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Research Article

Effect of rice hull biochar as an additive on the shear strength parameters of silty sand

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ABSTRACT.

Silty sand is a common soil type in the Philippines. While it exhibits moderate

bearing capacity, its mechanical properties may not be adequate to support heavier structural loads without additional stabilization. This study investigates the use of rice hull biochar as a stabilizer for silty sand. Rice hull biochar is an emerging soil amendment derived from the pyrolysis of agricultural waste, which contains high amounts of silica and has been shown to influence the physical and mechanical behavior of soils. In this study, soil samples were amended with varying percentages of rice hull biochar (0%, 2%, 5%, 8%, 10%, and 12% by weight) combined with 5% cement. Shear strength was assessed under both drained and undrained conditions through direct shear tests and unconsolidated-undrained triaxial tests, respectively. The results revealed that the addition of rice hull biochar improved the cohesion and internal friction angle of the silty sand, contributing to overall enhancement in shear strength. Statistical analysis indicated that a 10% biochar concentration yielded significant improvements to the shear strength parameters compared to the control soil sample. These findings suggest that rice hull biochar, when used with partial cement, can effectively enhance the geotechnical properties of silty sand.

Keywords: silty sand, rice hull biochar, soil stabilization, shear strength

1. INTRODUCTION

Soil is a fundamental component in civil engineering and geotechnical practices, playing a critical role in determining the mechanical properties and overall behavior of structures, including their stability and strength. The behavior of different soil types varies significantly when subjected to structural loads. Based on geotechnical reports from various sites, silty sand is a common soil type found in the Philippines. Silty sand is predominantly a coarse-grained soil, making it suitable as a construction material. However, careful considerations must be taken when dealing with silty sands as foundation material due to the plasticity and impervious nature of silt. In addition, it generally has lower shear strength and load-bearing capacity than clean sands, especially under saturated conditions. Silty sand, a prevalent soil type in the University of the Philippines Los Baños (UPLB), is susceptible to collapse upon contact with water compared to other soil types due to its lower plasticity [1]. Silty sand has good shearing strength when compacted and saturated and fair workability as a construction material [2]. In comparison, clean sand was listed as having an excellent rating for both shear strength and workability. Furthermore, silty sand contains both cohesive and cohesionless soil particles, making it necessary to quantify both its cohesion and friction angle when evaluating its shear strength and overall mechanical behavior.

Soil stabilization is the process of altering soil to enhance its strength, stability, and suitability for construction projects. Different methods of soil stabilization have been developed and are being utilized. These include mechanical stabilization, compaction, drainage improvements, grouting, and chemical stabilization [3]. Mechanical stabilization techniques physically alter the arrangement of soil particles, such as particle-size distribution and void ratio, while chemical stabilization modifies and adjusts the chemical properties of the soil through additives. While effective in improving the strength of soil, chemical stabilization is less common than mechanical stabilization due to the higher costs involved.

Stabilization through the addition of cement and/or ash is a form of chemical stabilization. The hydration of cement acts as a binder for soil particles, thus increasing the strength and stability of the soil [4]. It is effective in improving soils that have low plasticity indices. The calcium oxide present in cement reacts with the natural moisture present in soil, reducing the moisture content of the soil and producing calcium and hydroxyl ions. Silica and alumina present in soils react with the calcium and hydroxyl ions to form calcium-silicate and calcium-aluminate gels through a process called pozzolanic reaction, which increases the stability and stiffness of soil. Cement hydration also occurs, where tricalcium silicates and dicalcium silicates in cement react with water to produce calcium-silicate-hydrate (C-S-H) gels. These also improve the strength and stiffness of the soil. This process can be further improved by additives high in silica or alumina, as it further promotes the pozzolanic reaction.

Cement production accounts for more than 5% of CO2 emissions in the atmosphere, highlighting the need for finding a more environmentally friendly substitute. Materials rich in amorphous silica may be added to the soil-cement mixture to improve the pozzolanic reaction. Biochar has been shown to be a more sustainable substitute for cement in the production of concrete as it is organic and environmentally benign [5]. It is produced through pyrolysis of biomass, which may be in the form of agricultural residues and byproducts [6].

There have been studies that investigated the effects of biochar on the physical and hydraulic properties of soils, particularly in the field of agriculture. It has been shown to improve the water retention as well as improve the wheat yields in clayey soils, while having no significant effect on the hydraulic conductivity [7]. Blanco-Canqui [8] conducted a comprehensive study to evaluate the effects of biochar on various physical and hydraulic soil properties. It was observed that biochar reduces soil bulk density by 3-31%, enhances soil consistency, and decreases saturated hydraulic conductivity in coarse-grained soils while increasing it in fine-grained soils. It was highlighted that the effects of biochar are more pronounced in sandy soils than in clayey soils.

There have also been efforts to explore the effect of biochar on the mechanical properties of soil. Sadasivam and Reddy [9] evaluated the effect of different waste-wood biochar on the compressibility and shear strength of landfill cover soils. It was observed that amending waste-wood biochar to soil increased the compressibility of the soil. However, an increase in both the cohesion and shear strength of the soil was also noted. This improvement in strength was attributed to the enhanced binding of soil particles, which led to the formation of larger soil aggregates. They further tested the effect of biochar amendment to the slope stability of the soil and obtained higher factors of safety for the biochar amended soils than the soils without amendment. The effect of biochar produced from mesquite, a genus of deep-rooted shrubs and small trees, on the compaction and shear strength of clayey sand was studied [10]. Biochar amendment (5–15% by weight) reduced dry density while increasing cohesion and internal friction angle, likely due to its surface roughness and active functional groups. Undrained shear strength decreased at higher compaction densities but increased at lower ones, showing that initial density strongly influences strength under undrained conditions. Overall, biochar improved shear strength behavior, suggesting potential benefits for bearing capacity improvement and slope stability applications.

Rice hull biochar (RHB) is obtained from the pyrolysis of rice hull. Large production of rice generates a substantial volume of agricultural waste that is underutilized for further uses in the engineering industry, accounting for sustainability considerations. Rice husk biochar has been shown to contain high amounts of SiO2 and thus can be used as a suitable cement replacement in the construction industry [11]. Its viability as a partial cement replacement was studied by observing its effect on the physical, mechanical, microstructural, and radiation shielding properties of ordinary concrete by Mahmoud et al [12]. Results indicated an optimal increase in compressive and tensile strength of concrete at 10% and 15% substitution ratios by cement weight. This shows its effectiveness as a natural pozzolan.

The Philippines is a major rice-producing country. In the Philippines, a total of 2 million metric tons of rice hull waste are being produced annually [13]. This study utilized varying concentrations of RHB (0%, 2%, 5%, 8%, 10%, 12%) and 5% partial cement to improve the strength of silty sand soils. In line with the United Nations Sustainable Development Goals (UN SDGs), this study intends to contribute to the industry, innovation, and infrastructure for sustainable cities and communities. Production of rice hull waste will be allocated efficiently towards sustainable use in the industry.

The objective of this study was to evaluate the effect of RHB on the shear strength parameters of silty sand. Soil samples were prepared with RHB contents of 0%, 2%, 5%, 8%, 10%, and 12% by weight, each combined with a fixed 5% cement content. The shear strength parameters were obtained through direct shear and triaxial tests. In addition, the study aimed to assess the significance of the observed differences and determine the optimal RHB content through statistical analyses.

METHODOLOGY

2.1 Material Procurement and Characterization

Rice hull biochar was produced through the pyrolysis of rice hull. The procured RHB is shown in Figure 1.

Figure 1. Procured RHB

The RHB was subjected to X-ray fluorescence (XRF) analysis. This is a non-destructive method used to identify and quantify the elemental composition of materials. In this technique, samples are irradiated by high-energy primary X-rays, causing atoms in the samples to emit secondary X-rays. The energies of these emissions are measured to identify and quantify the elements present in the samples [14]. The results indicate that the inorganic fraction of the sample is mainly composed of amorphous silica. It must be noted that XRF analysis cannot quantify light elements such as carbon. The concentrations are shown in Table 1.

Table 1. Composition of RHB

Chemical Composition	Concentration (excluding carbon)
SiO_2	96.89%
K	2.39%
Ca	0.40%
Other chemical compounds	0.32%

The soil used for the study was obtained near the New Dormitory Residence Hall within the UPLB. It was subjected to index tests, including particle-size analysis, Atterberg limits tests, and the compaction test in accordance with ASTM standards to determine the soil classification and the optimum moisture content.

Sieve analysis was conducted following ASTM D6913 [15]. Figure 2 shows the particle-size distribution curve. The soil contains 5.12% gravel, 79.60% sand, and 15.28% fine soil particles, indicating a sandy soil with a significant amount of fine soil.

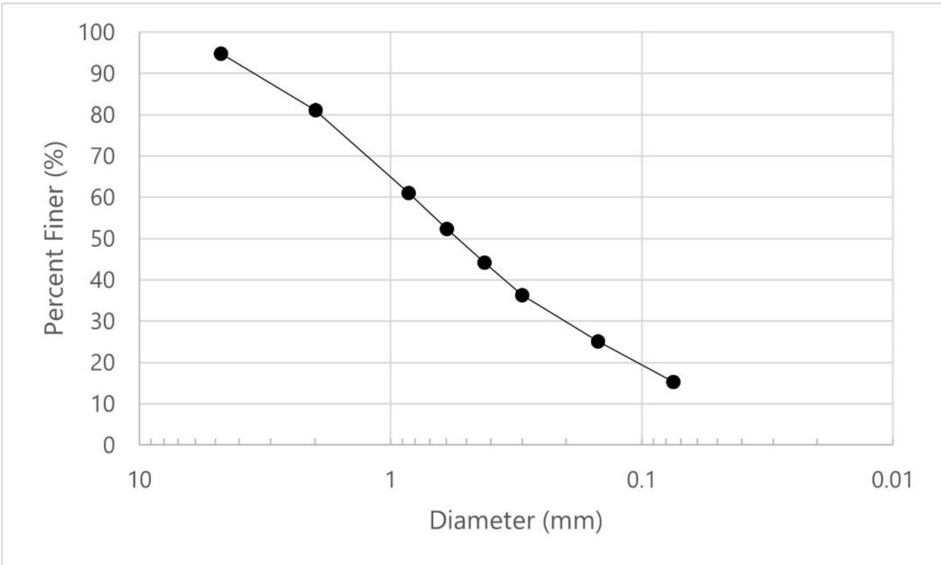

Figure 2. Particle-Size Distribution Curve of Soil

Atterberg limits tests were conducted following ASTM D4318 [16] to determine the liquid limit and the plastic limit. The plasticity index was calculated as the difference between the liquid and plastic limits. Table 2 shows the results of the Atterberg limits test, indicating that the fine particles of the soil are silty in nature.

Table 2. Consistency of procured soil.

Liquid Limit	Plastic Limit	Plasticity Index	A-line Plasticity Index
33.19%	29.50%	3.69%	9.63%

Following ASTM D2487 [17], the soil is classified as silty sand. Lastly, the standard proctor test showed that the soil had an optimum moisture content of 18.24%

Portland Cement Type I with a specific gravity of 3.1 was used, and a constant percentage of 5% was incorporated for every setup in the experiment.

The direct shear testing machine used in the study is the “DIGISHEAR”, a product of CONTROLS, an Italian manufacturer of materials and testing instruments. For triaxial testing, the “TRIAX” Triaxial Load Frame, which is also a product of CONTROLS, was utilized.

2.2 Specimen Preparation

Water equivalent to 18.24% of the weight of the soil was added to simulate the optimum moisture content. The soil was then mixed with 0%, 2%, 5%, 8%, 10%, and 12% RHB, along with the 5% partial cement, based on the dry weight of the soil. For the direct shear test, this mixture was transferred and compacted in shear box molds with a size of 60 mm by 60 mm by 20 mm. Ninety samples were prepared for the direct shear test, corresponding to six concentrations, three applied normal loads, and five trials per set. These were allowed to be cured for 28 days.

For the triaxial test, the mixture was transferred and compacted in a cylindrical mode with a size of 36 mm by 78 mm. Similarly, ninety samples were prepared for the direct shear test corresponding to six concentrations, three confining pressures, and five trials per set. However, only one mold was available for the triaxial test. After compaction, they were extracted before being allowed to cure for 28 days. Table 3 shows the experimental design while Figure 3 shows the prepared specimens being cured for direct shear and triaxial testing.

Table 3. Summary of experimental design

Test	RHB Concentration (%)	Cement Concentration (%)	Stress Variable	Stress Levels (kPa)	Trials	Total Samples
Direct Shear Test	0, 2, 5, 8, 10, 12	5	Normal Stress	27.25, 54.50, 81.75	5	90
Triaxial Test	0, 2, 5, 8, 10, 12	5	Confining Pressure	98, 196, 392	5	90

Figure 3. Prepared specimens being cured for direct shear and triaxial test.

2.3 Direct Shear Test

Direct shear tests were conducted in accordance with ASTM D3080-23 [18]. Normal loads of 10, 20, and 30 kg were applied on the soil samples, equivalent to normal stresses of 27.25 kPa, 54.50 kPa, and 81.75 kPa. A constant shear displacement rate of 1.00 mm/min was applied to the samples. The test was stopped once the proving ring reading reached a maximum value and began to decrease, indicating failure of the soil specimen. The shear stress at failure was obtained by multiplying the proving ring reading by a calibrated conversion factor of 2 N/mm.

The shear stress at failure was plotted against the normal stress and a best-fit line was obtained for each trial. Following the Mohr-Coulomb failure criterion, the y-intercept of the line represents the cohesion of the soil while the inverse tangent of the slope of the line represents the friction angle of the soil. This is shown by Eq. (1)

$$\tau_f = c + \sigma \cdot tan(\phi) \quad (1)$$

Where:

τ_f is the shear stress at failure

c is the cohesion of the soil

σ is the normal stress acting on the shearing plane

ϕ is the friction angle of the soil

2.4 Triaxial Test

Triaxial tests were conducted in accordance with ASTM D2850-23 [19]. To simulate the optimum moisture condition of the soil, the saturation stage was not conducted, and the soil was tested under unsaturated conditions, leading to both cohesion and friction angle being measured by the test. Confining pressures of 98 kPa, 196 kPa, and 392 kPa were applied and the deviator stress was increased until the soil specimen failed. The corresponding Mohr's circles at failure were plotted, and a line tangent to the circles represented the Mohr-Coulomb failure criterion of the soil. Similarly, the cohesion and friction angle were obtained from these lines following Eq. (1).

2.5 Statistical Analysis

One-way Analysis of Variance (ANOVA) was conducted to evaluate whether the results from different concentrations showed significant differences in both the direct shear test and the triaxial test. Statistical significance was set at $p < 0.05$. If the ANOVA indicated significance, a post hoc Tukey's Honestly Significant Difference (HSD) Test was performed to identify the specific group pairs that differed, using the same threshold $p < 0.05$.

RESULTS AND DISCUSSION

3.1 Direct Shear Test Results

Table 4 presents the average shear stress values corresponding to varying concentrations of rice hull biochar at three levels of normal stress: 27.25 kPa, 54.50 kPa, and 81.75 kPa. Figure 4 shows the mean cohesion for each concentration while Figure 5 shows the mean friction angle for each concentration. Standard errors are also shown. For comparison, the friction angle and cohesion of silts and sands range from 26° to 38°, depending on the soil density [20]. In the specimen preparation, the samples were naturally densified by a tamping apparatus, leading to higher values of the friction angle. Furthermore, while cohesion of untreated coarse-grained soils is typically low and ranges from 0kPa to 10kPa, the inclusion of 5% cement introduced cementitious bonding. This modification created an artificial cohesion within the soil-RHB matrix, leading to the higher strength values observed in this study.

Table 4. Average shear stress at failure (kPa) obtained from the direct shear test.

Concentration of RHB	Shear Stress (kPa)		
	$\sigma = 27.25\ kPa$	$\sigma = 54.50\ kPa$	$\sigma = 81.75\ kPa$
0%	27.78	42.11	61.78
2%	30.33	52.56	69.78
5%	31.67	55.44	73.89
8%	35.56	59.89	75.67
10%	40.44	63.78	77.33
12%	42.44	58.67	73.11

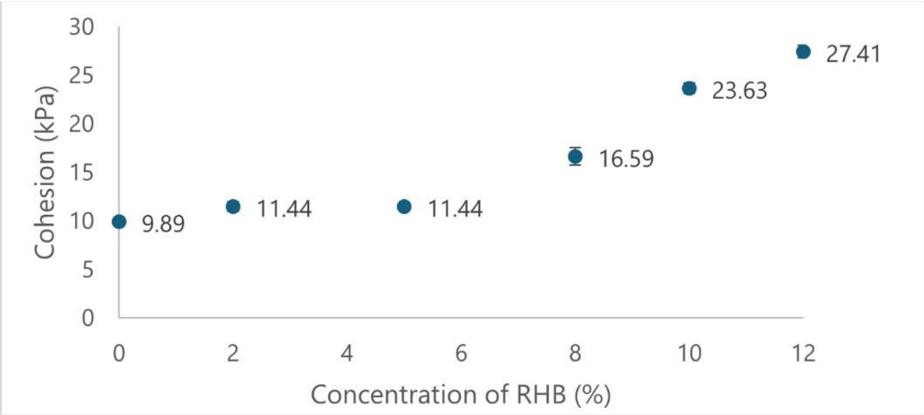

Figure 4. Cohesion obtained from direct shear test for each concentration of RHB

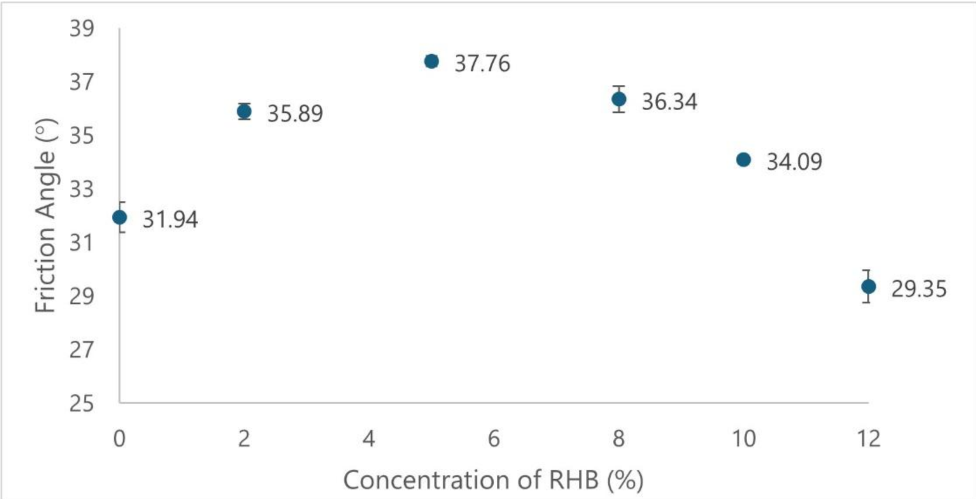

Figure 5. Friction angle obtained from the direct shear test for each concentration of RHB

The results indicate that as the concentration of rice hull biochar increases, the average shear stress generally shows an increasing trend across all normal stress levels, suggesting improved soil resistance to shear forces. Specifically, for the lowest normal stress (27.25 kPa), the average shear stress ranges from 27.78 kPa at 0% biochar concentration to 42.44 kPa at 12% concentration. Similarly, at 54.50 kPa and 81.75 kPa normal stresses, the average shear stress increases from 42.11 kPa to 58.67 kPa and from 61.78 kPa to 73.11 kPa, respectively, as the biochar concentration rises.

There is an increasing trend observed for cohesion, from 9.89 kPa to 27.41 kPa as the concentration of RHB increases. This implies that the addition of RHB causes an observable improvement to the cohesion of the soil. The friction angle increased from 31.94° to 37.76° at 5% concentration but decreased to 29.35° at 12% concentration. This result slightly contrasts with the findings of Hussain et al. [10], where the friction angle continued to increase up to a 15% amendment of biochar derived from mesquite. The difference in results may be attributed to the physical difference between mesquite and rice husk biochar. Hussain et al attributed the increase in friction angle to the roughness present in the surface of the mesquite biochar. Mesquite, a hardwood derivative, has higher robustness and rigidness than rice husk. It is expected that biochar derived from mesquite exhibits higher surface roughness and friction than biochar derived from rice husk. In Sadasivam and Reddy [9], both cohesion and friction angle increased between 0% and 10% amendment of wood-derived biochar in soil. A similar effect was observed in the present study for the amendment of RHB to silty sand.

ANOVA shows significant differences for the direct shear test results, both for cohesion and friction angle. Cohesion exhibited a generally increasing trend with increasing biochar content, suggesting that the addition of RHB enhanced the apparent bonding between soil particles, possibly due to improved cementation process. On the other hand, the friction angle initially increased with RHB concentration, indicating better interparticle interaction and resistance to sliding. This can be attributed to a larger effective particle size after cementation of the soil particles. However, a decrease in higher concentrations was observed. This behavior may be attributed to the excess biochar particles interfering with particle interlock or contributing to a more lubricated interface, which could reduce frictional resistance at higher contents.

Tukey's HSD test was performed for both cohesion and friction angle. Significant differences were observed between cohesions obtained at different concentrations for all pairs except those between 0% and 2%, 0% and 5%, and 2% and 5%. Meanwhile, significant differences in friction angles were observed between pairs at different concentrations, except for 2% and 8%, 2% and 10%, and 5% and 8%.

3.2 Triaxial Test Results

Table 5 presents the average shear stress values corresponding to varying concentrations of rice hull biochar at three levels of confining pressure: 98 kPa, 196 kPa, and 392 kPa. Figure 6 shows the mean cohesion for each concentration while Figure 7 shows the mean friction angle for each concentration. Standard errors are also shown.

Table 5. Average shear stress at failure (kPa) obtained from triaxial test.

Concentration of RHB	Shear Stress (kPa)		
	$\sigma_1 = 98\ kPa$	$\sigma_1 = 196\ kPa$	$\sigma_1 = 392\ kPa$
0%	466.04	674.86	940.99
2%	467.23	760.00	971.81
5%	514.57	753.97	1008.61
8%	526.51	831.86	1128.40
10%	558.94	798.81	1205.37
12%	554.10	861.30	1253.66

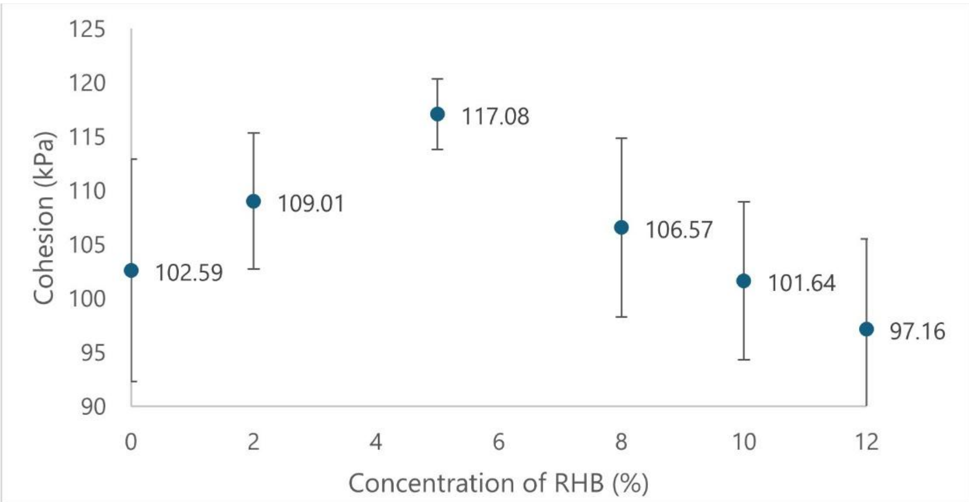

Figure 6. Cohesion obtained from triaxial test for each concentration of RHB

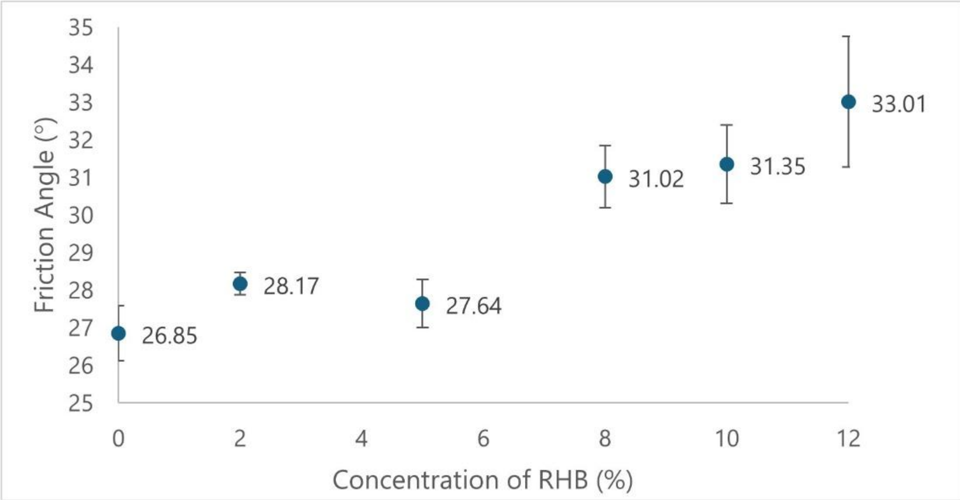

Figure 7. Friction angle obtained from triaxial for each concentration of RHB

An increasing trend was observed for the deviator stress as rice hull biochar content increases. Cohesion increased from 102.59 kPa to 117.07 kPa at 5% concentration, then decreased to 97.16 kPa at 12% concentration. Significantly higher values of cohesion are observed in this test than in the direct shear test due to the undrained conditions of the test. However, friction angles were measured by the test, which is usually not the case for unconsolidated-undrained triaxial tests. This is attributed to the specimens not being fully saturated before testing in an effort to maintain the target optimum moisture content. The friction angle generally increased from 26.85° at 0% concentration to 33.01° at 12% concentration. This aligns with the results obtained in previous research on shear strength of biochar-amended soils [9, 10].

Significant differences were not observed for the cohesion obtained from the undrained triaxial test. Figure 6 shows large standard errors, indicating high variability of results. The observed inconsistency may again be attributed to unsaturated conditions during testing. The different concentrations of RHB may have absorbed varying amounts of water for reaction, resulting in uneven pore pressure conditions during the tests. In contrast, the results still showed a statistically significant difference for the friction angle. This is because the test was interpreted using total stress parameters, and despite the absence of pore pressure control, the trend in shear strength remained consistent across all confining pressures. As the RHB concentration increased, the total shear strength also increased, which led to a noticeable increase in the apparent friction angle. Since the changes were consistent and less variable compared to cohesion, the difference in friction angle with increasing biochar content was found to be statistically significant. Tukey's Honestly Significance Difference test further shows that significant differences were observed between 0% and 10%, 0% and 12%, 2% and 12%, and 5% and 12%.

CONCLUSION

Rice hull biochar was able to improve the shear strength of soil. Based on direct shear test results, cohesion was increased from 9.89 kPa at 0% concentration to 27.41 kPa at 12% concentration. A peak friction angle of 37.76° was observed at 5% concentration compared to 31.94° at 0% concentration. Direct shear test showed good reliability, as supported by the significant differences reported by statistical analysis. In contrast, the triaxial test results were more uncertain, likely due to the unsaturated conditions of the samples during testing and possible changes in the moisture content after the cementation process. The highest cohesion was observed at 5% concentration with a value of 117.08 kPa; however, no significant difference was observed between the different concentrations. The friction angle, on the other hand, significantly increased from 26.85° at 0% concentration to 33.01° at 12% concentration.

Based on the results of the statistical analysis, an optimum concentration of 10% RHB is recommended, as significant increases in all shear strength parameters are observed when compared to the control sample. Increasing further to 12% may decrease or have no significant effect on the friction angle. This suggests the need for dosage control. The increase in shear strength parameters can be attributed to the high amorphous silica content of the RHB, which promotes the pozzolanic reaction with the cement and enhances the cementation of soil particles. This leads to both higher cohesion and friction angle; cohesion is directly related to the cementation, while the increase in friction angle may be attributed to the increase in the effective particle size of the soil particles after binding.

Rice hull biochar shows promise as an environmentally friendly stabilizer for silty sand, especially in areas where rice by-products are readily available. To build on these results, future work should examine how RHB-treated soils behave over time under different moisture levels and loading conditions, while also considering the role of curing and compaction practices. Field-scale trials are also encouraged to confirm the laboratory outcomes and to better understand the cost-effectiveness and sustainability of using RHB in real geotechnical projects.

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Conflicts of Interest: The authors declare no conflicts of interest.

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