Evaluation the Effects of Waste Glass Powder Mixed with Hydrated Lime on the Unconfined Compressive Strength of Clayey Soil

Asmaa G. Salih[1, a *], Ahmad S. A. Rashid[1,b], and Nihad B. Salih[2,c]

[1] School of Civil Engineering, University Teknologi Malaysia, Johor Bahru, Johor, Malaysia

[2] Department of Water Resources Engineering, University of Sulaimani, Sulaimaniyah, Iraq

[a]asmaagheyathsalih@gmail.com, [b]ahmadsafuan@utm.my, [c]nihad.salih@univsul.edu.iq

*Corresponding author

Abstract. Stabilization of clayey soil is commonly used to enhance unfavorable engineering properties. The effects of silica additives on soil improvement have been considered recently, and documented research studies on the characteristics of problematic clays stabilized by silica additives are interesting for many researchers. Alternative waste disposal strategies that would be both economically beneficial and environmentally friendly have been identified by this study. In the present study, waste silica-based addition is used to stabilize clayey soil, and the time-dependent changes in strength properties are investigated. Unconfined compressive strength (UCS) tests were conducted on stabilized samples at various curing durations to investigate macro-level properties. The UCS test results revealed that the 7.5% of GP+ 5% L content was optimal for the clayey soil as the strength was increased by 166.06%. The addition of the glass powder with hydrated lime components to the clayey soil resulted in stabilized samples, indicating a dense and compact matrix and reduced soil porosity, which increased the mechanical strength, according to the SEM analysis. This curing reaction technique is very beneficial and economical for geotechnical engineering applications.

Keywords: Clayey soil; soil stabilization; waste glass powder; unconfined compression strength.

1. INTRODUCTION

In many cases, soft soils, which comprise the majority of subgrade foundations, may behave actively as plastics or liquids when wetness penetrates them [1-3]. Variations in moisture content control a major portion of the behavior of fine-grained soils. Such soils are described as "expansive" or "swelling" soils because of their expansive tendency when in contact with water [4]. Wetting and drying processes periodically impact the subgrade materials' engineering properties and durability efficiency, especially for soils with high clay content [5-8]. Clays are generally considered problematic when employed in a number of geotechnical engineering applications like foundation support because of their potential for having low strength, high compressibility, and a large propensity for swelling [9]. Identically, it is occasionally difficult to find high-quality soil with excellent bearing capacity in many areas of the world. The modification of soils to improve their physical characteristics is known as soil stabilization. It can improve a soil's ability to support loads, manage its shrink-swell characteristics, and raise its shear strength. When subsoils are unsuitable for construction, soil stabilization can be used on roadways, embankments, foundations, and many other projects. Additionally, it can treat a variety of subgrade materials, including expansive clays and granular soils [10-14]. An expansive or problematic soil's characteristics can be improved by raising its compressive strength and permeability, lowering its plasticity and compressibility, and enhancing its durability. To simplify the idea, "soil stabilization" is primarily the process of enhancing the soil's chemical composition by adding chemical admixtures [15].

The key factors influencing swelling in expansive soils are the amount, variety, and interaction of pore spaces with water. When foundations and pavements are first constructed, the phenomenon of swelling starts and may last for a certain time, as long as 5 to 8 years [16]. Utilizing diverse industrial solid waste products enhances the geotechnical characteristics of problematic soil [17-19]. These materials harm the environment and are created through various industrial processes [20]. Therefore, during the past few decades, numerous researchers have attempted to employ these waste products to stabilize expensive soil, and some of them have even been suggested for use as building materials [21-24]. The utilization of waste materials for various geotechnical applications and to reduce their environmental impact is now widely recognized. Various eco-friendly and cost-effective waste items can be used to increase the clay soil's bearing capacity and stabilization. Fly ash, lime, copper slag, blast furnace slag, rice husk, marble dust, and other waste products are among those used to stabilize the soil [21]. Wasted glass is a significant waste resource that might be taken into account for soil stabilization [1,25,26]. The physical characteristics of the crushed glass demonstrate high permeability, low strain stiffness, and high crushing resistance, which might enhance its application in many geotechnical engineering projects for soil stabilization [27].

The optimal property for soil stabilization is achieved at 10% of glass powder and 8% of lime powder, according to a study by Modi et al. This study came to the conclusion that using glass powder for soil stabilization is a better method of disposing of glass than simply dumping it on the ground [28]. According to a study by Olufowobi et al., adding powdered glass results in more noticeable improvements in the clay soil's obtained characteristics [10]. It appears that between 5% and 10% of the soil's mass must be composed of glass powder to have the optimum effects in terms of clay soil properties. According to the results, the powdered glass can be used to stabilize soil because it significantly improves its physical properties. These improvements included increasing the maximum dry density (MDD) value from 25.37 kN/m3 for the control sample to 25.90 kN/m^3 for the sample containing 5% powdered glass by mass of the soil, achieving the highest CBR values of 14.90% and 112.91% at 5% powdered glass content for both the unsoaked and soaked treated samples, respectively, and achieving the highest values of cohesion and angle of internal friction of 15.0 and 17.0 respectively at 10% powdered glass content [10].

Furthermore, a study by Javed and Chakraborty found that the waste glass powder can enhance the clay soil, according to [24]. As this material is widely and economically available locally, using waste glass for stabilization contributes to reducing the impact on the environment and economical solutions. Based on the findings, it can be concluded that consistency limits LL, PL, and PI continually dropped as the glass powder percentage increased, potentially improving the subgrade. When the waste glass was added up to 8% of the dry weight of the soil, the MDD value reached from 1.83 to 2.03%, and it remained steady when adding 10%. On the other side, optimum moisture content (OMC) reduced with the addition of glass powder, decreasing from 17.53 to 10.5%. At 8% glass powder (GP) of the dry weight of soil was added, the unconfined compressive strength (UCS) increased to 133.5 kN/m^2, and when 10% of the dry weight of soil was used, it decreased to 119.7 KN/m2. With the addition of more glass powder, the shear strength parameters also increase. However, the increment rate decreased after adding 8% glass powder. As a result, 8% is determined to be the ideal percentage of waste glass powder (WGP) for improving the soil [27].

Blayia et al. conducted a study to investigate the utilization of waste glass powder, a product created by mechanically crushing waste glasses, in geotechnical engineering applications to reduce the amount of this waste material and decrease the negative environmental impact of landfill disposal [1]. By adding 2.5%, 5%, 10%, 15%, and 25% by dry weight of the sample, the impacts of WGP on the expansive soil characteristics were considered. Results showed that as WGP increased up to 25%, Atterberg's limits, including LL, PL, and PI, decreased significantly by around 49.6%, 33.7%, 69.9%, and 71.3%, respectively. Due to an increase in WGP percentages up to 25%, the free swelling of treated and untreated expansive soil also decreased by 83.3%. WGP was gradually added to the samples, reducing the OMC while increasing the MDD by 11.5%, up to a maximum of 15%, before being gradually reduced. The UCS results in the studied specimens enhanced by approximately 75.6%, with percentages of WGP increasing up to 15% before decreasing by 7.7% at 25% of the WGP. According to the direct shear test results, it was observed that the internal frictional angle increased by 61 %. In contrast, it was found through testing that when WGP percentages increased up to 25%, the cohesiveness of mixtures decreased by 19%. Since the geotechnical characteristics of the expansive soil continue to decline after this level, 15% of the dry weight of the soil sample is the ideal percentage of WGP to improve CL [1].

However, waste disposal strategies that would be both economically advantageous and environmentally friendly have been identified by this study. This research study aims to evaluate the effect of utilizing waste glass powder as a soil stabilizer. As a result, the current study investigated glass powder as an eco-friendly option to improve clayey soils. The additives were added to clayey soil samples in a range of percentages. Then, a comparison between the natural soil and waste glass powder-hydrated lime-treated soil was done to evaluate the possibility of such additions in enhancing the engineering properties of the clayey soil.

2. MATERIALS AND TEST METHODS

2.1 Soil

In this study, the clayey soil in the southern areas of Sulaymaniyah City/Iraq was examined. Plastic bags collected soil samples from a depth close to the surface. Classification tests based on the ASTM standards [29-32] were conducted to identify the most important geotechnical characteristics of the obtained soil. Preliminary observations of the soil revealed that it is fine-grained soil. The properties of the soil were established by performing the fundamental tests necessary for soil categorization. According to the sieve analysis test findings, the soil sample comprises 3.39% sand, 45.44% silt, and 51.17% clay, and the grain distribution curve is shown in Figure 1. The soil sample also has a 2.67 specific gravity that depends on the amount of mineral matter present and the percentage of organic matter. The geotechnical properties of the soil are listed in Table 1. The Unified Soil Classification System (USCS) categorized the natural soil sample as low plasticity clay (CL) [33]. The natural soil sample's optimal moisture content (OMC) and maximum dry density (MDD), which are shown in Table 1, were determined by the standard proctor test. In order to prepare remolded soil samples for the study tests, these results were utilized.

2.2 Waste Glass Powder

Glass bottles were collected from the waste of food. The glass bottles were carefully washed with water multiple times and then crushed into a homogeneous mixture. Accordingly, the study employed an average particle size of less than 425 μm, which was obtained using a sieve size of 425μm (sieve No. 40).

Table 1: Geotechnical properties of clayey soil.

Physical Properties	Standard	Clay
Liquid Limit (LL)%	ASTM D 4318	48
Plastic Limit (PL)%		23
Plasticity index (PI) %		25
Sand content %	ASTM D 422	3.39
Silt content %		45.44
Clay content %		51.17
%Passing sieve no. 200		96.61
Soil classification	ASTM D 2487	Lean Clay, CL
Optimum moisture content%	ASTMD 1557	20
Max dry density (gm/cm3)		1.694
Specific gravity, Gs		2.67

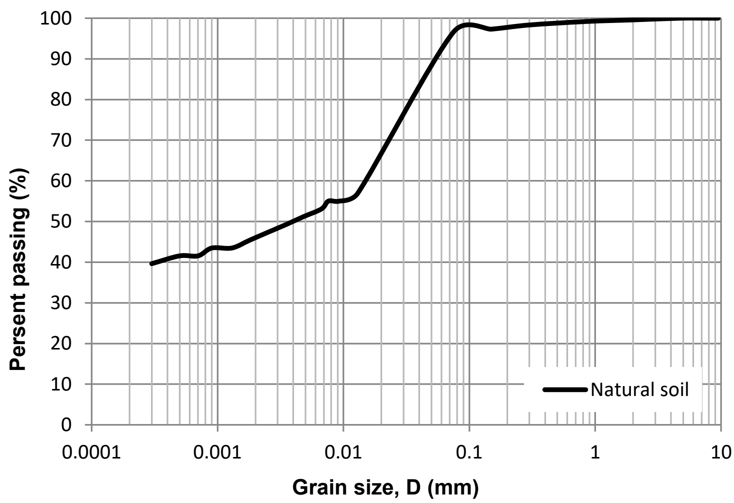

Figure 1: Particle size distribution curve for the natural clayey soil.

According to X-ray Fluorescence (XRF) testing, Table 2 lists the materials' chemical compositions by the weight % of their overall chemical composition. Based on Table 2, the clay soil sample has a high silica content (SiO_2= 49.4%) and a low alumina percentage (Al_2O_3= 9.25%). On the other hand, the glass powder's oxide composition revealed that it was mostly composed of silicon dioxide (68.55%), calcium oxide (11.6%), and sodium oxide (9.86%). In contrast, calcium oxide (86.79%) comprised most of the hydrated lime.

Table 2: The chemical composition obtained from (X-ray fluorescence analysis) of the natural soil and the additives for soil stabilization under study.

Chemical Compound	Minerals	Clay Soil (%)	Glass powder (%)	Hydrated lime (%)
Silicon dioxide	SiO_2	49.4	68.55	1.32
Sulfur trioxide	SO_3	0.44	0.17	4.25
Iron(III) oxide	Fe_2O_3	6.37	1.82	0.49
Aluminum oxide	AL_2O_3	9.25	1.5	0.53
Calcium oxide	CaO	16.45	11.6	86.79
Magnesium oxide	MgO	9.003	0.94	2.15
Potassium oxide	K_2O	4.28	0.55	0.081
Chlorine	Cl	0.7	0.027	0.007
Sodium oxide	Na_2O	-	9.86	-
Phosphorus pentoxide	P_2O_5	0.07	0.11	0.061

2.2 Sample Preparation and Methods

Glass powder was added to the oven-dried natural soil sample in proportions of 2.5%, 5%, 7.5%, and 10% to the dry weight of the soil with 5% of hydrated lime. Every component was manually mixed, and each step was closely monitored to ensure a consistent composition. The Standard Proctor test was used to assess the compaction properties of soil samples mixed with varied GP addition percentages. The samples, which had been carefully compacted into specific molds, were removed from the molds, put in plastic bags, and stored in secure containers at around 25°C in the laboratory for various curing periods. To look at the effects of the GP with the hydrated lime mix and investigate the geotechnical characteristics of the treated clayey soil.

The unconfined compressive tests were performed on cylindrical samples with dimensions of 38 mm in diameter and 76 mm in height by ASTM D2166/D2166M-16 [34]. 20% of the original water content was taken into account in both the untreated and treated remolded soil samples. As a result, the samples were remolded using the moist tamping method, yielding samples with a dry density of 1.694 g/cm^3 (95% of MDD) and 20% water content (OMC). The samples were remolded, sealed in plastic bags, and cured at constant humidity for 7 and 28 days to allow for a chemical reaction. The stress-strain curves were generated to compare the tested materials' strength (UCS) behavior. To evaluate the optimal combinations of soils and stabilizing agents, these materials and additives percentages were employed and compared to address the strength development of materials. To better understand the micro-scale interactions between the GP and the soil particles, as well as the hydrated lime combination, SEM and X-ray diffraction (XRD) studies were conducted. The specimens were gathered from the middle of the samples.

3. RESULTS AND DISCUSSION

3.1. Effect of Glass Powder-Lime Mix on Consistency Limits

The addition of glass powder-lime influences PL, LL, and PI variations for all treated soil samples with 5%L and GP mix, as presented in Figure 2. The figure shows that additives decreased LL and PI values with the increased percentage of GP. LL and PI values showed a decreasing trend of 2.5%, 5%, 7.5%, and 10% of GP mix. However, the PL behavior followed a different trend during the increase in additives percentage. The diffuse layer, influenced by the soil particle size and surface area, impacts the behavior of consistency parameters; with stabilizers, the PL of the fine-grained soil declines.

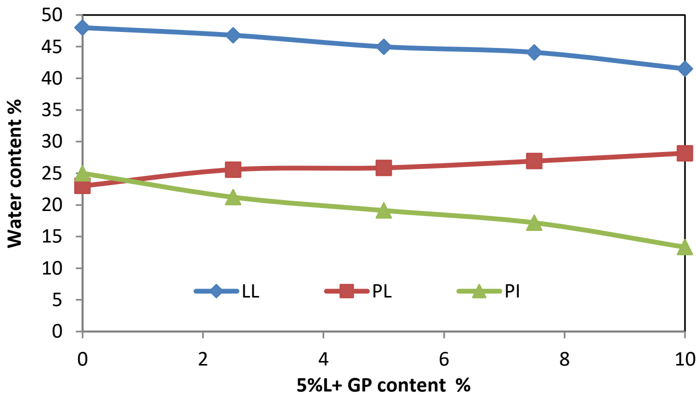

Figure 2: Variation of LL, PL, and PI of the lime-glass powder clay samples.

3.2. Effect of glass powder-lime mix on unconfined compressive strength

The treated soil's unconfined compressive strength (UCS) values serve as the primary criterion for assessing its enhanced strength. Figure 3 shows the relationship between UCS and axial strain for samples containing soil with GP of 2.5%, 5%, 7.5%, and 10% with 5%Lime mix throughout a 7-day treatment period. These curves show how GP affects clay soil sample unconfined compressive strength (UCS). All GP+5%L-clay samples have significant increases in UCS values. It can be seen that the UCS increased and reached its maximum resistance with the addition of GP up to 10%. The maximum UCS was 167.993 kPa for the percentage of 7.5% of GP, as the UCS of the clayey soil was increased by 152.11%. The clay soil's UCS values were increased by the presence of hydrated lime and glass powder in the soil samples, which made the conditions ideal for long-term pozzolanic reactions.

According to Figure 4, samples treated with 7.5%GP + 5%L showed the highest UCS strength compared to other samples, for the treatment period of 28 days as the strength value was 177.284kPa and the UCS of the clayey soil was increased by 166.06%. By comparing figures 3 and 4, after the treatment duration of 28 days, the strength of the samples increased due to the time effect, which produced the conditions for long-term pozzolanic reactions; consequently, extending the curing period promoted the growth of mechanical strength, which was brought on by the completion of chemical reactions.

The results further demonstrated that increasing the curing duration increased strength, failure strain, and the treated sample's stiffness. Overall, the treated soil samples showed higher stiffness compared to the untreated soil sample. In order to improve soil stiffness and brittleness, it was advised to combine GP with hydrated lime for soil stabilization.

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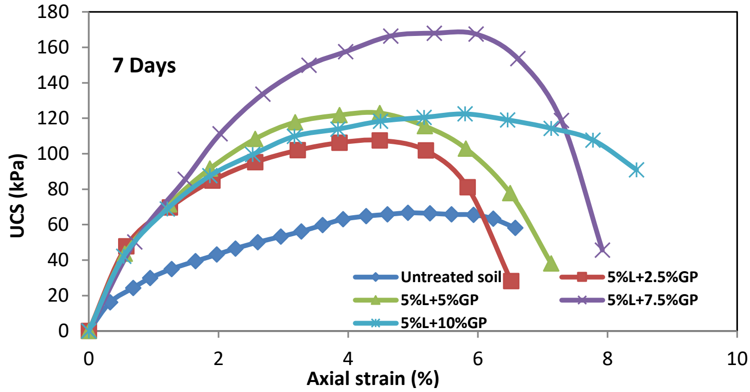

Figure 3: UCS results for different GP % contents at 7 days.

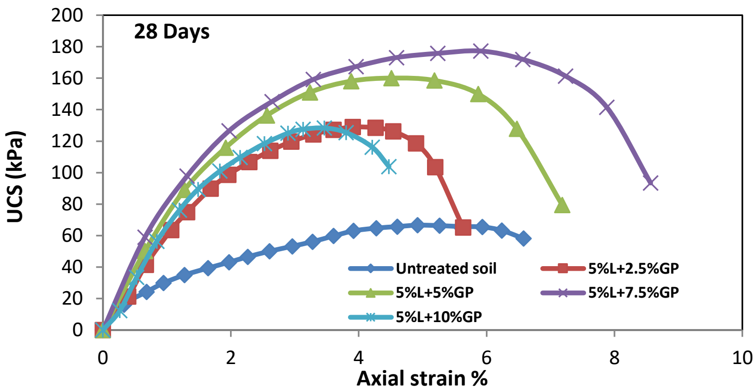

Figure 4: UCS results of for different GP % contents at 28 days.

3.3. Microstructural Mechanisms of The Glass Powder-Lime Mix on The Microstructure

Figures 5 and 6 show the scanning electron microscopy (SEM) image and elemental spectrum of a chosen particle that was discovered using energy-dispersive X-ray spectroscopy (EDS) analysis. Untreated clayey soil exhibits clear voids between soil particles that appear as dark patches, as seen in Figure 5 (a). The creation of C-A-S-H in high quantities is encouraged by the addition of lime-GP mix to the clayey soil, which affects the sample texture. SEM microstructural analysis revealed denser materials for the treated samples, which reduced spaces between the soil particles, as seen in Figure 5 (b). These denser material particles come into closer contact and create stronger connections when 7.5% GP+5%L is added to the soil as a soil stabilizer. Accordingly, the compressive strength of the treated clayey soil will, therefore, be improved by increasing the soil density.

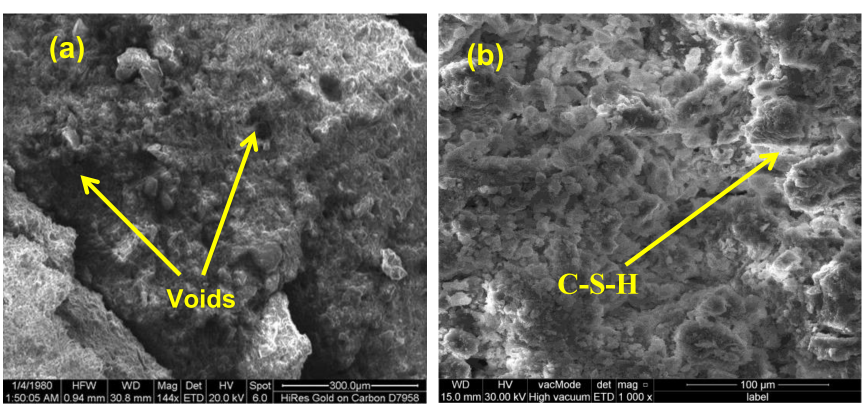

Figure 5: SEM images of (a) untreated soil, (b) sample treated with 7.5%GP+5%L after 28 days.

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The distribution of cementitious gel, or calcium silicate hydrate (C-S-H), in a soil sample is depicted in Figure 5. This is due to the fact that the input of lime in clayey soil is sufficient to generate a significant quantity of C- S- H gel for the pozzolanic process. Additionally, Figure 6 presents the scanning electron microscopy (SEM) image and elemental spectrum of a chosen particle that was discovered using (EDS) analysis. The presence of lime combined with GP (silica), according to the data, was more effective in promoting the production of C-S-H at high proportions. Essentially, silica-based stabilizers and lime are usually utilized to strengthen the soil during the hydration and pozzolanic processes.

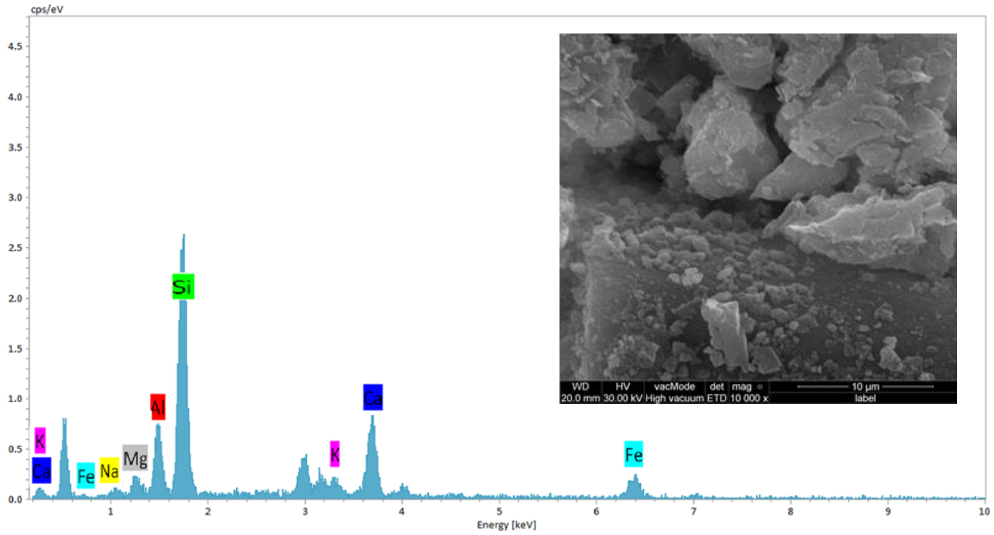

Figure 6: SEM micrograph and its elemental spectrum of a selected particle obtained by EDS analysis of sample 7.5%GP+5%L.

4. CONCLUSIONS

Reducing the amount of waste materials in landfills is made possible by using these waste materials for soil stabilization. Numerous studies showed that adding various waste items to parent clay greatly enhances the mechanical properties of soil. In this study, the interaction between wasted glass powder and hydrated lime in a clay matrix was investigated. The conclusions obtained throughout the investigations for this research can be listed as follows:

- The study yielded that liquid limit and plasticity index values decrease as the additives with content increase; however, the plastic limit increases.
- The 7.5%GP+5%L mix provided the best improvement for the soil strength, as the strength increased by 166.06%, according to the findings of unconfined compression tests, which were considered to be the primary indicator used to evaluate the performance of GP as a stabilizer.
- The addition of the additive components resulted in the stabilized samples displaying a dense and compact matrix and decreased soil porosity, which increased the mechanical strength, according to the SEM analysis.
- This curing reaction technique is very beneficial and economical for geotechnical engineering applications.

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