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Enhancing the Geotechnical Properties of Black Cotton Soil with Granite Powder Addition

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Abstract

This study investigates the effect of adding granite powder to black cotton soil, focusing on its impact on the strength and mechanical properties of the soil. Different percentages of granite powder (5%, 10%, 15%, and 20%) were added to the soil, and various laboratory tests were performed to evaluate soil properties, including shrink-swell behavior, compaction, and Atterberg limits. The results show significant improvements in the mechanical properties of the soil, with the highest enhancement observed at a 20% granite powder addition. The study also explores the potential of granite powder to reduce soil swelling and shrinkage, enhance compaction characteristics, and increase the soil's ability to bear load. The findings of this study contribute to understanding the potential of using granite powder as a soil stabilizer in geotechnical engineering applications, particularly for improving soil stability in construction and agricultural projects.

Keywords

Black Cotton Soil, Granite Powder, Soil Improvement, Expansive Soil, Swelling Behavior, Shrinkage Limit, Compaction Characteristics, Soil Stabilization, Mechanical Properties, Load-Bearing Capacity

1. Introduction

Black cotton soil is one of the most significant and widely distributed soil types found across the globe, especially in agricultural regions with subtropical and tropical climates [1] [2]. These regions are typically characterized by significant seasonal fluctuations in temperature and rainfall, which directly affect soil moisture content and agricultural productivity [3]. Black cotton soil stands out due to its rich mineral composition, including essential nutrients like calcium, magnesium, and potassium, which make it one of the most fertile and agriculturally productive soils [4]. Its high moisture retention capacity further contributes to its ability to support crops that require constant availability of water [5] [6]. However, despite these beneficial attributes, black cotton soil presents considerable challenges due to its expansive and variable nature, which limits its applications beyond agricultural uses, especially in civil engineering and construction projects [7].

One of the primary challenges associated with black cotton soil is its high shrinkage and expansion potential, a characteristic that arises from fluctuations in its moisture content [4] [8]. During the rainy season, black cotton soil absorbs large quantities of water, causing it to swell and increase in volume [6]. Conversely, during dry spells or drought conditions, the soil loses moisture, leading to shrinkage, surface cracking, and the formation of deep fissures that extend into the underlying layers of soil [9]. This unstable behavior leads to structural instability, causing significant damage to infrastructure, including building foundations, roads, and other structures. The continuous cycle of swelling and shrinkage over time further exacerbates these structural issues, leading to increased costs for maintenance, repair, and rehabilitation [10] [11].

In light of these challenges, recent research in soil engineering has increasingly focused on finding effective solutions to enhance the geotechnical properties of black cotton soil [4]. Such improvements aim to make the soil more stable and suitable for broader applications beyond agriculture. Among the most promising solutions is the use of additives, such as industrial by-products that modify the internal structure of the soil and reduce its moisture sensitivity [12]. One notable additive is granite powder, which is a by-product of the granite cutting and polishing industries. This powder is rich in minerals such as silica (SiO_2), alumina (Al_2O_3), calcium oxide (CaO), and iron oxide (Fe_2O_3)—all of which are known for their beneficial role in enhancing soil cohesion and improving the soil's resistance to volumetric changes [13] [14].

The use of granite powder as a soil stabilizer holds several advantages. First, it is a cost-effective and environmentally friendly material, as it contributes to the recycling of industrial waste while minimizing its environmental impact [15]. Additionally, it has been shown that the incorporation of granite powder into black cotton soil can significantly improve several key properties, including maximum dry density, optimum moisture content, unconfined compressive strength, and the soil's behavior in terms of expansion and shrinkage [1] [7]. These improvements make granite powder a viable option for stabilizing expansive soils, improving their engineering properties and making them more resilient to environmental stresses [13].

Therefore, this research aims to evaluate the effects of adding granite powder on the engineering and mechanical properties of black cotton soil. The study specifically focuses on examining how different proportions of granite powder (5%, 10%, 15%, and 20%) influence the soil's volumetric behavior and its load-bearing capacity. The expected results from this research will contribute to improving the stability and sustainability of black cotton soil, offering new opportunities for its use in both construction and agricultural applications.

The underlying hypothesis of this study is that the introduction of granite stone powder into black cotton soil alters its microstructure by filling voids and reducing porosity, which enhances its mechanical properties and makes it more stable under fluctuating environmental conditions [5]. The potential outcomes of this research are not limited to improving soil properties for construction purposes but also extend to enhancing agricultural sustainability in regions that rely heavily on black cotton soil for farming. By providing insights into soil stabilization, this study opens avenues for the application of integrated engineering and environmental solutions in natural resource management and sustainable land use.

2. Related Work

2.1. Soil Improvement Using Additives and Granite Powder

The enhancement of soil properties is achieved by adding organic and inorganic materials that improve soil structure, cohesion, and bearing capacity [16]. For example, fly ash and lime have been used to improve soil properties, with a study in India showing that adding fly ash to expansive clayey soil significantly increased dry density and compressive strength while reducing swelling and shrinkage [17]. Recently, granite powder, a by-product of the granite industry [11], has emerged as a promising soil additive. A study conducted in Indonesia on expansive clayey soil showed that adding 10% - 15% granite powder by soil weight improved soil bearing capacity, increased dry density, and reduced swelling and shrinkage. The silica content in granite powder is thought to be the key, as it enhances cohesion between soil particles, improving the soil's permeability, structural stability, and overall strength for both agricultural and construction uses [18].

2.2. Need for Current Research

Despite numerous studies on soil improvement using additives such as ash, lime, and quarry dust, granite powder remains a relatively novel material that has not been extensively explored for soil enhancement, particularly for black cotton soil. Therefore, this study aims to provide a comprehensive analysis of the effects of granite powder addition on black cotton soil properties, contributing to future solutions for enhancing soil sustainability in construction and agricultural projects.

3. Materials and Methodology

3.1. Materials

3.1.1. Black Cotton Soil and Granite Powder

Samples of black cotton soil were collected from a site characterized by integrated properties of water retention capacity and high fertility. This soil exhibited a clayey composition, making it susceptible to physical issues such as swelling and shrinkage [14]. The samples were air-dried to reduce natural moisture content, passed through a fine sieve to remove larger particles, and stored in a laboratory environment to determine their fundamental properties. **Figure 1** shows an image of the black cotton soil used in the study.

Figure 1. Illustrating an image of black cotton soil.

Prior to the addition of granite powder, preliminary physical properties of the soil were tested, including liquid limit, plastic limit, organic matter content, and particle size distribution. These tests were essential to understand the soil's behavior in its natural state before the application of additives.

Granite stone powder, sourced from the granite industry, was used as an additive to enhance soil properties. This powder is characterized by its mineral-rich composition, including silica (SiO_2), calcium (CaO), alumina (Al_2O_3), and magnesium (MgO), all of which contribute to improving soil cohesion and physical stability [1]. The granite powder was ground to a fine particle size to facilitate uniform mixing with the soil. **Figure 2** illustrates the granite stone before and after its fracture and grinding.

(a)

(b)

Figure 2. (a) Illustrating the granite stone before its fracture, (b) Illustrating the granite stone after its fracture and grinding.

The granite powder was added to the black cotton soil at proportions of 5%, 10%, 15%, and 20% of the soil weight. These percentages were selected to evaluate the effect of increasing powder content on soil properties, particularly in reducing swelling and shrinkage and increasing dry density.

3.1.2. Sample Preparation and Mixing Procedure

Granite powder was mixed with black cotton soil at predetermined weight percentages (5%, 10%, 15%, and 20%) to study the effect of different dosages on the soil properties. The mixing process was done manually to ensure uniform distribution of the powder in the soil. After mixing, the samples were compacted in molds according to the standard Proctor compaction test. After compaction, the samples were left to cure in a controlled environment at room temperature for 7 days to ensure the stabilization of the soil before conducting the tests. The sample depth was maintained at 10 cm for consistency across all tests. In previous studies on soil improvement using granite powder, the sample depth ranged from 10 cm to 20 cm, as these depths have been shown to yield accurate results in tests such as CBR, Atterberg limits, and swell-shrink tests.

3.1.3. Effect of Granite Powder on Soil Microstructure

Although this study focused on the changes in the physical and mechanical properties of the soil due to the addition of granite powder, it is important to include a deeper analysis of the underlying microstructural mechanisms through which granite powder influences soil behavior [13] [19]. Previous studies suggest that granite powder contributes to filling the voids between soil particles, which improves cohesion and reduces porosity [20]. For instance, earlier research utilized Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) techniques to study the effect of mineral additives on soil structure, showing that granite powder can reduce porosity and enhance the cohesion between soil particles (e.g., Wang *et al.* 2024; Liu *et al.* 2025; Lu *et al.* 2024) [21]-[23].

3.2. Methodology

A series of physical and mechanical tests were conducted to assess the effects of granite powder addition on soil properties. The tests performed included:

1) Grain Size Analysis

rain size analysis was carried out to evaluate the distribution of soil particle sizes after the addition of granite powder [24]. This process involves passing the soil through a series of sieves to separate particles based on their sizes, classifying them as coarse or fine. By doing so, this test helps in understanding how granite powder alters the structural integrity of the soil [21]. The key effect expected is an improvement in cohesion and a reduction in porosity, leading to increased soil stability [25]. The standard followed for this test was ASTM D422, Standard Test Method for Particle-Size Analysis of Soils. The formula Equation (1) to calculate the fine content percentage is:

$$\%\text{fine} = \frac{\text{Weight of particles passing through sieve}}{\text{Total weight of the sample}} \times 100 \quad (1)$$

This formula allows for the classification of the soil into coarse and fine categories, which is crucial for understanding the overall soil structure.

2) Atterberg Limits Test

In this test, the liquid limit (LL) and plastic limit (PL) of the soil were determined to evaluate its plasticity and flexibility [26]. The liquid limit refers to the moisture content at which the soil changes from a liquid to a plastic state, while the plastic limit indicates the moisture content at which the soil starts to behave like a solid [7] [10]. With the addition of granite powder, a reduction in both limits is expected, which would enhance the soil's overall stability. This test follows ASTM D4318, Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils. The Plasticity Index (PI), Equation (2) calculated as the difference between the liquid limit and the plastic limit, is given by:

$$\mathrm{PI} = \mathrm{LL} - \mathrm{PL} \tag{2}$$

This measure is important for assessing the workability of the soil, which is essential for determining its suitability for construction projects.

3) Shrinkage Limit Test

The shrinkage limit test was conducted to measure the shrinkage that occurs in the soil when it dries from a fully saturated state to a dry state [27]. This test is particularly important for expansive soils, as it helps determine how additive materials affect shrinkage. Granite powder is anticipated to reduce shrinkage, contributing to greater soil stability [16] [25]. The method employed followed ASTM D427, Standard Test Method for Shrinkage Factors of Soils by the Mercury Method. Equation (3) To determine the shrinkage limit (SL), the formula used is:

$$\mathrm{sl} = \frac{V_{\mathrm{sat}} - V_{\mathrm{dry}}}{V_{\mathrm{sat}}} \times 100 \tag{3}$$

where V_{sat} represents the saturated volume of the soil and V_{dry} represents the volume after drying. This formula measures the volume change as the soil dries, indicating its shrinkage potential.

4) Swelling Test

This test aims to quantify the soil's potential for expansion upon absorbing water. It is essential for assessing the stability of soils, such as black cotton soil, that are prone to swelling, which can cause severe damage to structures [28]. The addition of granite powder is expected to reduce this swelling, making the soil more stable under varying moisture conditions [13]. This test adheres to ASTM D4546, Standard Test Methods for One-Dimensional Swell or Settlement Potential of Cohesive Soils. In Equation (4) The swelling is calculated using the formula:

$$\mathrm{Swelling}\left(\%\right) = \frac{H_{\mathrm{final}} - H_{\mathrm{initial}}}{H_{\mathrm{initial}}} \times 100 \tag{4}$$

where H_{final} is the final height of the soil sample after swelling and H_{initial} is the height before swelling. This calculation helps in understanding the extent of expansion the soil undergoes when exposed to water.

5) Compaction Test (Proctor Test)

To determine the optimum moisture content and the maximum dry density of the soil, the Proctor compaction test was carried out. This test provides crucial information about the soil's ability to support loads in construction applications [29]. The expected outcome is an increase in dry density with the addition of granite powder, which will enhance the soil's stability and cohesion. The standard followed for this test was ASTM D698, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Standard Effort. Equation (5) The Maximum Dry Density (MDD) is calculated using the formula

$$\text{MDD}\left(\text{g/cm}^2\right) = \frac{\text{Dry weight of soil}}{\text{volume of soil sample}} \tag{5}$$

This calculation ensures that the soil reaches its highest possible density at the optimal moisture content.

6) Bearing Capacity Test

In the bearing capacity test, the soil's ability to resist applied loads was measured to determine how much pressure the treated soil can withstand before failing. This test is particularly important for evaluating soil stability in engineering projects, as the addition of granite powder is expected to improve the load-bearing capacity [1] [25]. The test follows ASTM D1883, Standard Test Method for CBR of Laboratory-Compacted Soils. In Equation (6) The California Bearing Ratio (CBR) is calculated using the formula:

$$\text{CBR}\left(\%\right) = \frac{P_{\text{sample}}}{P_{\text{standard}}} \times 100 \tag{6}$$

where P_{sample} is the load required to penetrate the soil sample, and P_{standard} is the load required for standard penetration. This formula helps to assess the soil's resistance to deformation and its suitability for construction.

3.3. Data Collection and Analysis

Data obtained from the experiments were collected and analyzed using appropriate statistical methods. Means and standard deviations were calculated for each tested parameter to determine the effects of granite powder addition on soil properties. The results of untreated soil were compared with those of soil treated with granite powder at different concentrations.

The analysis aimed to identify trends, correlations, and significant improvements in soil behavior due to the additive, providing a comprehensive understanding of the efficacy of granite powder in enhancing the engineering properties of black cotton soil.

3.4. Test Replicates and Statistical Analysis

All tests in this study were conducted in triplicate (three replicates per test) to ensure the accuracy and reproducibility of the results. To determine the differences between the various granite powder percentages, the results were compared using descriptive analysis. The means and standard deviations for each soil property tested (such as shrinkage, swelling, and Atterberg limits) were calculated to compare the effects of granite powder on the soil properties.

4. Results and Discussion

4.1. Engineering Properties of Black Cotton Soil

The Black Cotton Soil used in the present investigation was collected from the Al-Jereif East area in Khartoum, Sudan. The properties of the Black Cotton Soil are presented in Table 1.

Table 1. Engineering properties of black cotton soil.

S. No.	Particulars	Test Results
1	Soil Classification (AASHTO)	A-7-6 (High plasticity clay)
2	Grain Size Distribution	Sand = 10%, Silt + Clay = 90%
3	Specific Gravity	2.6
4	Plasticity Index, (%)	28.41
5	Liquid Limit, (%)	54.5
6	Plastic Limit, (%)	26.09
7	Shrinkage Limit, (%)	16.5
8	Swelling Characteristics (DFS, %)	28
9	California Bearing Ratio (CBR) (%)	2
10	Compaction Characteristics	Optimum Moisture Content (OMC) = 17.5%, Maximum Dry Density (MDD) = 1.56 gm/cm^3

4.2. Grain Size Analysis Test

As shown in Table 2, the untreated soil contains a high percentage of fine particles (clay), leading to high porosity and susceptibility to expansion and shrinkage. This makes the soil unsuitable for construction or agriculture in some cases due to volume changes that occur with changes in moisture.

Table 2. Grain size analysis test results.

Characteristics	Fine Content	Porosity
Untreated Soil	High	High
Soil + 5% GP	Slight decrease	Low
Soil + 10% GP	Improved cohesion	Low
Soil + 15% GP	Increased structural stability	Lower
Soil + 20% GP	Highest stability	Lowest

Upon adding 5% granite powder to the soil, a slight decrease in porosity was observed, reflecting an initial improvement in the cohesion between particles.

This improvement became more evident with increasing the powder percentage to 10%, 15%, and 20%, where porosity was further reduced and the granular structure of the soil became more cohesive. This improvement makes the soil more stable and less prone to expansion or shrinkage. In Figure 3, the results of grain size analysis are shown. In Table 2, we find that the soil containing 20% granite powder became more structurally stable, making it more suitable for construction or agriculture.

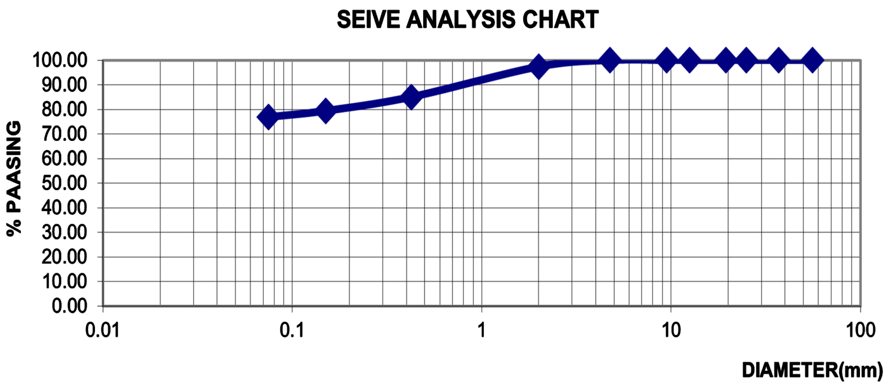


Figure 3. Grain size analysis.

4.3. Atterberg Limits Test

As shown in Table 3, the untreated soil had a very high liquid limit (LL) of 54.5%, indicating the soil's high susceptibility to deformation when exposed to moisture. This raises concerns in construction applications, as it can lead to loss of foundation stability under high moisture conditions.

Table 3. Atterberg limits test results.

Characteristics	Liquid Limit (LL) %	Plastic Limit (PL) %	Plasticity Index (PI) %
Untreated Soil	54.5	26.09	28.41
Soil + 5% GP	49	24.91	24.09
Soil + 10% GP	45.1	24	21.1
Soil + 15% GP	44.5	23.7	20.8
Soil + 20% GP	40	21.05	18.95

However, after adding 5% granite powder, a slight decrease in the liquid limit and plastic limit was observed, reflecting a slight improvement in soil stability. With an increase in the powder percentage to 10%, 15%, and 20%, the reduction in the liquid limit and plastic limit continued gradually, reflecting increased soil stability. The soil containing 20% granite powder showed significant improvement in this area, meaning the soil became less plastic and more capable of bearing loads under changing environmental conditions. Figure 4 illustrates the liquid limit (LL) of the soil at different granite powder percentages.

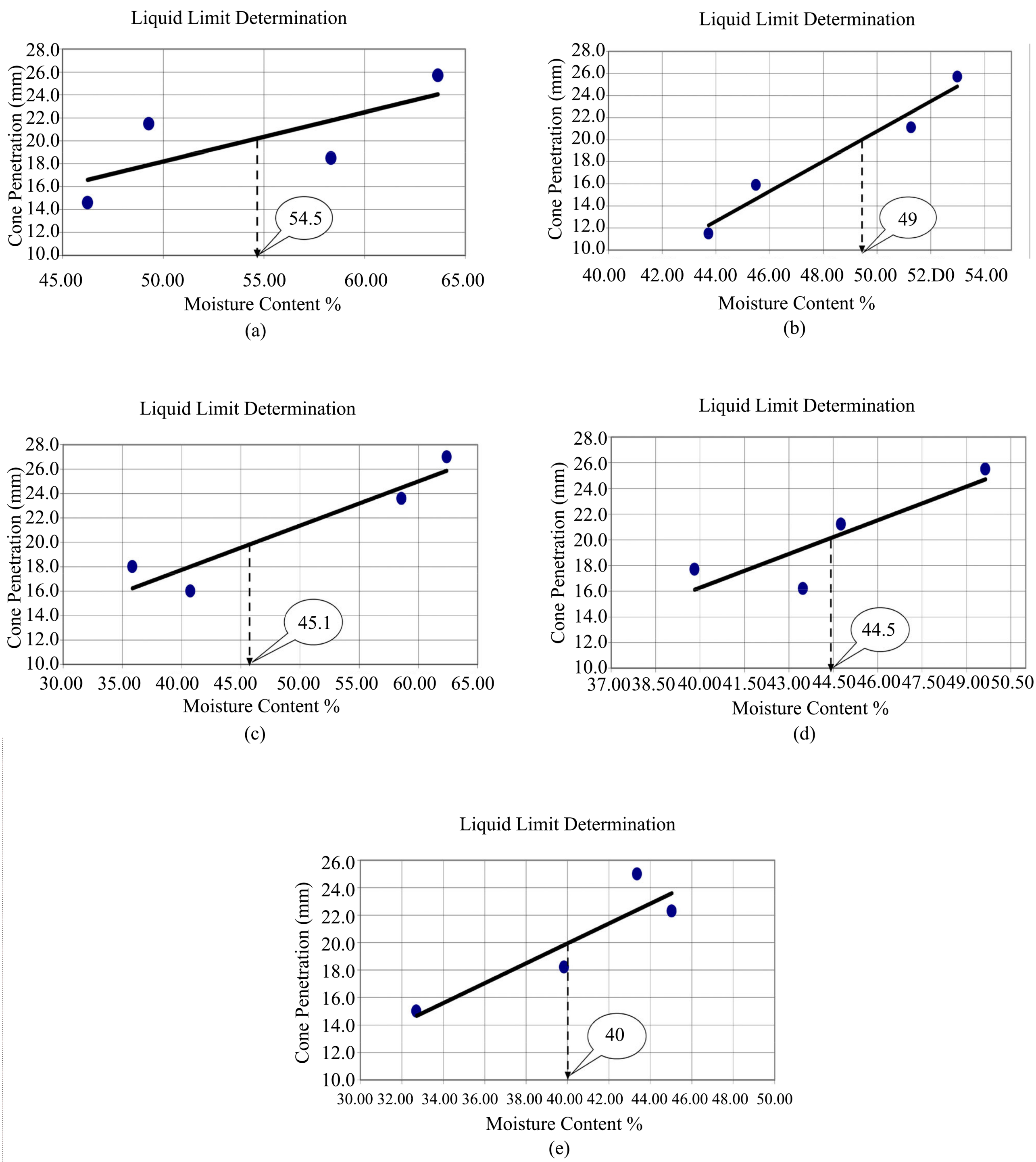


Figure 4. Liquid limit (LL). (a) Untreated Soil, (b) Soil + 5% GP, (c) Soil + 10% GP, (d) Soil + 15% GP, (e) Soil + 20% GP.

4.4. Shrinkage Limit Test

In Table 4, the shrinkage test results show that the untreated soil was susceptible to significant shrinkage, with a shrinkage percentage of 16.50%. This indicates that the soil was prone to substantial contraction upon drying, suggesting it is entirely unsuitable for use in construction projects.

Table 4. Shrinkage limit test results.

Characteristics	Shrinkage Limit %
Untreated Soil	16.5
Soil + 5% GP	14.3
Soil + 10% GP	10.8
Soil + 15% GP	8.6
Soil + 20% GP	6.5

With the addition of 5% granite powder, shrinkage was slightly reduced to 14.3%, reflecting a minor improvement in soil stability. As the powder percentage increased to 10%, 15%, and 20%, shrinkage decreased significantly, indicating that the soil became more stable under drying conditions. Figure 5 shows the effect of granite dust on the shrinkage limit.

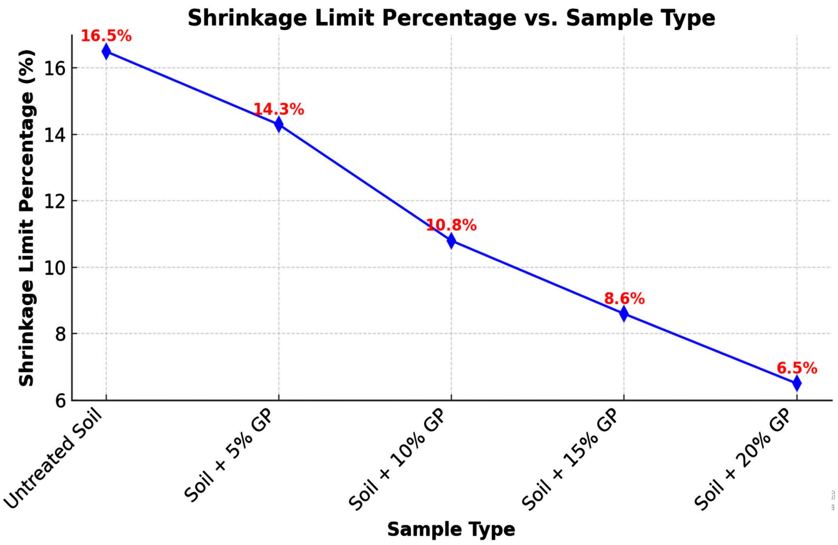


Figure 5. Effect of granite dust on shrinkage limit.

4.5. Swelling Test

As shown in Table 5, the untreated soil was highly susceptible to expansion upon water absorption, with swelling reaching 28%. This percentage is considered high and could lead to significant problems in construction projects due to continuous volume changes.

Table 5. Swelling test results.

Characteristics	Swelling %
Untreated Soil	28
Soil + 5% GP	24
Soil + 10% GP	19
Soil + 15% GP	14.7
Soil + 20% GP	10.8

Upon adding 5% granite powder, swelling was reduced to 24%. With increases to 10%, 15%, and 20% granite powder, swelling was further reduced, reflecting a significant improvement in soil stability under the influence of moisture. Figure 6 demonstrates the effect of granite dust on swelling.

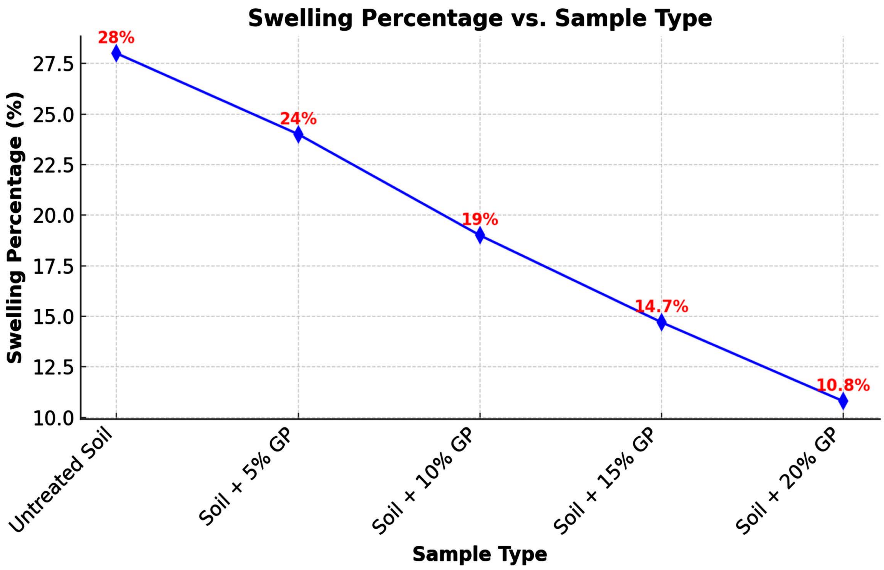


Figure 6. Effect of granite dust on swelling.

4.6. Compaction Test

As shown in Table 6, the untreated soil had a high optimum moisture content (17.5%), indicating that the soil requires a large amount of water to cohere. Meanwhile, the maximum dry density was 1.56 gm/cm^3, which is lower than the ideal standard for construction.

Table 6. Compaction test results.

Characteristics	Optimum Moisture Content (%)	Maximum Dry Density (gm/cm^3)
Untreated Soil	17.5	1.56
Soil + 5% GP	17	1.59
Soil + 10% GP	16.1	1.6
Soil + 15% GP	15	1.62
Soil + 20% GP	13	1.63

After adding 5% granite powder, the optimum moisture content was reduced to 17%, and the dry density increased to 1.59 gm/cm^3. As the percentage increased to 10%, 15%, and 20% granite powder, the optimum moisture content decreased further and the dry density increased noticeably, indicating improved soil stability. Figure 7 shows the results of the compaction test at various granite powder contents.

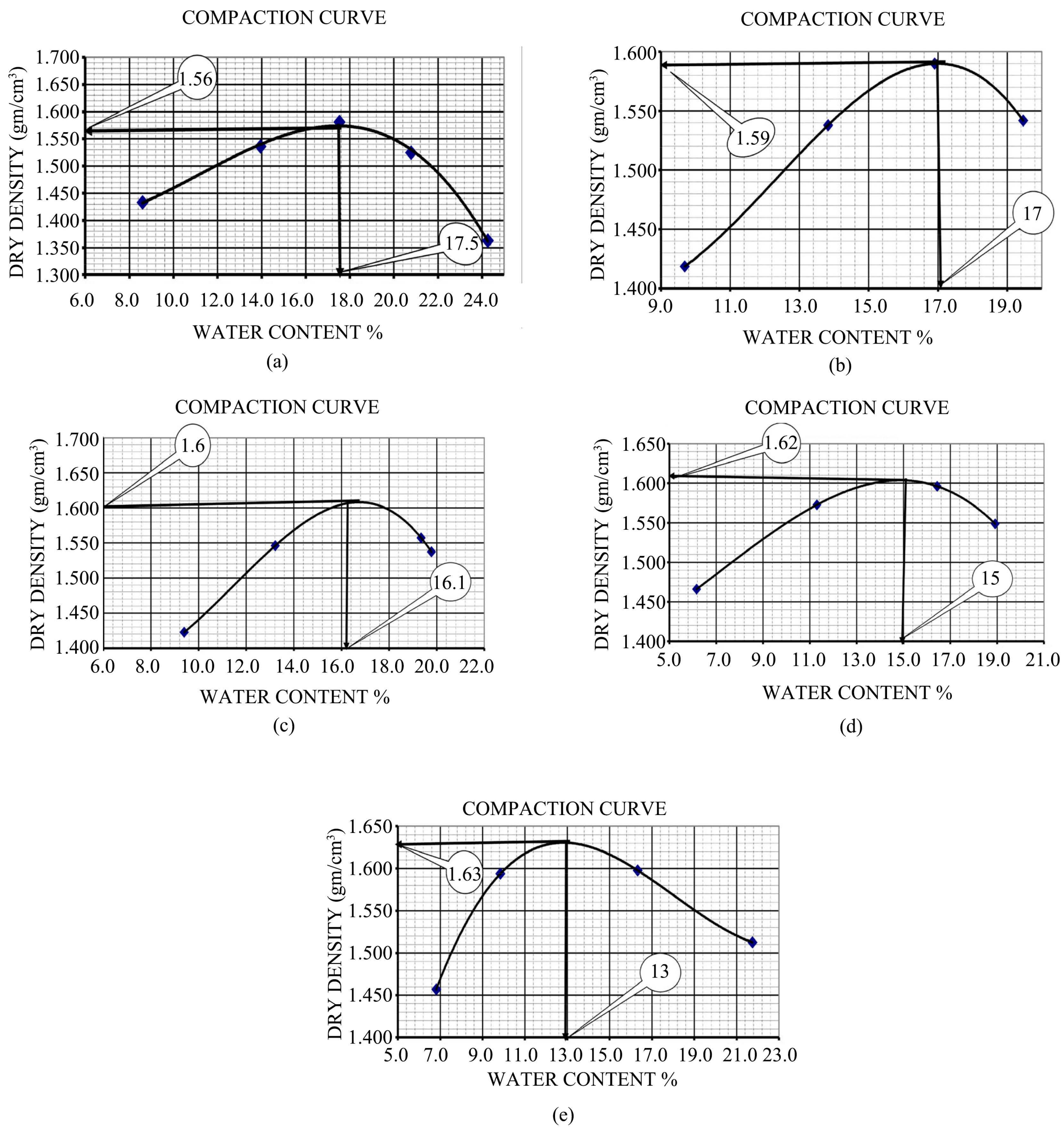
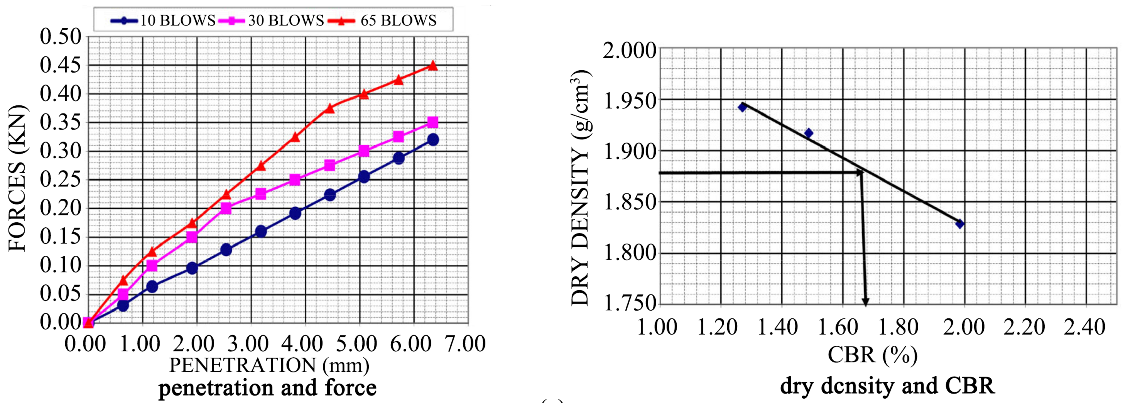


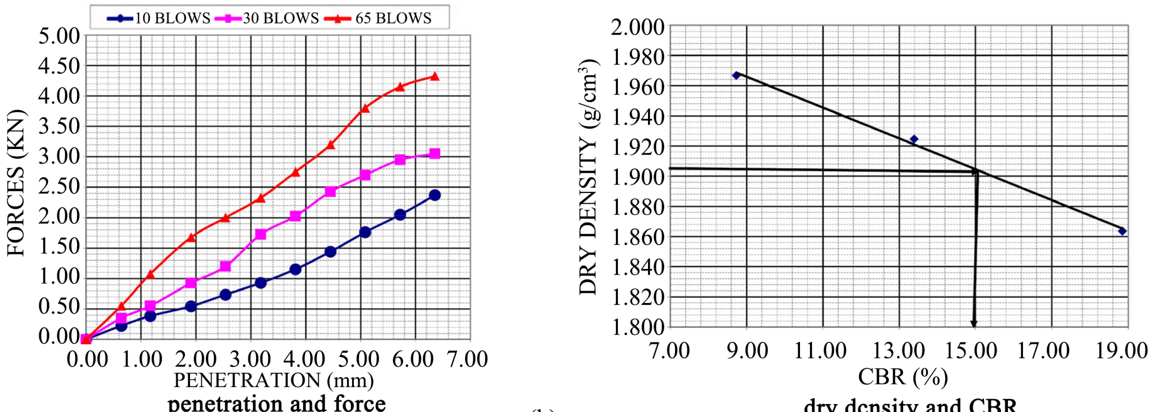
Figure 7. Compaction test. (a) Untreated Soil, (b) Soil + 5% GP, (c) Soil + 10% GP, (d) Soil + 15% GP, (e) Soil + 20% GP.

4.7. Bearing Capacity Test

As shown in **Table 7**, the California Bearing Ratio (CBR) was very low (1.7%), making the soil unable to bear heavy loads in construction applications. However, upon adding 5% granite powder, California Bearing Ratio (CBR) improved to 15%. With increases to 10%, 15%, and 20%, the compressive strength increased significantly, reflecting improved soil stability under loads. **Figure 8** illustrates the bearing capacity test results for different granite powder additions.


10 BLOWS
30 BLOWS
65 BLOWS
FORCES (KN)
PENETRATION (mm)
penetration and force
DRY DENSITY (g/cm³)
CBR (%)
dry dcnsity and CBR

(a)


10 BLOWS
30 BLOWS
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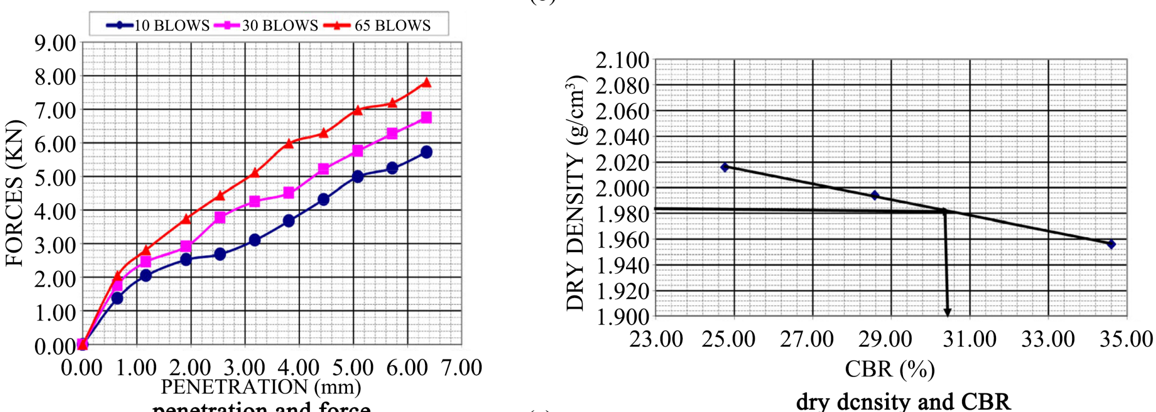
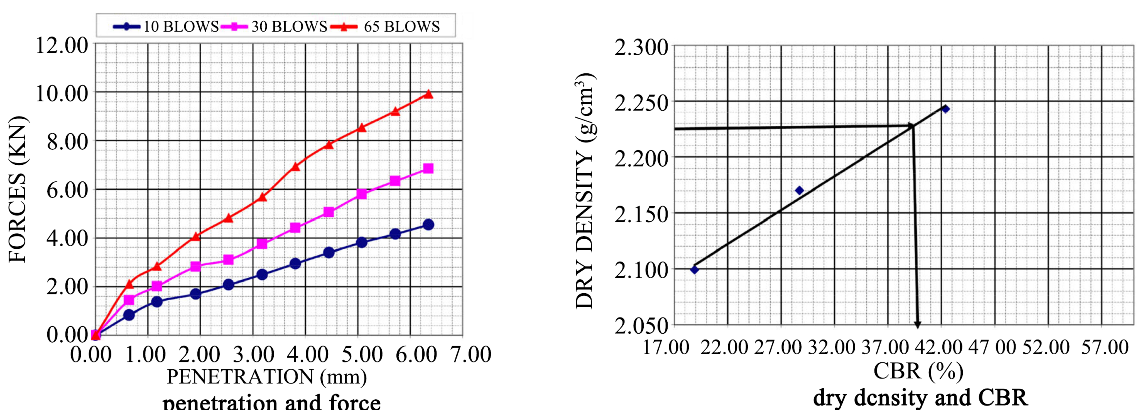
penetration and force
DRY DENSITY (g/cm³)
CBR (%)
dry dcnsity and CBR

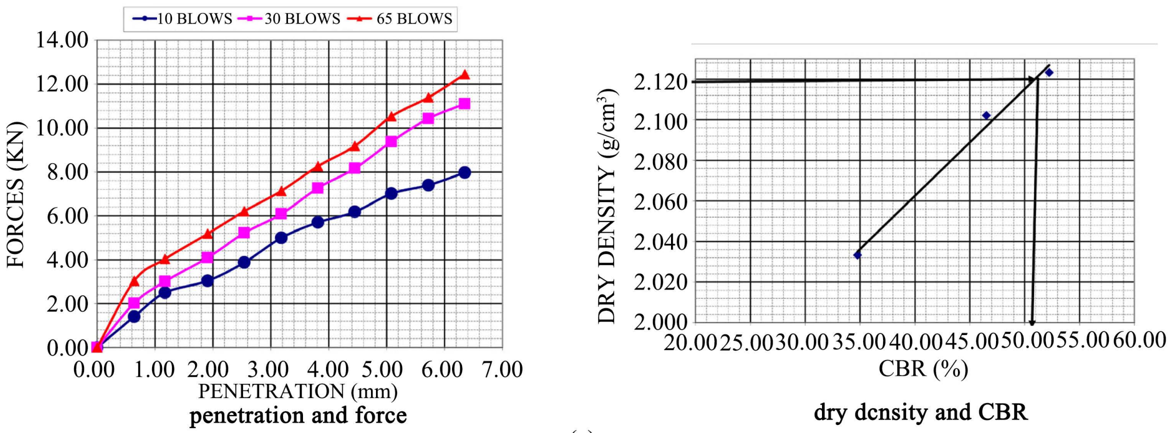
(b)


10 BLOWS
30 BLOWS
65 BLOWS
FORCES (KN)
PENETRATION (mm)
penetration and force
DRY DENSITY (g/cm³)
CBR (%)
dry dcnsity and CBR

(c)


10 BLOWS
30 BLOWS
65 BLOWS
FORCES (KN)
PENETRATION (mm)
penetration and force
DRY DENSITY (g/cm³)
CBR (%)
dry dcnsity and CBR

(d)



(e)

Figure 8. Bearing capacity test. (a) Untreated Soil, (b) Soil + 5% GP, (c) Soil + 10% GP, (d) Soil + 15% GP, (e) Soil + 20% GP.

Table 7. Bearing capacity test.

Characteristics	California Bearing Ratio (CBR) (%)
Untreated Soil	1.7
Soil + 5% GP	15
Soil + 10% GP	30.5
Soil + 15% GP	40
Soil + 20% GP	54

5. Conclusion and Recommendation

5.1. Conclusion

- Granite powder improves the physical and mechanical properties of the black cotton soil.
- Expansion, shrinkage, and swelling were significantly reduced with increasing granite powder percentage.
- Increased dry density and compressive strength made the soil more capable of bearing loads and less susceptible to structural problems.
- Soil treated with 20% granite powder is considered more suitable for construction, with significant improvement in compressive strength and structural stability.

5.2. Recommendation

This study recommends further research to expand the applications of granite powder in soil improvement by testing its effects on different soil types across various geographical regions, thereby broadening its use in agricultural and geotechnical engineering. It is also advised to conduct studies under diverse environmental conditions, such as high temperatures and varying moisture levels, to investigate the long-term sustainability of granite powder's impact on soil properties. Additionally, research should explore the potential of combining granite powder with other supplementary materials, such as fly ash and lime, to achieve greater improvements in soil stability and load-bearing capacity. The economic feasibility of using granite powder for soil enhancement should also be evaluated, taking into account its environmental and economic costs. Furthermore, its agricultural applications in regions experiencing soil shrinkage and expansion issues warrant investigation. Finally, the environmental impacts of granite powder usage, particularly concerning natural resources such as water and plants, should be thoroughly assessed.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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