Enhancing Geotechnical Properties of Ahvaz Fine Soil with Biochar: A Preliminary Study for Landfill Cover Systems

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Abstract

The final cover of a landfill is crucial for preventing rainwater infiltration, snowmelt, and greenhouse gas emissions while complying with regulatory standards. Effective landfill covers can be made from various materials, including modified clay, to enhance soil properties. This study investigates the effects of biochar on enhancing the geotechnical properties of fine soil in Ahvaz for potential use in landfill cover systems. Different biochar percentages (7%, 12%, and 20%) were analyzed for their impact on key soil properties, including residual shear strength, permeability, unconfined compressive strength (UCS), swelling index, and compaction characteristics. The results show that the addition of biochar improves the shear strength, with the most significant increase observed at 12% biochar (70% improvement compared to untreated soil). However, beyond this percentage, the strength improvement rate declines. Furthermore, higher biochar content increases permeability and reduces UCS. The study identifies 7% biochar as the optimal content, providing a balance between strength enhancement and minimizing negative effects on other soil properties such as permeability and compressibility. This study demonstrates that biochar can be a valuable additive for landfill cover systems, though careful consideration of its concentration is essential to avoid compromising hydraulic performance. These findings provide valuable insights for geotechnical engineering applications, particularly in regions with similar soil conditions to Ahvaz.

Keywords: Landfill, Biochar, Final cover, Ahvaz Soil, Geotechnical characteristics

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1. Introduction

The final cover of a landfill, as its outermost layer, serves multiple critical functions including reducing rainwater and snow infiltration, curbing greenhouse gas emissions, and maintaining structural stability. This cover must withstand diverse climatic conditions—ranging from extreme heat and cold to dry and wet, as well as withstand freezing and thawing cycles. It must also resist various environmental stresses such as wind, floods, and hail, and remain stable against potential cracking, tilting, slipping, and creeping. Furthermore, it should accommodate land shifts and the release of geogenic gases, while also being resilient to additional loads, such as those from vehicles, and deformations caused by seismic activity. Additionally, the cover needs to be resistant to disturbances from plant roots and burrowing animals [1]. A major environmental concern associated with landfills is the leachate produced from the decomposition of waste, which can contaminate groundwater. Thus, selecting an appropriate protective layer is crucial [2]. Compacted clay is frequently employed as an effective and cost-efficient barrier to prevent leachate leakage and gas emissions in landfills [3]. Globally, modified clay is used as a type of final landfill cover, where additives are mixed with clay to reduce its permeability, thereby preventing gas leaks and odors. These additives aim to enhance the mechanical, hydraulic, and geotechnical properties of the soil, ensuring it meets the necessary standards for landfill covers. Engineered artificial coatings, despite their initial impermeability, are prone to damage during and after installation and lack the ability to dampen impacts. In contrast, natural clay compounds can reduce pollutant flux through high absorption, oxidation, biological degradation, precipitation, and filtration processes. The type of clay used significantly influences its shrinkage potential, absorption capacity, erosion resistance, and permeability, all of which affect its performance as a landfill cover [4]. Biochar, produced through the pyrolysis of organic materials such as wood and agricultural residues in low-oxygen conditions, has gained attention for its high porosity, specific surface area, and absorbency [5]. When used to modify clay, biochar has been proposed as a sustainable alternative for landfill covers due to its ability to alter the physical, hydrological, and mechanical properties of soil [6]. However, the diverse characteristics of biochar and soil make it challenging to generalize its effects on soil engineering properties [7]. Various studies have explored the impact of biochar on soil properties. Research by Bian et al. [8] explored the effects of biochar on soils with high moisture content, revealing its potential for improving geotechnical properties. Their findings indicate that biochar-treated soil exhibits characteristics that make it particularly suitable for applications in soil reclamation or as a filler in landfill operations. Chen et al. [9] conducted a study focused on the impact of freeze-thaw cycles on the saturation permeability of clay soils and the role of biochar as an eco-friendly amendment. Their results suggest that biochar can effectively reduce saturation permeability in cold environments, thereby enhancing the stability of geo-environmental structures under such conditions. Further investigation by Manahiloh et al. [10] into the behavior of fat clay, known for its susceptibility to liquefaction, demonstrated that the incorporation of biochar led to a reduction in the maximum dry unit weight and an increase in optimal moisture content. This adjustment in soil properties ultimately results in decreased compressibility, highlighting biochar's effectiveness in mitigating issues associated with problematic soils. Yadav and Bag [11] found that incorporating bamboo biochar into low plasticity clay (CL) and silty sand (SM) altered moisture content and reduced soil compressibility and relative density. Unconfined compressive strength (UCS) in CL soil initially increased with up to 2% biochar addition, then decreased, while in SM soil, UCS consistently decreased. Hussain and Ravi [12] conducted a study to evaluate how incorporating biochar into soil affects its shear strength and bearing capacity, specifically for use in embankment construction. Their findings demonstrate that adding biochar leads to improvements in key geotechnical parameters: both cohesion (c) and the angle of internal friction (ϕ), which are critical measures of shear strength, are significantly enhanced. Additionally, the soil's load-bearing capacity is increased, while its dry unit weight is reduced, suggesting a favorable modification of the soil's structural properties for embankment applications. Wan et al [13] investigated biochar's effect on the permeability and physical properties of compacted silty clay, noting an initial increase followed by a decrease in permeability. They also observed that smaller biochar particles effectively reduced the permeability coefficient, with 5% biochar being optimal for soil amendment. Other research, such as that by Soundara et al [5], demonstrated that adding biochar to soil decreased compaction and cohesion but increased the friction angle, which benefits landfill cover slope stability. Hussain et al [14] explored how biochar affects soil water retention capabilities. They concluded that biochar addition significantly enhances the soil's ability to retain water. This enhancement, however, is influenced by various factors, including the type of raw material used for biochar production, the temperature at which pyrolysis occurs, the particle size of the biochar, the type of soil, and the sample density. Ganesan et al [15] investigated the impact of biochar pyrolysis temperature on soil properties, particularly focusing on a clayey sand (SC) soil. They compared the effects of biochar produced at two different temperatures, 350°C and 550°C, and found that a 10% biochar addition at 350°C was most effective for improving soil properties. Their findings suggest that careful control of the pyrolysis temperature is crucial when using biochar to enhance the properties of landfill cover soils. Zhang et al [16] concluded that higher biochar content reduces soil compressibility and influences settlement under pressure, with fine biochar being more effective than coarse. Research by Jyoti Bora et al [17] has shown that the impact of biochar on uniaxial strength depends significantly on the type of biochar used. Sun et al [6] focused on using biochar to improve hydraulic conductivity in landfill cover clay, while Zong et al [18] found that biochar reduces soil cohesion and enhances its internal friction angle. Xu et al [2] observed that biochar addition increases soil shear strength, decreases cohesion, and reduces surface cracks. Reddy et al [19] found that biochar enhances hydraulic conductivity, reduces soil compressibility, and significantly increases shear strength.

Despite significant advancements in understanding biochar's influence on soil properties, encompassing aspects like hydraulic conductivity, shear strength, swelling behavior, and uniaxial compressive strength, comprehensive conclusions are hampered by the diverse and complex nature of soil systems across varying environmental and geological settings. In this research, the type of biochar and its pyrolysis temperature were selected based on previous studies, such as Ganesan et al. [15], to create more optimal conditions. While prior studies, including those by Hussain and Ravi [12], Soundara et al. [5], Zong et al. [18], Xu et al. [2], and Reddy et al. [19], have measured residual shear strength, they often faced limitations with the direct shear test method due to device movement. This study addresses these limitations by employing a more accurate method to measure residual shear stress, thereby improving on past research. Additionally, while most related studies have focused on specific parameters of soil behavior under the influence of biochar, this research provides a comprehensive evaluation of multiple geotechnical parameters of fine-grained soil modified with biochar. This holistic approach allows for better correlation between various parameters, enabling a more informed decision about the suitability of biochar for use in landfill final covers. Furthermore, this study explores the use of high percentages of biochar for soil amendment, whereas most previous research has focused on lower percentages (up to 10%). This variability underscores the need for region-specific investigations. This study focuses on the fine soils of Ahvaz city, aiming to evaluate their potential application in landfill final covers. Employing rigorous laboratory testing methods, the research systematically examines the soil's characteristics, providing detailed analyses and insights. These findings will not only contribute to the local understanding of biochar's effectiveness in soil enhancement but also pave the way for future research initiatives tailored to optimize biochar use in diverse environmental contexts.

2. Materials and Methods

2.1. Materials

In this study, the fine soil from Ahvaz, the capital of Khuzestan province, was used. Ahvaz, situated at an elevation of 12-18 meters above sea level in the Khuzestan plain, is characterized by diverse soil layers ranging from fine-grained, low-permeability materials to sandy soils. The sediments in this area predominantly consist of clays or layered soils, with occasional layers of fine sand exhibiting low permeability. Geologically, Ahvaz is located on Quaternary deposits composed mainly of clastic and alluvial materials. To determine the basic properties of the soil, various tests were performed, including hydrometric tests, Atterberg limit tests, specific gravity determination, and soil compaction tests.

Biochar was produced by the pyrolysis of branches and leaves of trees in a rotary kiln at a temperature of 350°C to improve the geotechnical and hydraulic properties of the soil (Figure 1). This biochar, with an initial moisture content of 2% and a pH of 8, was utilized in the study. The pH of the soil was measured using the saturated paste method in accordance with ASTM D 4972 standards, revealing a pH of 7.2. Both the soil and biochar were found to be nearly neutral in pH, indicating a close alignment in their acidity or alkalinity levels.

Figure 1: Biochar particles after manual crushing and sieving through a No. 40 sieve

2.2 Sampling Methods and Measurements

To prepare samples for the various tests in this research, the biochar was initially crushed manually using a weight and then passed through a No. 40 sieve. The soil was oven-dried to minimize the impact of initial moisture on the test results. The dried soil and sieved biochar were thoroughly mixed in proportions of 0%, 7%, 12%, and 20% by weight of soil. To maintain sample integrity and prevent moisture loss, the remaining biochar and clay were stored in sealed plastic bags. To prepare all the samples, after thoroughly mixing the soil and biochar using palette knives, 18% water by weight was added to each sample. According to the test procedure outlined in Section 2.3, the samples were manually compacted. All tests were performed in accordance with the relevant standards.

2.3 Methodology

First, a hydrometer analysis was conducted on the fine soil, which had been passed through a No. 10 sieve, following the ASTM D7928-21 standard. Subsequently, the Atterberg limit tests were performed according to ASTM D4318-18 to determine the plasticity characteristics of the soil. The specific gravity of the soil was measured using the ASTM D854-14 standard to estimate its density. For soil compaction parameters, including optimal moisture content and maximum dry density, the modified Proctor test was performed according to ASTM D1557-21. To evaluate soil consolidation properties, the consolidation test was carried out following ASTM D2435/D2435M-11. Samples were compacted at an 18% moisture content in three equal layers to achieve consistent density. These samples were then subjected to incremental loading with weights of 0.5, 1, 2, 4, 8, and 16 kg, and measurements were taken after 24 hours. For assessing the residual shear strength in highly consolidated cohesive soils, the direct shear test was performed in accordance with ASTM D5080-12. This test focused on soils containing planar clay minerals, which develop significant shear displacement along primary planes, as described by Terzaghi et al [20]. During testing, the cutting machine was set to reset every 5.6 mm to ensure complete sample shearing. Samples for the direct shear test were compacted at 18% moisture in three equal layers within the mold, then saturated and consolidated under stresses of 70, 100, and 140 kPa for 24 hours. Finally, a loading rate of 0.05 mm/min was selected for the slow shear test, similar to the methodology used by Askarani and Pakbaz [21]. The unconfined compressive strength of the soil was determined using a uniaxial compression test in line with ASTM D2166-10. This test was performed on various samples: the original soil without biochar, soil containing 7% biochar (soil+0.07bc), soil with 12% biochar (soil+0.12bc), and soil with 20% biochar (soil+0.2bc). The controlled strain method was employed, and for sample preparation, each was compacted in three equal-weight layers at 18% moisture content. Figure 2 shows the prepared samples prior to testing.The permeability test was conducted to assess the hydraulic conductivity of water through the soil. Two types of cells were used in this experiment: rigid wall and flexible wall. For determining the permeability of clay, the falling head permeability test was performed using the rigid wall setup, following the ASTM D5333-92 standard. This test utilized a rigid wall cell with a height of 70 mm and an internal diameter of 3.2 mm. Initially, the samples were saturated before taking measurements. To evaluate the impact of biochar on surface cracks in the soil, qualitative samples were prepared. These samples were placed in rectangular aluminum containers measuring 30 cm in length and 15 cm in width. For this experiment, one sample of the original clay and another sample of clay mixed with 7% biochar were prepared, as shown in Figure 3. The samples were stored at room temperature for three months, after which the results were documented based on visual observations.

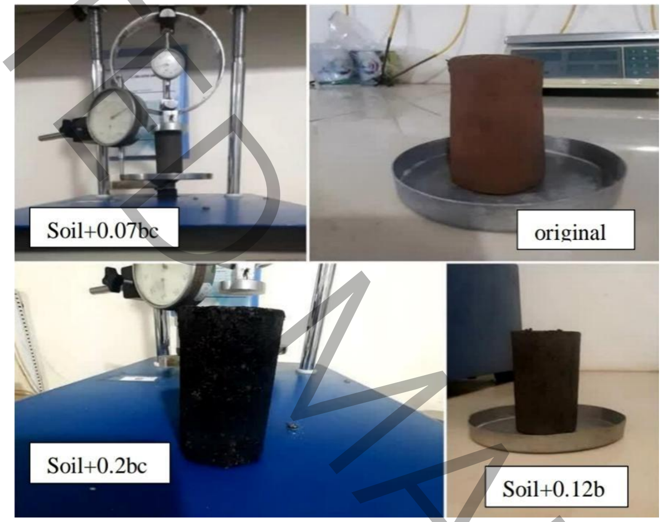


Figure 2: Initial preparation of uniaxial test samples

Figure 3: Cracking samples on the first day (Right image: original soil; Left image: soil with 0.07% biochar added).

3. Results and Discussion

This study investigates the effects of biochar incorporation on the geotechnical properties of the fine soil prevalent in Ahvaz city. The ensuing sections offer an in-depth analysis of the experimental findings, elucidating how biochar influences various soil characteristics. By examining these test results, this study provides a comprehensive understanding of biochar's role in enhancing soil performance, particularly in the context of its application for landfill cover systems in this specific region. This discussion will highlight the critical implications of biochar amendment on soil behavior, offering insights into its potential benefits and practical applications in geotechnical engineering.

3.1 Atterberg Limits and Specific Gravity Tests

According to the gradation analysis, including hydrometer and Atterberg limits tests, the soil is classified as CL-Lean clay. Atterberg limits graph shown in Figure 4. The Atterberg limits tests showed that adding biochar to the soil samples increased the liquid limit (LL), plastic limit (PL), and plasticity index (PI). These findings were observed in samples with no biochar (original), and those with 7% biochar (0.07bc), 12% biochar (0.12bc), and 20% biochar (0.2bc). The observed increase in the Atterberg limits aligns with Yadav and Bag's research on clay soils [11]. However, their study used lower biochar percentages (0%, 1%, 2%, 3.5%, and 5%) compared to the present study.

Figure 4 shows that for the original soil, the LL and PL were recorded at 41% and 23%, respectively. However, with the incorporation of 20% biochar, these limits rose to 57% and 31%, reflecting a substantial increase in the soil's capacity to retain moisture and remain plastic under varying conditions. These changes can be attributed to biochar's high water retention capacity and its porous structure, which modifies the moisture interaction within the soil matrix.

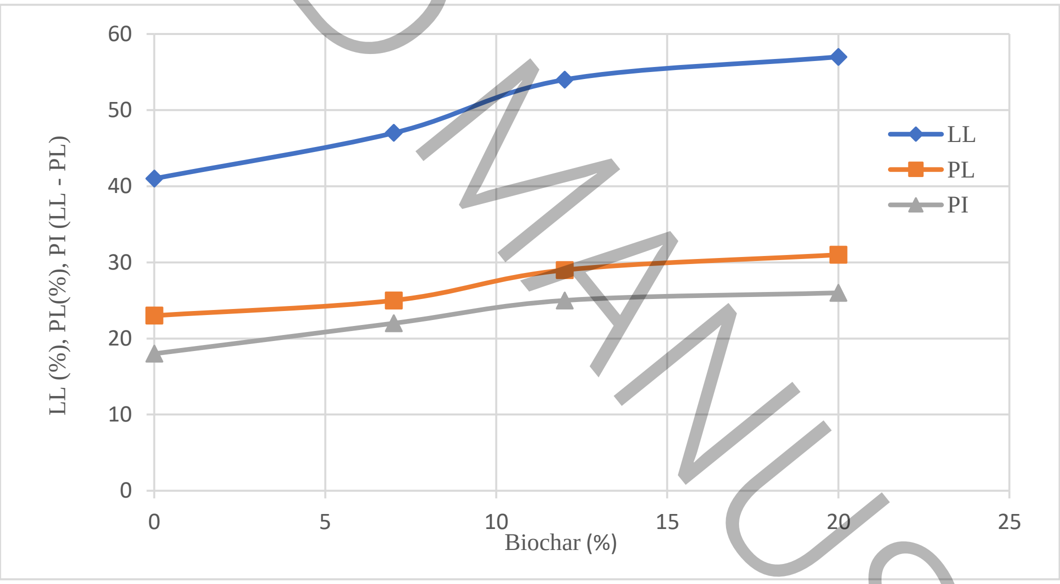


Figure 4: Atterberg limits of the soil

The results of the specific gravity (Gs) tests are presented in Table 1, while the hydrometer analysis is depicted in Figure 5. The Gs of untreated soil is recorded at 2.65. However, with increasing biochar content, a notable decrease in Gs is observed—from 2.65 for the untreated soil to 2.18 for soil amended with 20% biochar. This reduction can be attributed to the inherently lower density of biochar compared to the mineral constituents of the soil. Similar trends have been documented by Blanco-Canqui et al. [22] and Jien et al. [23] in various soil types, underscoring biochar's effectiveness in reducing soil density. This characteristic enhances the soil's flexibility and suggests its suitability for applications in dynamic environments such as landfill cover systems.

Table 1: Gs values of different samples.

Parameter	original	0.07bc	0.12bc	0.2bc
Gs	2.65	2.48	2.36	2.18

3.2 Compaction Characteristics and Unconfined Compressive Strength (UCS)

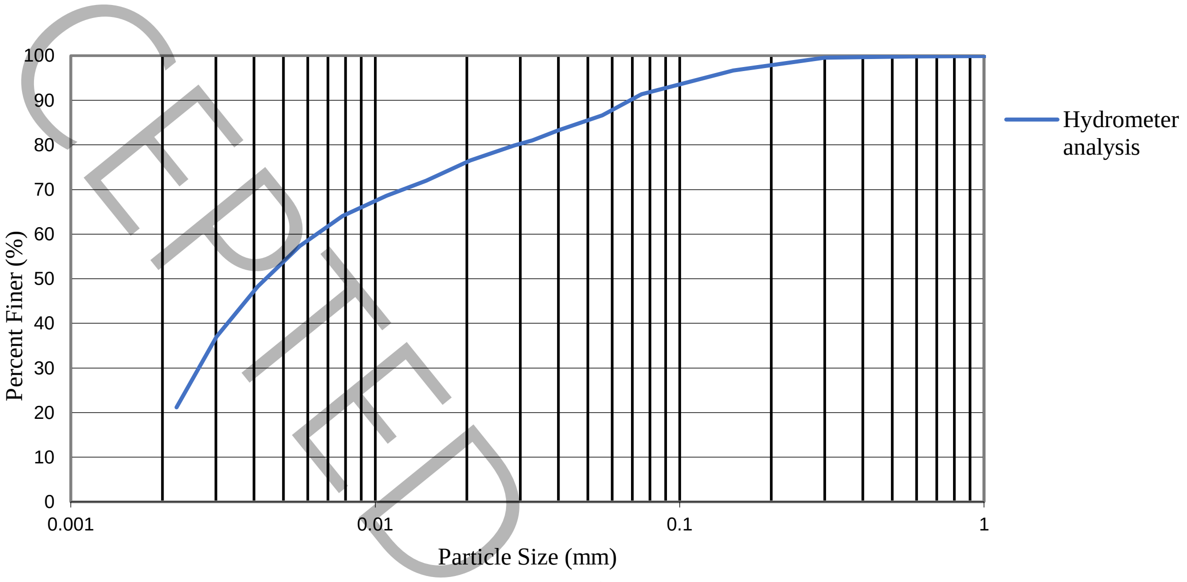
The laboratory compaction test was conducted using the modified effort method to assess the soil's compaction properties. According to the standard modified effort test, the virgin soil achieved an optimum moisture content of 17.45% and a maximum dry unit weight of 1.81 grams per cubic centimeter (g/cm³). Figure 6 illustrates the graphical representation of these test results. The uniaxial compression tests conducted on soil samples with varying biochar content revealed a progressive decrease in UCS. Specifically, UCS declined by 7%, 30%, and 72% as the biochar content increased. These results indicate that higher biochar additions reduce the soil's cohesion and overall strength. This reduction is likely due to the dilution effect of biochar, which, despite enhancing certain soil properties, reduces the cohesive forces and load-bearing capacity of the soil matrix. The UCS for untreated soil was 134.4 kPa, while the UCS for soil with 20% biochar dropped to 59.82kPa. This reduction in compressive strength can be attributed to the decreased soil cohesion due to biochar's low density and weak bonding properties. Biochar particles, by replacing soil grains, introduce more voids and reduce the overall interparticle friction, leading to lower resistance to compressive loads.

The reduction in UCS with increasing biochar content can be primarily attributed to the decreased soil cohesion due to biochar's low density and weak bonding properties. As biochar particles replace soil grains, they introduce more voids and reduce the overall interparticle friction, leading to lower resistance to compressive loads. This phenomenon is supported by Baiamonte et al. [24], who observed similar reductions in UCS in biochar-amended sandy loam soils**.** While Jyoti Bora et al. [17] reported an increase in uniaxial strength for silty sand (SM), which enhances ductility, Williams, Latifi et al. [25] demonstrated that for clay soils, uniaxial strength increases with biochar additions up to 10%, followed by a decline—similar to the findings of this study. However, differences in biochar type, particle size, and clay properties must be considered when drawing comparisons between these studies. Yadav and Bag [11] also observed that for low-plasticity clay (CL), the UCS first increased and then decreased at biochar percentages of 0%, 1%, 2%, 3.5%, and 5%, which is consistent with the results presented here. In addition, Reddy et al. [19] reported that biochar exhibits nonlinear compressibility behavior, with lower initial settlement compared to silty clay under incremental loads, and undergoes secondary consolidation at higher loads due to its brittle nature and porous structure. This is consistent with our findings, where biochar reduced unconfined compressive strength (UCS) but improved shear strength. Similar to our results, Reddy et al. highlighted that biochar's porous structure can reduce soil cohesion while enhancing overall stability and long-term performance, particularly in settlement control.

To mitigate this reduction in strength, future research could investigate the synergy between biochar and other stabilizing agents, such as lime or cement. These additives might enhance the compressive strength while preserving biochar's environmental benefits. Furthermore, fine-tuning the particle size distribution and application rates of biochar could offer a strategic approach to optimizing soil stabilization. This dual approach could balance the mechanical and ecological advantages of biochar in geotechnical applications.

Additionally, the plasticity of the soil decreases as biochar content increases. These test outcomes are depicted in Figure (7), while Figure (8) shows images of the samples after failure.

According to the uniaxial test graphs presented in Figure 7, the deformation modulus (E50) for samples with 0%, 7%, 12%, and 20% biochar content is 17.55, 14.76, 14.02, and 13.63 Kg/cm^3, respectively, showing an increase in hardness after the addition of biochar. Additionally, the area under the curve has decreased as the biochar content increases, indicating greater brittleness in the samples. Thus, it can be concluded that as biochar content increases, the plasticity of the samples decreases, making them more brittle and rigid, yet harder.



Gravel%	Sand%	Fine%	<2µm	Silt%
0.00	8.64	91.36	21.18	70.18

Figure 5: hydrometer analysis graph of the soil

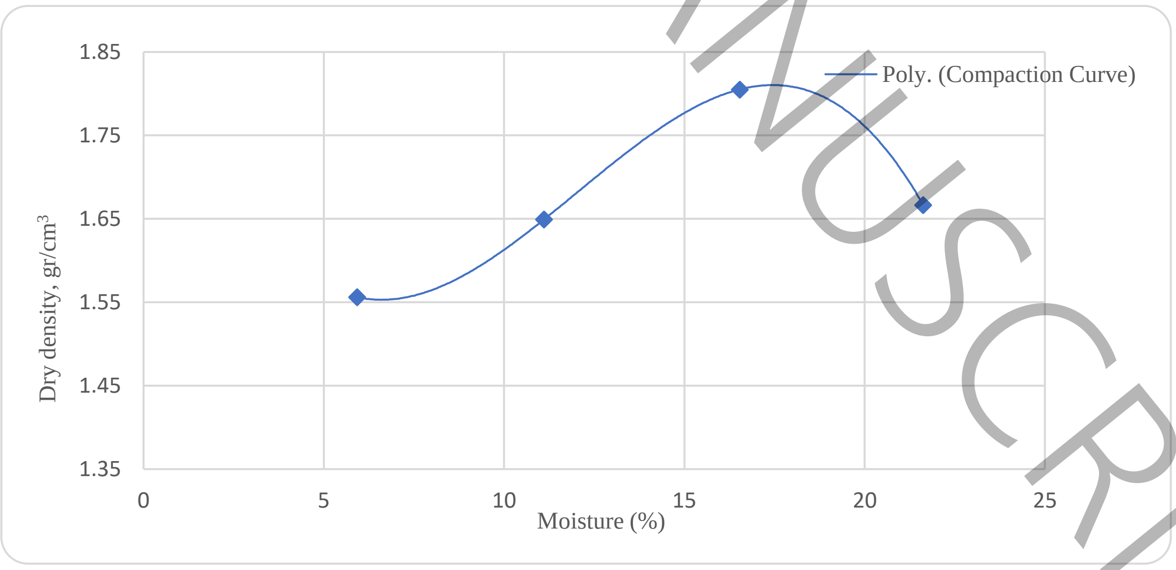


Figure 6: Compaction curve of soil utilizing modified compaction method

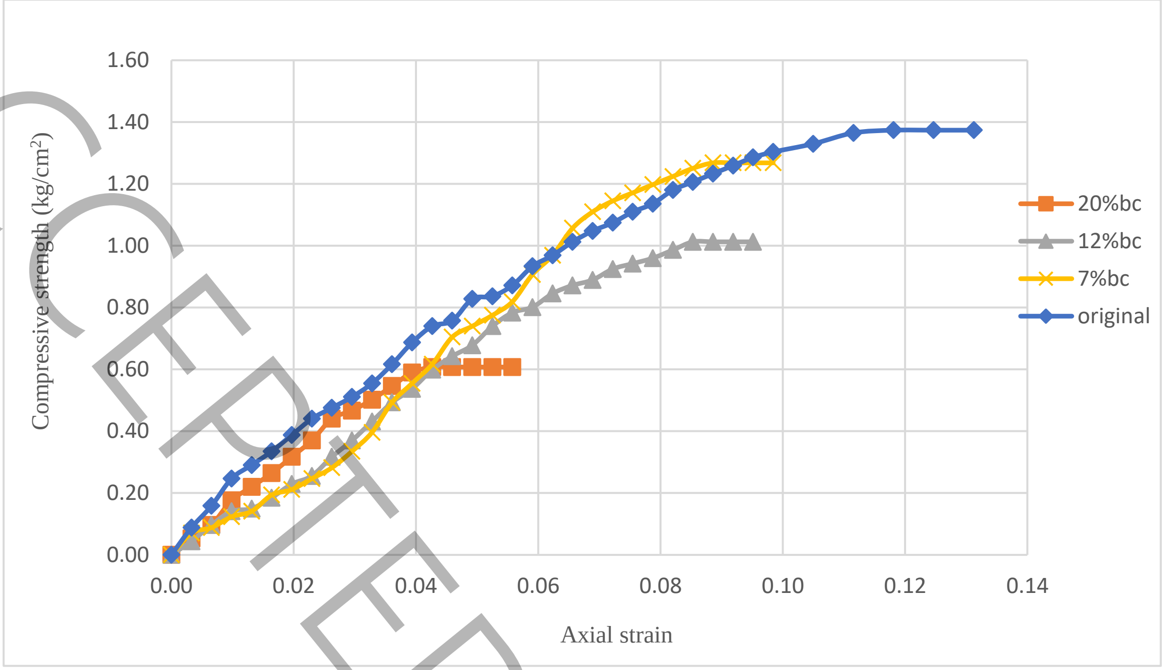


Figure 7: Results of compressive strength tests

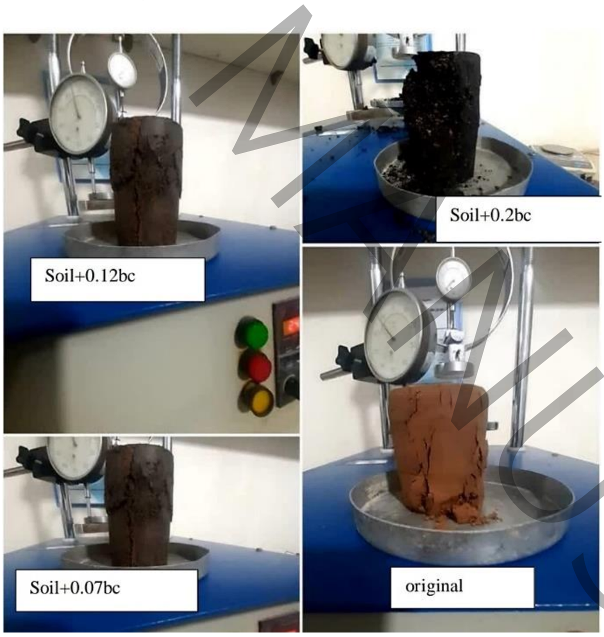


Figure 8: Samples of uniaxial compressive strength post-failure

3.3 Shear Strength and Friction Angle

In the residual state of soil, shearing continues until residual cohesion effectively drops to zero, making the residual friction angle (φ_r) the criterion for assessing soil resistance. Figure 9 illustrates the direct shear test results, with detailed data provided in Table 2. As indicated in Table 2, the incorporation of biochar into the soil markedly increases the internal friction angle (φ). Specifically, the internal friction angle rose by 23%, 70%, and 58% with biochar additions of 7%, 12%, and 20%, respectively. This enhancement is notable, with the internal friction angle increasing from 14° in untreated soil to 35° in soil containing 20% biochar. These findings demonstrate a significant improvement in the soil's internal friction angle due to biochar addition, consistent with the studies by Liu et al. [26] and Hussain and Ravi

[12]on clay soils. The increase in the internal friction angle suggests that biochar particles improve soil structure and interparticle interactions, enhancing the soil's overall resistance to shear forces. This improvement in geotechnical properties underscores biochar's potential as a valuable amendment in enhancing the stability and performance of soils, especially in applications requiring high shear strength**.** Studies by Hussain and Ravi [12], Soundara et al. [5], Zong et al. [18], and Reddy et al. [19] demonstrate improvements in shear strength with different biochar percentages in various soil types. However, none of these works investigated shear strength in the residual state.

Biochar's impact on the internal friction angle can be linked to its high surface roughness and ability to enhance interparticle contact within the soil. This increased friction is beneficial for improving the soil's shear resistance, making biochar-amended soils more stable under lateral loads. The findings align with Xu et al. [2] , who reported similar increases in the friction angle in clayey soils with biochar addition. However, managing the trade-offs between increased friction angle and other properties like permeability and compressive strength is crucial. Techniques like controlled compaction and the use of biochar blends could be explored to optimize these properties for practical applications. Notably, prior to this study, the influence of biochar on soil shear strength in the residual state had not been quantified. However, the increased friction angle comes with the challenge of managing the soil's compressive strength and permeability. Practical applications in landfill covers must consider these trade-offs to ensure overall system stability and performance. Techniques like controlled compaction and the use of biochar blends could be explored to optimize these properties.

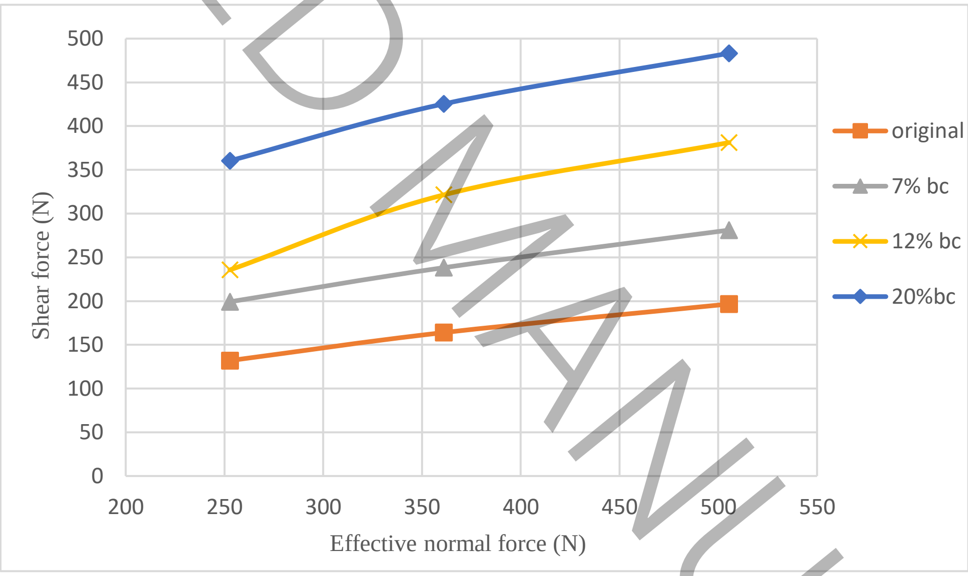


Figure 9: Shear strength curves

Table 2: Results of the direct shear test

soil	C_r	φ_r
	0	14
Soil +0.07bc	0	18
Soil +0.12bc	0	30
Soil +0.20bc	0	26

3.4 Odeometric consolidation results and Permeability

Figure 10 illustrates the relationship between the void ratio (e) and logarithmic pressure. The void ratio, defined as the ratio of the volume of voids to the volume of solid particles within the soil, directly correlates with soil porosity. As depicted in the graph, an increase in biochar content leads to a higher void ratio, indicating enhanced soil porosity. This increase in porosity is due to the biochar particles introducing additional void spaces within the soil matrix, thereby reducing the overall density and increasing the volume of voids relative to the solid components. The increase in soil porosity can be attributed to the low specific density of biochar, which is approximately 0.3 g/cm³. As shown in Table 3, the addition of biochar results in higher values for both the compressibility index (Cc) and the swelling index (Cs). This phenomenon is likely influenced by biochar's high water absorption capacity and the consequent increase in sample porosity as biochar content increases. Moreover, the settlement of the samples tends to increase with higher percentages of biochar, while their compressibility decreases. Previous research by Zhang et al. [27] similarly demonstrated that the swelling characteristics of clay soils are enhanced with the addition of small amounts of biochar.

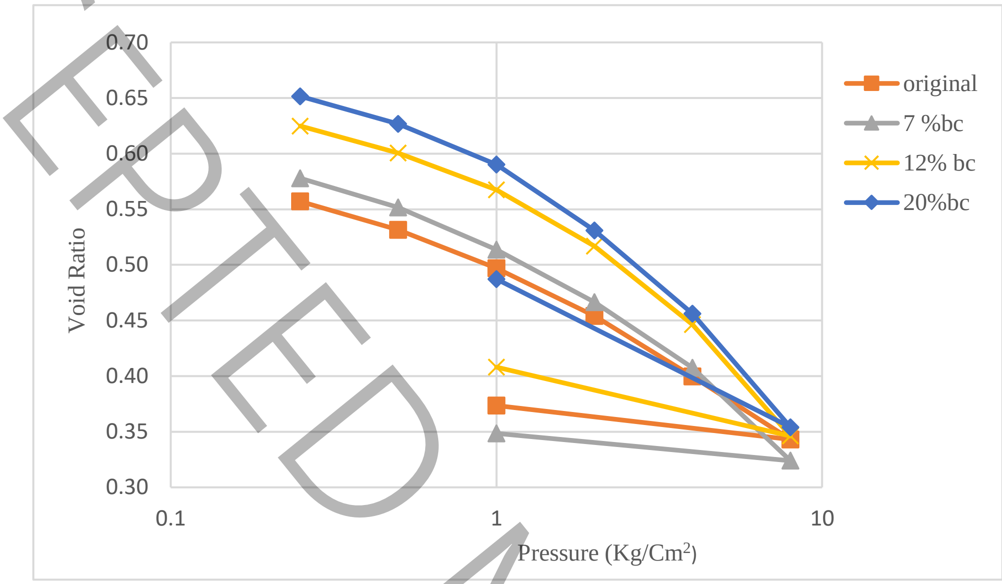


Figure 10: Relationship between void ratio and logarithmic pressure

Table 3: Compression index (Cc) and swelling index (Cs) from the consolidation test

Parameter	**Original**	**Soil+ 0.07bc**	**Soil+ 0.12bc**	**Soil+ 0.2bc**
Cc	0.189	0.278	0.333	0.339
Cs	0.034	0.027	0.068	0.147

The results from the falling head permeability test, conducted on various soil samples including untreated soil (original), soil with 7% biochar (Soil +0.07bc), soil with 12% biochar (Soil +0.12bc), and soil with 20% biochar (Soil +0.20bc), indicate a clear relationship between the permeability and the addition of biochar. Specifically, as the biochar content in the soil increases, the permeability of the samples also increases. These findings are detailed in Table (4).

Table 4: The results of the falling head permeability test

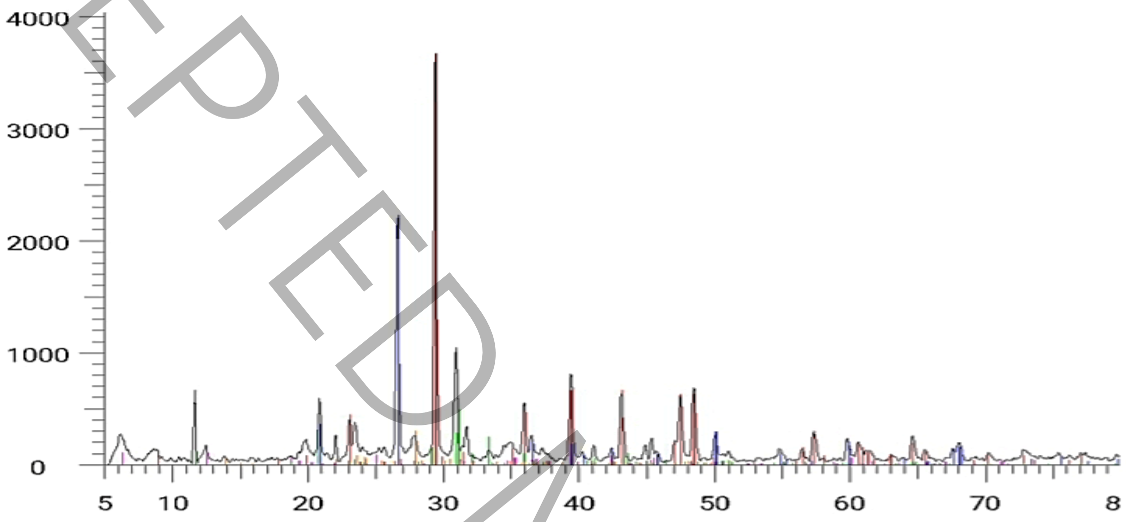
Sample name	**Permeability rate (*cm / s*)**
Original	2.25×10^{-8}
Soil+ 0.07bc	5.8×10^{-8}
Soil+ 0.12bc	6.33×10^{-7}
Soil+0.2bc	3.21×10^{-7}

According to this table, the hydraulic conductivity for untreated soil was 2.25×10^{-8} cm/s, which increased to 3.21×10^{-7} m/s for soil with 20% biochar. This increase in permeability is due to biochar's porous nature and its tendency to enhance soil porosity, facilitating faster water infiltration through the soil matrix. For clay soils, where the particle size is equal to or smaller than that of the biochar, biochar becomes part of the soil's structural matrix. This integration leads to an increase in soil porosity and, consequently, higher saturated hydraulic conductivity. Conversely, in materials with larger particle sizes, such as sand or organic soils, biochar acts as a pore filler, reducing soil porosity and lowering the saturated hydraulic conductivity of the mixed soils (Sun et al. [3], Sun et al. [6]; Kumar and Kumari [28]). Additionally, Wan et al. [13] noted that the type and particle size of biochar influence soil permeability. As a result, permeability tests on clay with low biochar percentages show an initial decrease, followed by an increase. These results align with research conducted by Lim et al [29], which observed increased permeability in clay samples with biochar addition. This research supports these observations, showing that biochar-amended soils exhibited higher permeability rates, which could be beneficial for applications requiring rapid drainage but might pose challenges for barrier systems. Future research should focus on balancing these properties, perhaps through the integration of biochar with low-permeability materials or adjusting the application rates to maintain desired hydraulic performance. However, contrasting results were reported by Yadav and Bag [11], who found that adding biochar to sandy soils actually decreased soil permeability. According to the qualitative test results, the quantity and length of surface cracks in the samples over a 90-day period substantially decrease as the biochar content increases compared to the untreated soil, as shown in Figure (11). Biochar's effectiveness in reducing surface cracking is likely due to its water retention capacity and the resulting increase in soil moisture content, which helps to maintain soil cohesion and flexibility. This property is particularly beneficial for landfill covers exposed to varying moisture conditions and can significantly enhance their durability and lifespan. The reduction in surface cracking observed in this study aligns with findings by Cheng et al [30], who noted that biochar amendments led to fewer and less severe cracks in agricultural soils. These insights suggest that biochar could play a vital role in maintaining the structural integrity of landfill covers, especially in arid and semi-arid regions where soil desiccation is a common issue.

Figure 11: Results of crack formation over 90 days (Right image: original soil; Left image: soil with 0.07% biochar added).

Figure 12 presents the XRD test results, identifying calcite (50.9%) and quartz (30.9%) as the primary compounds in the soil, which are critical for its mineralogical composition and engineering properties. The presence of these minerals suggests inherent stability and resilience to environmental changes. Secondary minerals such as dolomite, clinochlore, muscovite, gypsum, and albite also contribute to the soil's stability. The interaction of these minerals with biochar influences the soil's physical and mechanical behavior, enhancing its geotechnical performance. The addition of biochar modifies the mineral matrix, which impacts key properties such as soil strength and permeability. The addition of biochar modifies the mineral matrix, which impacts key properties such as soil strength and permeability.

Additionally, Figures 13, 14, 15, and 16 present the SEM test results (magnified at 2 μm), demonstrating a significant increase in porosity with biochar content of up to 12%. The SEM images reveal the enlargement and formation of interconnected voids within the soil structure, which corresponds to a measurable decrease in sample strength and increased permeability, aligning with results from uniaxial and permeability tests. Specifically, the visible void spaces in the SEM images highlight how biochar particles create a more porous network. This microstructural change explains the enhanced water movement through the soil and its weakened mechanical strength. These observations provide a clear link between the increased porosity due to higher biochar content and the observed changes in permeability and soil strength at the macroscopic level. Furthermore, this is consistent with findings by Kumar and Kumari [28], who documented similar microstructural transformations in biochar-amended soils. This analysis of SEM images underscores the importance of understanding how biochar influences the microstructure of soils, leading to significant changes in their hydraulic and mechanical behavior.



Line Color	Compound Name	Formula	PDF Number	score
🟥	Calcite, syn	$CaCO_3$	05-0586	50.9
🟦	Quartz, syn	SiO_2	46-1045	30.9
🟩	Dolomite	$CaMg(CO3)_2$	36-0426	3.9
🟪	Clinochlore-ITMIIb-4 RG	$Mg_5Al\ (Si,Al)_4O_{10}(OH)_8$	46-1322	1.6
🟥	Muscovite	$H_2KAl_3(SiO_4)_3$	01-1098	1.9
🟧	Gypsum	$CaSO_4{\cdot}2H_2O$	21-0816	6.8
🟩	Albite, ordered	$NaAlSi_3O_8$	09-0466	4.1

Figure 12: Results of the XRD test

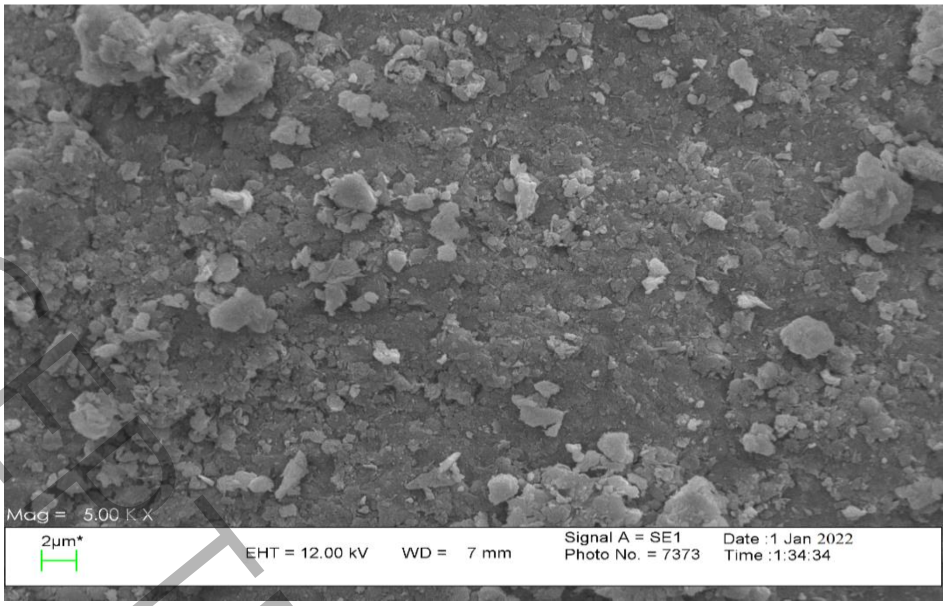


Figure 13: SEM test results on powder sample original

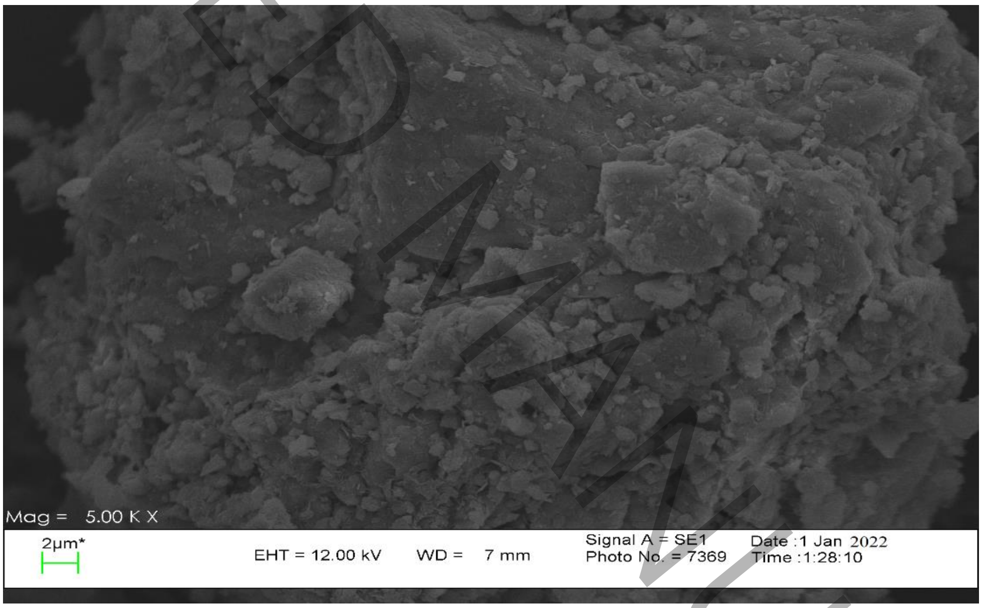


Figure 14: SEM test results on powder sample soil+0.07bc

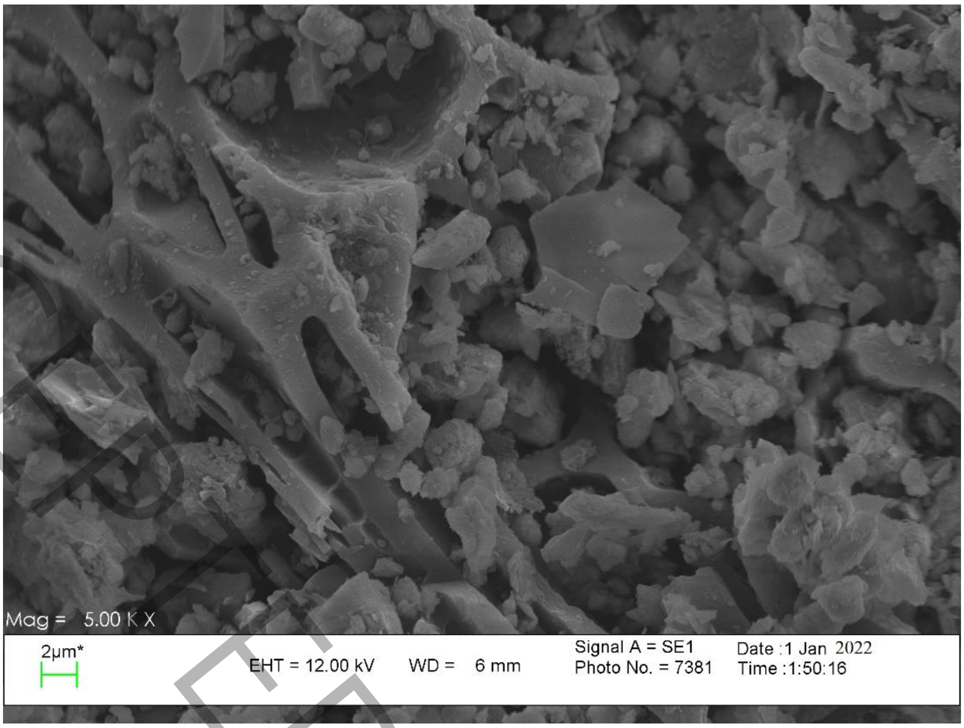


Figure 15: SEM test results on powder sample soil+0.12bc

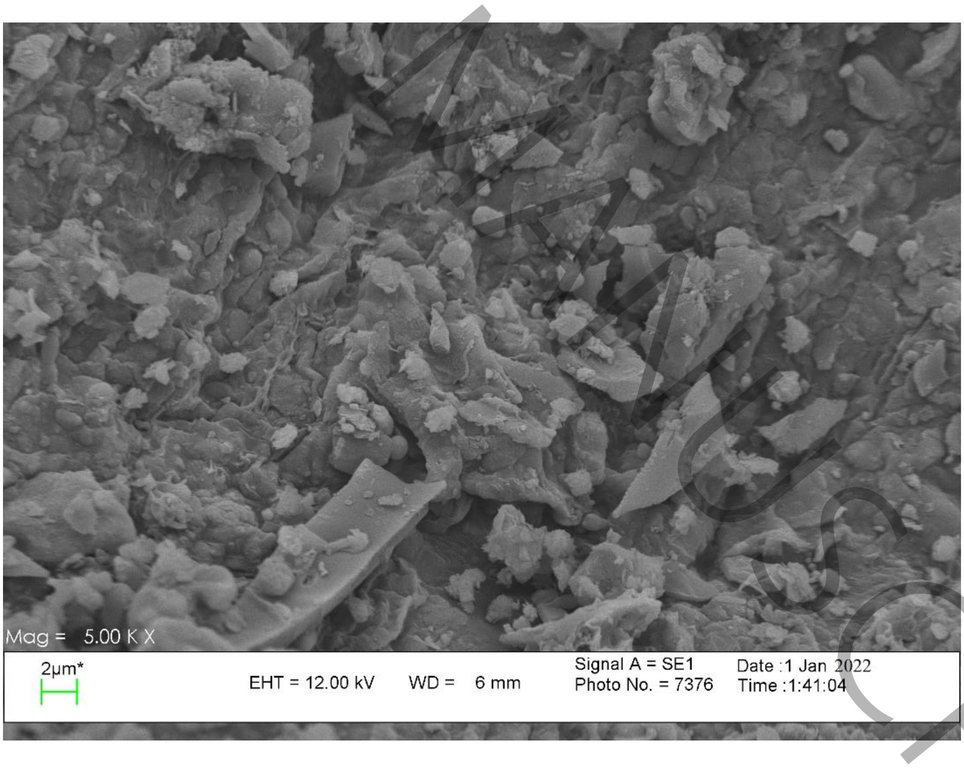


Figure 15: SEM test results on powder sample soil+0.2bc

4. Conclusion

This study examined the effects of biochar on the geotechnical properties of fine soil in Ahvaz, with a focus on its potential use in landfill cover systems. The findings indicate that while higher biochar percentages improve the soil’s shear strength, they also increase permeability and reduce unconfined compressive strength. Based on a comprehensive analysis of all geotechnical parameters, incorporating biochar at a 7% ratio appears to offer the best balance between enhanced strength and minimized negative impacts, making it the most suitable option for practical applications in landfill cover.Key findings from the research are summarizedblow:

1. Soil Composition and Limits: The soil analyzed is silty clay. The addition of biochar significantly raises the soil’s liquid limit, plastic limit, and plasticity index.

2. Unconfined Compressive Strength: Introducing biochar to the soil reduces its unconfined compressive strength. This is because the cohesion of the soil samples diminishes with higher biochar content, causing them to fracture sooner.

3. Shear Strength and Soil Properties: The direct shear test results show that the soil's internal friction angle in the residual state increases with biochar additions of 0%, 7%, 12%, and 20% by weight. Additionally, biochar increases the compression coefficient (Cc) and swelling coefficient (Cs) due to its high-water absorption and porosity.

4. Hydraulic Conductivity: Hydraulic conductivity also rises with higher biochar percentages. Thus, using biochar in concentrations above 12% is not advisable for landfill cover systems due to its impact on hydraulic conductivity.

In summary, while biochar offers some benefits, its application in soil should be carefully balanced to avoid adverse effects. Future research could explore enhancing specific geotechnical properties with new, eco-friendly materials like nanoclays and biochar blends. Furthermore, the long-term stability of biochar-stabilized soil samples under aggressive environmental conditions (e.g., wetting-drying cycles) is suggested for future investigation. Additionally, in conjunction with XRD and SEM, it would be beneficial for future studies to consider infrared spectroscopic analysis to deepen insights into clay-biochar interactions.

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Data availability: The data associated with this study will be provided on request.

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