

Improvement of Bentonite Soil Strength Using Glass Powder

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ABSTRACT

This study examines how adding powdered glass at 10%, 20%, and 25% improves the strength properties of bentonite soil. Laboratory tests, including Atterberg limits, compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS), were conducted to evaluate the effects of glass powder. The results indicate that increasing the glass powder decreases soil plasticity, with reductions in Liquid Limit (LL) and Plasticity Index (PI), while the Maximum Dry Density (MDD) increased from 16.5 g/cm³ to 17.1 g/cm³ and the Optimum Moisture Content (OMC) decreased from 16% to 14%. The CBR values improved notably, rising from 18.8% to 48.2% at 0 days, and reaching 179.9% in 28 days with 10% glass powder, although higher percentages showed variable long-term results. UCS also increased from 33.3 kg/cm² to 56.5 kg/cm² at 0 days and from 156.2 kg/cm² to 211.6 kg/cm² at 28 days, as the glass content increased. These improvements are due to the pozzolanic reactions between the glass powder and soil minerals, which enhance the particle bonding and soil strength. The study concludes that adding glass powder effectively strengthens bentonite soil, with 10% identified as the optimal amount for strength enhancement and material efficiency.

Keywords-soil stabilization; glass powder; California Bearing Ratio; unconfined compressive strength

I. INTRODUCTION

Soil improvement is a crucial part of geotechnical engineering, especially when working with problematic soils, such as bentonite. Bentonite is known for its high plasticity, low strength, and significant volume changes under varying moisture conditions [1]. These characteristics make it unsuitable for bearing structural loads in its natural state. To enhance its engineering properties, researchers have investigated various stabilizing agents, including lime, cement, and industrial by-products [1, 2]. In the modern world, the rapid accumulation of waste materials has become a serious environmental issue. Non-biodegradable materials like glass are particularly problematic due to their resistance to natural decomposition [3]. As a result, civil engineers are increasingly

exploring ways to reuse such wastes in environmentally beneficial applications, including soil stabilization. Materials, such as fly ash, rice husk ash, marble dust, shredded tires, and especially waste glass, have been studied as soil additives to improve the performance of weak soils like clay and sand. This approach not only enhances the soil properties but also supports sustainable waste management by recycling materials that would otherwise harm the environment [4]. The improvement of clayey soils with glass powder occurs through both physical and chemical mechanisms. Finely ground glass fills the voids between the soil particles and reduces plasticity, leading to improved compaction and strength. The angular shape and hard texture of the glass particles further reinforce the soil structure mechanically [5]. Additionally, the high silica content of glass can promote pozzolanic reactions with

alumina-rich clay minerals in the presence of moisture. These reactions produce cementitious compounds that strengthen particle bonding, reduce swelling potential, and increase the overall soil strength. Therefore, glass powder represents a promising, sustainable, and cost-effective material for enhancing the engineering performance of bentonite and other clayey soils [6].

Glass waste constitutes a large portion of global solid waste and poses a significant disposal problem. When processed into a fine powder, crushed glass exhibits favorable engineering properties, such as high permeability, stiffness at small strains, and strong resistance to crushing, making it a promising material for geotechnical applications. On the other hand, clayey soils, particularly bentonite, are known for their low strength, high plasticity, and tendency to swell and shrink with moisture changes [7]. These traits make them unsuitable for foundations and other load-bearing structures unless they are stabilized. Given these challenges, this study investigates the potential of using finely ground Waste Glass Powder (WGP) as a stabilizing agent to improve the strength characteristics of bentonite clay [8]. Glass waste is processed into powder form and incorporated into bentonite soil to evaluate its impact on compaction and strength through laboratory testing. The results aim to identify the optimal glass powder content that yields significant improvement while offering a sustainable approach to waste management and soil stabilization [9]. Enhancing the strength and durability of clayey soils using alternative materials is both a technical necessity and an environmental responsibility [8]. The use of non-biodegradable materials such as glass powder in soil stabilization provides dual benefits: it enhances the engineering properties of weak soils and reduces the environmental impact of glass waste accumulation [10]. This sustainable approach aligns with modern construction practices, promoting the reuse of industrial waste in civil engineering. By adopting such methods, the construction industry can effectively address geotechnical challenges and environmental concerns within a unified, sustainable framework. This study aims to investigate the effectiveness of stabilizing bentonite soil using WGP as an environmentally friendly and cost-effective solution. By utilizing recycled glass, this approach addresses geotechnical challenges and environmental concerns related to solid waste management. A series of laboratory tests, including index properties and strength-related geotechnical tests, was conducted to evaluate the influence of varying percentages of glass powder on the behavior of cohesive soil.

II. MATERIALS AND METHODS

A. Materials

The materials used in this study consisted of cohesive soil and finely crushed WGP. A series of laboratory tests was performed to determine the initial engineering properties of the natural soil and to assess how different proportions of glass powder affect its behavior. The cohesive soil sample was obtained from a site in the Alapli area at a depth of approximately 1 m below ground level. After collection, the soil was air-dried and sieved through a No. 40 sieve to achieve a uniform particle size suitable for testing. Figure 1 shows the prepared soil sample used in the experiments. The waste glass

additive was derived from discarded green glass bottles. The bottles were thoroughly cleaned, ground into a fine powder using a grinding machine, as depicted in Figure 2, and then sieved through a No. 200 sieve to obtain a consistent particle size distribution.



Fig. 1. A cohesive soil sample.

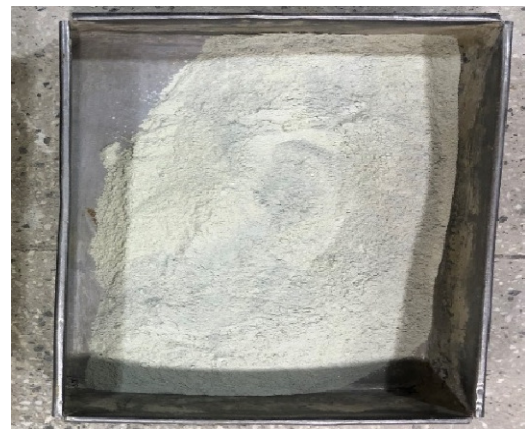


Fig. 2. Finely ground glass powder after sieving.

B. Methods

The Atterberg limits tests, including the LL, Plastic Limit (PL), and PI, were conducted to evaluate the consistency and plasticity characteristics of both untreated and glass powder-treated bentonite soil samples. These tests followed the standard procedure outlined in [12], which determines the water content at which soil transitions between the liquid and plastic states, and between the plastic and semi-solid states [11]. The PL was calculated as the difference between the LL and the PL. The results provided insights into the soil's engineering behavior and the influence of glass powder on its plasticity. To prepare the samples for strength testing, a mini compactor device was used. This device includes a hammer, mold, and body assembly. The mold dimensions were 7.7 cm in height and 3.8 cm in internal diameter. The UCS test was performed according to the procedure followed in [13], which is a widely used and efficient method for determining the shear strength of saturated cohesive soils [12]. The compacted

samples were placed in a loading frame, and a constant strain rate of 0.5 mm/min was applied using a standard plunger with a capacity of 4.5 kN. During the test, axial load and deformation were continuously recorded until sample failure. The resulting data were used to calculate the UCS and analyze the stress-strain behavior of the specimens. The CBR test was carried out in accordance with [14] to assess the subgrade strength of the soils, which is essential for road and pavement design. Developed by the California Division of Soils, this empirical test evaluates the load-bearing capacity of subgrade and base materials under controlled loading conditions [13]. The laboratory setup consisted of a mold with a 150 mm diameter, a base plate, a collar, a loading frame, and dial gauges for measuring penetration and expansion. A surcharge weight was placed on each specimen, and the load was applied using a standard plunger at a constant rate of 2 mm/min. Load values corresponding to penetrations of 2.5 mm and 5 mm were recorded, and a load-penetration curve was plotted. The CBR value was determined by comparing the measured load to standard reference loads, where a CBR of 100% corresponds to 1370 kg at 2.5 mm penetration and 2055 kg at 5 mm penetration. When the CBR at 5 mm was consistently higher than that at 2.5 mm, the 5 mm value was adopted.

C. Sample Preparation

Glass powder was added to the soil in percentages of 10%, 20%, and 25% by weight of the dry soil sample. The dry materials were thoroughly mixed by hand for 3 to 5 min until a homogeneous mixture was achieved. The experimental testing program consisted of two phases. The first phase involved testing the original soil to determine its baseline engineering properties. The second phase focused on studying the effect of adding WGP to the soil through tests, such as Atterberg limits in [12], UCS, and CBR. For the UCS test, six samples were prepared for each glass powder percentage for day 0 and day 28. The samples were compacted using a mini compactor device in three layers, each receiving 55 blows. Three samples for each percentage were tested immediately, while the remaining samples were sealed in plastic bags and labeled carefully, as portrayed in Figure 3. The samples were then placed in a bucket with a small amount of water at the bottom, separated by a tin sheet to maintain moisture and protect them from the weather effects. The bucket was covered securely. After 28 days, these samples were tested for UCS.



Fig. 3. Labeled UCS soil-glass powder samples.



Fig. 4. Labeled CBR samples in plastic bags.

III. REGARDING THE CONTENT

A. Maximum Dry Density and Optimum Moisture Content

The effect of glass powder on MDD and OMC was evaluated according to [17]. MDD increased from 16.5 g/cm³ to 17.1 g/cm³ with 10% glass powder and remained stable with higher percentages, as displayed in Figure 5. In contrast, OMC decreased from 16% to 14% as the glass content increased to 25%. The rise in MDD is attributed to the higher specific gravity of the glass powder, while the drop in OMC is due to the reduced water absorption, as shown in Figure 6.

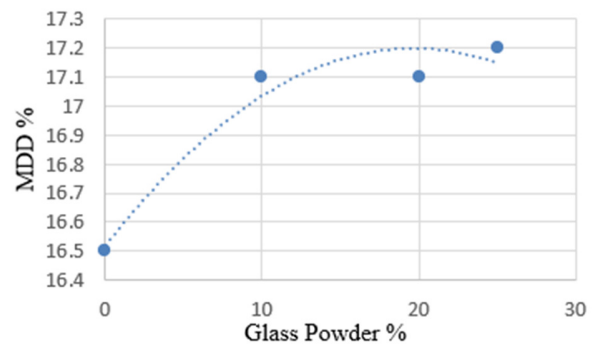


Fig. 5. Results of MDD with glass content.

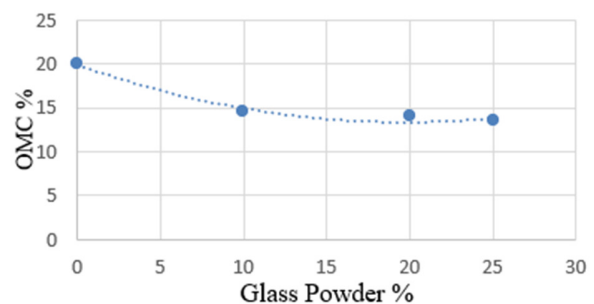


Fig. 6. Results of OMC with glass content.

B. Atterberg Limits

Figure 4 illustrates the variation in LL, PL, and PI with increasing glass powder content. As the percentage of glass powder increased from 0% to 25%, LL decreased from 35% to 30%, while the PI declined from 17% to 10%. In contrast, the PL showed a slight increase from 18% to 20%, as presented in

Figure 7. The observed reduction in LL and PI indicates a decrease in soil plasticity, compressibility, and swelling potential, factors that contribute to improved subgrade performance. Although the soil's classification under the USCS remained CL, the AASHTO classification improved, confirming the enhanced engineering behavior of the soil with the addition of glass powder [14–16].

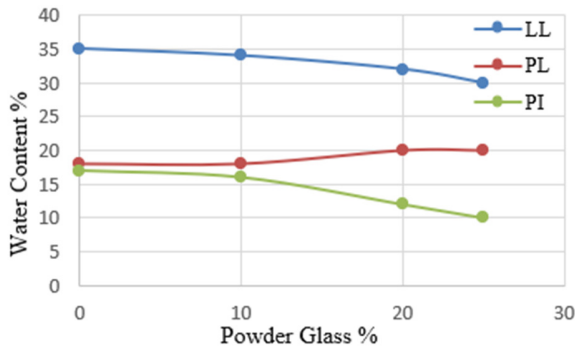


Fig. 7. LL, PL, and PI with glass content.

C. California Bearing Ratio

The CBR test was conducted to evaluate the load-bearing capacity of the soil mixed with varying percentages of glass powder at 0 days and 28 days. For the unsoaked condition, the CBR value of the untreated Alapli soil was significantly enhanced with the addition of glass powder. When 10% glass powder was added, the CBR increased to 18.8%. This improvement continued with higher levels of glass content: 29.8% at 20% glass powder and 48.2% at 25%. The continuous increase in CBR with increasing glass powder content can be attributed to the shear transfer mechanism between the soil particles and the angular, rigid particles of glass. Additionally, the strength gain is likely influenced by the pozzolanic reaction between the glass powder and soil minerals, leading to the formation of cementitious compounds that bind the particles more effectively. The variation of the CBR values with glass powder content under 0-day curing is illustrated in Figure 8.

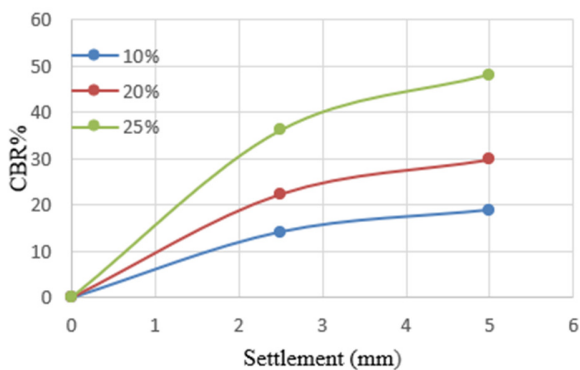


Fig. 8. CBR (0-Day) with Glass Content.

In contrast, the soaked (28-day) CBR results show a different trend. The CBR value peaked at 179.9% with 10%

glass powder, indicating a significant improvement in strength due to prolonged curing and potential pozzolanic activity. However, with 20% glass powder, the CBR sharply decreased to 54.4%, and further declined to 27.28% with 25% glass powder. This reduction at higher percentages could be due to excess glass powder interfering with the soil matrix, leading to poor bonding and increased brittleness. The variation of 28-day CBR values with glass powder content is presented in Figure 9. These findings suggest that while the glass powder can significantly improve the short-term and early-age strength of clay soil, the/its long-term behavior is sensitive to the proportion used, and optimal performance appears to be achieved at around 10% content.

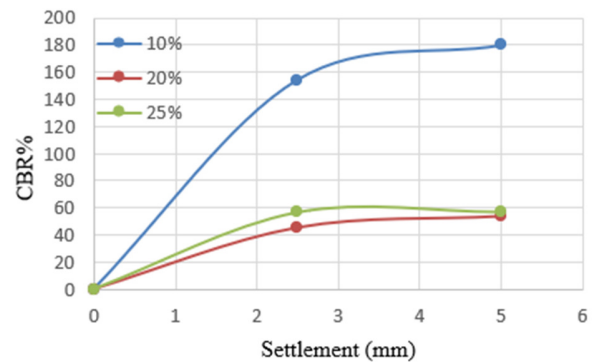


Fig. 9. CBR (28-Day) with glass content.

D. Unconfined Compressive Strength

The effect of glass powder on the UCS of clay soil was evaluated at two curing periods: 0 days and 28 days. The results are presented in Figures 10 and 11. At 0-day curing, the UCS increased consistently with the addition of glass powder. The strength was recorded at 33.3 kg/cm² with 10% glass powder, then increased to 44.9 kg/cm² at 20% and reached 56.5 kg/cm² with 25% glass powder. This trend indicates that even without curing time, glass powder contributes positively to the strength of the soil. For the 28-day curing condition, a more significant improvement in UCS was observed. With 10% glass powder, the UCS reached 156.2 kg/cm². Further increases in glass content raised the strength to 178.4 kg/cm² at 20% and 211.6 kg/cm² at 25%. The marked improvement is attributed to the presence of lime in the glass powder, which reacts with the clay minerals through pozzolanic activity. This chemical reaction enhances bonding and reduces plasticity, ultimately improving the soil structure and strength over time. These results demonstrate that the glass powder significantly enhances UCS, especially with longer curing, confirming its potential as a stabilizing agent in clay soils.

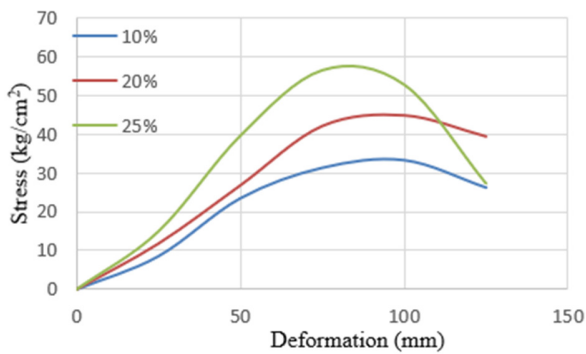


Fig. 10. UCS at day 0 with glass content.

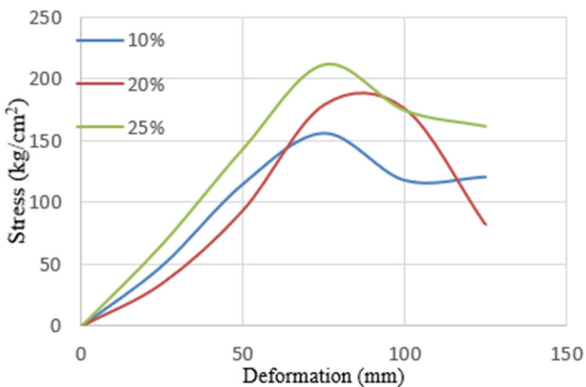


Fig. 11. UCS at day 28 with glass content.

The addition of powdered glass to clay soil has proven to be an effective technique for enhancing its geotechnical properties. The results of this study demonstrate that incorporating 10%-25% glass powder reduces soil plasticity, increases density, and improves the overall strength. These enhancements are attributed to two main factors: the physical contribution of glass particles, which improve the particle packing and load distribution, and the chemical pozzolanic reactions that strengthen the bonding within the soil matrix. Overall, the findings indicate that glass powder improves both short-term properties, such as compaction and early-age strength, and long-term strength development, particularly after 28 days of curing. The best performance was achieved with 10%-20% glass content, providing an optimal balance between strength improvement and material efficiency. Consequently, the use of glass powder not only enhances soil stabilization but also promotes sustainable construction practices by recycling waste glass into valuable engineering materials.

IV. CONCLUSIONS

This study evaluated the impact of strengthening bentonite soil using glass powder in various proportions, leading to the following conclusions:

- The study employed laboratory testing to assess the effect of adding powdered glass at 10%, 20%, and 25% on the geotechnical properties of bentonite soil, including Atterberg limits, compaction, California Bearing Ratio (CBR), and Unconfined Compressive Strength (UCS).

- The plasticity of the soil was reduced with the addition of glass powder, as shown by the decrease in Liquid Limit (LL) and Plastic Limit (PL), indicating improved soil workability and reduced swelling potential.
- The Maximum Dry Density (MDD) increased from 16.5 to 17.1 g/cm³, while the Optimum Moisture Content (OMC) decreased from 16% to 14%. This improvement is due to the higher specific gravity of glass powder and its lower water absorption capacity.
- The CBR values at 0 days increased significantly with glass addition, reaching 48.2% at 25% glass content. At 28 days, a peak of 179.9% was observed at 10% glass content, with subsequent decreases at higher percentages due to potential particle interference and matrix disruption.
- The UCS also improved with curing time. It increased from 33.3 kg/cm² to 56.5 kg/cm² at 0 days, and from 156.2 kg/cm² to 211.6 kg/cm² at 28 days, attributed to the pozzolanic reactions forming cementitious compounds that enhance the bonding between soil particles.
- The results confirm that glass powder, especially at 10%–20% content, can serve as a sustainable and effective stabilizing agent in clay soils. It improves strength, reduces plasticity, and recycles industrial waste, making it suitable for applications such as subgrade improvement, embankments, and foundation support.

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