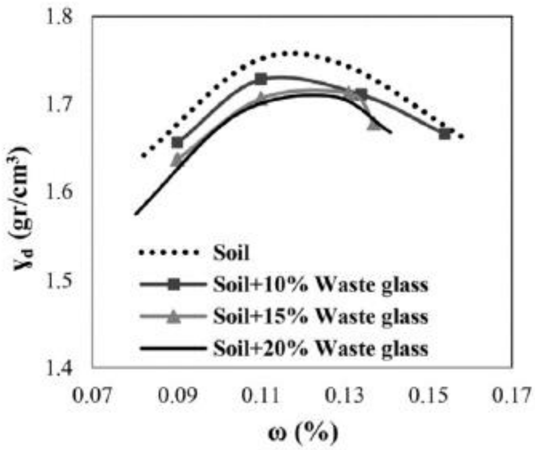

Figure 2- 2: Compaction curves for the soil with different percentages of glass powder [56]

As shown in Figure 2-2, adding glass waste has decreased the maximum dry density and increased the optimum moisture content. Figure 2-3 shows the stress-strain curves from the uniaxial compressive strength tests on the soil samples with different percentages of glass waste at 14-day curing period. According to the figure, the final strength and elastic modulus increase by increasing the percentage of glass waste in the soil.

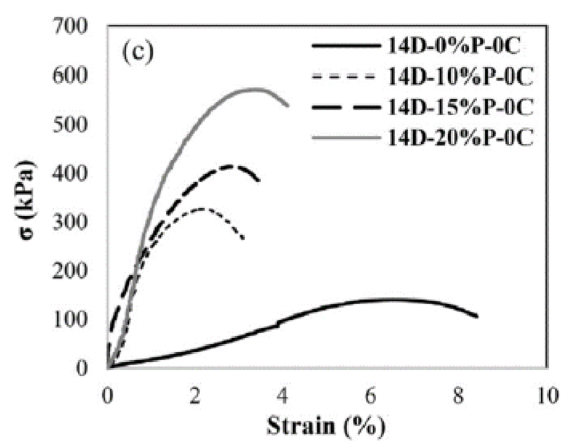

Figure 2- 3: Stress-strain curves of soil with different percentages of glass waste at 14-day curing [56]

The results showed that recycled glass can help improve soil in terms of compressive strength [56].

Canakci et al. [52] reported that the uniaxial compressive strength of soil increased with the addition of glass powder. This increase in strength occurred up to 6% glass powder content, beyond which a decrease in strength was onserved for larger amounts. Adding 12% glass powder soda lime reduced the amount of clay swelling from 5.5% to 0.65%.

Chen et al. [53] concluded that mixed glass powder can be used as a pozzolan when replaced with 20% cement. Güllü et al. [54] showed that the addition of glass powder up to 3% increased the unconfined compressive strength and decreased it for higher percentages. They investigated the use of a cement-based mortar with glass powder as a new type of additive for the deep mixing technique. The cement they used was Portland cement, which was used as an adhesive for the mortar mixture in the deep mixing technique. The glass powder used in this research as a stabilizing agent, was obtained by pulverizing the green glass of beverage bottles in Gaziantep, Turkey. Also, the clay used for the deep mixing technique was from the clay of Gaziantep city, which is classified as a clay with low plasticity (CL) based on the unified classification system. Geotechnical characteristics, Atterberg limits, unconfined compressive strength and ultrasonic pulse velocity tests were performed. Figure 2-4 shows the performance of uniaxial compressive strength of the stabilized samples with different water contents and various curing times.

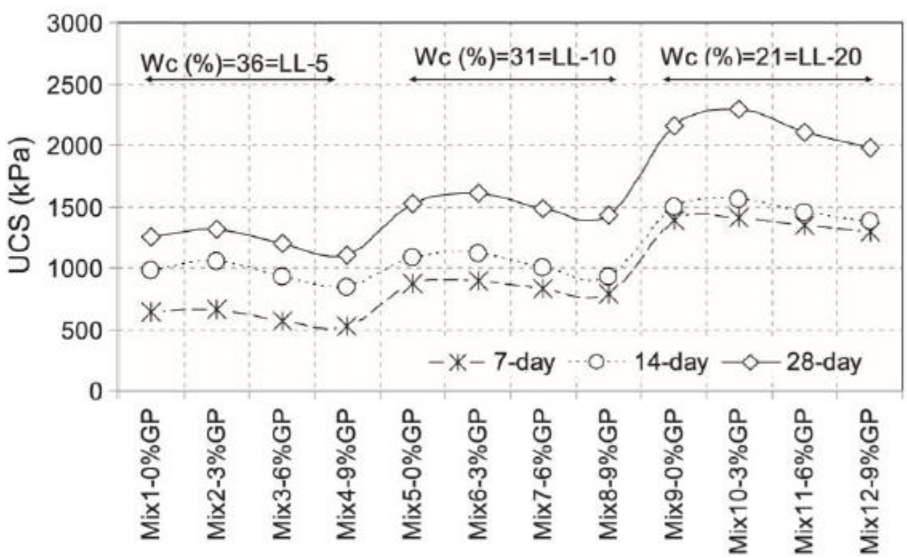

Figure 2- 4: Uniaxial compressive strength performance of the samples [54]

As can be seen in the figure, the strength of the samples increased with increasing the curing time. Also, by reducing the amount of water in the mixture, the strength of the samples increased. It is also clear in the figure that the addition of glass powder up to 3% increased the strength while beyond 3%, the strength was decreased [53].

Bilondi et al [29] found that, in terms of unconfined compressive strength, the addition of 9% glass powder had almost the same effect as the addition of 5% Portland cement. The highest strength was related to 15% glass, which increased the strength from 0.2 MPa to 2.2 MPa. After adding 15% glass powder, a slight drop in strength was observed.

Parihar et al. [55] reported that the greatest improvement in soil properties (such as maximum dry density, optimum moisture content, free swelling index and California Bearing Ratio) was achieved with 6-9% glass, which was considered as the optimal amount. They compared the results with their previous study, which was about adding microfine slag (MFS) to the same type of soil. Their soil was obtained from Badhora village in Gana district in India. Based on Atterberg limit tests, this soil was classified as silt with high plasticity (MH). They used broken glass from drink bottles and broken pieces of window glass from a recycling site as the stabilizing material. At first, some preliminary tests were conducted to detect the physical and chemical properties of the soil and the broken glass. These tests included grain size distribution, Atterberg limits, compaction, swelling, California Bearing Ratio (CBR) and chemical analysis. They added broken glass in percentages of 3, 6, 9 and 12% to the soil and examined the changes. Figure 2-5 shows the compaction curves for 5 samples of soil only and soil with 3, 6, 9, and 12% glass powder.

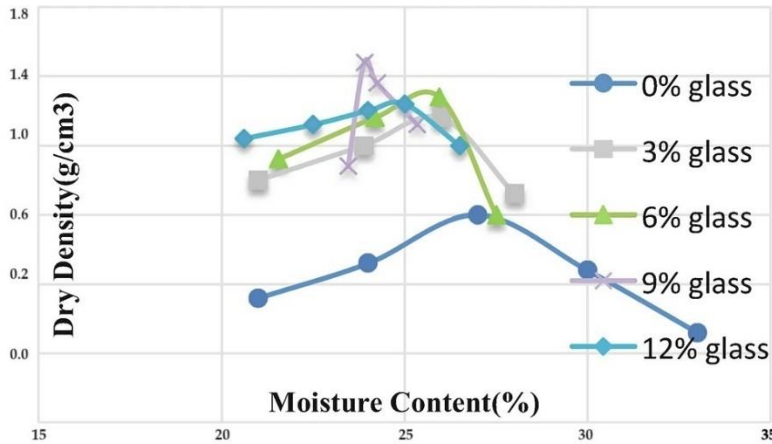

Figure 2- 5: Compaction curves for soil alone and soil with 3, 6, 9 and 12% glass powder [55]

According to Figure (2-5), by increasing the glass powder content up to 9% the dry unit weight increased, but it decreased beyond 9%. Also, the optimum moisture content decreased with increasing the glass powder content up to 9%, but it slightly increased beyond 9%. Figure (2-6) shows a comparison of the effects of two additives, broken glass and microfine slag (MFS), on the plasticity index.

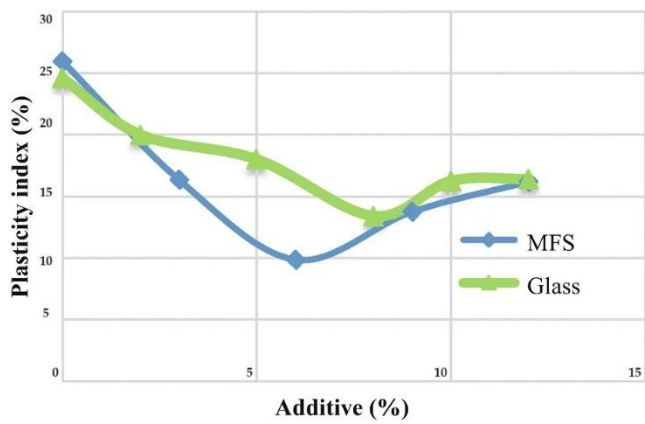

Figure 2- 6: Comparison of the effect of glass powder and very soft slag powder on the plasticity index [55]

According to Figure (2-6), both additives have reduced the plasticity index, but the microfine slag had a greater effect. In Figure (2-7), the effects of these two additives on the plastic limit are compared. Both additives have increased the plastic limit, which is desirable but the microfine slag was slightly more effective.

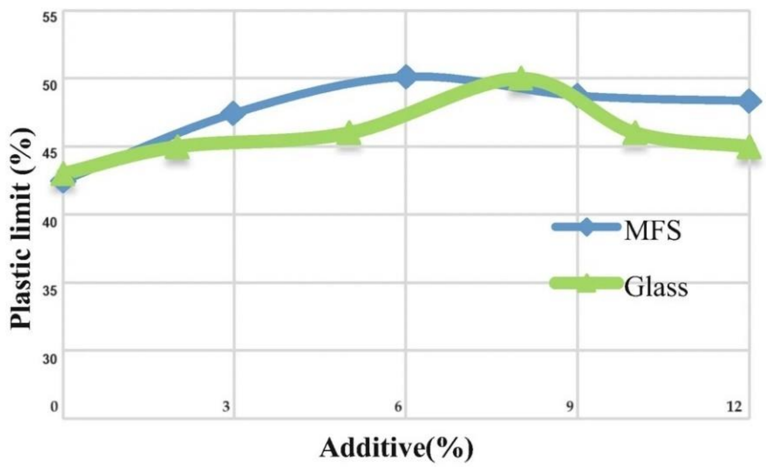

Figure 2- 7: Comparing the effects glass powder and very soft slag powder, on the plastic limit [55]

The results of their experiments showed that the greatest improvement in soil properties, such as maximum dry density, optimum moisture content, free swelling index and CBR can be achieved with 6-9% glass powder. Therefore, 6-9% glass powder content was considered as the optimal range. The effect of glass on the CBR values was more obvious in the dry state, while it had little effect on saturated soil samples [55].

Woldesenbet [58] investigated the California bearing ratio (CBR) for a clay soil stabilized with lime and waste glass powder in a laboratory. The result of their research showed that the most optimal condition was clay with 10% lime and 4% waste glass powder; this composition changed the soil CBR from 27.73% to 75.91%.

Javed et al., [59] studied the effect of waste glass powder on the improvement of soil infrastructure. They investigated the stabilization of cohesive soils by adding glass powder in percentages of 2, 4, 6, 8 and 10%. Atterberg limits, standard compaction, CBR (in dry and saturated states), uniaxial compressive strength and direct shear tests were performed on the samples. Based on the experimental results, they concluded that the liquid limit, the plastic limit and the plasticity index decreased continuously with the addition of glass powder. Also with the addition of powder, the maximum dry density increased and the optimum moisture content decreased. The CBR value, in both dry and saturated conditions, increased with the addition of glass powder. The uniaxial compressive strength increased up to 8% glass powder content and decreased slightly beyond 8%. Also, the shear strength parameters increased with the increase of glass powder content. Figure (2-8) illustrates that as the percentage of glass powder added to the soil increases up to 10%, there is a corresponding increase in the soil's cohesion. It is likely that the fine particles of glass powder may fill the voids between clay particles, potentially creating a denser soil structure. This improved arrangement of particles could strengthen inter-particle bonding, which might result in greater cohesion. This result indicates that incorporating waste glass powder into the soil enhances its cohesive properties, which can improve the soil's strength and stability. Such an outcome suggests that waste glass powder could be effectively used to improve soil performance in construction applications, such as road building and other infrastructure projects, by providing better support and durability.

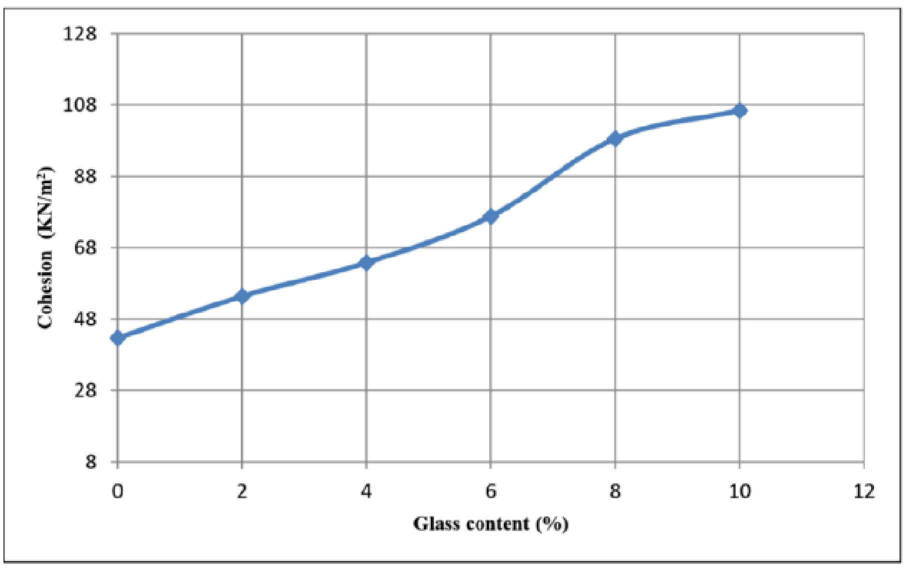

Figure 2-8: Changes in cohesion with different percentages of glass powder [59]

Figure (2-9) shows the changes in the values of the internal friction angle at different percentages of glass powder content. The results show that, increasing the percentage of glass powder up to 10% gradually increased in the internal friction angle of the soil from 28 degrees for the virgin soil to 43 degrees with 10% glass powder [59].

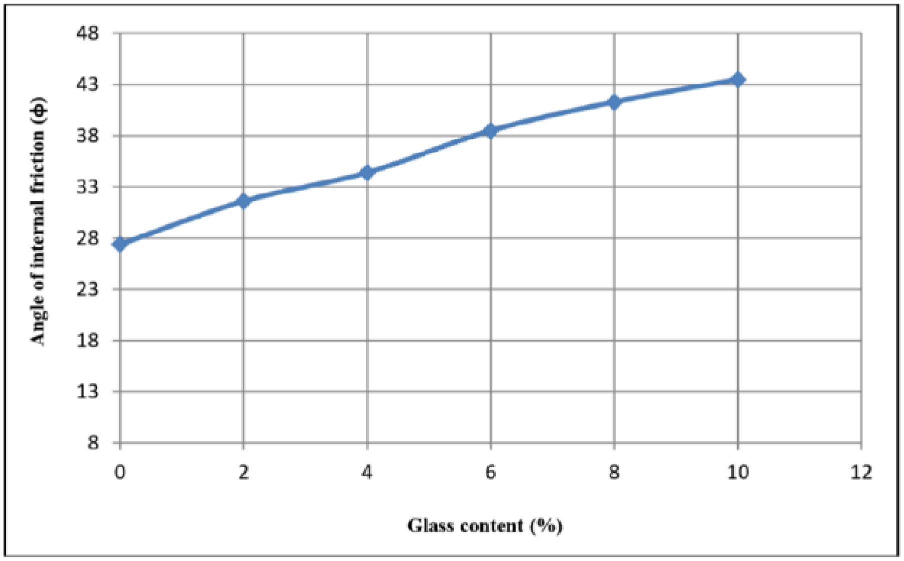

Figure 2- 9: Changes in angle of internal friction with different percentages of glass powder [59]

Among other methods of using glass powder in soil stabilization is its use in road construction to achieve a good foundation for roads. For this purpose, combinations of lime or cement with glass powder can be used. In general, the operational steps for this method include preparing the soil, spreading the stabilizing agent along with glass powder, mixing and spraying, levelling and processing the mixture [60]. It may be possible to find other ways to use this material to stabilize the soil, but currently, due to the limited research done on it, little information is available on its actual use and application methods.

As a result of recent studies, glass powder, derived from waste glass, is emerging as a promising material for soil stabilization due to its potential to significantly enhance soil properties. When integrated into soil, glass powder has been shown to improve various aspects such as cohesion and compaction, which in turn increases the soil's strength and stability. The fine particles of glass powder serve as an effective filler, reducing voids and refining the soil matrix, thereby enhancing its load-bearing capacity and reducing settlement. This sustainable approach not only provides a valuable use for waste materials but also offers a cost-effective solution for improving soil conditions in construction projects. The body of research indicates that incorporating glass powder into soil can effectively modify its engineering properties, making it a viable option for a range of infrastructure applications.

Despite the promising benefits of using glass powder for soil stabilization, a notable gap exists in its application without alkali activators. Many studies have focused on the effectiveness of glass powder when combined with alkali activators, which significantly enhance its binding properties and soil stabilization potential. However, the performance of glass powder alone, without the use of such activators, remains less well-documented. This gap highlights the need for further research to evaluate how glass powder can be optimized for soil stabilization independently. Investigating its performance in the absence of alkali activators could lead to more sustainable and cost-effective stabilization solutions and expand the practical applications of waste glass powder in soil engineering.

Chapter 3: Materials and Methods

3-1 Introduction

This chapter describes the materials used and the methods employed to conduct the experiments, sample preparation, and the equipment used to study the stabilization of clay with glass powder.

3-2 Materials

3-2-1 Soil

The clay soil used in this research was sourced from the vicinity of Shiraz city, Iran. Table 3-1 shows the chemical composition of the soil, offering valuable information about its elemental makeup.

Table 3-1. Chemical composition of Shiraz clay soil

Clay Soil's Chemical Composition							
SiO_2	59.98%	MgO	1.29%	CaO	0.54%	SO_3	0.74%
Al_2O_3	15.36%	K_2O	1.44%	TiO_2	0.44%	LOI	6.5%
Fe_2O_3	12.95%	Na_2O	0.12%	P_2O_5	0.14%		

3-2-2 Glass Powder

Table 3-2 displays both the chemical composition and physical characteristics of glass powder, including its elemental composition, which were obtained from the Shiraz chemical laboratory. The particle sizes of the glass powder were less than 20 micrometers (<20µm).

Table 3-2. Chemical composition and physical properties of the glass powder

Glass Powder Chemical Composition	SiO_2	77-80%	Al_2O_3	2-4%
	B_2O_3	9-13%	K_2O	1%
	Na_2O	4-5%	ZrO_2	0-1%
Glass Powder Physical Properties	Moisture Content	<0.5%	Oil Absorption Rate	32ml/100gr
	Density	2.25 gr/cm^3	Conductivity	134 µS/cm*

	Refractive Index	1.47	* µS/cm = microsiemens per centimeter

3-3 Sample Preparation

The clay and different contents of glass powder were mixed thoroughly to ensure uniform distribution of glass particles within the clay matrix.

3-4 Experimental procedures

A comprehensive program of tests was conducted to evaluate the impact of varying glass powder content on several key soil properties, with the glass powder content ranging from 0% to 25%. Previous studies have explored glass powder concentrations between 0% and 40%, with findings indicating that the most effective improvements in soil properties were observed within the lower range of 0% to 20%. This effective range suggested that higher percentages did not yield proportionally better results and, in some cases, could lead to diminishing returns. Based on these insights, the tests focused on a refined range of 0% to 25% to balance effectiveness and practicality, aiming to determine the optimal amount of glass powder for enhancing soil stabilization while avoiding the potential inefficiencies associated with higher concentrations. These tests encompassed soil compaction analysis, Atterberg limits determination, consolidation testing, direct shear testing, and assessment of unconfined compressive strength. Through this systematic approach, we aimed to reveal the influence of glass powder incorporation across a spectrum of soil behaviours and mechanical characteristics.

3-4-1 Soil compaction test

The soil compaction test was performed to determine the maximum dry unit weight and optimum moisture content of the soil. It has been found that adding water to the soil during compaction makes this operation easier. Adding moisture lubricates the particles and makes compaction easier. But if the amount of water exceeds a certain limit, the density of the soil decreases and compaction does not take place well. So there is an optimum moisture content that engineers aim to achieve.

The Proctor compaction test was conducted for each mix (0%, 5%, 10%, 15%, 20%, and 25% glass powder content) according to ASTM D1557 standard. The soil was compacted in 3 layers, with each layer receiving 25 blows of a standard Proctor hammer, applying a compactive energy of 600 kJ/m³. In the standard Proctor test, the hammer typically weighs 2.5 kg (5.5 lbs) and is dropped from a height of 30.5 cm (12 inches). This results in a specific amount of energy being applied to each layer of soil. The total compactive energy is calculated based on the number of blows and the weight of the hammer. For the standard Proctor test, this energy is approximately 600 kJ/m³. This value is derived from the hammer's weight, drop height, and the number of blows applied to each layer of soil. The equipment used in the Proctor compaction test is calibrated to ensure that the compactive energy remains consistent across different tests. This standardized approach means that the energy applied is always around 600 kJ/m³, regardless of whether the test is performed by hand or using automated equipment. The compaction curves were plotted from the results of the tests, and the maximum dry density and optimum moisture content were determined for each mix. Figure 3-1 shows the sample preparation and the test procedures.

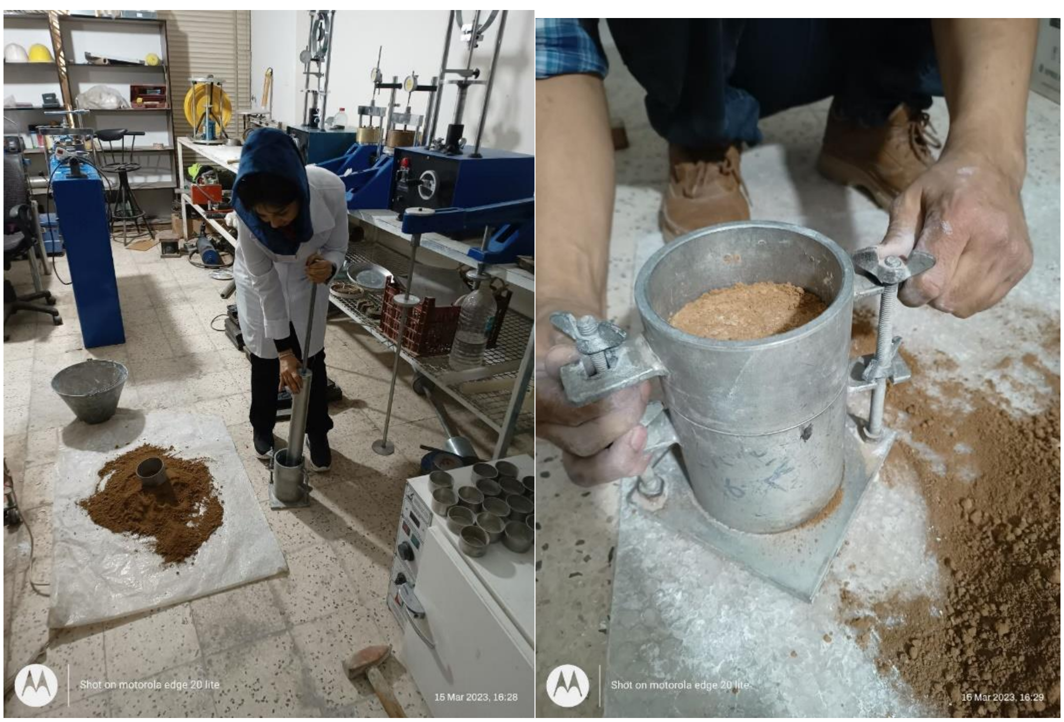

Figure 3- 1: Sample preparation for soil compaction test

3-4-2 Atterberg limit test

The Atterberg limit test was conducted to ascertain the values across different levels of glass powder content. This test is crucial for determining the soil's plasticity and liquidity indices, providing essential insights into how the presence of glass powder influences these properties. Through testing at varying glass powder concentrations, we aimed to obtain a comprehensive understanding of the soil's behaviour under different conditions, aiding in the development of effective soil stabilization strategies.

3-4-3 Consolidation test

One-dimensional (oedometer) consolidation tests were performed on samples of the clay mixed with different percentages of glass powder. To simplify the concept of the consolidation test, a saturated clay sample can be envisioned as undergoing loading. If the soil remains undrained, water pressure within the sample will increase, while draining the soil will result in water expulsion, causing the volume of the soil sample to diminish. This process is known as soil consolidation. This test primarily aims to assess one-dimensional consolidation parameters.

The soil sample must maintain its integrity throughout the test to ensure accurate results. Initially, a load equivalent to 5 kPa is applied to the sample, and the resulting displacement is recorded. If the sample is saturated or below the groundwater level, a water cylinder saturates it. The sample's initial height is measured, and subsequent loadings are applied with displacements recorded, increasing loading every 24 hours. The sample's weight and moisture percentage are measured at the beginning and end of the test. Upon completing the loading phase, the sample is removed from the force application device and dried in an oven. This procedure allows for the estimation of one-dimensional consolidation parameters.

Figure 3-2 shows a view of the used consolidation device and the sample.

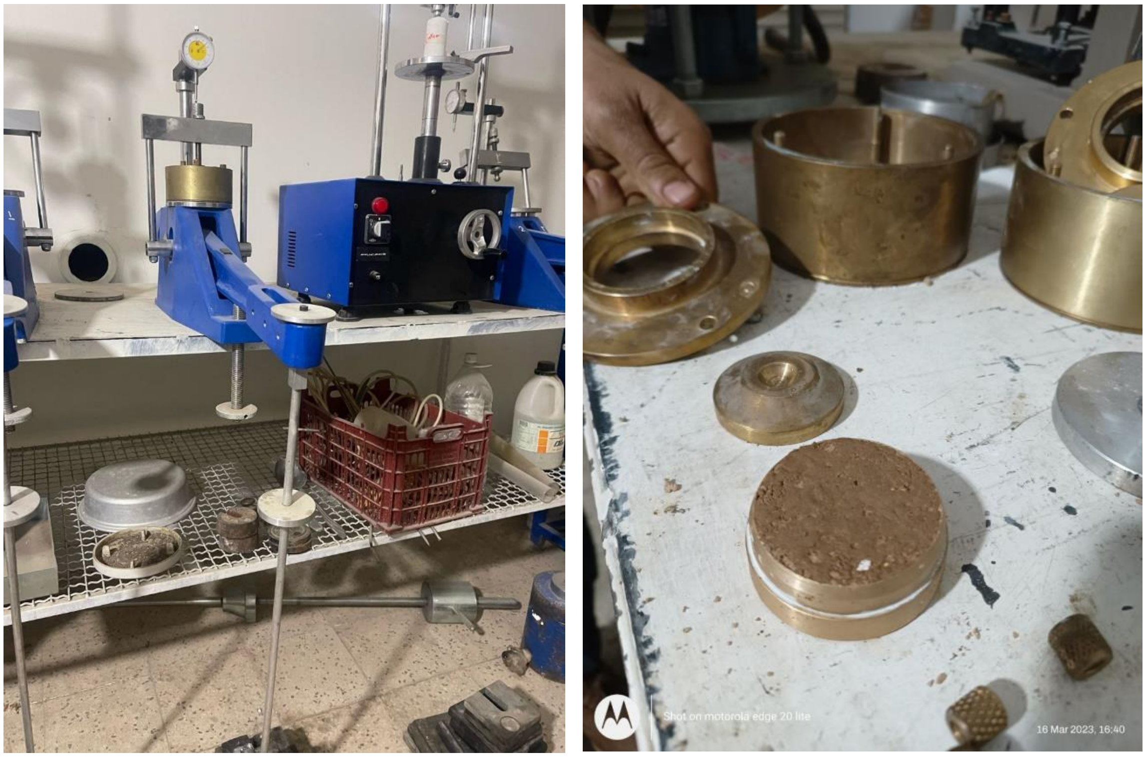

Figure 3- 2: The consolidation device and the sample

3-4-4 Uniaxial compressive strength test

The uniaxial compressive strength test is used to determine the unconfined compressive strength of cohesive soil in the intact restored or modified state, using axial load, under strain control conditions. In this method, an approximate value for the unconfined strength is obtained in terms of total stresses. This method can only be used for cohesive materials such as clays or cemented clays, which will not be drained during loading (the water drained from the soil is due to deformation or consolidation) and will maintain their inherent resistance after removing all-round confining pressures.

Cylindrical specimens of stabilized clay at different glass powder contents were prepared. Two frictionless bearing plates were placed on the top and bottom of the sample. The specimen was positioned between the end plates on the base plate of the load frame. A hardened steel ball was positioned onto one of the bearing plates. It was ensured that the center line of the specimen aligned with both the proving ring and the steel ball. A dial gauge was attached to measure the vertical compression of the specimen. The gear position on the load frame was adjusted to achieve suitable vertical displacement.

Loading was commenced while the readings of both the proving ring dial gauge and compression dial gauge were recorded for every 1mm of compression. Loading was continued until complete failure occurred.

Figure 3-3 shows a view of the uniaxial compressive strength test device and preparation of sample for this test.

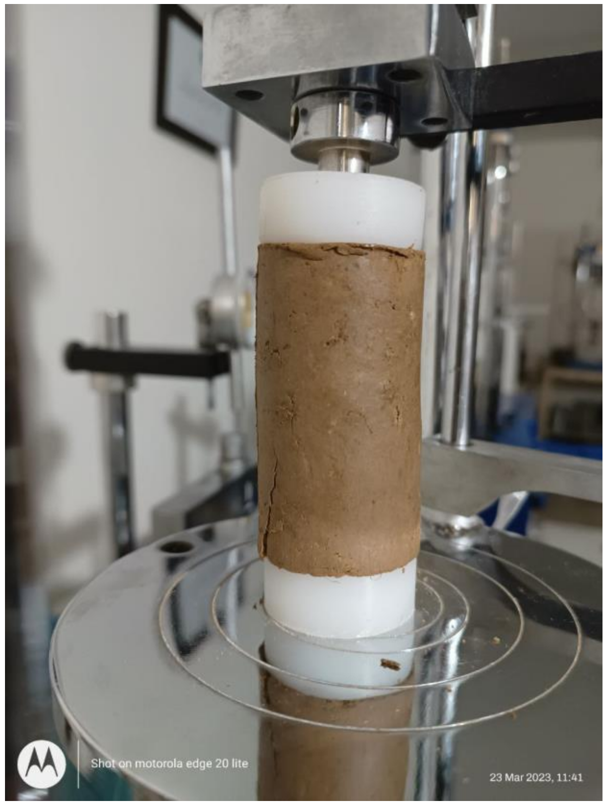

Figure 3- 3: Uniaxial compressive strength device and prepared sample for the test

The UCS tests were conducted on these specimens. The specimens were axially loaded at a constant displacement rate of 1mm/min until failure and the compressive strength was measured at failure. The UCS values of different mixes were compared to evaluate the impact of glass powder on the compressive strength of the stabilized clay.The results provide valuable data in the form of stress-strain curves, which depict the relationship between applied stress and resulting strain for different specimens containing varying contents of glass powder.

3-4-5 Direct shear test

Direct soil shear test is used to determine the shear strength of soil. Shear strength parameters are the most important parameters defining soil characteristics because the ruptures that occur in projects related to geotechnics are shear ruptures. The estimation of soil shear strength is necessary for engineering projects such as slope stability, pit wall stability, bearing capacity of foundations, and lateral earth pressure calculations and the design of retaining wall. One of the common methods to determine the shear strength of soil is to use direct soil shear test. The direct shear test is of interest because it is quick and cheap, despite its shortcomings.

Direct soil shear test is one of the oldest tests used in geotechnical practice. Shear strength is the maximum strength that the soil can withstand under shear stress until it fails. In this test, a direct shear test device is used to determine the shear strength of the soil. In direct shear test, the soil sample is placed in a special chamber and a vertical stress is applied to the soil. Then shear stress is applied to the soil and increased until the soil reaches rupture. As a result of this test, a shear stress-horizontal displacement diagram can be drawn and the maximum shear stress that the soil can bear under a certain vertical stress can be obtained. This test is performed several times for different vertical stresses on the soil and in each test the maximum shear stress is determined corresponding to the vertical stress on the sample. After completing the test, a shear stress-vertical stress diagram is drawn by connecting the failure points corresponding to different vertical stresses representing the Mohr-Coulomb failure envelop.

Samples of the stabilized clay at different glass powder contents (0%, 5%, 10%, 15%, 20%, 25%) were remolded with the same density directly into the shear box. The inner dimension of the soil container was measured, and the parts of the soil container were assembled. The volume of the container was calculated and the container was weighed. The soil was placed in layers, approximately 10 mm thick, and if a dense sample was desired, the soil was tamped. The soil container was weighed again, and the difference in weight indicated the weight of the soil, with the density of the soil subsequently calculated. The surface of the soil was leveled, and the upper grating was positioned on the porous stone while the loading block was placed on top of the soil. The thickness of the soil specimen was measured, and the desired normal load was applied. The shear pins were removed, and the dial gauge was attached to measure the change in volume, with the initial reading of the dial gauge recorded. The motor was started with the velocity 0.5mm/min, and the shear force readings were recorded, followed by continuous volume change readings until failure. Three normal stresses were applied by adding 50 N, equivalent to 0.5 MPa, 1.0 MPa, and 1.5 MPa, and the experiment was continued until failure. Finally, all readings were carefully recorded. Direct shear tests were performed on these samples using a direct shear apparatus according to ASTM D3080 standard. The shear strength parameters including cohesion and angle of internal friction were determined. Figure 3-4 shows the direct shear test device and a prepared sample for this test.

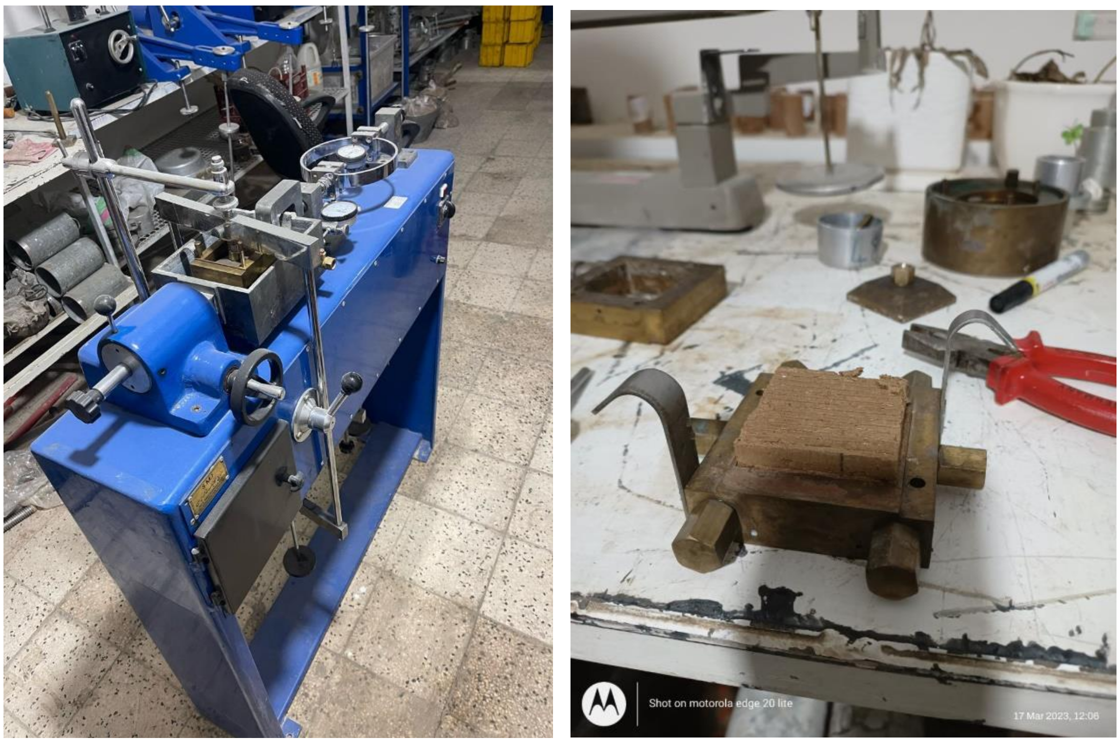

Figure 3- 4: Direct shear test device and it’s sample

In this research, samples with 0%, 10%, 15%, 20%, and 25% glass powder were tested in the direct shear test. The specimens were carefully prepared for direct shear testing at three distinct time intervals: 3 days, 7 days, and 28 days, to evaluate the influence of varying glass powder content. The objective of testing the specimens at three distinct time intervals was to understand how the incorporation of glass powder affects the soil's shear strength and stability over time. By conducting direct shear tests at these intervals, it can be observed how the soil’s properties change with different curing periods and glass powder contents. Such detailed temporal analysis is crucial for determining the optimal conditions for using glass powder in practical applications and ensuring its effectiveness as a soil stabilizer. This systematic approach allowed for the examination of how the mechanical properties of the specimens evolved over time, providing valuable insights into the short-term and long-term effects of glass powder incorporation Figure 3-5 shows a view of the samples prepared for the 28-day test.

Figure 3- 5: Prepared samples for 28-day test

All the samples were subjected to direct cutting test in all three time periods and the results were recorded. Figure 3-6 shows the apparatus of direct shear during recording the test results.

Figure 3- 6: Recording of results in direct shear test

The clay sample and the glass powder which were used in the tests are shown in figure 3-7.

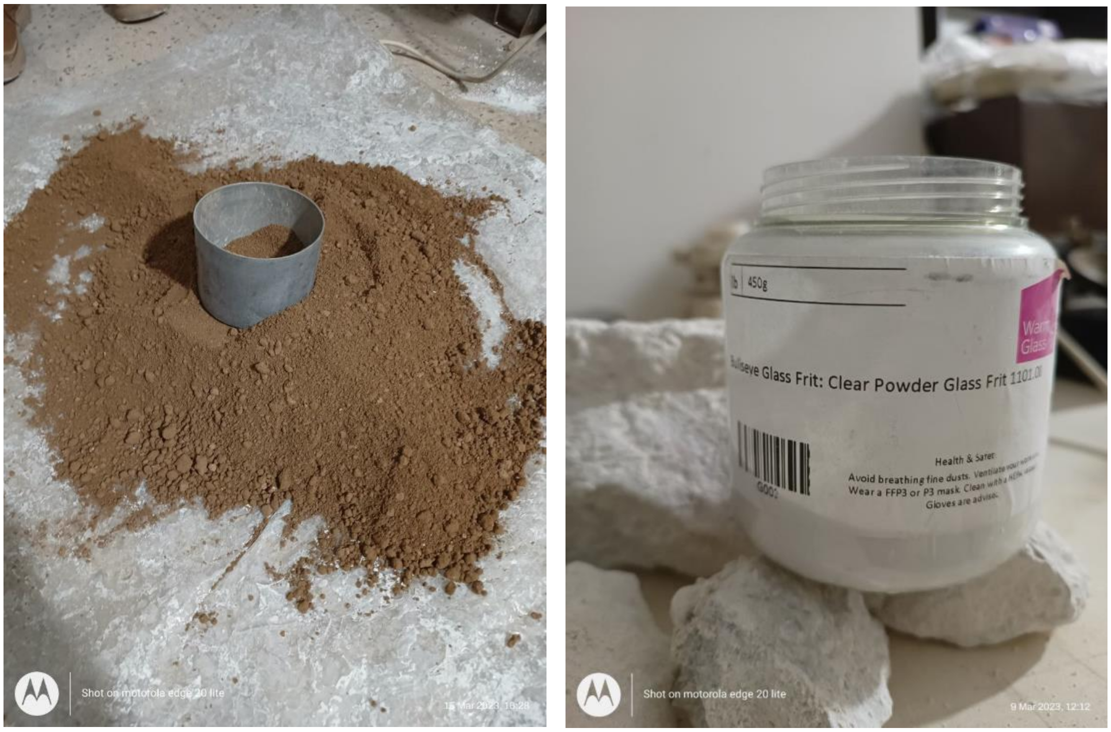

Figure 3- 7: Clay and glass powder used in the tests

3-5 Summary

In this chapter, the methods of testing clay stabilized using different percentages of glass powder were presented. The procedures for conducting one-dimensional consolidation, direct shear, Atterberg limits, unconfined compressive strength (UCS), and soil compaction tests were outlined. The devices used and the methods of sample preparation and testing were presented in detail. In the next chapter, the experimental results will be presented.

Chapter 4: Results and discussion

4-1 Introduction

In this chapter, the results of the experiments investigating the effects of glass powder in different weight ratios on the behaviour of the clay are presented and discussed. It should be noted that in the uniaxial and direct shear tests, the samples were prepared in a plastic bag (in order to maintain the moisture), and were kept for three periods of 3 days, 7 days and 28 days before they were tested.

In this research, different percentages of glass powder were used to stabilize the soil. In total, 6 samples were prepared for the tests, whose specifications are presented in Table 4-1:

Table 4-1: Specifications of test samples

Sample	Clay (gr)	Water (gr)	Glass Powder (gr)
S1 (0%)	167	21.71	0
S2 (5%)	158.65	21.71	8.35
S3 (10%)	150.3	21.71	16.7
S4 (15%)	141.95	21.71	25.05
S5 (20%)	133.6	21.71	33.4
S6 (25%)	125.25	21.71	41.75

In the following sections, the test results will be presented and discussed.

4-2 Compaction test results

In this experiment, the optimum moisture content (OMC) and the maximum dry desity (MDD) were determined. The results are shown in Figure 4-1. For a=100%, 95% and 90% the corresponding values are referred to as Gs=2.55, 2.65 and 2.75 respectively. The specific gravity (Gs) was determined in the laboratory (Gs=2.65).

Table 4-2 shows the results of these experiments.

Table 4-2: Results of the compaction tests

Sample	MDD (kg/m^3)	OMC (%)
S1 (0%)	1720	17
S2 (5%)	1730	16.7
S3 (10%)	1750	16.3
S4 (15%)	1770	15.9
S5 (20%)	1780	15.5
S6 (25%)	1780	15.4

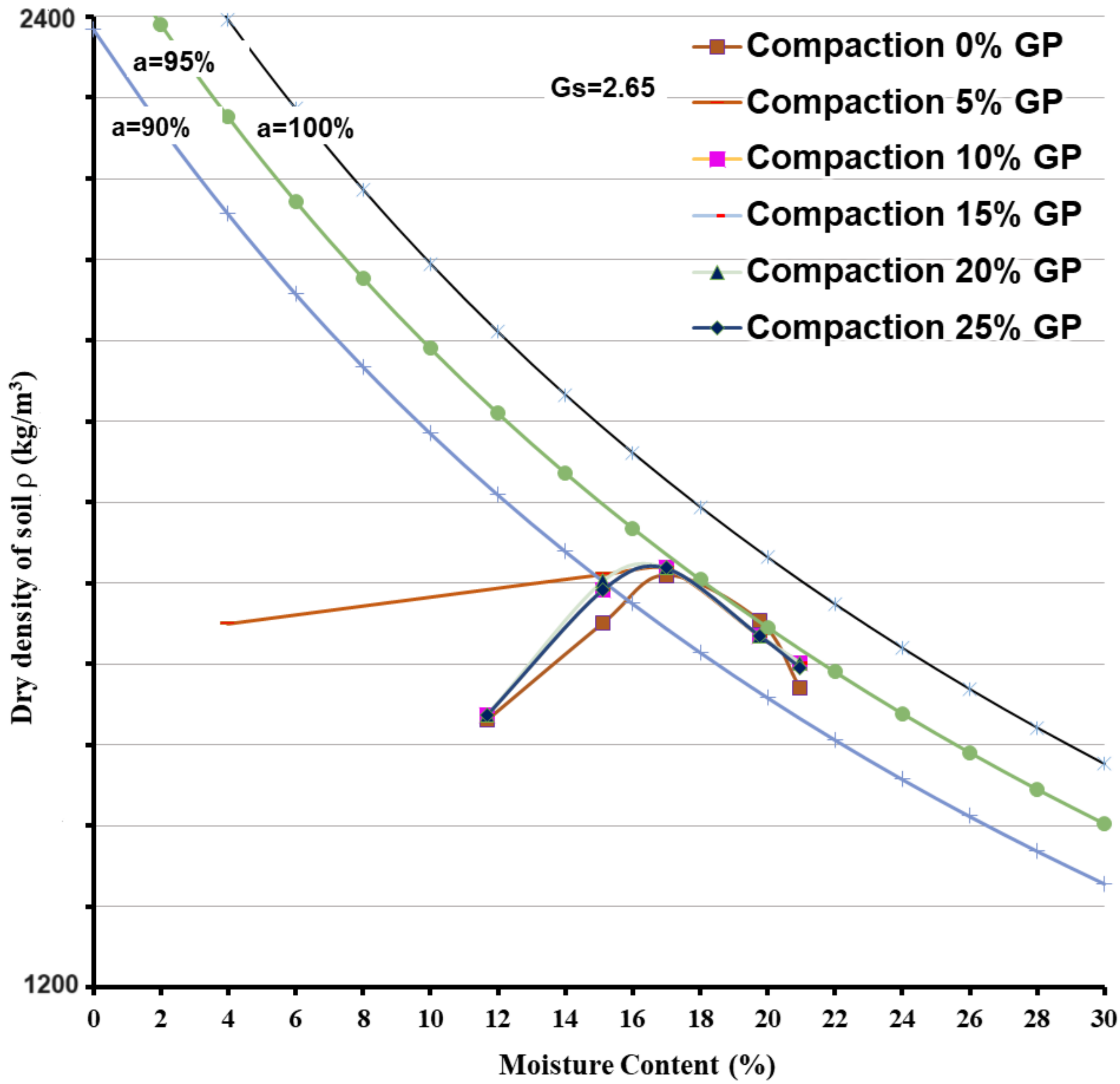

Figure 4-1: Compaction test results with different contents of glass powder

The findings indicate that as the glass powder content increases up to 20%, the optimum moisture content for compaction decreases while the maximum dry density increases. However, beyond this threshold, both the optimum moisture content and maximum dry density stabilize. This suggests a consistent compaction behaviour within this range of glass powder content, emphasizing a point where these important factors remain steady. Such consistency could be valuable for managing and forecasting compaction traits in situations with different levels of glass powder content.

4-3 Atterberg Limits

Results from the Atterberg limit tests provide crucial insights into the behaviour of fine-grained soils and their potential for various engineering applications. These tests determine the consistency limits of soils, which include the liquid limit (LL), plastic limit (PL), and plasticity index (PI). The liquid limit signifies the boundary between the plastic state and the liquid state, while the plastic limit determines the boundary between the plastic state and the semi-solid state. The plasticity index quantifies the range of moisture content over which a soil exhibits plastic behaviour.

Table 4-3: The results of Atterberg Limits

Sample	Liquid Limit (LL)	Plastic limit (PL)	Plastic Index (PI)
S1 (0%)	35	23	12
S2 (5%)	34	22	12
S3 (10%)	33	22	11
S4 (15%)	32	22	10
S5 (20%)	31	21	11
S6 (25%)	29	21	8

The results of Table 4-3 are presented and compared graphically in Figure 4-2 in the form of variations of LL, PL and PI with the glass powder content.

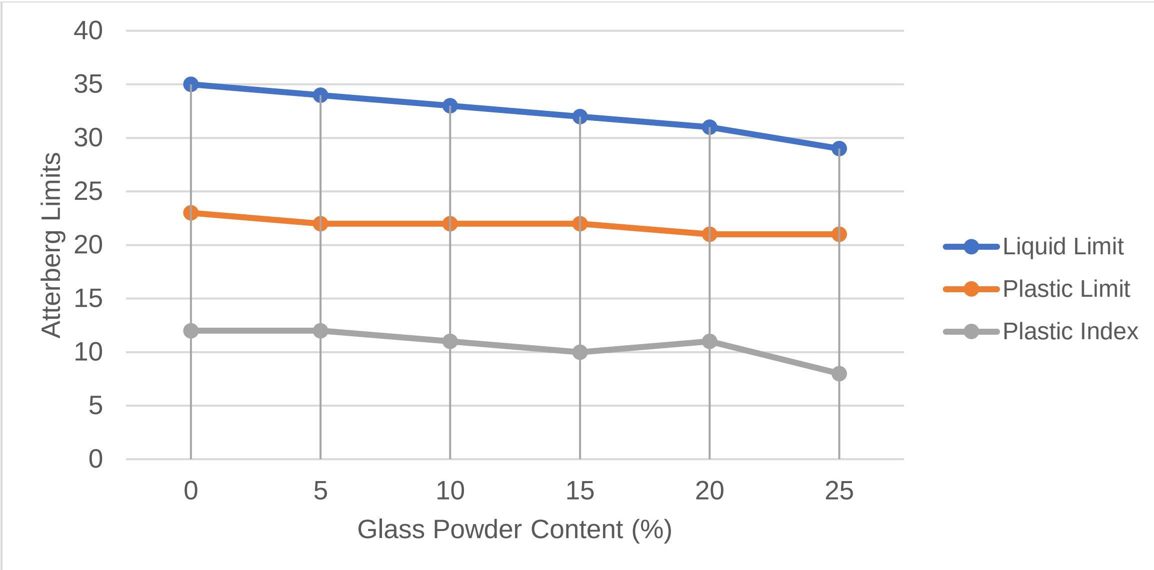

Figure 4- 2: Variations of Atterberg Limits in samples

The results in Figure 4-2 show that with the increase of glass powder content in the clay, the Atterberg limits have decreased.

4-4 Direct shear test results

The dimensions of the specimens for direct shear test were length 6cm, width 6cm and height 2.5cm. Three tests were carried out under three normal stresses of 0.5, 1 and 1.5 kg/cm^2. The results of the direct shear tests are presented in Figures 4-3 to 4-8. Table 4-4 presents the values of normal stress, maximum shear stress and maximum shear strain in different contents of glass powder (GP) obtained from direct shear tests. The values of cohesion (kg/cm^2) and internal friction angle (degree) are shown in Table 4-5 for all different contents of glass powder.

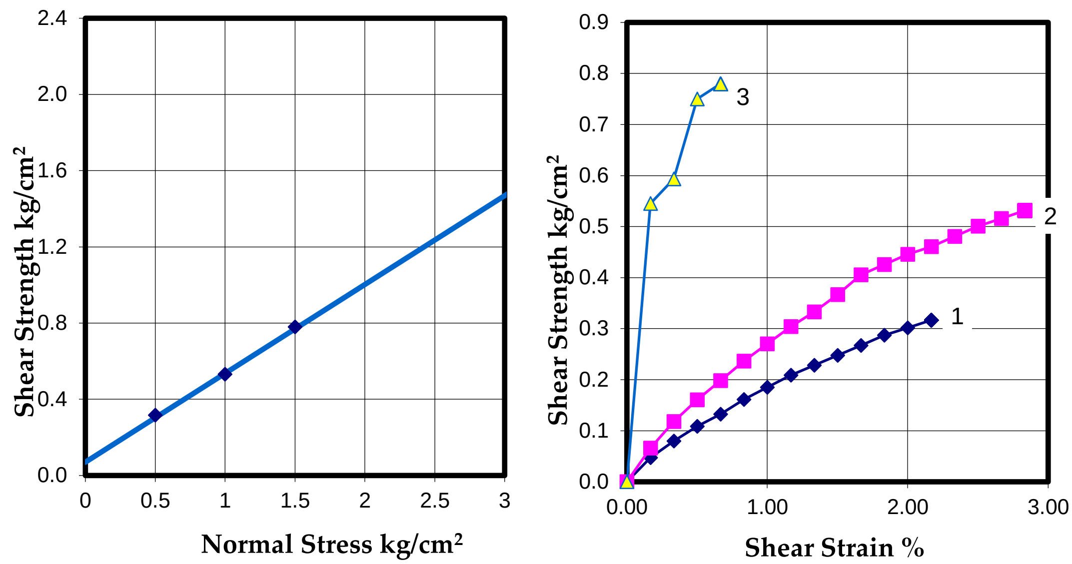

Figure 4- 3: Direct shear test results with 0% GP content

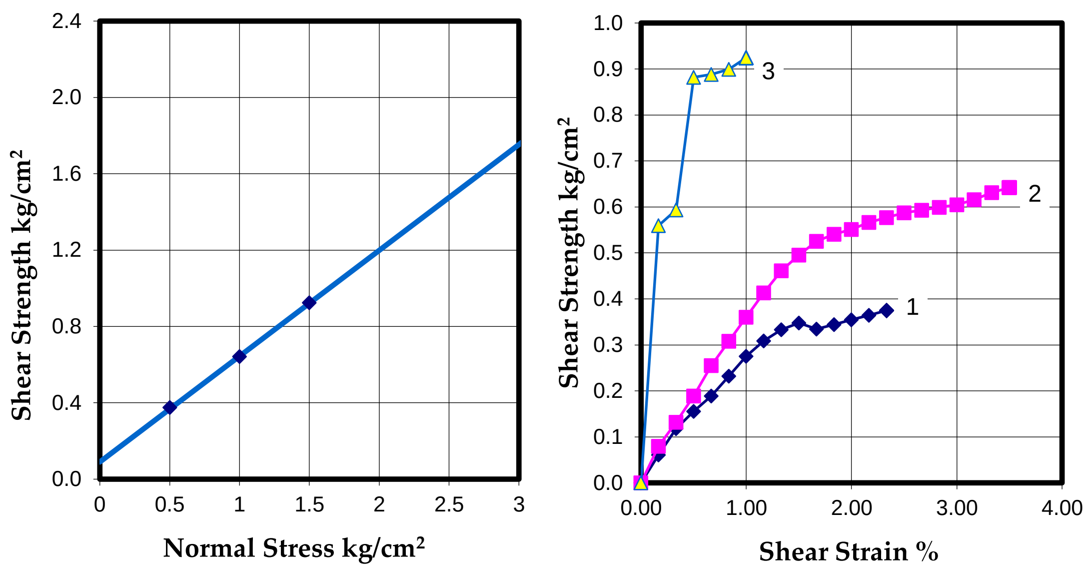

Figure 4- 4: Direct shear test results with 5% GP content

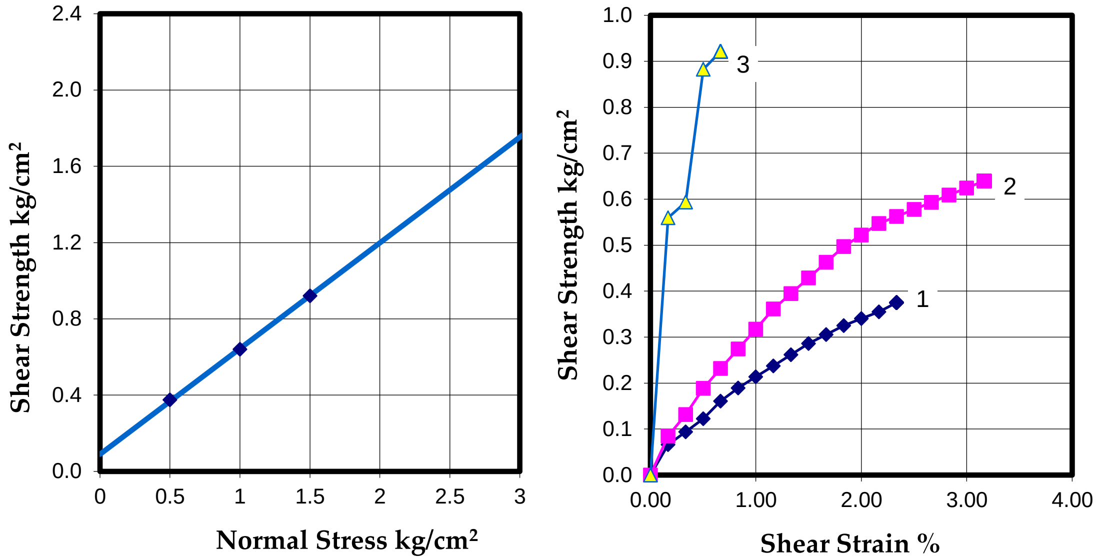

Figure 4- 5: Direct shear test results with 10% GP content

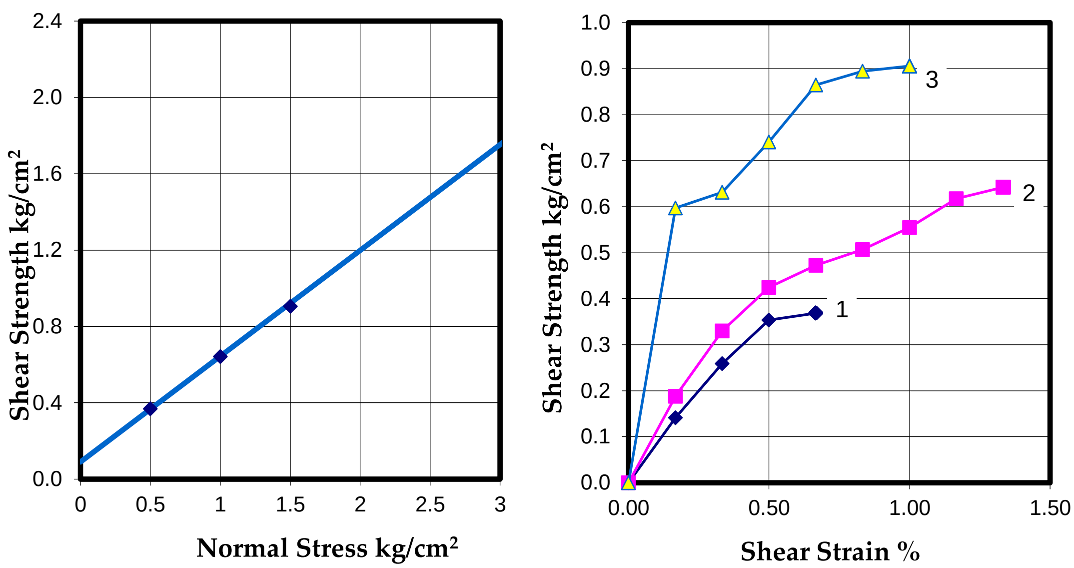

Figure 4- 6: Direct shear test results with 15% GP content

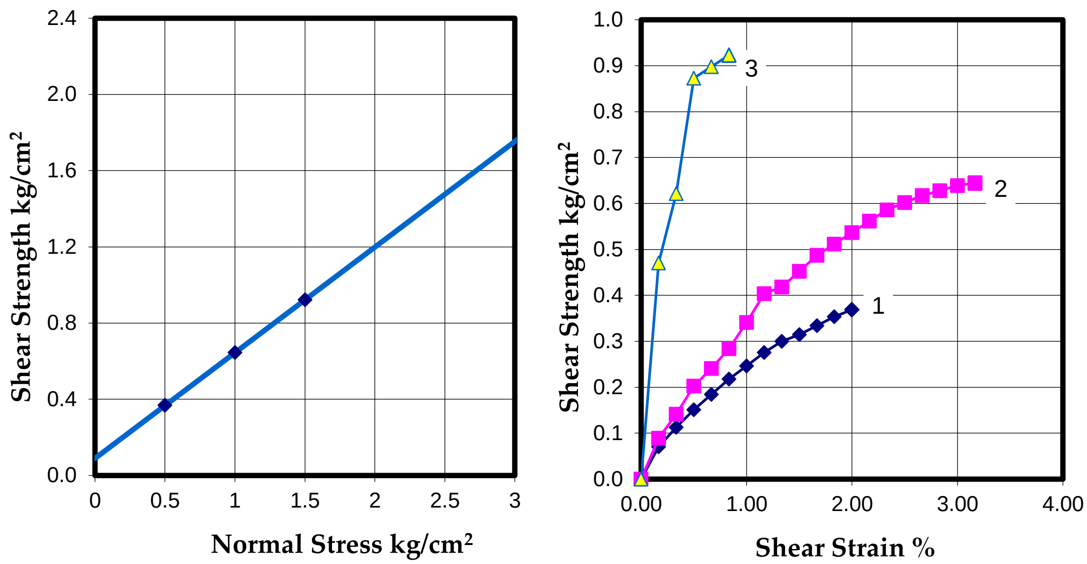

Figure 4- 7: Direct shear test results with 20% GP content

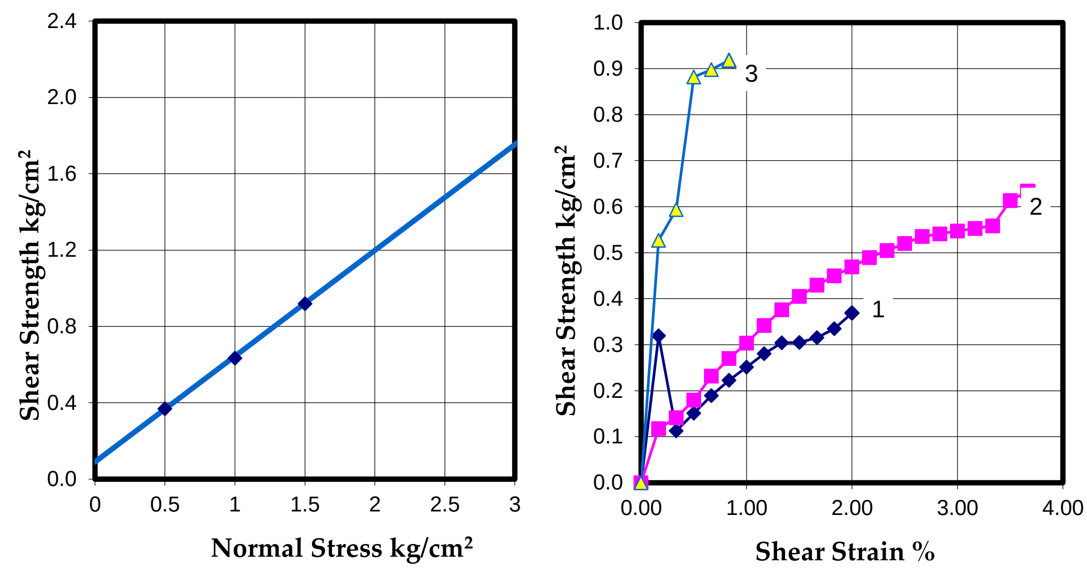

Figure 4- 8: Direct shear test results with 25% GP content

In this test, all the samples were subjected to three normal stresses of 50 kPa, 100 kPa, and 150 kPa. The maximum shear strength and corresponding shear strain are presented in Table 4-4. The values of cohesion (kg/cm2) and internal friction angle (degree) are shown in Table 4-5 for all different contents of glass powder.

Table 4-4 Values of normal stress, maximum shear strength and the corresponding shear strain at different GP contents, obtained from direct shear tests

Test No.	Normal Stress (kg/cm²)	Max Shear Strength (kg/cm2)						Shear Strain (%)					
		GP (0%)	GP (5%)	GP (10%)	GP (15%)	GP (20%)	GP (25%)	GP (0%)	GP (5%)	GP (10%)	GP (15%)	GP (20%)	GP (25%)
1	0.5	0.32	0.37	0.37	0.37	0.37	0.37	2.17	2.33	2.33	0.67	2.00	2.00
2	1.0	0.53	0.64	0.64	0.64	0.64	0.63	2.83	3.50	3.17	1.33	3.17	3.67
3	1.5	0.78	0.92	0.92	0.91	0.92	0.92	0.67	1.00	0.67	1.00	0.83	0.83

Table 4-5 Values of cohesion and internal friction angle in direct shear tests for different GP contents

Content of Glass Powder (%)	0	5	10	15	20	25
Cohesion (kg/cm²)	0.07	0.09	0.09	0.09	0.09	0.09
Internal friction angle (Degree)	25	29	29	29	29	29

The effect of glass powder content on the properties of the stabilized clay shows an interesting trend. Across the range from 5% to 25% glass powder content, there is a noticeable absence of significant influence on crucial factors like maximum shear strength, cohesion, and internal friction angle (Tables 4-4 and 4-5). Particularly striking is the stability observed in shear strain percentages, notably hovering consistently around 20% to 25% glass powder content. This stability, especially under normal stresses of 50 kPa and 150 kPa, signifies a fascinating resilience, suggesting a threshold where the addition of glass powder ceases to substantially alter these critical properties of the stabilized clay. The lack of significant change in these soil properties with the given range of glass powder additions may be attributed to the physical and chemical characteristics of the powder and the nature of the soil itself. Furthermore, the amount of glass powder used, while seemingly substantial, might not be sufficient to produce noticeable changes in internal friction and cohesion if it does not significantly alter the soil's structure.

4-5 Uniaxial compressive strength test results

In this test, the uniaxial compressive strength of the samples were determined in three time periods of 3 days, 7 days and 28 days. The results of this test are presented in Table 4-6.

Table 4-6: Results of uniaxial compressive strength tests

Sample	Compressive strength (kPa)		
	In 3 days	In 7 days	In 28 days
S1 (0%)	136	134	131
S2 (5%)	139	144	148
S3 (10%)	159	161	165
S4 (15%)	200	205	202
S5 (20%)	184	187	189
S6 (25%)	175	176	178

Figure 4-9 shows the variations of the uniaxial compressive strength for different glass powder contents.

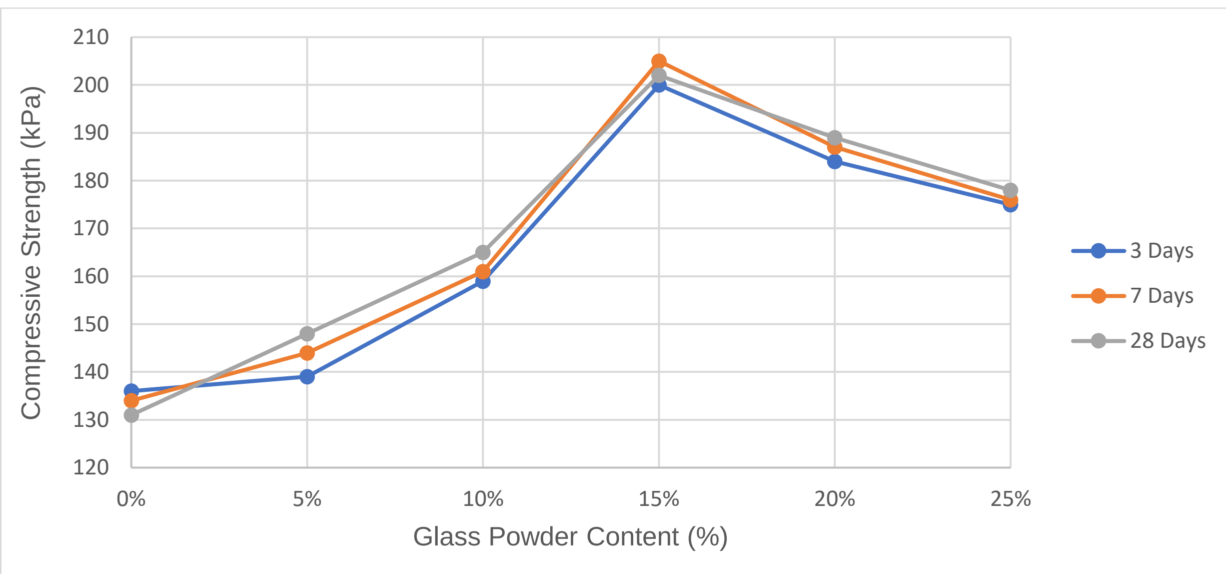

Figure 4- 9: Changes in uniaxial compressive strength of samples with GP content

As the results show, the highest compressive strength of the samples was related to 15% glass powder content. Figure 4-10 illustrates the outcomes derived from the unconfined compressive strength tests, showcasing the relationship between stress and strain. These tests provide valuable insights into the material's behaviour under axial loading conditions, offering crucial data for assessing its structural integrity and performance.

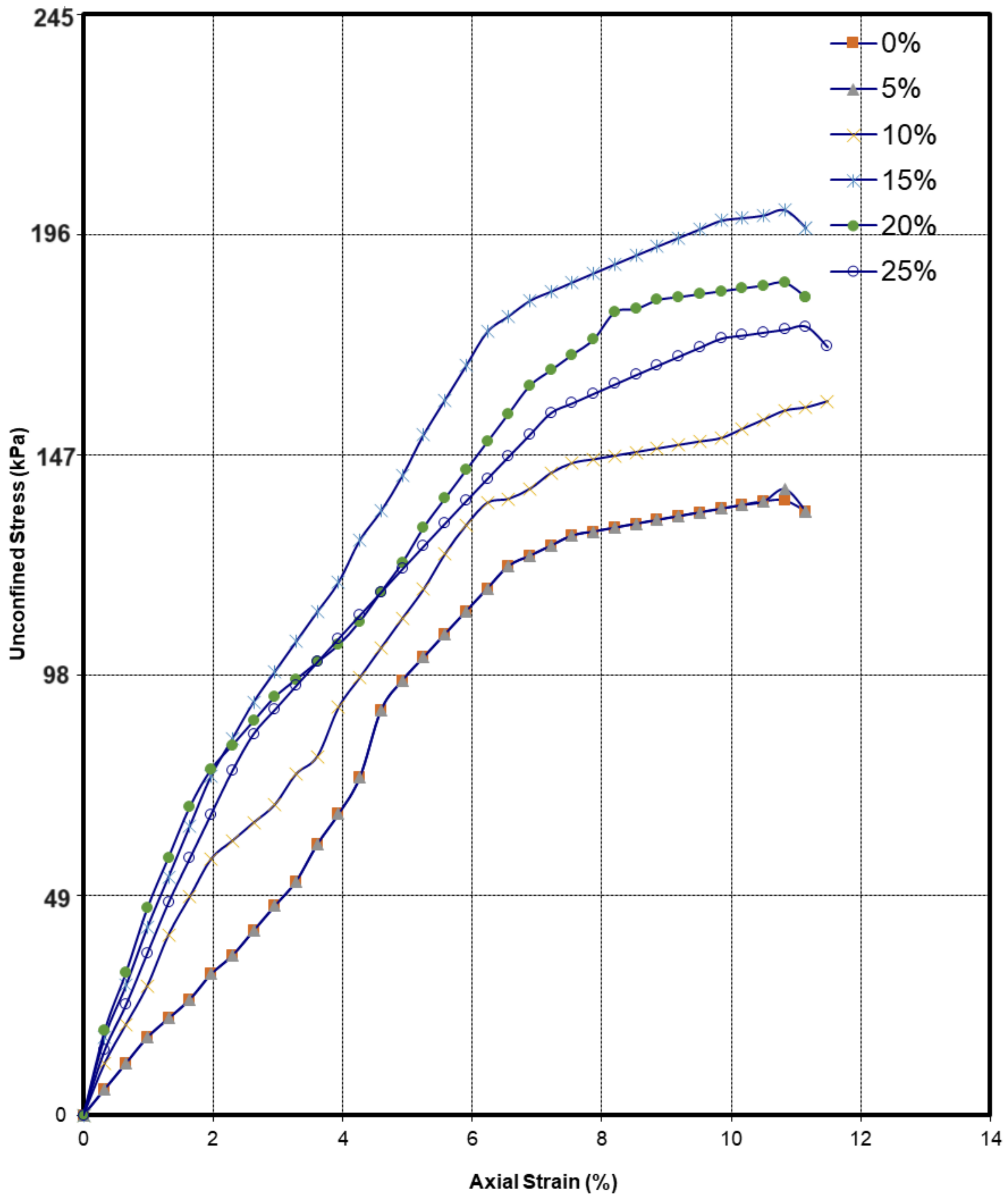

Figure 4- 10: Unconfined compressive strength test results with different GP content

Table 4-7 summarizes the unconfined compressive strength values corresponding to various levels of glass powder content.

Table 4-7 Values of unconfined compressive strength from UCS tests in different GP contents

Glass Powder Content (%)	(0%)	(5%)	(10%)	(15%)	(20%)	(25%)
Unconfined Compressive Strength (kPa)	136	139	159	200	184	175

The results of the unconfined compressive strength tests highlight a clear correlation between the highest strength values and stabilized clay compositions featuring 15% glass powder contents. These specific compositions emerge as the pinnacle, showcasing the highest strength within the tested range. This discernible trend emphasizes the significant impact of glass powder content on enhancing the strength characteristics of the stabilized clay, specifically at these concentration levels, underscoring their potential for robust structural applications.

4-6 Consolidation test results

Finally, in order to evaluate the consolidation characteristics of the soil, the values of compression index (Cc) and swelling index (Cs) were calculated and the results of this test are presented in Table 4-8.

Table 4-8: Results of consolidation tests

Consolidation Test Results	Cc			Cs	
	196.2 (kPa)	392.4 (kPa)	784.8 (kPa)	196.2 (kPa)	784.8 (kPa)
0% GP	0.38	0.31	0.23	0.26	0.23
5% GP	0.38	0.32	0.23	0.27	0.23
10% GP	0.39	0.32	0.24	0.27	0.24
15% GP	0.39	0.33	0.25	0.27	0.25
20% GP	0.40	0.33	0.25	0.26	0.25
25% GP	0.40	0.33	0.26	0.26	0.26

As indicated in Table 4-8, the consolidation indexes increased with an increase in the glass powder content, implying a correlation between glass powder and consolidation.

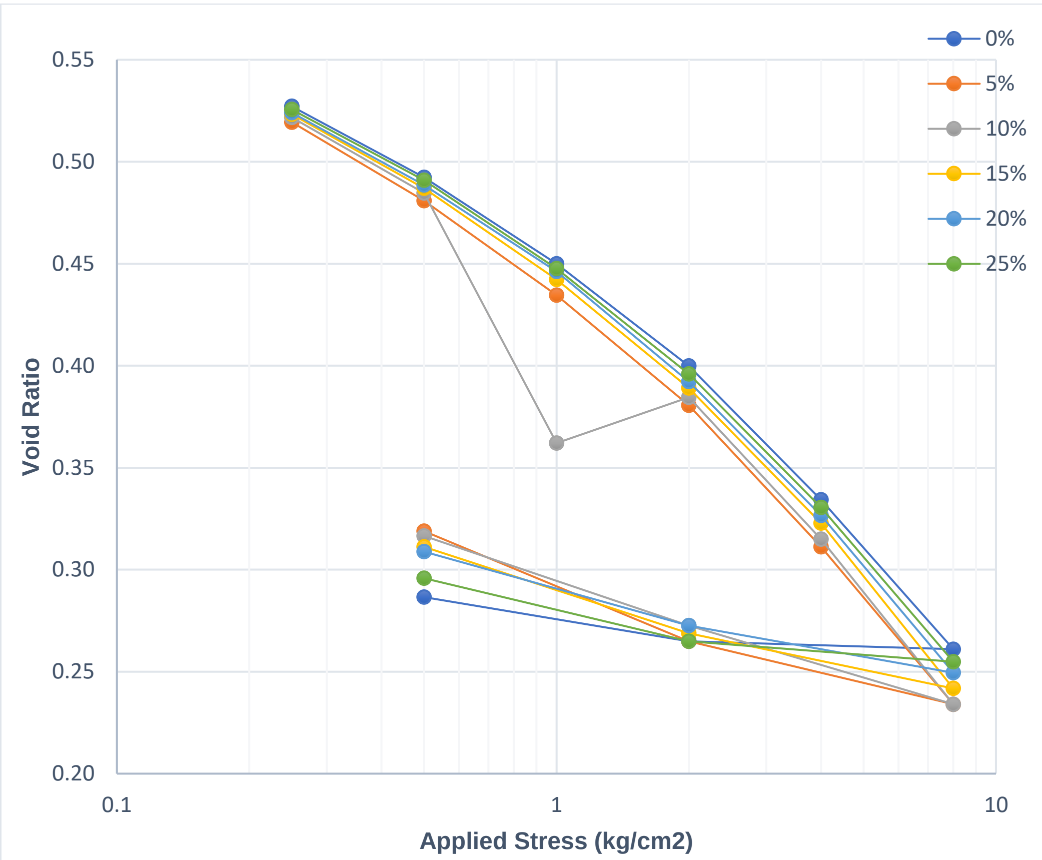

Figure 4- 11: Changes in void ratio of samples based on consolidation test

Figure 4-11 shows the variations of void ratio with applied pressure in consolidation test for the soil with different percentages of GP. The results show that the sample without glass powder has the maximum initial void ratio.

4-7 SEM Analysis

Figure 4-12 presents the scanning electron microscopy (SEM) images of glass powder, offering a detailed view at both 200x and 1000x magnifications. Figures 4-13 to 4-18 delve further into the SEM images, revealing the intricate placement of glass powder particles within clay particles. The images illustrate the complex microstructures of clay with different concentrations of glass powder, ranging from 0% to 25%. Each image presents a distinct viewpoint, illuminating the dynamic development of microstructures and exposing subtle details in their configuration. This examination enables a deeper comprehension of how microstructures interact and organize themselves at varying levels of glass powder incorporation. As the GP content rises, SEM images depict alterations in how GP is dispersed within the matrix, alongside the emergence of interfacial regions between the GP and the matrix material, highlighted by yellow circles in Figures 4-15 to 4-18. These interfaces play a role in influencing mechanical characteristics like reinforcement and fracture behaviour. The absence of glass powder results in a smoother surface morphology with fewer voids and cracks. However, the lack of interlocking bonds between particles suggests weaker cohesion within the matrix compared to the clay-glass powder composite. This difference in microstructure likely contributes to variations in mechanical properties, such as strength and stiffness, between the two samples.

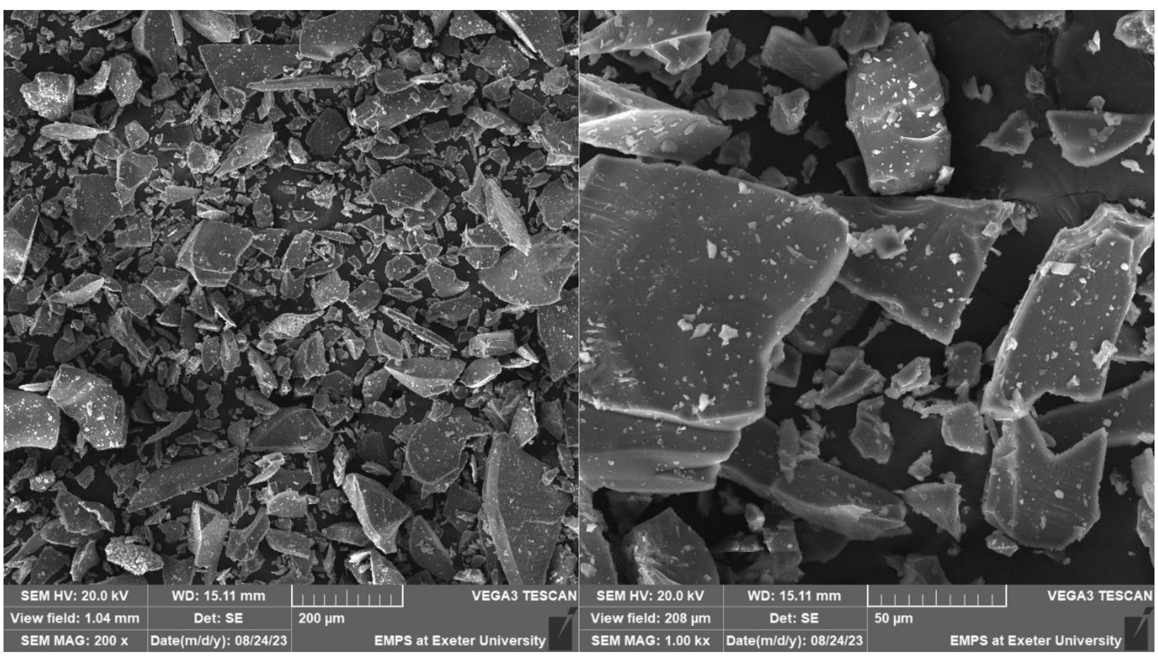

Figure 4- 12: SEM images of the glass powder at 200x and 1000x magnification

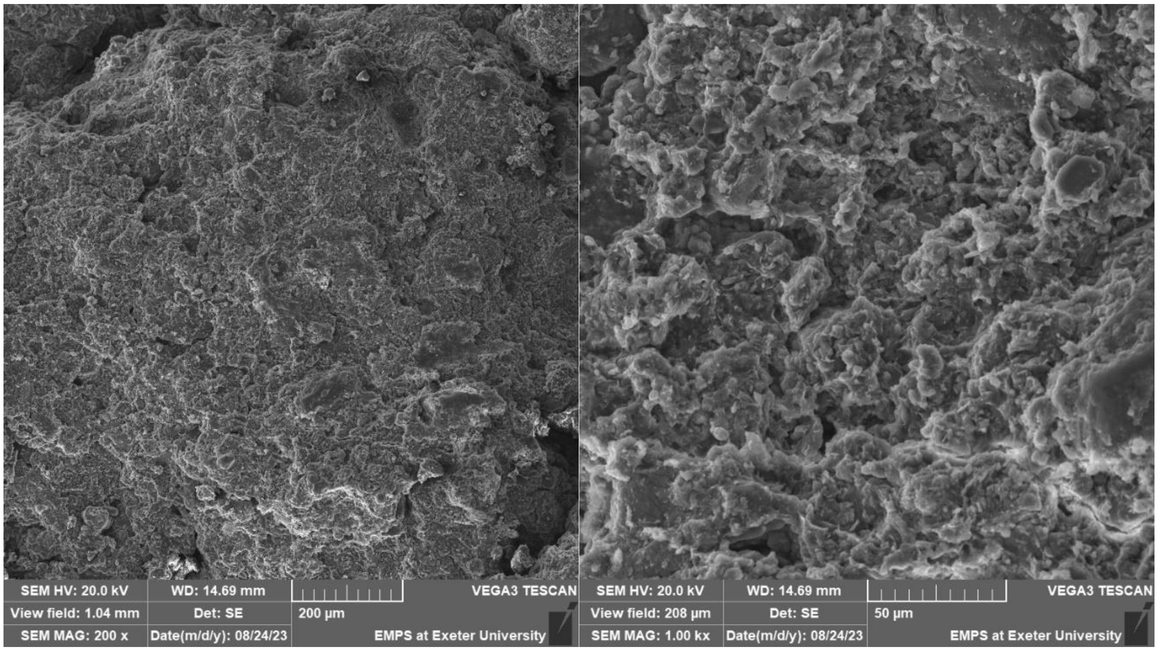

Figure 4- 13: SEM images of the specimen with 0% glass powder at 200x and 1000x magnification

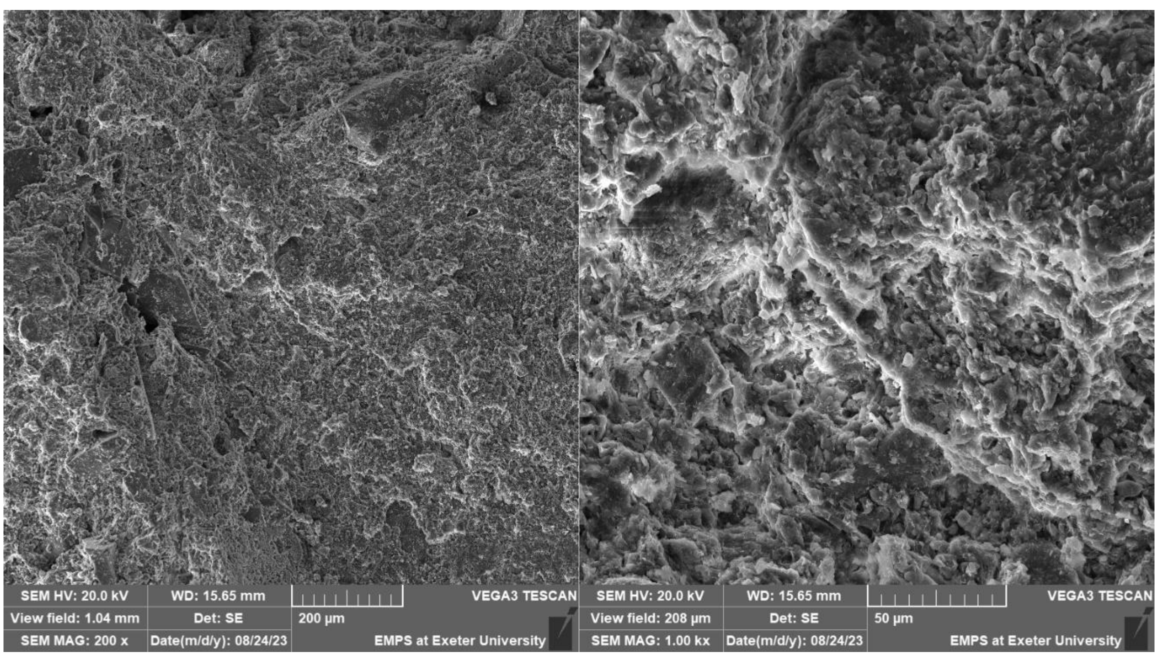

Figure 4- 14: SEM images of the specimen with 5% glass powder at 200x and 1000x magnification

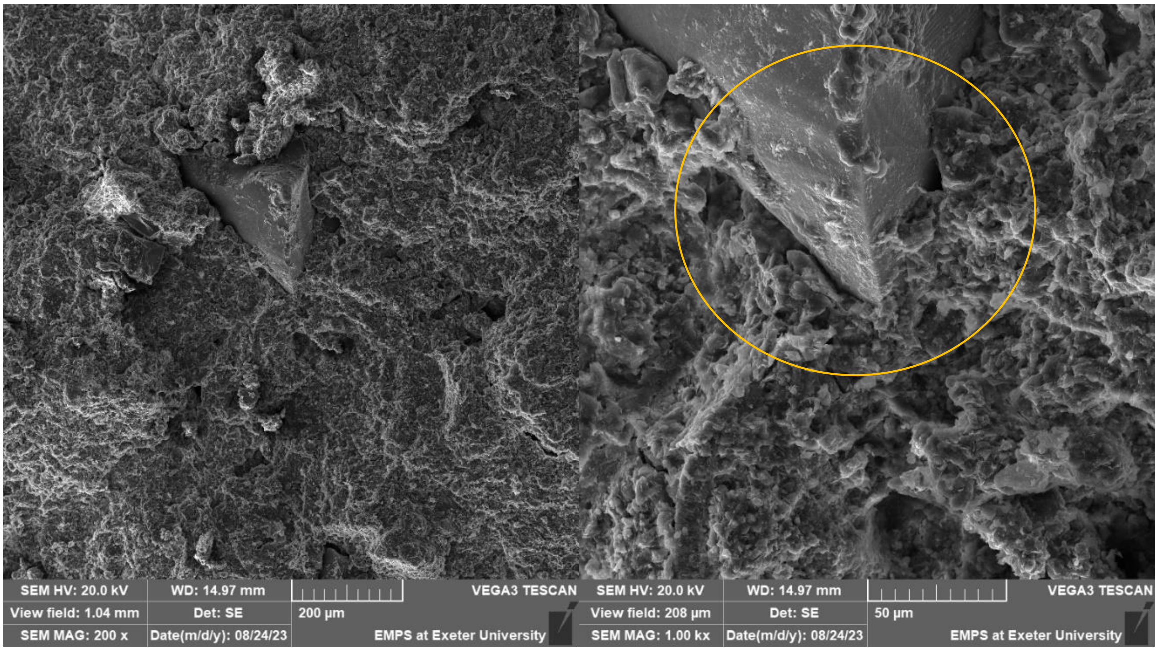

Figure 4- 15: SEM images of the specimen with 10% glass powder at 200x and 1000x magnification

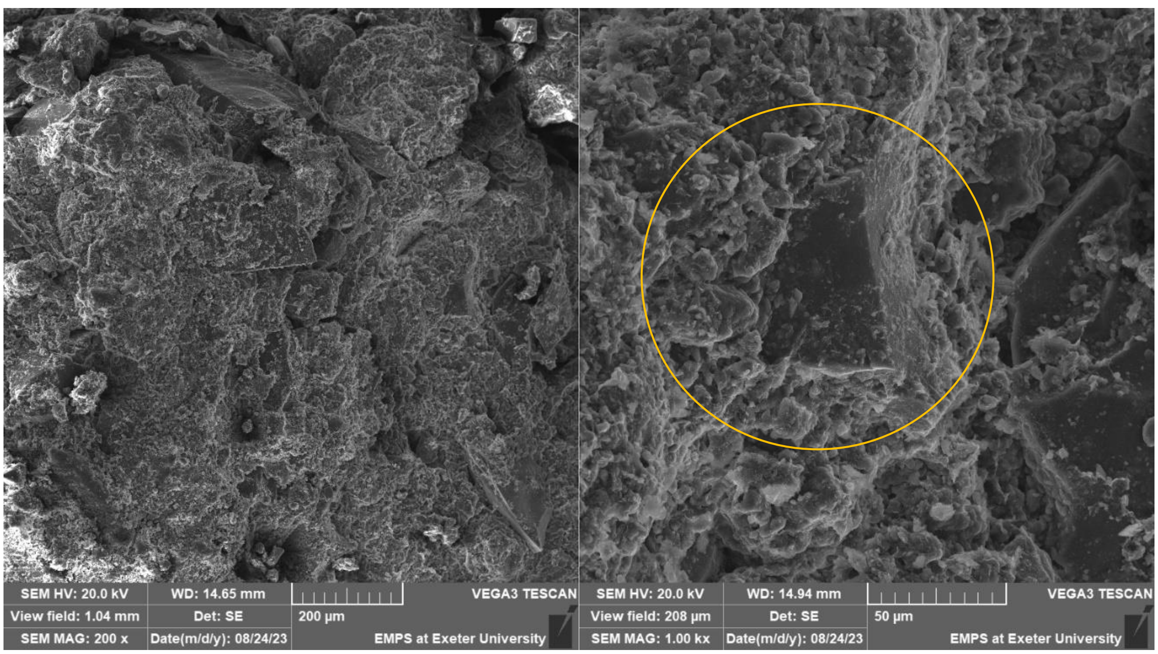

Figure 4- 16: SEM images of the specimen with 15% glass powder at 200x and 1000x magnification

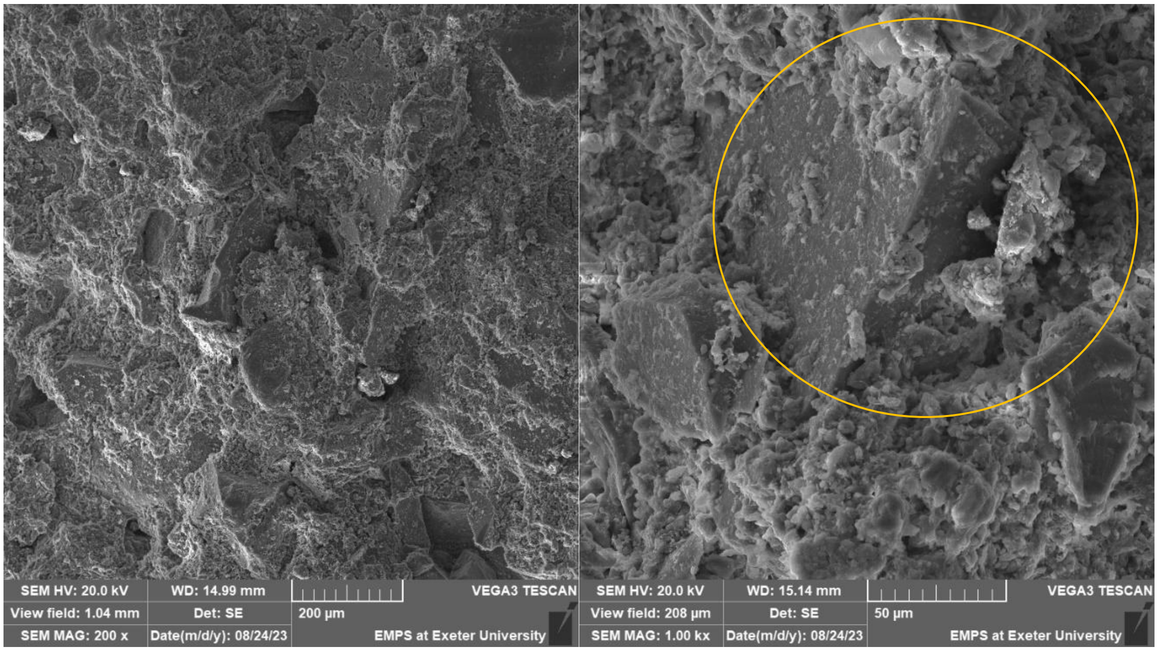

Figure 4- 17: SEM images of the specimen with 20% glass powder at 200x and 1000x magnification

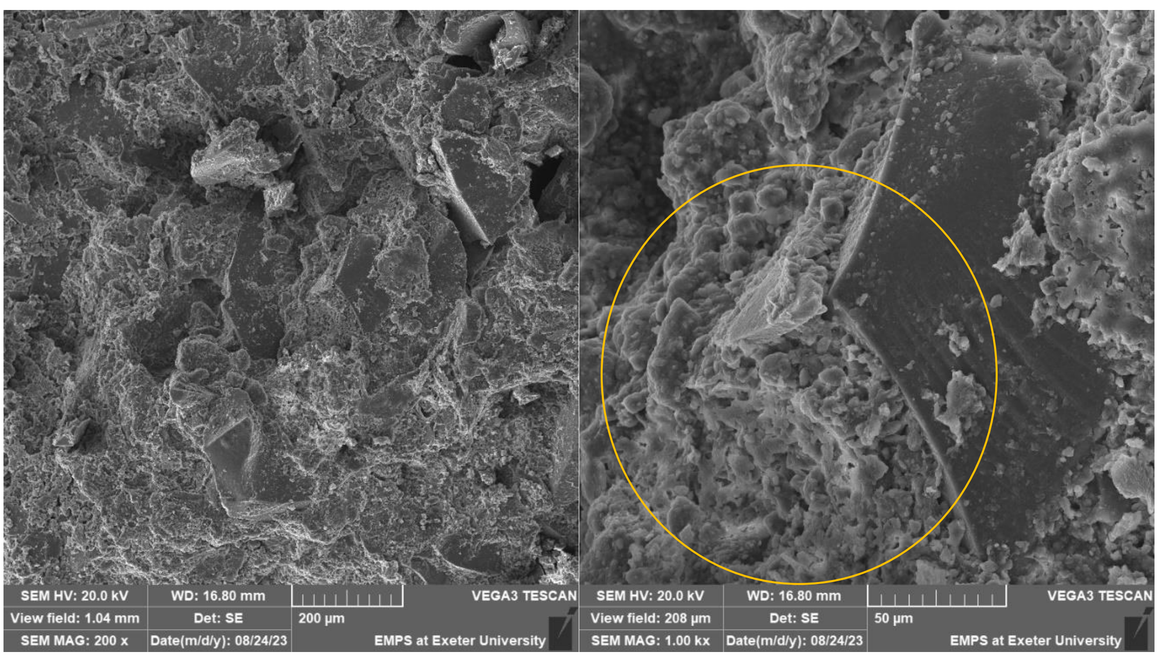

Figure 4- 18: SEM images of the specimen with 25% glass powder at 200x and 1000x magnification

The results of this study provide significant insights into the use of glass powder (GP) as a sustainable and effective material for soil stabilization, aligning well with the findings of recent studies. Glass powder, derived from waste glass, has been increasingly recognized for its ability to enhance soil properties, compaction, and overall soil stability. The fine particles of GP effectively fill voids within the soil matrix. These properties have made GP a promising candidate for soil stabilization, offering both environmental and economic benefits by repurposing waste materials. The experimental outcomes from this research underscore the potential of GP to modify soil behavior, even in the absence of alkali activators. This is a critical area of exploration, as most existing studies have focused on the performance of GP in conjunction with such activators. The findings suggest that GP alone can sufficiently stabilize soil, with noticeable improvements in mechanical properties observed at specific concentrations. This is particularly evident in the results from compaction, direct shear and unconfined compressive strength (UCS).

One of the key findings of this research is the identification of an optimal range for GP content in soil stabilization. The results indicate that increasing GP content up to 20% enhances the soil's compaction characteristics, as evidenced by a decrease in optimum moisture content and an increase in maximum dry density. Beyond this threshold, these parameters stabilize, suggesting that higher GP content does not necessarily lead to further improvements and may, in fact, results in diminishing returns. This aligns with previous studies that have highlighted the effectiveness of lower GP concentrations (0% to 20%), reinforcing the practical upper limit for its application.

Moreover, the study reveals that while GP content between 5% and 25% does contribute to a consistent shear strain, particularly under varying normal stresses. This consistency suggests that GP stabilizes these mechanical properties within a specific range, which could be advantageous for maintaining soil behavior under different loading conditions. Knowing that GP content in this range contributes to desirable properties allows for more efficient use of materials. Engineers and construction professionals can optimize the amount of GP to achieve the best balance between cost and soil performance.

The unconfined compressive strength tests further support the benefits of incorporating GP into soil, with the highest strength observed at 15% GP content. This specific concentration emerges as optimal, providing the best balance between enhancing soil strength and maintaining other desirable properties. These results emphasize the role of

GP in reinforcing the soil matrix, making it more resistant to compressive forces, which is crucial for structural applications.

Regarding consolidation behavior, the inclusion of glass powder (GP) seems to significantly impact the void ratio and consolidation indexes.

The SEM analysis offers a microstructural view of how glass powder (GP) influences soil stabilization. The images show the distribution of GP within the soil matrix and the creation of interfacial regions that enhance the mechanical properties of the stabilized soil. The incorporation of GP results in a more intricate microstructure with interlocking bonds, which likely explains the observed increases in soil strength. Conversely, the smoother morphology and absence of interparticle bonds in soil without GP indicate weaker mechanical properties, emphasizing the reinforcing role of GP.

In conclusion, this study demonstrates that glass powder can effectively stabilize clay soil without the need for alkali activators, with the optimal performance observed at around 15% to 20% GP content. These findings contribute to the broader understanding of GP as a viable and sustainable option for soil stabilization, with implications for a range of construction and infrastructure projects. Further research could explore the long-term durability of GP-stabilized soils and investigate other waste materials that could complement or enhance the stabilization process.

Chapter 5: Conclusion

5-1 Conclusion

In general, soils of construction sites are not always completely favourable and sometimes their mechanical properties need to be modified by mixing the soil with other additives. In recent years, research on reuse of waste materials has attracted huge interest. One of the cases of reusing waste materials is the use of waste glass powder to improve soil behaviour. In this study, a clay with a specific gravity of 2.65 and an optimal moisture content of 17% was used as the main soil. Then glass powder was used with content ratios of 0%, 5%, 10%, 15%, 20% and 25% in order to improve soil properties. The particle size of glass powder was below 20 μm. One-dimensional consolidation, Atterberg limits, uniaxial compression, direct shear and compaction tests were performed to evaluate the stability, strength and settlement characteristics of the clay stabilized with glass powder. Based on the results, the following conclusions can be drawn:

- With the increase in the percentage of glass powder, the value of maximum dry density (MDD) increased and the optimum moisture content (OMC) decreased. In the samples with 15% to 25% glass powder content, these changes were constant.

- By increasing the percentage of glass powder in the clay, the liquid limit and plastic limit decreased.

- The direct shear tests manifested a consistent trend across glass powder contents from 5% to 25%, showcasing minimal influence on critical factors such as maximum shear strength, cohesion, and internal friction angle.

- The highest compressive strength was obtained in the sample with 15% glass powder content.

- With the increase of glass powder in the soil, soil consolidation indexes (Cc and Cs) increased.

- The results of the unconfined compressive strength tests indicate that the samples exhibited the highest compressive strength when they contained a 15% glass powder content. This suggests that the incorporation of glass powder at this specific percentage yielded the greatest strength properties among the tested samples.

The scanning electron microscopy (SEM) images further illuminated the interaction between glass powder particles and clay across varying concentrations. As the proportion of GP increases, SEM images illustrate changes in the distribution of GP within the matrix, accompanied by the formation of interfacial regions between the GP and the matrix material.The findings suggest that incorporating an optimal amount of glass powder, typically ranging between 15% and 20%, can substantially enhance the strength of stabilized clay without the need for alkali-activated materials (AAMs). This range of glass powder content demonstrates a notable improvement in the mechanical properties of the stabilized clay, such as compressive strength and shear strength.

Further research could delve into the specific mechanisms through which glass powder interacts with clay particles to improve its strength characteristics, paving the way for more tailored and efficient stabilization techniques. Additionally, exploring the durability and long-term performance of clay stabilized with glass powder can provide valuable insights into its suitability for various engineering applications, from road construction to land remediation projects.

5-2 Recommendations

Based on the conclusions drawn from this study, several recommendations can be made to further advance the use of glass powder (GP) in soil stabilization:

1. **Optimization of GP Content**: Future research should focus on refining the optimal percentage of glass powder for different soil types. While this study suggests that 15% to 20% GP content offers the most significant improvements in clay stabilization, further testing across a wider range of soil types and conditions could help tailor the GP content for specific engineering applications.
2. **Long-Term Performance Studies**: To ensure the long-term viability of using glass powder for soil stabilization, it is crucial to conduct extended studies on the

durability and performance of GP-stabilized soils under various environmental conditions. This includes evaluating the effects of factors such as freeze-thaw cycles, moisture variation, and chemical exposure on the stabilized soils over time.

3. **Mechanistic Studies**: Further investigation into the microstructural mechanisms by which GP enhances soil properties would provide valuable insights into the stabilization process. Advanced analytical techniques, such as X-ray diffraction (XRD) and energy-dispersive X-ray spectroscopy (EDS), could complement SEM analysis to better understand the interaction between GP particles and the clay matrix.

4. **Field Applications and Scale-Up**: While laboratory tests provide controlled conditions to assess the effectiveness of GP in soil stabilization, field trials are essential to evaluate its performance in real-world scenarios. Large-scale field studies should be conducted to assess the practicality, economic feasibility, and environmental impact of using GP in various construction projects.

5. **Exploration of Other Waste Materials**: In line with the sustainable approach of utilizing waste materials, future research could explore the potential of combining glass powder with other industrial by-products, such as fly ash or slag, to further enhance soil stabilization. Such combinations could potentially offer synergistic effects, leading to even more effective and sustainable soil stabilization solutions.

6. **Standardization and Guidelines**: As the use of waste materials like glass powder in soil stabilization becomes more prevalent, developing standardized guidelines and protocols for their application will be essential. This would include establishing recommended practices for the selection, testing, and implementation of GP in various engineering contexts, ensuring consistency and reliability in its use.

By addressing these areas, the application of glass powder in soil stabilization can be further optimized, making it a more robust and sustainable solution for improving soil properties in construction and infrastructure projects.

References

1. Stout, J., K. Goh, and T. Rafter, *Chemistry and turnover of naturally occurring resistant organic compounds in soil.* Soil biochemistry, 1981. **5**: p. 1-73.
2. Kubiena, W., *The classification of soils.* Journal of Soil Science, 1958. **9**(1): p. 9-19.
3. C242-15, A. *Standard terminology of ceramic whitewares and related products*. 2015. Am. Soc. Test. Mater.
4. Churchman, G.J., et al., *Clay minerals as the key to the sequestration of carbon in soils.* Clays and Clay Minerals, 2020. **68**(2): p. 135-143.
5. Khalifa, A.Z., et al., *Advances in alkali-activation of clay minerals.* Cement and Concrete Research, 2020. **132**: p. 106050.
6. Sabzi, Z., *Environmental friendly soil stabilization materials available in Iran.* Journal of Environmental Friendly Materials, 2018. **2**(1): p. 33-39.
7. Mahmudi, M., T. Eskisar, and S. Altun, *The Effects of Electric Arc Furnace (EAF) Slag on Engineering Properties of Clay–Slag Mixtures.* Arabian Journal of Geosciences, 2022. **15**(2): p. 184.
8. Casagrande, A., *Classification and identification of soils.* Transactions of the American Society of Civil Engineers, 1948. **113**(1): p. 901-930.
9. Wanyama, P., *Experimental study of shear behaviour of high density polyethylene reinforced sand under triaxial compression.* 2017.
10. Aziz, M., *Mechanical properties of a high plasticity clay mixed with sand and low-plastic silt.* Materials Today: Proceedings, 2023.
11. Firoozi, A.A., et al., *Fundamentals of soil stabilization.* International Journal of Geo-Engineering, 2017. **8**: p. 1-16.
12. Barman, D. and S.K. Dash, *Stabilization of expansive soils using chemical additives: A review.* Journal of Rock Mechanics and Geotechnical Engineering, 2022. **14**(4): p. 1319-1342.
13. Huang, J., et al., *A state-of-the-art review of polymers used in soil stabilization.* Construction and Building Materials, 2021. **305**: p. 124685.
14. Fatehi, H., et al., *Biopolymers as green binders for soil improvement in geotechnical applications: A review.* Geosciences, 2021. **11**(7): p. 291.
15. Onyejekwe, S. and G.S. Ghataora, *Soil stabilization using proprietary liquid chemical stabilizers: sulphonated oil and a polymer.* Bulletin of Engineering Geology and the Environment, 2015. **74**: p. 651-665.
16. Kired, F., et al., *Stabilization of Different Soil Types Using a Hydraulic Binder.* Buildings, 2023. **13**(8): p. 2040.
17. Harichane, K., M. Ghrici, and S. Kenai, *Effect of the combination of lime and natural pozzolana on the compaction and strength of soft clayey soils: a preliminary study.* Environmental earth sciences, 2012. **66**: p. 2197-2205.
18. Amini, O. and M. Ghasemi, *Laboratory study of the effects of using magnesium slag on the geotechnical properties of cement stabilized soil.* Construction and Building Materials, 2019. **223**: p. 409-420.
19. Fakhrabadi, A., A.J. Choobbasti, and S.S. Kutanaei, *Durability Evaluation of Clayey Sandy Soil Stabilized with Copper-Slag-Based Geopolymer Under Freezing–Thawing Cycles.* International Journal of Pavement Research and Technology, 2023: p. 1-18.
20. Lopes, E.C., et al., *Chemical, mineralogical, microstructural and engineering properties of tropical soils stabilised with the combined and individual use of different types of steel slag.* Road Materials and Pavement Design, 2023: p. 1-21.

21. Nabizadeh Mashizi, M., et al., *Mechanical and Microstructural properties of a stabilized sand using geopolymer made of wastes and a natural pozzolan.* Sustainability, 2023. **15**(4): p. 2966.
22. Olufowobi, J., et al., *Clay soil stabilisation using powdered glass.* Journal of Engineering Science and Technology, 2014. **9**(5): p. 541-558.
23. Federico, L. and S. Chidiac, *Waste glass as a supplementary cementitious material in concrete–critical review of treatment methods.* Cement and concrete composites, 2009. **31**(8): p. 606-610.
24. Zheng, K., *Pozzolanic reaction of glass powder and its role in controlling alkali–silica reaction.* Cement and Concrete Composites, 2016. **67**: p. 30-38.
25. Zeybek, Ö., et al., *Influence of replacing cement with waste glass on mechanical properties of concrete.* Materials, 2022. **15**(21): p. 7513.
26. Arrieta Baldovino, J.d.J., et al., *Sustainable use of recycled-glass powder in soil stabilization.* Journal of Materials in Civil Engineering, 2020. **32**(5): p. 04020080.
27. Baldovino, J.J., et al., *Strength, durability, and microstructure of geopolymers based on recycled-glass powder waste and dolomitic lime for soil stabilization.* Construction and Building Materials, 2021. **271**: p. 121874.
28. Gol, M.S. and V. Toufigh, *Feasibility study of sandy soil stabilization with glass powder and natural pozzolan based geopolymer.* Amirkabir Journal of Civil Engineering, 2019. **51**(1): p. 169-182.
29. Bilondi, M.P., M.M. Toufigh, and V. Toufigh, *Experimental investigation of using a recycled glass powder-based geopolymer to improve the mechanical behavior of clay soils.* Construction and building Materials, 2018. **170**: p. 302-313.
30. Li, Y., et al., *Comparative Study on the Effects of Different Soil Improvement Methods in Blueberry Soil.* Agronomy, 2024. **14**(1): p. 125.
31. Hertel, T. and Y. Pontikes, *Geopolymers, inorganic polymers, alkali-activated materials and hybrid binders from bauxite residue (red mud)–Putting things in perspective.* Journal of Cleaner Production, 2020. **258**: p. 120610.
32. Provis, J.L. and J.S.J. Van Deventer, *Geopolymers: structures, processing, properties and industrial applications*. 2009: Elsevier.
33. Hasan, H., et al., *Remediation of expansive soils using agricultural waste bagasse ash.* Procedia engineering, 2016. **143**: p. 1368-1375.
34. MolaAbasi, H., et al., *Low plasticity clay stabilized with cement and zeolite: An experimental and environmental impact study.* Resources, Conservation and Recycling, 2022. **184**: p. 106408.
35. Kaza, S., et al., *What a waste 2.0: a global snapshot of solid waste management to 2050*. 2018: World Bank Publications.
36. Lima, D., J. Arrieta-Baldovino, and R.L. Izzo, *Sustainable Use of Recycled Asphalt Pavement in Soil Stabilization.* Civil Engineering Journal, 2023. **9**(9): p. 2315-2329.
37. Gupta, J., N. Lata, and B. Nagar, *Strength of Concrete Partially Replacing Fine Aggregates by Glass Powder.* 2018.
38. Huang, Y. and L. Wang, *Experimental studies on nanomaterials for soil improvement: a review.* Environmental Earth Sciences, 2016. **75**: p. 1-10.
39. Patel, A., *Geotechnical investigations and improvement of ground conditions*. 2019: Woodhead Publishing.
40. Jani, Y. and W. Hogland, *Waste glass in the production of cement and concrete–A review.* Journal of environmental chemical engineering, 2014. **2**(3): p. 1767-1775.
41. Tiseo, I., *Key figures on glass recycling worldwide as of 2018.* Energy and Environment, 2020.
42. Blayi, R.A., et al., *Strength improvement of expansive soil by utilizing waste glass powder.* Case Studies in Construction Materials, 2020. **13**: p. e00427.
43. Pascual, A.B., M.T. Tognonvi, and A. Tagnit-Hamou, *Waste glass powder-based alkali-activated mortar.* Int. J. Res. Eng. Technol, 2014. **3**(13): p. 32-36.

44. Benny, J.R., et al., *Effect of glass powder on engineering properties of clayey soil.* International Journal of Engineering Research & Technology, 2017. **6**(5): p. 228-231.
45. Ibrahim, H.H., Y.I. Mawlood, and Y.M. Alshkane, *Using waste glass powder for stabilizing high-plasticity clay in Erbil city-Iraq.* International Journal of Geotechnical Engineering, 2021. **15**(4): p. 496-503.
46. Torres-Carrasco, M. and F. Puertas, *Waste glass as a precursor in alkaline activation: Chemical process and hydration products.* Construction and Building Materials, 2017. **139**: p. 342-354.
47. Marcin, M., M. Sisol, and I. Brezani. *Effect of waste glass addition on mechanical properties of slag based geopolymers*. in *IOP Conference Series: Materials Science and Engineering*. 2018. IOP Publishing.
48. Puertas, F. and M. Torres-Carrasco, *Use of glass waste as an activator in the preparation of alkali-activated slag. Mechanical strength and paste characterisation.* Cement and Concrete Research, 2014. **57**: p. 95-104.
49. Liu, G., M. Florea, and H. Brouwers, *Waste glass as binder in alkali activated slag–fly ash mortars.* Materials and Structures, 2019. **52**: p. 1-12.
50. Shao, Y., et al., *Studies on concrete containing ground waste glass.* Cement and concrete research, 2000. **30**(1): p. 91-100.
51. Sheob, M., et al., *Using a blend of cement and waste glass powder to improve the properties of clayey soil.* Materials Today: Proceedings, 2023.
52. Canakci, H., A. Aram, and F. Celik, *Stabilization of clay with waste soda lime glass powder.* Procedia engineering, 2016. **161**: p. 600-605.
53. Chen, Z. and C.S. Poon, *Comparing the use of sewage sludge ash and glass powder in cement mortars.* Environmental technology, 2017. **38**(11): p. 1390-1398.
54. Güllü, H., H. Canakci, and I.F. Al Zangana, *Use of cement based grout with glass powder for deep mixing.* Construction and Building Materials, 2017. **137**: p. 12-20.
55. Parihar, N.S., V.K. Garlapati, and R. Ganguly, *Stabilization of black cotton soil using waste glass.* Handbook of environmental materials management, 2018: p. 1-16.
56. Asl, M.T. and E. Taherabadi, *Modification of silty clay strength in cold region's pavement using glass residue.* Cold Regions Science and Technology, 2018. **154**: p. 111-119.
57. Canakci, H., H. Güllü, and M.I.K. Dwle, *Effect of glass powder added grout for deep mixing of marginal sand with clay.* Arabian Journal for Science and Engineering, 2018. **43**(4): p. 1583-1595.
58. Tsegaye Woldesenbet, T., *Experimental study on stabilized expansive soil by blending parts of the soil kilned and powdered glass wastes.* Advances in Civil Engineering, 2022. **2022**.
59. Javed, S.A. and S. Chakraborty, *Effects of waste glass powder on subgrade soil improvement.* World Scientific News, 2020(144): p. 30-42.
60. Belkhatir, M., et al., *Laboratory study on the liquefaction resistance of sand-silt mixtures: effect of grading characteristics.* Granular Matter, 2011. **13**(5): p. 599-609.