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Enhancing Geotechnical Properties of Clayey Soil with Recycled Plastic and Glass Waste

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ABSTRACT

Expansive clay soils, characterized by their propensity to undergo significant volume changes in response to moisture variations, present considerable challenges in construction engineering. These challenges manifest as structural damage, including fractures, asymmetrical settlements, and erosion. This study investigates the application of sustainable waste materials, specifically a mixture of plastic and glass waste, as an innovative approach to soil stabilization. In the context of Anbar, Iraq, laboratory experiments were conducted to evaluate the efficacy of incorporating plastic and glass waste in various proportions (0%, 4%, 5%, 6%) into clayey soil. The primary focus was to assess changes in geotechnical properties, notably the reduction in swelling potential and alterations in the maximum dry unit weight of the soil. Results indicated that the inclusion of waste materials in the specified proportions significantly mitigated the soil's swelling behavior, with reductions of 2%, 3%, and 5% observed for the respective waste content. Concurrently, enhancements in soil density were recorded, with increases in the maximum dry unit weight by 4%, 5%, and 9% corresponding to the same proportions of waste additives. These findings underscore the potential of using recycled waste materials in soil stabilization, aligning with environmental sustainability goals through the repurposing of waste. Additionally, this approach offers an economically viable alternative to traditional stabilization methods. The utilization of waste materials not only addresses the environmental impact of construction activities but also contributes to the broader goal of waste management and resource conservation.

1. INTRODUCTION

Structural integrity challenges in construction engineering are often attributed to the diminished bearing capacity of soft clays, leading to compressive failure and excessive settlement [1-3]. The financial implications of maintaining infrastructure affected by these soils are substantial, with estimated annual costs in the UK, USA, and South Africa being approximately $0.15 billion, $1 billion, and over $4 million respectively as of 1993 [4]. Additionally, the maintenance of underground pipelines, extending over 850 kilometers and experiencing a fracture rate of 0.27 breaks per kilometer per year, may incur costs exceeding $2 million annually [5].

The primary causative factor for these structural issues is identified as the presence of basic and ultrabasic montmorillonite clay minerals, derivatives of the decomposition of igneous rocks [6-8]. These minerals exhibit expansion upon moisture absorption and contraction upon its removal. It is noted that under conditions of extreme heat, such as during droughts, expansive soils exhibit pronounced contraction and shrinkage [6-12]. Research indicates that the soil's swelling/shrinkage behavior is influenced by the relative proportions of various clay minerals in the soil matrix, along with the soil's dry density and prevailing load conditions [13].

Further studies suggest that expansive soil characteristics are also influenced by arid climatic conditions, local geological factors, and the surrounding alkaline environment [9, 14]. To facilitate construction on such soils, stabilization is imperative to mitigate their swelling characteristics and enhance mechanical properties. A range of soil stabilization techniques has been documented in the literature, reflecting the evolution of methodologies in this domain [15, 16].

The scarcity of conventional soil improvement materials has escalated construction costs, highlighting the need for novel materials and techniques to process local substances efficiently. In this context, the utilization of waste materials for soil stabilization has gained attention. According to the United Nations Development Program, Iraq generates around 30,000 tons of solid waste daily, with over 25% being recyclable, predominantly comprising glass and plastic. This study presents an experimental investigation into the efficacy of using a glass and plastic waste mixture as a reinforcing agent for stabilizing expansive clayey soil samples from Fallujah, Anbar, Iraq.

1.1. Classification of expansive soil

The categorization of soil's swellability is undertaken through various methodologies, focusing predominantly on geotechnical characteristics, especially the Atterberg limits. Most classification techniques incorporate factors such as plasticity, clay content, and natural water content [15]. The literature delineates soil swelling capacity into four distinct categories: low, medium, high, and very high [17]. Based on the plasticity index, soils with a ratio between 0 and 15% are classified as having low swelling potential, 10% to 35% as moderate, 20% to 55% as high, and those above 55% as exhibiting extremely high swelling. The soil investigated in this study, possessing a plasticity index of 39%, falls into the high swelling category.

1.2 Glass and plastic waste

Glass, characterized as an inert material, undergoes a gradual breakdown akin to rocks in soil [18, 19]. Crushed glass, owing to its mechanical durability, reduced water absorption, light weight, workability, and other construction-friendly properties, is recognized as a valuable material in civil engineering applications [20-22]. Its utilization extends to various civil engineering projects, including its incorporation in concrete as part of geo-polymers [23], in asphalt layers (termed 'Glassphalt') [24-26], and as a constituent in pavement base and subbase [27]. The perpetual accumulation of non-biodegradable waste glass in landfills poses significant environmental and ecological challenges [28].

Investigations have revealed that the addition of powdered plastic and glass waste, in proportions ranging from 4% to 6% of the dry soil weight, enhances the geotechnical properties of clayey soil. It was observed that the admixture of glass and waste plastic powder to soil samples leads to an increase in maximum dry unit weight and a decrease in optimal moisture content. Moreover, the presence of waste glass and plastic has been noted to reduce the soil's liquid limit, plastic limit, and plasticity index [29].

Further research involved adding circular plastic waste pieces in various weight ratios (0, 2%, 4%, 6%, 8%) to sandy and clayey soils to evaluate their impact [30]. Due to their low density and optimal moisture content, these plastic materials were found to decrease the maximum dry unit weight of the soils.

2. MATERIALS AND METHODS

Similar to the previous studies in the literature, the authors propose adding a mixture of plastic and glass waste at 4%, 5%, and 6% of the dry soil's weight. The main goal of this paper is to review the properties of clay soil that have a significant impact on geotechnical features. The physical properties of the soil's mass and its particles, such as the initial water content and dry unit weight, the type and amount of clay mineral present, and the type of coarse-grained fraction, are the main factors that affect how much these soils swell.

The volume changes of this bulging soil over time are the main cause of damage to buildings and houses, such as cracks and collapse. Fluid transport processes, bio- geochemical alteration, and mineral dissolution may also contribute to some deformation along with effective stress changes. While loss or addition of solid material can cause surface movements and engineering issues, these are not necessarily shrink-swell soils. These processes can be challenging to distinguish from genuine shrink-swell processes that may be occurring concurrently because they are frequently combined with effective stress reductions and/or fluid movement patterns. Figure 1 shows the distribution and degree of swelling of expansive soils in Al-Anbar.

Clayey soil samples, which are called in Iraq (Al-Hujaira), were collected from the city of Fallujah in Anbar, Iraq. They were stored in boxes intended for research, and then the samples were transferred to the laboratory for processing to get them ready for testing.

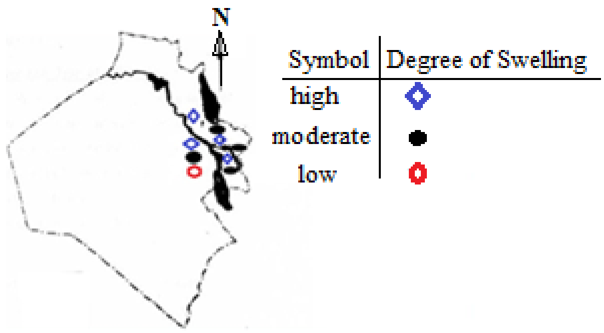

Figure 1. Expansive soils' distribution and degree of swelling in Al-Anbar [31]

2.1 Testing methods

A series of experimental studies were conducted including tests for classification, compaction, swelling, and compressive strength. These experiments were done on soils that contained 4%, 5%, and 6% of plastic fibers and glass powder, except for the grain size distribution.

-*Atterberg Limits Tests*: ASTM D 4318-11, 12.

-*Specific Gravity Tests*: Using a density bottle with a 500ml capacity, the specific gravity of soils was calculated in accordance with BS 1377: part2: 1990: 8.3.

-*Grain Size Distribution Tests*: According to ASTM D421-72 and D422-72, the grain size distribution tests (hydrometer and sieve analysis) were carried out.

-*Compaction Tests*: The soil's optimum moisture content and maximum dry unit weight were defined using the procedure outlined in BS 1377: Part 4:1990: 3.3 using the "Ordinary" compaction test (2.5 kg rammer method).

-*Swelling tests*: Free Swell and Swelling Pressure.

The odometer consolidation ring, which has an internal diameter of 50 mm and a height of 20 mm, was statically compressed to a predetermined weight of soil with its ideal moisture content.

To guarantee that the specimen well stays laterally constrained during swelling, the specimen height was made to be 4mm lower than the consolidation ring's height. This was accomplished by using a metal disk with a thickness equal to the height difference between the specimen and the consolidation ring, i.e., 4 mm. The ring's internal diameter was 1mm larger than the diameter of the disk. The specimen's height is measured using a dial gauge with a sensitivity of 0.002 mm. The specimen's height affects the percentage of swell. The swell of the specimen was calculated by using Eq. (1):

$$Swell(\%) = \frac{\Delta H}{H} \times 100 \quad (1)$$

where,

ΔH: increase in height.

H: the specimen's initial height.

Following the installation of the specimen into the oedometer apparatus, a load was positioned at the top of the weight hanger to apply a 7 kPa stress to the specimen. Following the addition of distilled water and the start of free swell, the sample was then consolidated back to its original height. Swelling pressure is the amount of force needed to restore the specimen to its initial height.

-Unconfined Compressive Strength Test: In accordance with ASTM D2166, unconfined compressive strength tests were performed on samples that had been compacted.

2.2. Materials

The clayey soil used in the experimental works was mixed with glass and plastic waste collected from a garbage dump in the area, as shown in Figure 2. The waste was broken down according to the required specifications. In this research, the waste glass and plastic were crushed using a machine crusher, as shown in Figure 3. The grain size distribution curve is shown in Figure 4 for the soil, and Table 1 lists the physical characteristics of the soil.

Figure 2. Soil mixture, plastic fibers and glass powder used in the research

Figure 3. The glass and plastic waste used in the study

The clayey soil appears expansive based on the data. The clay's high liquid limit of 71% and plasticity index of 39%, indicate that it can change volume with moisture content. The 32% plastic limit highlights the soil's plasticity. According to the Unified Classification System (USCS), The absence of sand and nearly equal proportions of 49% silt and 51% clay indicate that the sample is clayey soil and is labeled as CH (High Plasticity Clay). The high maximum dry unit weight indicates favorable compaction potential, a crucial factor in construction. The soil compacts best at 20% optimum water content. According to the data presented in the table, the soil's 10% free swelling highlights its susceptibility to volume changes upon saturation, which can cause subsidence or heaving during construction. In geotechnical engineering, understanding these characteristics helps prevent differential settlement by designing and building for expansive soils.

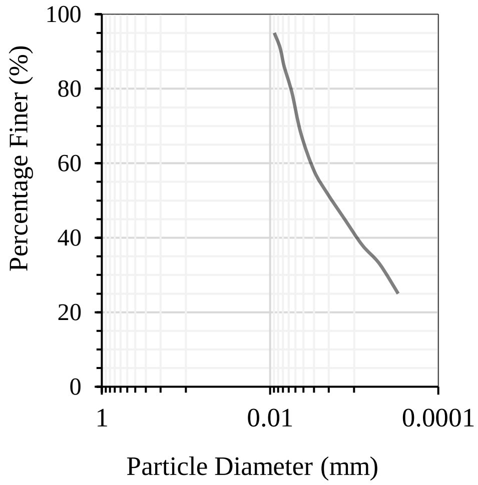

Figure 4. The grain size distribution of the soil

Table 1. Geotechnical engineeringproperties of the clayey soil

Characteristics	Values
Liquid limit (%)	71
Plastic limit (%)	32
Plasticity index (%)	39
Specific Gravity, G_S	2.7
Sand (%)	0
Silt (%)	49
Clay (%)	51
Max. dry unit weight (gr/cm^3)	1.5
Optimum Moisture Content (%)	20
Free swelling (%)	10
Classification based on USCS	CH

The engineering properties of the polyethylene terephthalate plastic waste and the chemical composition of the glass waste are listed in Table 2 and Table 3, respectively. All experiments were carried out in the laboratory of the Iraqi Engineers Association in Fallujah, Al-Anbar.

Table 2. Engineering properties of the plastic waste

Properties	Test Results
Length (mm)	10
Width (mm)	1.5
Thickness (mm)	0.25
Specific gravity	1.3

Table 3. The glass waste's chemical composition

Component	Amount (%)
Silicic Acid (SiO_2)	70.22
Oxide of Calcium (CaO)	14.1
Oxide of Sodium (Na_2O)	10.5
Oxide of Magnesium (MgO)	2.4
Oxide of Aluminium (Al_2O_3)	1.93
Oxide of Iron (Fe_2O_3)	0.45
Other elements	0.4

3. RESULTS AND DISCUSSION

The purpose of adding a mixture of glass and plastic waste into expansive clayey soil for stabilization is to enhance its engineering characteristics. This technique has the potential to enhance stability, reduce plasticity, increase shear strength, and enhance compaction characteristics. Utilizing waste materials can provide environmental advantages through the recycling of glass and plastic, thus promoting sustainability. Nevertheless, the efficacy is dependent on parameters such as the nature and volume of waste implemented, soil properties, and desired application. Comprehensive laboratory testing is necessary to evaluate the influence on soil characteristics and ensure long-term durability. It is of highest importance to carefully take into account local regulations and environmental factors when responsibly implementing this technique.

The current experimental study was conducted on clayey soil to assess the applicability of adding different ratios of waste materials on stabilizing the soil. For this purpose, four ratios of plastic and glass waste mixture were mixed with the soil. Ratios were 0, 4, 5, and 6% by weight of dry soil, as shown in Table 4.

Table 4. Summary of the tests results

	Natural Soil, No Added Mixture	**Soil with 4% of Plastic and Glass Waste Mixture**	**Soil with 5% of Plastic and Glass Waste Mixture**	**Soil with 6% of Plastic and Glass Waste Mixture**
Liquid Limit (%)	71	66	62	60
Plastic Limit (%)	32	30	29	28
Plasticity Index (%)	39	36	33	32
Maximum Dry Unit Weight (gr/cm^3)	1.5	1.56	1.58	1.63
Optimum Moisture Content (%)	20	18.3	17.7	15
Free Swell (%)	10	8	6.5	5
Swell Pressure (kPa)	400	325	295	265
UCS (kPa)	170	185	200	230

Once the intended experiments were performed on the soil samples, the results of each test were obtained and discussed as follows:

3.1 Atterberg limits test

The plastic and liquid limits test have been performed with various percentages of clayey-plastic and glass waste mixture. The results for the consistency limits were acquired from the tests. The effect of plastic and glass waste mixture content on the plasticity index for the clayey soil specimens is plotted in Figure 5. The plasticity index value dropped with the rising plastic and glass waste mixture content. Its potential reason is that the consistency limits have changed (the soil swelling capacity changed from the high swelling clay category to the moderate swelling clay).

A lower plasticity index indicates reduced sensitivity to moisture variations, enhancing stability and reducing the soil's potential for swelling and shrinkage. This outcome leads to increased shear strength, improved compaction characteristics, and decreased susceptibility to erosion.

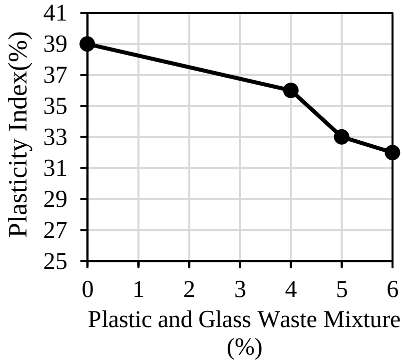

Figure 5. Effect of plastic and glass waste mixture on plasticity index

3.2 Compaction parameters

The addition of plastic and glass waste mixture impacted the compaction parameters of clayey soil with plastic and glass waste mixtures. It was noticed that the maximum dry unit weight rose with the addition of waste mixture, and the optimum moisture content decreased, as shown in Figure 6 and Figure 7.

When plastic and glass waste are added to clayey soil, the optimum moisture content decreases and the maximum dry unit weight increases. These modifications indicate increased compaction efficiency and improved soil strength, making it more appropriate for construction purposes. A lower optimum moisture content signifies a more effective compaction process, resulting in reduced water needs and enabling accelerated construction. The higher maximum dry unit weight enhances load-bearing capacity and foundation stability.

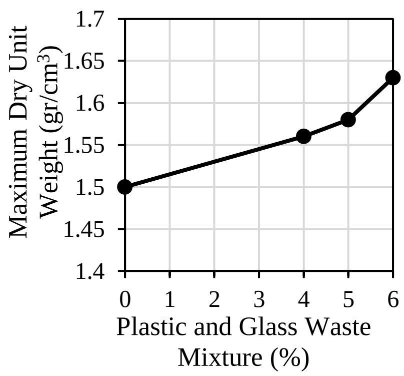

Figure 6. Effect of plastic and glass waste mixture content on maximum dry unit weight

3.3 Free swell

The swelling-time relationships for different mixture ratios are plotted in Figure 8. It appears that the swelling may progress at various rates with respect to time for different plastic and glass waste mixture percentages. The rapid increase in swell potential following the addition of a mixture of plastic and glass waste into expansive soil can be related to factors such as initial hydration, chemical reactions, modification of pore structure, consolidation effects, and achievement of saturation limits. These processes play a role in the initial changes of soil behavior. Over time, the total effect decreases, resulting in a reduced rate of increase in the potential for swelling.

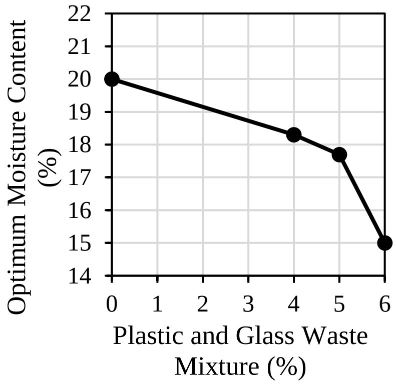

Figure 7. Effect of plastic and glass waste mixture content on optimum moisture content

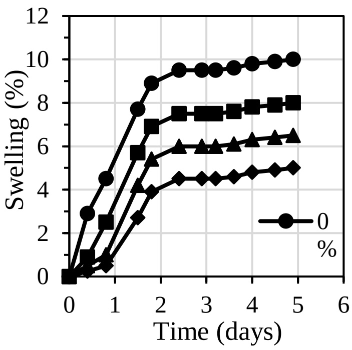

Figure 8. Time versus percent swell using different percentage of plastic and glass waste mixture

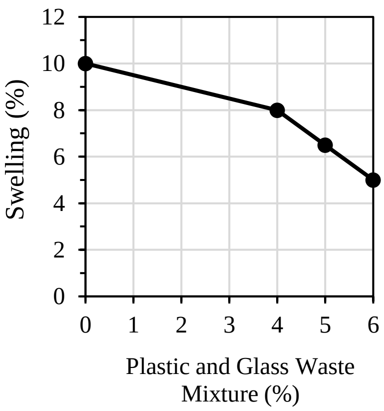

Figure 9. Effect of plastic and glass waste mixture content on free swell percentage

The swelling of composite soil and natural clayey soil samples containing plastic and glass waste mixture can be seen in Figure 9. As shown in these figures, plastic and glass waste mixture decreased the swelling of clayey soil. The free swell decreased from 10% to 5% by adding 6% plastic and glass waste mixture. Professional engineering applications have advanced by reducing swell potential in expansive clayey soil with plastic and glass waste. This improvement improves construction project foundation stability, surface distress, and erosion control. The method increases infrastructure resilience and may save money, making it economically viable.

3.4 Swell pressure

The values of the swelling pressure gradually decreased with increasing plastic and glass waste mixture content. With the addition of waste mixture, the swelling pressure of stabilized samples containing 6% plastic and glass waste mixture reduced from an initial value of 400 kPa for the prepared clay to 265 kPa for the treated sample, as shown in Figure 10.

The decrease in pressure can be related to several factors, such as changes of the soil's pore structure, improved drainage, reduced water absorption, chemical interactions, compaction effects, and the possible stabilization of clay minerals. The decrease in swell pressure that was observed indicates that waste materials have a positive effect in reducing the soil's tendency to expand.

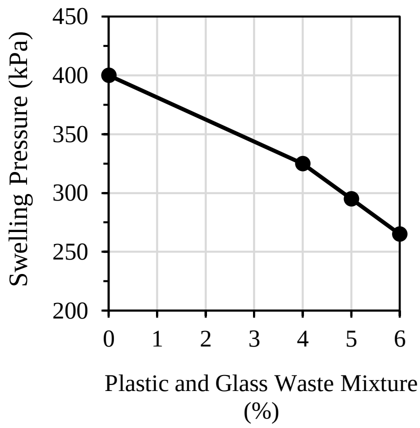

Figure 10. The Effect of the plastic and glass waste mixture content on swell pressure

3.5 Unconfined Compressive Strength (UCS)

The Unconfined Compressive Strength (UCS) test is a widely accepted method for determining the cohesive strength of soil. This experiment utilizes unidirectional force without any lateral constraints. The observed magnitude of strength is directly proportional to the axial strength. Figure 11 depicts the impact of mixing plastic and glass waste on the unconfined compressive strength of stabilized expansive clayey soil. The graph reveals a significant correlation between the proportion of waste mixture (ranging from 0% to 6%) and the strength of the soil. Plastic particles serve as reinforcement, forming connections that hinder the movement of soil particles and enhance compressive strength. However, glass particles have a negligible effect on UCS because they lack the necessary strength to provide effective reinforcement. The results suggest that higher amounts of waste material added lead to an increase in unconfined compressive strength at specific axial strains.

Figure 12 demonstrates that a greater percentage of plastic and glass waste ultimately improves the unconfined compressive strength. To summarize, the higher the proportion of plastic and glass waste in the mixture, the greater the unconfined compressive strength.

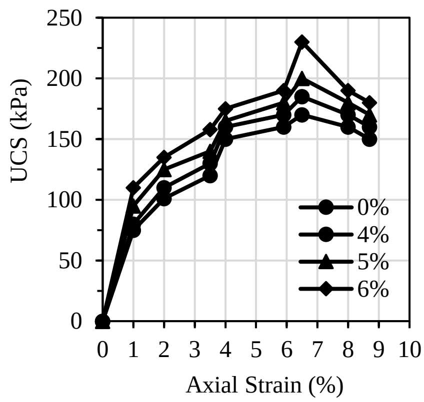

Figure 11. Axial stress versus strain for used soil containing various amounts of glass and plastic waste mixture

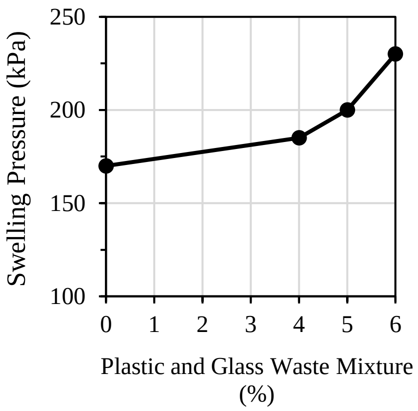

Figure 12. Effect of plastic and glass waste mixture content on unconfined compressive strength

4. CONCLUSION

This paper presented an experimental study to investigate the efficiency of using different ratios of mixture of glass and plastic waste as reinforcing material for the stabilization of expansive soil. The waste material was added in different percentages of the dry weight of the expansive soil. The experimental tests that were performed in this study included compressive strength, swelling percentage, swelling pressure, compaction, grain size distribution, and Atterberg limits tests. Once the results were obtained, the significance of waste material on improving the engineering properties of the tested soils were discussed.

The laboratory tests revealed that as the percentage of waste plastic and glass mixture added to the clayey soil increased, the values of the samples' plasticity index and the optimal moisture content decreased. By increasing the percentage of plastic and glass waste mixture, the swelling rate and the swelling pressure value were decreased, while the compressive strength increased. As a suggestion, stabilized clay with glass and plastic waste can be used for road construction, landfill restricting, erosion control, building construction, retaining walls, flood protection, and green infrastructure projects. In engineering and environmental applications, the material's strength, durability, and sustainability make it ideal for stable foundations, impermeable barriers, erosion-resistant structures, and environmentally friendly solutions. Safe and effective implementation of these applications requires careful consideration of local regulations and engineering standards.

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