Combined Influence of Vegetation Roots and Biochar Amendments on Soil Water Characteristics of Silty Sands

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Abstract

Shallow slope failures are often caused by water infiltration during heavy rainfall, which reduce soil shear strength and leads to instability of slope. The hydraulic behavior of unsaturated soils such as soil water characteristics plays a critical role in maintaining slope stability under such conditions. This study investigates the effects of vegetation roots and biochar on the soil water characteristics of sandy soils. The one-dimensional soil column experiment was conducted, incorporating moisture sensors and tensiometers to capture monitoring data. The *van Genuchten* model was applied to characterize the water retention behavior of treated soils. Results demonstrate that integration of vegetation roots and biochar significantly improve soil water retention and suction characteristics. These findings offer quantitative insights valuable for geotechnical engineers, and researchers, supporting the development of predictive models for rainfall-induced slope stability and sustainable slope management.

Keywords: Soil-water characteristics curve, Van Ganuchten model, One-dimensional column test, Silty sand

1. Introduction

The soil water characteristic curve (SWCC) is a key concept in unsaturated soil mechanics, describing the relationship between water content and soil suction [1]. First introduced by Edgar Buckingham in 1907, SWCC has become an essential index for unsaturated soils, serving as a proxy for permeability and shear strength [11]. It also provides insights into hydraulic properties and pore-size distribution [5].

Studies [11, 20] show that vegetation enhances soil water retention. For example, soils with orange jasmine, vetiver roots [20], and Heptaphylla trees [13] exhibit higher air-entry values[1] (AEV) and water retention than bare soil. However, the adsorption rate remains unchanged. These findings highlight the role of plant roots in modifying soil structure and improving water-holding capacity.

Historically, SWCC has been modelled as a relationship between water storage and energy, leading to various measurement methods [1]. Researchers use lysimeters with soil sensors [22] and fitting models like van Genuchten and Campbell [22, 29] to improve accuracy. Since SWCC is highly nonlinear, it is often plotted on a logarithmic scale to cover the full suction range (0 to 10^6 kPa) [5]. Factors such as soil layering, compaction, and clay content further complicate estimation [22].

Understanding SWCC is crucial for water management, contaminant transport, and geotechnical applications [1, 24]. As the globe became more industrialized, concrete and steel took over as the primary materials in various forms of infrastructural development and construction projects, including slope stabilisation. In general, engineers and designers have a greater sense of safety and security; thus, they prefer these man-made materials because they are more controllable and predictable. However, individuals are looking for more environmentally friendly and green solutions to a variety of technical difficulties. The public's desire to leave a more sustainable planet for future generations has increasingly prompted authorities and engineers to rediscover vegetation as an engineering material [13].

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In arid regions like Maowusu sandy soil, understanding SWCCs and infiltration capacity is key to vegetation recovery and water management [26]. Drought-resistant species with low planting density improve water retention and infiltration [30]. Root morphology influences SWCC and soil suction, with root volume ratio aiding SWCC prediction in vegetated slopes [26, 28].

A slope stability analysis by [19] found vetiver roots most effective for slopes under 45°, emphasizing the importance of preserving vegetation at the slope base. However, [9] caution against relying solely on lab-tested root tensile strength for real-world slope stability assessments.

Recent studies [3, 12, 29] have shown that, Biochar improves soil porosity and bulk density, enhancing water retention and supporting plant growth. However, some studies show mixed results on its impact on soil water retention, while in contrary, [14] found no SWCC changes by biochar addition, but increasing biochar in compacted clay (0–20%) can raise permeability tenfold and water content by 40%. [29]. Conversely, it was noted by [2] that biochar could reduce sandy soil's saturated permeability. Fig 2 shows the process through which biochar improves soil water characteristics in vegetated soils.

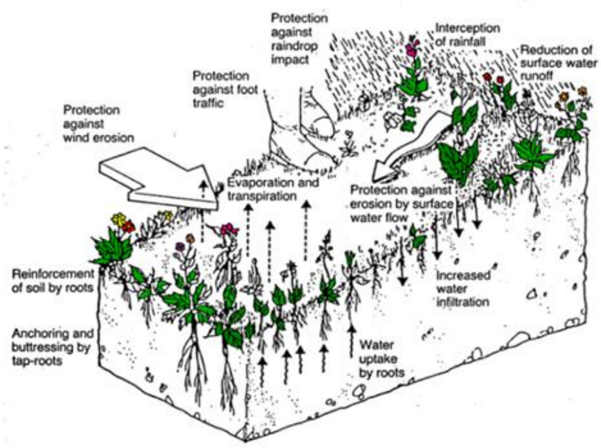

Fig. 1 Various effects of vegetation on slopes [4].

Biochar-amended soil increased near-saturated volumetric water content by 18% but did not affect AEV, acting as additional capillaries to retain water. Acacia mangium Willd., widely used in soil bioengineering, improves lateritic soil water retention by increasing suction, AEV, and saturated water content [17].

Vegetation roots also play a crucial role in slope stabilization and erosion control. Studies [15, 16, 18] compared two vetiver species, C. nemoralis and C. zizanioides. C. nemoralis showed strong root reinforcement potential, making it a viable alternative to C. zizanioides [16]. C. nemoralis had thicker roots growth [15]. Both species showed a linear relationship between root orientation and diameter. However, C. nemoralis deteriorated faster, reducing its long-term soil reinforcement effectiveness [18].

This study aims to examine the impact of vetiver grass roots and biochar on the SWCC of bare soil under varying moisture conditions. It also compares changes in the soil's physical and hydraulic properties when amended with biochar alone versus the combined effect of biochar and vetiver.

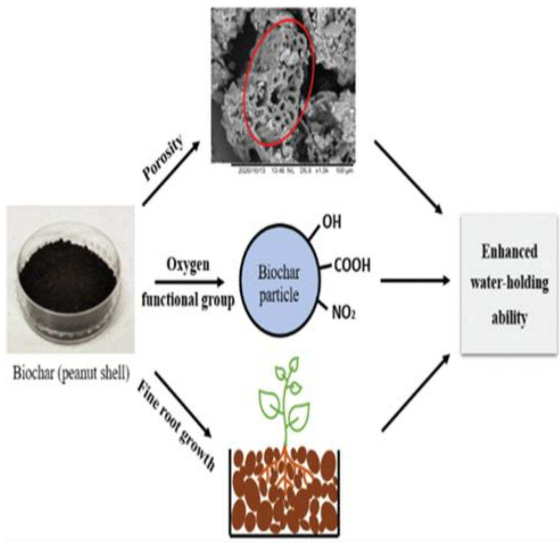

Fig. 2 The process through which biochar improves water retention in soil with vegetation [29]

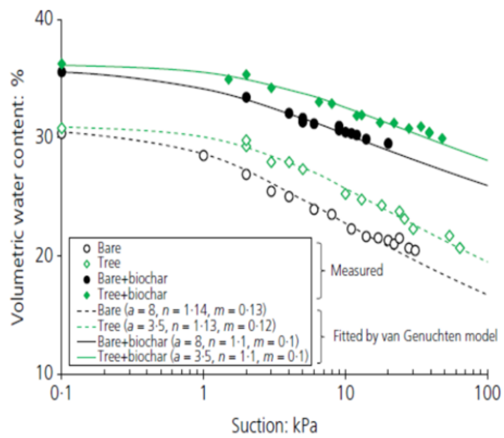

Fig. 3 SWRC of vegetated and bare CDG soil with and without the addition of biochar [14].

2. Materials and Methods

2.1 Materials

The soil sample used in this study was collected from Chachoengsao Province, eastern Thailand. As presented in table 1, the basic properties of the soil were tested, the liquid limit and plastic limit was found to be 20.86% and 12.96% and the specific gravity of bare and biochar-amended soils was found to be 2.62 and 2.09 respectively. Sieve analysis and hydrometer test were conducted following ASTM standards and gradation curve was plotted. The soil is classified as low-plasticity silt (USCS). The gradation curve and index properties of the soil are presented in figure 4 and table 1 respectively. Before experimentation, the soil was air-dried, and only particles passing through a No. 6 sieve were used in the soil columns.

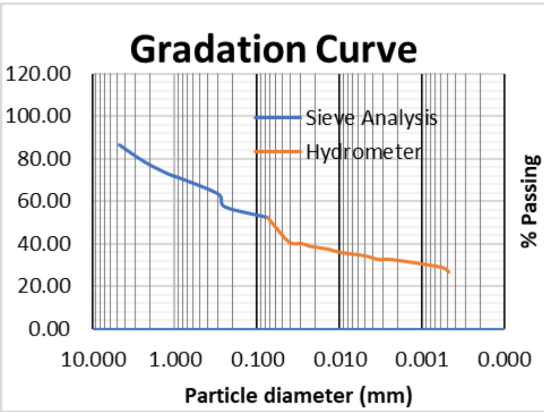

Fig. 4 Gradation Curve

Vetiver grass was selected as the vegetated species due to its high water-holding capacity and widespread availability in Thailand.

The biochar, produced from bamboo waste in Tak Province, Thailand, was sieved to a No. 16 mesh size. This selection aligns with [23], which found that plant biomass production was highest at intermediate biochar particle sizes (0.5–2.0 mm).

Table 1 Index properties of the soil sample

Index properties	Value
Liquid limit, %	20.86
Plastic limit, %	12.96
Plasticity index, %	7.90
Specific gravity (bare soil) Specific gravity (soil and biochar)	2.62 2.09
Unified Soil Classification System (USCS)	ML

2.2 Methods

2.2.1 Soil Compaction

The compaction of bare soil was conducted using Standard Proctor test. The results shows that the maximum dry density (MDD) and the optimum moisture content (OMC) of the soil are 1.98g/cm^3 and 12.46% respectively.

2.2.2 Experimental Setup and Instrumentation

This study utilized PVC pipes as experimental soil columns, arranged as follows: bare soil, soil mixed with biochar, soil planted with vetiver, and soil incorporating both vetiver and biochar. As shown in Fig 5, each column was cylindrical, measuring 100 cm in height and 15 cm in diameter. As depicted in Figure 3 three holes (P1, P2, and P3), each 16 mm in diameter, were drilled at depths of 37.5 cm, 62.5 cm, and 87.5 cm from the top to accommodate tensiometers. The miniature tensiometer was used to measure suction ranging from 0 to 80kPa. On the opposite side, two additional holes (M1 and M2) with a 20 mm diameter were drilled at 25 cm intervals to house soil moisture sensors. Moreover, a mini reservoir of acrylic pipe was stationed just above the PVC pipe to supply water at constant head.

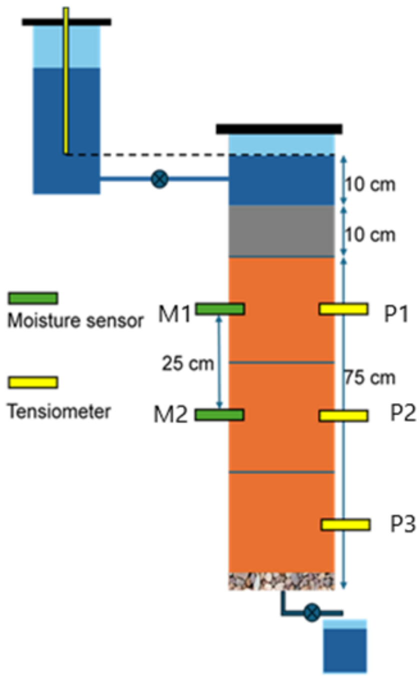

Fig. 5 Schematic diagram of 1D Soil Column

2.2.3 Testing Procedure

As shown in Figure 6, the instantaneous profile (IP) method was used to determine the SWCC of treatments. The volumetric water content and suction were measured by the moisture sensors and tensiometers connected to a data logger via cables.

The experiment was conducted within 90 days from January 2025 to March 2025. To ensure accuracy, the logger collects readings over a 10-minutes period, and the average readings is taken as single measurement. The process is repeated continuously following the same protocol for both wetting and drying cycles. A minimum interval of 2-3 days was maintained between each measurement

Fig. 6 Experimental Setup for SWCC measurement

2.2.4 Results Analysis Techniques

The data collected from the measurements is analyzed using the Van Genuchten (VG) model (van Genuchten, 1980), a widely used mathematical approach for representing the soil-water characteristic curve (SWCC). This model defines the relationship between soil suction and water content in unsaturated soils. Refer to Eq. (1) for details.

$$\theta(\psi) = \theta_r + \frac{\theta_s - \theta_r}{(1+(\alpha\psi)^n)^m} \quad (1)$$

Where:

$\theta(\psi)$ is the volumetric water content at a given suction (ψ),

θs is the saturated volumetric water content (maximum water-holding capacity),

θr is the residual volumetric water content (water content that cannot be removed by suction),

α is the inverse of the air-entry value, which controls the suction at which drainage begins,

n is a parameter that describes the pore-size distribution,

m is defined as $1 - 1/n$

3. Results and Discussions

Figure 7 shows the the soil-water characteristics curve (SWCC) of bare soil, soil and vetiver, soil, biochar and vetiver grass. The result was fitted using van Ganutchen model. The vegetated soil has higher air entry value (AEV is between 3-5 kPa) than the bare soil (2-3 kPa) indication higher water retention capacity. This can be due to root occupancy in the pores of the soil reducing the porosity of the soil and increased suction at a given water content [21]. Similar investigation by [13] concluded that the soil vegetated with *iv tree* have higher water holding capacity than the bare soil and the AEV was also higher by 2-4 kPa. Vegetated soils exhibit higher matric suction compared to non-vegetated soils at the same water content, suggesting that vetiver roots significantly enhance moisture retention capacity [8, 26].

On the other hand, the soil incorporated with biochar tend to have much higher AEV than the bare soil. It is found that, the AEV of soil and 20% of biochar is at least 1 kPa higher than that of bare soil, this is due to biochar's high porosity nature and large surface area. This shows that biochar used in this study can enhance water holding capacity of soil at a given suction. There was in volumetric water content in biochar amended soil increased by 6 - 8% compared to that of bare soil. A study of Incorporating soil and various biochar content was conducted by [6] also suggest that the biochar increase the volumetric water content at lower suction. From Engineering point of view, although it is favourable for plant growth, this is not advantageous for maximizing soil suction in slopes. The lower induced suction results in weakened the soil's shear strength and slope stability [14]. However, vegetation can perform better and live longer when planted in biochar-amended soils in the dry lands by the increase of water-holding capacity [10].

The suction range investigated in this study (1–80 kPa) is limited to the low-to-medium range of the soil-water characteristic curve. While this range is informative for near-saturated conditions, it does not capture the full spectrum of suction behavior, particularly in the higher suction range (>500 kPa) that is often critical in slope stability and unsaturated soil mechanics analyses. This limitation restricts the direct application of the results to scenarios where soils experience higher matric suctions, such as in arid climates or deeper unsaturated zones.

Despite this limitation, the observed improvements in water retention due to the addition of biochar and vetiver roots suggest promising implications for engineering applications. Enhanced moisture retention can lead to delayed onset of desaturation, reduced suction gradients, and greater root reinforcement, all of which contribute to increased slope stability and erosion resistance. These findings are particularly relevant for shallow slope stabilization and surface erosion control, where maintaining near-saturated conditions plays a critical role.

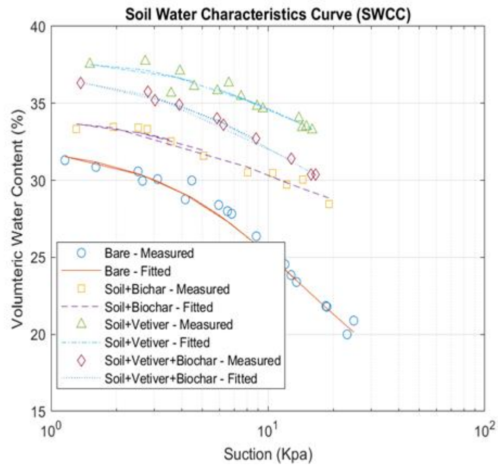

Fig. 7 Soil water characteristics curves (SWCC) of bare soil, vegetated soil, biochar amended soil, vegetated soil mixed with biochar

Table 2 *van Ganutchen* Model Parameters

Specimens	VG Model Parameters					R^2
	θ_r (%)	θ_s (%)	α	n	m	
Bare Soil	7.99	31.97	0.144	1.497	0.332	0.95
Vegetated Soil	14.20	34.36	0.202	1.219	0.179	0.97
Soil and Biochar	3.53	38.41	0.145	1.14	0.123	0.98
Soil, Vetiver and Biochar	4.98	37.09	0.144	1.212	0.175	0.98

Recent studies [7, 14] found that biochar generated from herbaceous feedstock had no significant impact on SWCC of sandy soils because of its hydrophobicity but result from [29] whose biochar was produced from peanut shells, and it was hydrophobic contradicts the above findings when determined by water drop penetration time test.

The ML (low plasticity silt) soil amended with biochar and reinforced with vegetation exhibited higher air entry value (4 -6 kPa) compared to other treatments. This indicates significant improvement on soil behavior to retain water under increasing suction. The rise in AEV can be attributed to the combined influence of vetiver roots and the fine particles of biochar, likely due to the roots occupying soil pores and the biochar particles further contributing to pore space reduction. The high AEV of soil with biochar and vetiver means that the soil retains more water longer before saturation begins leading to low infiltration thereby reducing the risk of erosion and shear failure when implemented for slope protection.

The higher water retention in soil treated with vetiver roots, compared to biochar amended soil could be attributed to several factors working together. Vetiver roots help improve soil structure by encouraging the formation of aggregates and releasing hydrophilic compounds that make it easier for the soil to hold onto moisture. Although biochar is known for its porous nature, it can be somewhat water-repellent at first, especially when freshly applied, which may reduce its ability to hold water immediately. On the other hand, the continuous interaction between living vetiver roots and the soil tends to support better and more consistent moisture retention.

The model parameters fitted from the observed values were presented in table 2. The lowest coefficient of determination of 0.95 was found in all the variables, indicating a very good fit. This value is way higher than the acceptable limit of $R^2 > 0.885$ as recommended by [25] that the van Genuchten equation provides a strong fit to the measured soil water retention data ($R^2 > 0.885$), making it a reliable tool for predicting soil water retention curves across various soil types

4. Conclusions

The study investigates the water retention of soil and the effects of biochar and vetiver grass on the SWCC of low plasticity silt. Laboratory tests were conducted on soil columns namely bare soil, soil and vetiver, soil and biochar and combination of soil biochar and vetiver.

1. Biochar made from bamboo waste was found to be effective in improving the water-holding capacity of soil with air entry value (AEV) of at least 1kpa higher than that of bare soil. While the volumetric water content of the soil increased by 6 – 8% at a given suction range, this may be due porous nature of the biochar.
2. The vetiver grass planted in soil exhibit significant change in the AEV from 2 – 3 kPa of bare soil to 3 – 5 kPa. As expected, the desaturation process was very slow due to the vetiver roots.
3. The combined effects of vegetation and biochar leads to significant increase of AEV (4 – 6kPa) than all other variables, although it is slightly higher than that of vegetated soil indicating little impact of biochar compared to vetiver root.

Therefore, attributing smaller particles of biochar (1mm or less) produced from bamboo waste on two different plant species is encouraged for future studies.

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