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Improving the Engineering Properties of Black Cotton Soil Using Gum Arabic: A Comparative Study with Granite Powder

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Abstract

This study evaluates gum arabic as a sustainable, biodegradable alternative to traditional stabilizers for Black Cotton Soil. We conducted standard laboratory tests—including Atterberg limits, shrinkage, swelling, compaction, and California Bearing Ratio (CBR)—on soil treated with gum arabic and compared the results to a previous study using granite powder. Our findings show that gum arabic consistently and significantly improved all tested engineering properties. It dramatically reduced both shrinkage and swelling, enhanced compaction, and caused a remarkable increase in the soil's CBR. The comparative analysis demonstrated that gum arabic outperformed granite powder in all tests. We conclude that gum arabic is a superior, sustainable stabilizer for improving the engineering properties of expansive clay soils.

Keywords

Black Cotton Soil, Gum Arabic, Soil Stabilization, Granite Powder, Expansive Soil, Atterberg Limits, CBR, Swelling Behavior, Mechanical Properties, Compaction Characteristics

1. Introduction

Black Cotton Soil (Black Cotton Soil) is classified as a type of expansive clay soil, which poses a significant engineering and environmental challenge in the regions where it is found [1] [2]. Despite its high fertility and ability to support agriculture, its engineering properties, characterized by significant expansion and shrinkage as its water content changes, cause severe damage to infrastructure [3] [4]. Cracks that appear on sidewalks and roads, damage to building foundations, and the deterioration of pipelines are all direct results of this unstable soil behavior [5]. Therefore, improving the properties of this soil has become an urgent necessity to ensure the long-term sustainability of construction and agricultural projects [6].

Traditionally, soil stabilization methods have relied on inorganic materials such as cement and lime [7], which have proven effective in improving the soil's mechanical properties. However, these materials are often high in cost and can have negative environmental impacts due to their industrial nature and energy-intensive production processes [8]. Recently, research interest has shifted toward exploring sustainable and eco-friendly solutions using natural materials [9]. These materials are emerging as a promising alternative, not only for their effectiveness but also for being biodegradable and locally available, which reduces the carbon footprint of engineering projects [10].

In this context, Gum Arabic stands out as one of the most promising natural solutions. Extracted from the Acacia tree, Gum Arabic is a natural polymer known for its ability to form strong bonds between soil particles [11]. From a chemical perspective, Gum Arabic consists of complex polymeric chains of polysaccharides and glycoproteins. When added to clay soil, these polymeric chains form strong hydrogen bonds with water molecules and clay minerals [12]. This process stabilizes the soil particles and coats them, preventing water molecules from penetrating the clay structure, thereby limiting the phenomena of expansion and shrinkage [13]. This mechanism is fundamentally different from the effect of mineral additives like granite, which primarily work by filling voids and improving friction between particles [14].

This study is an extension of a previous research project that evaluated the use of Granite Aggregate in improving the properties of Black Cotton Soil [15]. While the previous study showed that granite can significantly enhance the soil's bearing capacity, it did not fully address the issues of shrinkage and expansion [15]. Furthermore, its heavy mineral nature may not align with modern trends for sustainable environmental solutions. Based on this, the current paper focuses on Gum Arabic as an organic material aimed at achieving a comprehensive improvement in both the engineering and environmental properties of the soil.

The main objective of this paper is to evaluate the effect of different percentages of Gum Arabic (5%, 10%, 15%, 20%) on the engineering properties of Black Cotton Soil through a series of standard laboratory tests, such as the California Bearing Ratio (CBR) test, shrinkage tests, and dry density tests. Additionally, this study will provide a detailed comparison between the effectiveness of Gum Arabic and that of granite aggregate, highlighting the environmental and economic benefits offered by Gum Arabic. Through this comparison, we aim to provide scientific evidence that Gum Arabic is not only an effective alternative to traditional materials but also a more sustainable option for future civil engineering and agricultural applications.

2. Related Work

2.1. Research Background

Soil improvement is a fundamental aspect of geotechnical engineering and sustainable agriculture. This field has seen numerous studies focused on using various materials to achieve the desired stability [2] [16].

Many research papers have demonstrated the effectiveness of natural materials in improving soil properties. For instance, Mohammad *et al.* (2019) and Al-Dulaijan *et al.* (2017) investigated the effect of Gum Arabic on clay soil [3]. Their findings showed that adding Gum Arabic significantly improved the soil's structural stability, reduced its expansion and shrinkage, and increased both its dry density and bearing capacity [9]. In contrast, other studies by Chung *et al.* (2018) and Smith and Zhang (2016) explored using mineral materials like granite aggregate. They found that granite effectively increased the soil's bearing capacity and improved its density, though its effect on reducing expansion and shrinkage was limited [17].

Comparative studies show that the effectiveness of an additive depends on the property to be improved. For example, a study by Kumar *et al.* (2020) found that Gum Arabic is superior to granite in reducing soil expansion and shrinkage [9]. The researchers also highlighted that Gum Arabic represents a sustainable environmental solution [18], whereas granite could pose environmental challenges if used in large quantities [19]. Despite this valuable research, there remains a clear research gap in studies that conduct a direct and comprehensive comparison between an organic material (Gum Arabic) and a mineral material (granite) on the same type of soil and under identical experimental conditions. This paper aims to bridge that gap and provide a deeper understanding of the mechanisms by which both materials operate.

Although some studies have addressed the effectiveness of Acacia gum in improving soil properties, numerous other studies have explored the use of other natural materials such as natural acids, biopolymers, and agricultural waste. These studies include the use of components like soybean gelatin, rice husks, and other botanical materials, which have proven effective in improving the engineering properties of soil. In this context, Acacia gum is considered a promising material given its environmentally friendly, biodegradable properties and its potential for interaction with soil components.

2.2. Need for the Study

Although previous studies have shown the effectiveness of both Gum Arabic and granite in improving soil properties, there is a clear gap in the existing research: no comprehensive study has directly compared them on the same type of soil and under identical experimental conditions.

This research is necessary to bridge this gap. By using Black Cotton Soil as a standardized test bed and applying the same methodologies to both materials, we will provide a precise comparison between them. This will help determine which material is the most effective and sustainable solution for the geotechnical challenges this soil faces.

3. Materials and Methodology

3.1. Materials

3.1.1. Black Cotton Soil and Gum Arabic

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 [5]. The samples were air-dried to reduce the natural moisture content, passed through a fine sieve to remove larger particles, and stored in a laboratory environment to determine their fundamental properties.

Prior to the addition of gum arabic, 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.

Gum arabic, sourced from Acacia trees, was used as an additive to enhance soil properties [20]. This natural gum is rich in organic compounds such as polysaccharides, which contribute to improving soil cohesion and physical stability [18]. The gum was dissolved in water and added to the soil in various proportions [12].

Figure 1 shows an image of the gum arabic used in the study and it was added to the black cotton soil at proportions of 5%, 10%, 15%, and 20% of the soil's weight. These percentages were selected to evaluate the effect of increasing gum arabic content on soil properties, particularly in reducing swelling and shrinkage and increasing dry density.

(a) Gum Arabic before Grinding (b) Gum Arabic after Grinding

Figure 1. Gum arabic.

3.1.2. Experimental Procedure Gum Arabic (Before Grinding)

Gum arabic 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 gum arabic in the soil. After mixing, the samples were compacted in molds according to the standard Proctor compaction test. Following 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 organic additives, 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. Mechanisms of Gum Arabic in Soil Stabilization

Gum Arabic improves the microstructural properties of soil through several integrated mechanisms. As a natural polymer rich in polysaccharides, its polymeric chains adhere to the surface of fine clay particles, causing them to group into larger, more stable aggregates. This process not only increases soil cohesion and strength but also fills the inter-particle voids, which reduces overall porosity and increases dry density [21].

Furthermore, Gum Arabic forms an insulating layer around the clay particles, preventing water molecules from penetrating between their layers [22]. This effectively limits expansion and shrinkage phenomena. These microstructural improvements have been well-documented in numerous studies using Scanning Electron Microscopy (SEM), which clearly show Gum Arabic encapsulating soil particles and forming bridges between them [9]. This strengthens the soil's structure, ultimately leading to a significant increase in its bearing capacity, making it more suitable for engineering applications.

3.2. Methodology

A series of physical and mechanical tests were conducted to evaluate the effects of gum arabic addition on soil properties. The methodology focused on understanding the changes in the soil's fundamental and behavioral characteristics. All tests were performed in accordance with the established American Society for Testing and Materials (ASTM) standards.

1) Grain Size Analysis

Grain size analysis was carried out to evaluate the distribution of soil particle sizes after the addition of gum arabic. This process aims to determine the percentage of coarse and fine particles in the sample, providing a fundamental understanding of how the gum affects the soil's structure [12]. The gum's binding properties are expected to improve cohesion and reduce porosity, enhancing stability. This test followed ASTM D422. The fine content percentage was calculated using the formula (Equation (1)):

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

2) Atterberg Limits Test

To determine the soil's plastic properties, the Atterberg limits test was performed to measure the liquid limit (LL) and plastic limit (PL). These limits indicate the moisture content at which the soil changes its state. The addition of gum arabic is expected to lower the values of both limits, which signifies an increase in soil stability. This test was conducted in accordance with ASTM D4318. The Plasticity Index (PI) was calculated as the difference between the two limits (Equation (2)):

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

3) Shrinkage Limit Test

A shrinkage limit test was conducted to measure the volumetric change that occurs when the soil dries from a saturated state. This test is crucial for assessing the effectiveness of the additive in reducing soil shrinkage [23] [24]. Gum arabic is expected to reduce shrinkage due to its binding properties, which enhances soil stability. This test followed ASTM D427. The shrinkage limit (SL) was calculated using the formula (Equation (3)):

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

4) Swelling Test

This test aimed to measure the potential for the soil to expand upon absorbing water. This measurement is important for soils prone to swelling, as it can cause significant damage to structures [25]. Gum arabic is expected to reduce soil swelling, providing greater stability under varying moisture conditions. The test was performed according to ASTM D4546. The swelling percentage was calculated using the formula (Equation (4)):

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

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 [26]. The addition of gum arabic is expected to lead to an increase in the maximum dry density, which enhances the soil's cohesion and stability. The test followed ASTM D698. The Maximum Dry Density (MDD) was calculated using the formula (Equation (5)):

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

6) Bearing Capacity Test

The bearing capacity test was conducted to measure the soil's resistance to applied loads and its ability to support foundations. This test is essential for evaluating the soil's suitability for engineering projects [27]. Gum arabic is expected to significantly improve the soil's load-bearing capacity. The test followed ASTM D1883. The California Bearing Ratio (CBR) was calculated using the formula (Equation (6)):

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

3.3. Data Processing and Statistical Analysis

Experimental data from all tests were collected and processed using advanced statistical tools to ensure accurate evaluation. The means and standard deviations for each tested soil property were calculated, which allowed for a clear understanding of the data's variability.

To assess the statistical impact of adding gum arabic, a comparative analysis was conducted between the results of untreated soil samples and those treated with different concentrations of gum arabic. A direct statistical comparison was also made between the results of the gum arabic-treated samples and those of granite powder-treated soil, which were obtained from a previous study.

The analysis focused on identifying significant statistical differences among the various groups. This approach enabled a quantitative evaluation of gum arabic's effectiveness in improving the engineering properties of black cotton soil and a direct comparison of its impact versus that of granite powder on enhancing soil stability and reducing swelling and shrinkage.

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.

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

Continued

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, analyses revealed that untreated soil is characterized by a high content of fine clay particles, which explains its high porosity and lack of stability. These properties make the soil susceptible to significant volumetric changes (swelling and shrinkage) with moisture fluctuations, which severely limits its suitability for engineering or agricultural applications requiring structural stability.

Table 2. Grain size analysis test results.

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

With the addition of gum arabic, a gradual transformation in the soil's behavior was observed. The addition of a 5% concentration resulted in a slight decrease in porosity, indicating the initial action of the material as a binding agent that fills voids and enhances inter-particle cohesion. As the gum arabic concentration was increased to 10%, then 15% and 20%, its effect became more pronounced. The gum created a cohesive network between the particles, leading to a greater reduction in porosity and transforming the granular structure of the soil into a more stable and durable matrix. This fundamental improvement in structural properties effectively reduces the soil's susceptibility to shrinkage and swelling, making it more reliable for use in various projects.

4.3. Atterberg Limits Test

As shown in Table 3, the untreated soil exhibited a very high liquid limit (LL) of 54.5%, confirming its highly plastic nature and its significant susceptibility to deformation when exposed to moisture. This property presents a fundamental challenge in construction applications, as fluctuations in moisture content can lead to foundation instability.

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% Gum	43.07	19.09	23.98
Soil + 10% Gum	36.2	16.89	19.23
Soil + 15% Gum	30.06	14.23	15.83
Soil + 20% Gum	26.8	12.42	14.38

The addition of gum arabic led to a notable modification in the soil's plasticity properties. With the addition of a 5% concentration, a tangible decrease was observed in both the liquid and plastic limits, indicating the beginning of soil structure stabilization. This decrease continued progressively and consistently as the gum arabic concentration was increased to 10%, 15%, and up to 20%.

These results reflected a continuous reduction in the Plasticity Index, which indicates that gum arabic effectively works to make the soil less affected by water. The outstanding performance of the soil at a 20% gum arabic concentration demonstrates that the material successfully transformed the soil from a highly plastic material into a more stable and rigid substance, which enhances its ability to effectively bear loads under different environmental conditions.

4.4. Shrinkage Limit Test

As shown in **Table 4**, the untreated soil exhibited a high susceptibility to shrinkage, with a shrinkage percentage of 16.50%. This result indicates that the soil is prone to significant shrinkage upon moisture loss, a characteristic that severely limits its use in engineering projects, as shrinkage can lead to cracks and settlement in structures.

Table 4. Shrinkage limit test results.

Characteristics	Shrinkage Limit %
Untreated Soil	16.5
Soil + 5% Gun	7.2
Soil + 10% Gun	3.6
Soil + 15% Gum	1.5
Soil + 20% Gum	0.5

The addition of gum arabic led to a fundamental modification in the soil's behavior towards shrinkage. At a 5% concentration, the shrinkage percentage decreased to 7.2%, which reflects a notable improvement in volumetric stability. This improvement continued in a direct and proportional manner with the increase in gum arabic concentration to 10%, 15%, and 20%, as its binding properties worked to strengthen the soil structure.

The outstanding performance of the soil treated with a 20% gum arabic concentration demonstrates that the material successfully transformed the soil from a highly shrinking material into a more stable substance, making it more suitable for use in foundations and roads.

4.5. Swelling Test

As shown in **Table 5**, the untreated soil exhibited a significant swelling of 28% upon absorbing water. This high rate of volumetric expansion represents a serious engineering challenge, as continuous changes in soil volume can lead to instability and damage to structural foundations.

Table 5. Swelling test results.

Characteristics	Swelling %
Untreated Soil	28
Soil + 5% Gum	20
Soil + 10% Gum	13
Soil + 15% Gum	5.2
Soil + 20% Gum	1.1

The addition of gum arabic had a direct effect in reducing the soil's susceptibility to swelling. At a 5% gum arabic concentration, the swelling decreased to 20%, which represents a notable improvement in the soil's stability against moisture. This decrease continued proportionally with the increase in concentration to 10%, 15%, and 20%, indicating that gum arabic effectively limits water absorption and strengthens the bonds between soil particles.

The outstanding performance of the soil at a 20% gum arabic concentration demonstrates that the material successfully transformed the soil from a highly expansive substance into a more stable material resistant to volumetric changes, making it more reliable for use in variable environmental conditions.

4.6. Compaction Test

As shown in **Table 6**, the results of the compaction test revealed that the untreated soil had a high optimal moisture content (17.5%) and a low maximum dry density (1.56 g/cm^3). These characteristics indicate that the original soil required a large amount of water to achieve its maximum density and did not reach the density required for use in structural construction applications.

The addition of gum arabic led to a significant improvement in both properties. With each increase in the gum arabic concentration, a gradual and continuous decrease in the optimal moisture content was observed, accompanied by a clear and stable increase in the maximum dry density. This positive trend confirms that gum arabic acts as an effective binding agent, reducing the soil's water requirement and increasing its particle cohesion, thereby enhancing its density.

Table 6. Compaction test results.

Characteristics	Optimum Moisture Content (%)	Maximum Dry Density (gm/cm^3)
Untreated Soil	17.5	1.56
Soil + 5% Gum	15	1.68
Soil + 10% Gum	13	1.86
Soil + 15% Gum	11.9	2.08
Soil + 20% Gum	7.8	2.12

The outstanding performance of the soil at a 20% gum arabic concentration, where the maximum dry density reached 2.12 g/cm^3, demonstrates that this material is capable of fundamentally transforming soil properties to become more stable and durable, which makes it perfectly suited for supporting engineering loads.

4.7. Bearing Capacity Test

As shown in **Table 7**, the untreated soil exhibited a very low California Bearing Ratio (CBR) of 1.7%, confirming its poor resistance to loads. This low ratio makes it completely unsuitable for use as a sub-base or subgrade layer in road and structural projects.

Table 7. Bearing capacity test.

Characteristics	California Bearing Ratio (CBR) (%)
Untreated Soil	1.7
Soil + 5% Gum	42
Soil + 10% Gum	50
Soil + 15% Gum	61
Soil + 20% Gum	81

The addition of gum arabic led to a radical improvement in the soil's bearing capacity. With the addition of just 5% of gum arabic, the CBR value showed a dramatic jump to 42%, which represents a significant enhancement in compressive strength. This improvement continued in an incremental and continuous manner with each increase in gum arabic concentration, as the CBR reached 81% at a 20% concentration.

This dramatic rise in the CBR ratio proves that gum arabic effectively enhances the soil's internal structure, increasing its cohesion and ability to withstand heavy loads. These results confirm that adding gum arabic can transform weak soil into a material with excellent engineering properties, making it suitable for construction applications that require high levels of durability and stability.

5. Comparative Analysis: Gum Arabic vs Granite Powder

5.1. Comparison of the Effect of Gum Arabic and Granite Powder on Atterberg Limits

As shown in Figure 2, the results indicated that both materials contributed to the reduction of all limits. However, gum arabic consistently showed a more pronounced effect compared to granite powder at all additive percentages. For instance, the liquid limit of soil treated with 20% gum arabic decreased to 26.8%, while the addition of the same percentage of granite powder did not reduce the liquid limit to below 40%. This positive trend was also reflected in the plastic limit and the plasticity index, where the effect of gum arabic in reducing them was more effective. These findings confirm that gum arabic is superior to granite powder in reducing soil plasticity, which enhances its stability and improves its workability for engineering applications.

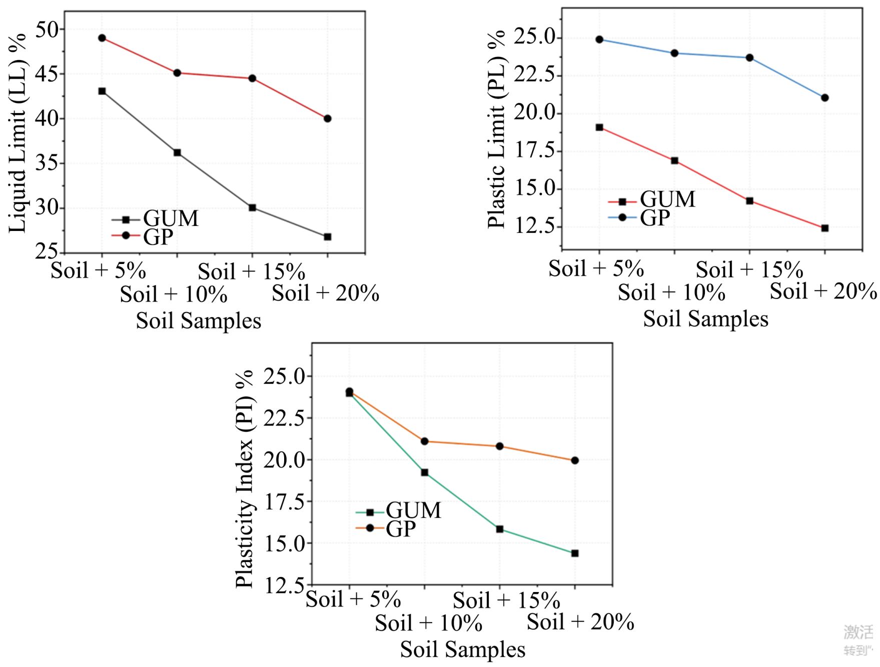

Figure 2. Atterberg limits.

5.2. Comparison of Effectiveness in Reducing Soil Shrinkage

The comparison between the effects of gum arabic and granite powder on soil shrinkage properties revealed a clear difference in outcomes. As shown in Figure 3, both materials were able to reduce the shrinkage percentage. However, gum arabic demonstrated a significant superiority in achieving this goal. While granite powder succeeded in gradually reducing shrinkage from 14.3% to 6.5% at a 20% addition, gum arabic led to a radical decrease in the same range, with the shrinkage percentage dropping from 7.2% at a 5% addition to only 0.5% at a 20% concentration. This outstanding performance proves that gum arabic works with exceptional effectiveness in strengthening the soil's internal bonds and preventing volumetric changes upon drying, making it a notably more efficient option than granite for addressing the problem of soil shrinkage.

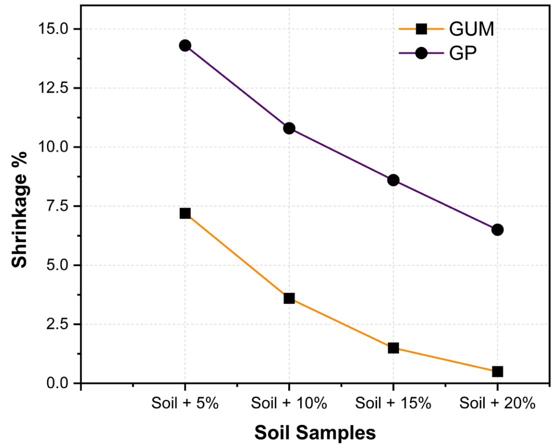

Figure 3. Soil shrinkage.

5.3. Comparison of the Effect of Gum Arabic and Granite Powder on Swelling Properties

As shown in **Figure 4**, the comparison between the effects of the two materials on soil swelling properties yielded clear results. The untreated soil had a high susceptibility to swelling, reaching 28%. Although both materials contributed to reducing swelling, gum arabic demonstrated a significantly more effective impact. While granite powder succeeded in gradually reducing swelling to 10.8% with a 20% addition, gum arabic led to a radical decrease in the same range, with swelling dropping to 20% with a 5% addition and reaching a mere 1.1% at a 20% concentration. This outstanding performance proves that gum arabic is superior to granite powder in reducing the soil's susceptibility to expansion upon water absorption, which enhances its stability under varying moisture conditions and makes it more suitable for engineering applications.

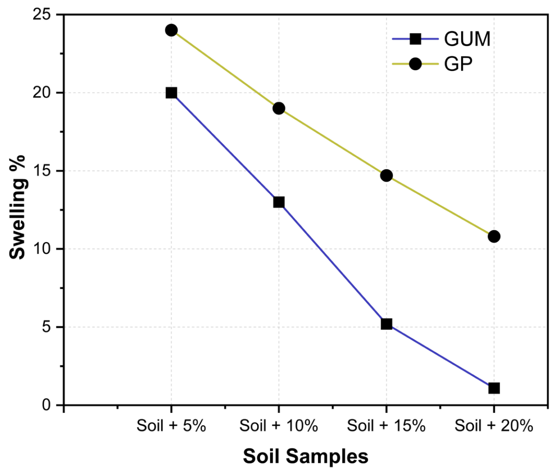

Figure 4. Soil swelling.

5.4. Comparison of the Effect of Gum Arabic and Granite Powder on Compaction Properties

As shown in **Figure 5**, the comparison of the two materials' effects on compaction properties yielded clearly distinct results. Regarding optimal moisture content (OMC), the addition of gum arabic led to a gradual and continuous decrease, indicating that the soil required less water to reach its maximum compaction. In contrast, the compaction of soil treated with granite powder generally required a higher moisture content, which demonstrates that gum arabic contributes to more efficient soil cohesion.

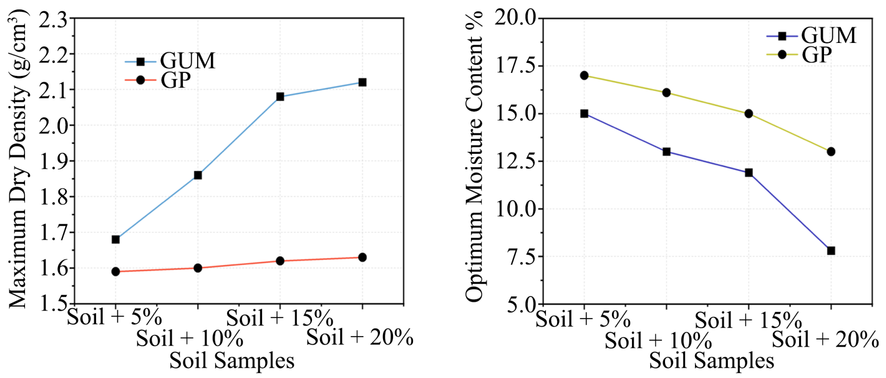

Figure 5. Compaction test.

Furthermore, the results for maximum dry density (MDD) showed a notable superiority for gum arabic. While the dry density of granite-treated soil reached 1.63 g/cm^3 at the highest additive percentage, the density of gum arabic-treated soil increased dramatically to 2.12 g/cm^3 at the same concentration. This radical increase in density proves that gum arabic works with exceptional effectiveness to increase soil cohesion and strengthen it, which significantly enhances its load-bearing capacity and makes it suitable for engineering applications.

5.5. Comparison of the Effect of Gum Arabic and Granite Powder on Bearing Capacity

As shown in **Figure 6**, the comparison between the effects of gum arabic and granite powder on the soil's California Bearing Ratio (CBR) revealed a clear superiority for gum arabic. With the addition of just 5%, the CBR of gum arabic-treated soil jumped to 42%, while granite powder-treated soil did not exceed 15%. This radical improvement in the early stages confirms the superior effectiveness of gum arabic as a soil stabilizer.

As the additive percentage increased to 20%, the CBR of gum arabic-treated soil continued to rise significantly, reaching 81%, while granite powder-treated soil only reached 54%. This dramatic increase in bearing capacity proves that gum arabic works with exceptional effectiveness to enhance soil cohesion and compressive strength, making it more capable of withstanding heavy loads and more stable for use in construction projects compared to granite-treated soil.

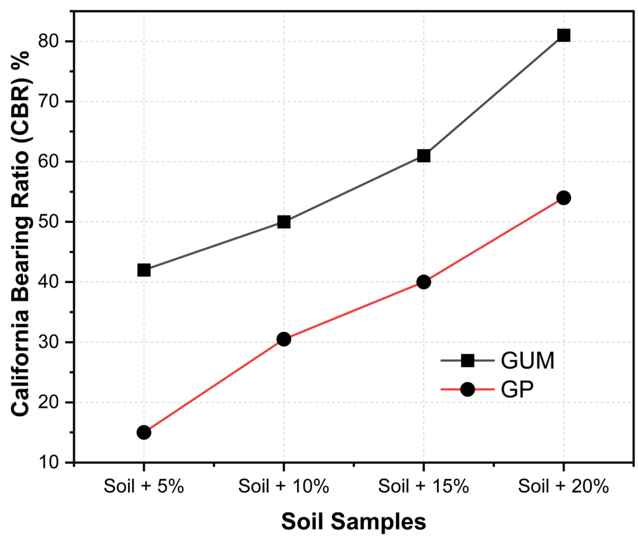

Figure 6. CBR test.

6. Conclusion and Recommendation

The study successfully demonstrated the remarkable effectiveness of Acacia gum (gum arabic) as a stabilizer for Black Cotton Soil, decisively outperforming granite powder. This superiority is attributed to Acacia gum's unique molecular bonding mechanism, where its polymer chains encapsulate clay particles and form strong hydrogen bonds, significantly enhancing the soil's mechanical stability.

This mechanism fundamentally transformed the soil's engineering properties, leading to a substantial reduction in liquid and plastic limits and the near-elimination of swelling and shrinkage at a 20% concentration. It also resulted in a drastic improvement in compaction characteristics and load-bearing capacity (CBR). In contrast, granite powder works via physical void filling and lacks the necessary chemical bonds to effectively control expansion and shrinkage.

6.1. Conclusions

Acacia gum (gum arabic) is a superior and sustainable solution for improving the engineering properties of Black Cotton Soil, moving beyond being a mere alternative to traditional materials. Its superior ability to mitigate both expansion and shrinkage while enhancing strength and stability makes it an ideal choice for improving road subgrade stability, foundation strength, and erosion control in civil and agricultural infrastructure projects.

Despite the excellent performance shown at the 20% concentration, an economic feasibility study is required to determine the optimal concentration that balances performance and cost. Based on the findings, concentrations ranging from 10% - 15% are expected to provide notable improvements in the soil's engineering properties while reducing overall costs.

6.2. Recommendation

Future research should focus on a long-term durability assessment of gum arabic-treated soil under various environmental conditions. Additionally, a comprehensive economic feasibility study is recommended to determine the cost-effectiveness of gum arabic for large-scale projects compared to traditional materials. Finally, we recommend conducting field-scale testing to validate the laboratory results and provide a more comprehensive understanding of gum arabic's performance in real-world scenarios.

Despite these encouraging results, further analysis is recommended using advanced techniques like Scanning Electron Microscopy (SEM) and X-ray Diffraction (XRD) to more deeply examine the chemical interactions between Acacia gum and the clay particles. These analyses would provide better insights into how Acacia gum bonds with the soil at the molecular level, which could further enhance our understanding of the soil stabilization mechanism.

Conflicts of Interest

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

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