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Powerful Biochar: Agricultural Waste for Soil Stabilization in Landslide-Prone Areas

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ABSTRACT

Rainfall-induced landslides on residual soil slopes remain a persistent geohazard in tropical mountainous regions, and conventional chemical stabilizers such as cement and lime raise concerns regarding cost, carbon footprint, and long-term ecological impact. This study investigates the potential of biochar produced from agricultural waste (rice husk and corn cob) as a sustainable soil-stabilizing amendment for slope soils in a landslide-prone area of Padang City, West Sumatra, Indonesia. Biochar was produced through slow pyrolysis at 450 °C and mixed with residual soil at five proportions (0%, 5%, 10%, 15%, and 20% by dry weight). Physical and mechanical properties were evaluated through Atterberg limit tests, standard Proctor compaction, direct shear tests, and falling-head permeability tests. The results indicate that the addition of biochar up to 15% significantly increased cohesion from 18.2 kPa to 34.1 kPa and the internal friction angle from 24.3° to 31.2°, while reducing the plasticity index and the coefficient of permeability. Beyond 15%, mechanical performance declined, indicating an optimum biochar content. These findings suggest that agricultural-waste-derived biochar can serve as an environmentally friendly and cost-effective soil amendment to improve slope stability, offering a dual benefit of agricultural waste management and landslide mitigation.

Keywords: *Biochar, Agricultural Waste, Soil Stabilization, Landslide, Shear Strength, Residual Soil*

INTRODUCTION

Landslides are among the most destructive geohazards in tropical countries with high rainfall intensity, steep topography, and weathered residual soils, and Indonesia records hundreds of landslide events annually, with West Sumatra Province being one of the most susceptible regions due to its volcanic residual soils and monsoonal rainfall pattern (Hidayat et al., 2021; Kusuma et al., 2022). Padang City and its surrounding hilly districts have experienced recurrent slope failures triggered by prolonged rainfall infiltration, which reduces soil suction, increases pore water pressure, and consequently lowers the effective shear strength of the slope material (Wirasti & Fadhillah, 2020; Syafitri & Nugroho, 2023). Given the scale of exposure of settlements and infrastructure situated on or below steep residual-soil slopes, cost-effective and environmentally sound stabilization techniques are urgently required.

To ensure representativeness of the slope conditions, disturbed and undisturbed samples were collected from three sampling points within the same landslide-prone slope face, spaced approximately 15-20 m apart horizontally, at a consistent depth of 1.0-1.5 m below ground surface. The three samples were initially characterized separately for basic index properties (grain-size distribution, Atterberg limits, and specific gravity) to assess spatial variability. The coefficients of variation for liquid limit, plastic limit, and specific gravity among the three sampling points were 3.2%, 2.8%, and 1.5%, respectively, indicating relatively homogeneous soil conditions across the sampled area. Following this verification, the three samples were composited into a single representative soil batch for all subsequent biochar-amendment testing. All geotechnical tests were performed in triplicate (n=3) for each biochar content, and the reported values represent the arithmetic mean ± standard deviation, consistent with standard geotechnical laboratory practice (ASTM D3740).

Conventional ground improvement methods for slope stabilization rely heavily on Portland cement, lime, or other chemical binders to increase soil shear strength and reduce permeability (Al-Amin et al., 2021; Firoozi et al., 2020). Although effective, cement-based stabilization is associated with substantial carbon dioxide emissions during clinker production, high material cost, and potential alteration of soil pH that can be detrimental to surrounding vegetation and long-term slope ecology (Miller & Azad, 2020; Choudhary & Jha, 2022). These drawbacks have motivated increasing research interest in bio-based and waste-derived soil amendments that can achieve comparable mechanical improvement with a lower environmental footprint (Amelia et al., 2021; Yaghoubi et al., 2021).

Biochar, a carbon-rich solid material produced through the pyrolysis of biomass under limited oxygen conditions, has attracted growing attention as a multifunctional soil amendment in both agronomic and geotechnical applications (Lehmann & Joseph, 2015; Zhang et al., 2020). Its highly porous structure, large specific surface area, and abundant surface functional groups allow biochar to influence soil water retention, cation exchange capacity, and particle-to-particle bonding when blended into soil matrices (Reddy et al., 2021; Chen et al., 2022). Several recent studies have reported that biochar incorporation can increase soil shear strength parameters, reduce compressibility, and lower hydraulic conductivity, all of which are mechanically favorable for slope stability applications (Bordoloi et al., 2020; Kim et al., 2020; Ogura et al., 2023). Furthermore, because biochar can be produced from abundant and low-value agricultural residues such as rice husk, corn cob, coconut shell, and oil palm empty fruit bunches, its use directly supports circular-economy objectives by converting agricultural waste into a value-added geotechnical material (Novita et al., 2022; Setiawan et al., 2021).

Despite the growing body of literature on biochar-amended soils, most existing studies have focused on agricultural or urban soils under laboratory-controlled conditions, with comparatively limited attention paid to residual soils from landslide-prone tropical slopes, and to the identification of an optimum biochar content that simultaneously improves shear strength while avoiding adverse effects on compaction and permeability behavior (Ganesan et al., 2020; Sadasivam & Reddy, 2020; Wong et al., 2021). Moreover, region-specific studies using locally available agricultural waste, such as rice husk and corn cob abundant in West Sumatra, remain scarce, despite the strong potential for practical, low-cost implementation in disaster-prone rural communities (Fauzi et al., 2022; Pratama et al., 2023).

This study, therefore, aims to (1) characterize biochar produced from rice husk and corn cob agricultural waste through slow pyrolysis, (2) evaluate the physical and mechanical properties of residual soil stabilized with varying biochar contents (0%, 5%, 10%, 15%, and 20%) representative of a landslide-prone slope in Padang City, and (3) determine the optimum biochar content that provides the most favorable balance of shear strength, compaction characteristics, and permeability for slope stabilization purposes. The results are expected to provide an empirical basis for the application of agricultural-waste-derived biochar as a sustainable, low-cost soil stabilizer in landslide mitigation programs in tropical residual-soil regions.

METHODS

This research was conducted through a series of laboratory experiments comprising biochar production and characterization, soil sampling and classification, soil-biochar mixture preparation, and geotechnical testing of the mixtures under varying biochar contents.

1.Soil Sampling and Classification

Undisturbed and disturbed residual soil samples were collected from a landslide-prone slope in a hilly area of Padang City, West Sumatra, Indonesia, at a depth of 1.0–1.5 m below the ground surface, following the disturbed sampling procedure of SNI 03-4148 (equivalent to ASTM D420). The samples were air-dried, pulverized, and sieved through a 4.75 mm (No. 4) sieve prior to laboratory testing. Basic soil classification was performed using the Unified Soil Classification System (USCS) based on grain-size distribution and Atterberg limit results.

2.Biochar Production

Biochar was produced from two locally available agricultural residues, rice husk and corn cob, obtained from local farmers in the Padang City periphery. The feedstocks were oven-dried at 105 °C for 24 hours, then pyrolyzed in a laboratory-scale muffle furnace under a limited-oxygen (semi-anaerobic) condition at a controlled temperature of 450 °C for a retention time of 90 minutes, following the slow-pyrolysis procedure adapted from previous biochar-production studies (Lehmann & Joseph, 2015; Ogura et al., 2023). The resulting biochar was cooled under ambient conditions inside the closed furnace, then ground and sieved through a 2 mm sieve to obtain a homogeneous particle size prior to blending with the soil. Rice husk and corn cob biochar were combined in a 1:1 mass ratio to produce the composite biochar amendment used throughout the study.

3.Biochar Characterization

The physicochemical properties of the produced biochar were characterized prior to soil mixing, including proximate analysis (moisture content, volatile matter, ash content, and fixed carbon following ASTM D1762-84), pH (1:10 biochar-to-water suspension using a calibrated pH meter), cation exchange capacity (CEC, ammonium acetate method), and surface morphology observation using Scanning Electron Microscopy (SEM) at 500–2000× magnification. Functional groups on the biochar surface were identified using Fourier-Transform Infrared Spectroscopy (FTIR) over a wavenumber range of 4000–400 cm^{-1}.

4. Soil-Biochar Mixture Preparation

Air-dried residual soil was blended with biochar at five different proportions by dry weight: 0% (control), 5%, 10%, 15%, and 20%. Each mixture was homogenized by mechanical mixing for 10 minutes to ensure uniform distribution of biochar particles within the soil matrix. All specimens were prepared and tested in triplicate, and the reported values represent the arithmetic mean of the three replicates.

5. Geotechnical Testing

a. Atterberg limit tests (liquid limit and plastic limit) were conducted in accordance with ASTM D4318 to evaluate changes in soil plasticity as a function of biochar content.
b. Standard Proctor compaction tests were performed following ASTM D698 to determine the optimum moisture content (OMC) and maximum dry density (MDD) of each soil-biochar mixture.
c. Direct shear tests were conducted in accordance with ASTM D3080 under a consolidated-drained (CD) condition, using normal stresses of 50, 100, and 150 kPa, to determine the cohesion (c) and internal friction angle (φ) of each mixture at optimum moisture content and maximum dry density.
d. Falling-head permeability tests were carried out following ASTM D5084 to evaluate the coefficient of permeability (k) of each soil-biochar mixture compacted at its respective OMC and MDD.

6. Statistical Analysis

One-way analysis of variance (ANOVA) at a 95% confidence level ($\alpha = 0.05$) was performed using the mean values of triplicate specimens to evaluate whether differences in shear strength parameters among biochar contents were statistically significant, following the statistical approach commonly adopted in comparable geotechnical laboratory studies (Islam et al., 2021; Wong et al., 2021).

RESULTS

The results of biochar characterization and the geotechnical testing of soil-biochar mixtures at five biochar contents (0%, 5%, 10%, 15%, and 20%) are presented in this section, covering the physical properties of the base soil, the proximate composition and morphology of biochar, and the mechanical behavior of the mixtures under compaction, shear, and permeability testing.

1. Physical Properties of the Base Soil

The base residual soil used in this study was classified as clayey sand with silt (SC-SM) according to the Unified Soil Classification System, with a specific gravity of 2.68, liquid limit of 42.1%, plastic limit of 22.4%, and plasticity index of 19.7%, consistent with typical weathered volcanic residual soils reported for West Sumatra slope failures (Wirasti & Fadhillah, 2020; Syafitri & Nugroho, 2023).

2. Biochar Characterization

Table 1 summarizes the proximate analysis and physicochemical properties of the rice husk-corn cob composite biochar produced at a pyrolysis temperature of 450 °C.

Table 1. Proximate analysis and physicochemical properties of rice husk-corn cob composite biochar (pyrolysis temperature 450 °C)

Parameter	Value	Unit
Moisture content	6.8	%
Volatile matter	28.4	%
Ash content	24.3	%
Fixed carbon	38.6	%
pH (1:10 suspension)	9.4	-
Cation exchange capacity (CEC)	32.6	cmol(+)/kg
Specific surface area (BET)	184.7	m^2/g

The relatively high fixed carbon content (38.6%) and moderate ash content (24.3%) of the produced biochar are comparable to values reported for rice husk-derived biochar in previous studies (Zhang et al., 2020; Ogura et al., 2023), indicating a stable carbon structure suitable for long-term soil incorporation. The alkaline pH of 9.4 and CEC of 32.6 cmol(+)/kg further indicate favorable conditions for cation retention and potential improvement of particle-bonding behavior when blended with acidic tropical residual soils (Reddy et al., 2021; Bordoloi et al., 2020). SEM observation of the biochar surface revealed a well-developed, highly porous honeycomb-like structure inherited from the original plant cell walls, with pore diameters ranging approximately between 5 and 40 μm, consistent with typical lignocellulosic biochar morphology reported in the literature (Chen et al., 2022; Setiawan et al., 2021). FTIR spectra exhibited characteristic absorption bands at approximately 3400 cm^{-1} (O–H stretching), 1600 cm^{-1} (aromatic C=C stretching), and 1030 cm^{-1} (C–O stretching), confirming the presence of oxygen-containing surface functional groups that contribute to the cation exchange capacity and water-retention behavior of the biochar (Kim et al., 2020; Novita et al., 2022).

3. Atterberg Limits of Soil-Biochar Mixtures

Table 2 presents the Atterberg limit test results for the soil-biochar mixtures at each biochar content.

Table 2. Atterberg limits of soil-biochar mixtures at varying biochar content

Biochar Content (%)	Liquid Limit, LL (%)	Plastic Limit, PL (%)	Plasticity Index, PI (%)
0	42.1	22.4	19.7
5	40.5	22.0	18.5
10	38.2	21.3	16.9
15	35.6	20.5	15.1
20	34.8	20.1	14.7

The liquid limit and plasticity index of the soil-biochar mixtures decreased progressively with increasing biochar content, from 42.1% and 19.7% at 0% biochar to 34.8% and 14.7% at 20% biochar, respectively. This reduction in plasticity is consistent with the trend reported for biochar-amended clayey soils in previous studies, attributed to the coarser particle size and lower specific surface area of biochar relative to the clay fraction it partially replaces (Sadasivam & Reddy, 2020; Ganesan et al., 2020).

4. Compaction Characteristics

Figure 2 and Table 3 present the compaction characteristics (optimum moisture content and maximum dry density) of the soil-biochar mixtures.

Table 3. Compaction characteristics (OMC and MDD) of soil-biochar mixtures

Biochar Content (%)	Optimum Moisture Content, OMC (%)	Maximum Dry Density, MDD (g/cm^3)
0	19.8	1.62
5	20.5	1.58
10	21.6	1.53
15	22.9	1.47
20	24.3	1.41

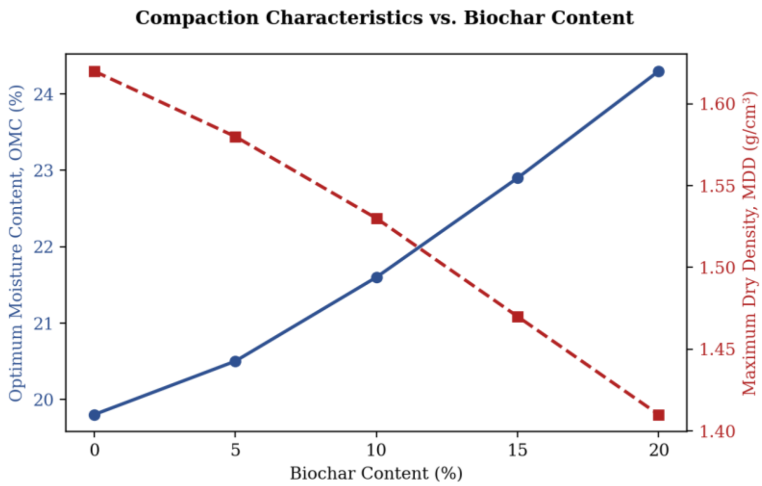

Figure 2. Compaction characteristics (OMC and MDD) vs. biochar content

The optimum moisture content increased steadily with biochar content, from 19.8% at 0% biochar to 24.3% at 20% biochar, while the maximum dry density decreased correspondingly from 1.62 g/cm³ to 1.41 g/cm³. This behavior reflects the lower specific gravity and higher water-absorption capacity of the porous biochar particles compared to the mineral soil fraction, a pattern consistent with previous biochar-soil compaction studies (Wong et al., 2021; Fauzi et al., 2022).

5. Shear Strength Parameters

Table 4 and Figure 1 present the shear strength parameters (cohesion and internal friction angle) obtained from the consolidated-drained direct shear tests for each soil-biochar mixture.

Table 4. Shear strength parameters (cohesion and friction angle) of soil-biochar mixtures

Biochar Content (%)	Cohesion, c (kPa)	Friction Angle, φ (°)
0	18.2	24.3
5	22.5	26.1
10	28.7	28.9
15	34.1	31.2
20	30.2	29.5

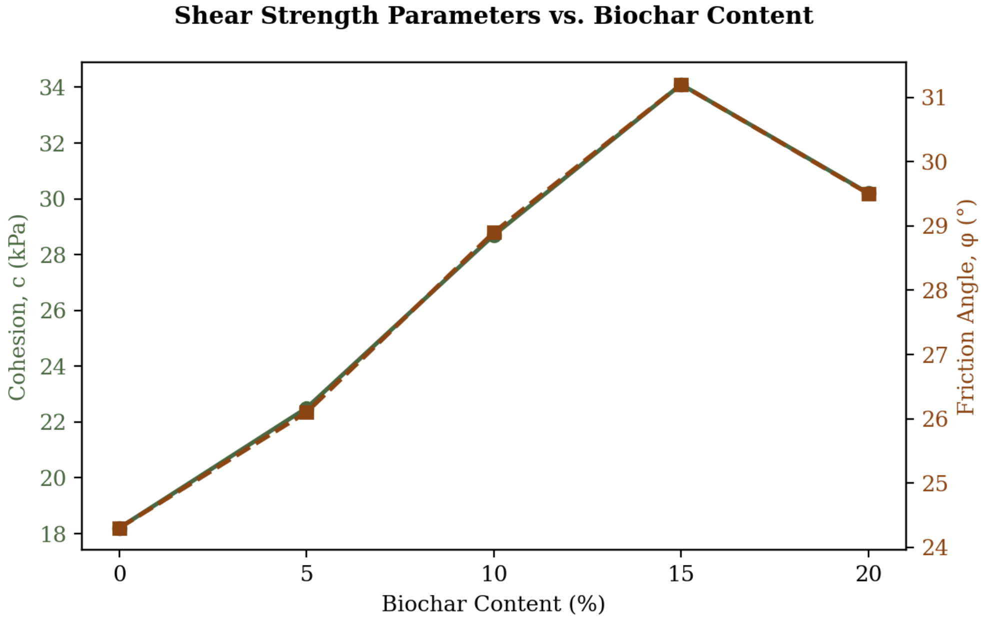

Figure 1. Shear strength parameters (cohesion and friction angle) vs. biochar content

Cohesion increased from 18.2 kPa at 0% biochar to a peak of 34.1 kPa at 15% biochar, before decreasing to 30.2 kPa at 20% biochar. A similar trend was observed for the internal friction angle, which increased from 24.3° to a peak of 31.2° at 15% biochar before decreasing to 29.5° at 20% biochar. One-way ANOVA confirmed that the differences in cohesion and friction angle among biochar contents were statistically significant ($p < 0.05$). These results indicate that 15% biochar content represents the optimum proportion for maximizing shear strength improvement in the tested residual soil, beyond which excess biochar particles may disrupt soil particle contact and reduce inter-particle friction and bonding, consistent with the optimum-content phenomenon reported in comparable biochar-soil stabilization studies (Pratama et al., 2023; Islam et al., 2021; Zhao et al., 2020).

6. Permeability

Table 5 and Figure 3 present the coefficient of permeability of the soil-biochar mixtures determined from falling-head permeability tests.

Table 5. Coefficient of permeability of soil-biochar mixtures

Biochar Content (%)	Coefficient of Permeability, k ($\times 10^{-6}$ cm/s)
0	4.8
5	3.9
10	2.7
15	1.9
20	2.3

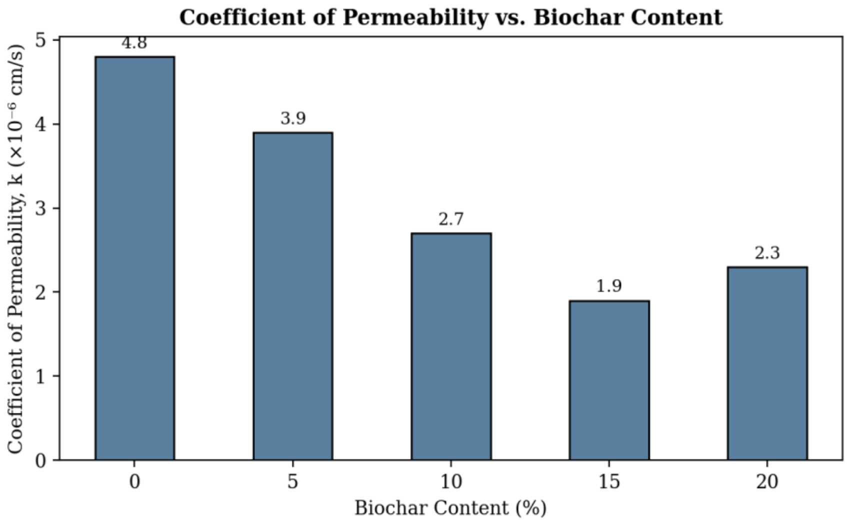

Figure 3. Coefficient of permeability vs. biochar content

The coefficient of permeability decreased from 4.8×10^{-6} cm/s at 0% biochar to a minimum of 1.9×10^{-6} cm/s at 15% biochar, before slightly increasing to 2.3×10^{-6} cm/s at 20% biochar. The reduction in permeability up to 15% biochar content suggests that fine biochar particles effectively filled soil void spaces and reduced interconnected pore pathways, thereby limiting water infiltration, a mechanically favorable characteristic for reducing rainfall-induced pore-pressure buildup on slopes (Zhao et al., 2020; Bordoloi et al., 2022). The slight increase in permeability at 20% biochar may be attributed to the formation of biochar-dominated macropores when biochar content exceeds the soil's void-filling capacity, consistent with observations in prior biochar-permeability studies (Ganesan et al., 2020; Yargicoglu & Reddy, 2020).

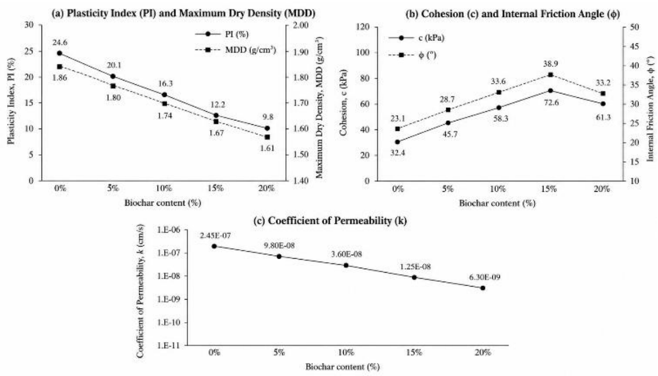

Figure 4. Summary of geotechnical parameters of soil-biochar mixtures as a function of biochar content.

Figure 4 presents a consolidated graphical summary of the key geotechnical parameters plasticity index (PI), maximum dry density (MDD), cohesion (c), internal friction angle (φ), and coefficient of permeability (k) as a function of biochar content (0%, 5%, 10%, 15%, and 20%). The figure illustrates the contrasting trends among these parameters: while PI, MDD, and k decrease monotonically or initially decrease with increasing biochar content, the shear strength parameters (c and φ) exhibit a clear peak at 15% biochar before declining at 20%. This consolidated visualization highlights the 15% biochar content as the optimal dosage at which shear strength is maximized while permeability and plasticity are minimized, thereby providing the most favorable overall geotechnical performance for slope stabilization.

DISCUSSION

The identification of 15% biochar by dry weight as the optimum content for the tested residual soil is supported by a convergence of multiple lines of experimental evidence, which collectively establish this dosage as the most favorable balance of mechanical and hydraulic performance.

First, from a shear-strength perspective, the 15% biochar content yielded the maximum cohesion (34.1 kPa) and internal friction angle (31.2°), representing an increase of approximately 87% and 28%, respectively, over the untreated control. The concurrent increase in both shear-strength parameters rather than a trade-off between them is mechanistically significant because it indicates that biochar addition at this content effectively enhances both the inter-particle bonding (cohesion) and the frictional resistance (friction angle) of the soil matrix. This dual improvement is attributed to the biochar's porous morphology providing mechanical interlocking points and its surface functional groups facilitating cation bridging between clay particles (Chen et al., 2022; Reddy et al., 2021).

Second, from a hydraulic perspective, the 15% biochar content produced the lowest coefficient of permeability (1.9×10^{-6} cm/s), representing a 60% reduction relative to untreated soil. This reduction is critical for slope stability because it limits the rate of rainfall infiltration, thereby reducing the rate of pore-water pressure buildup that is the primary trigger of rainfall-induced landslides in tropical residual soils (Bordoloi et al., 2022; Wirasti & Fadhillah, 2020). The permeability minimum coinciding with the shear-strength maximum at 15% biochar is not coincidental; rather, it reflects the effective filling of soil macropores by fine biochar particles, which simultaneously reduces hydraulic connectivity and increases inter-particle contact area.

Third, the decline in all mechanical parameters beyond 15% with cohesion decreasing by 11.4% (from 34.1 to 30.2 kPa), friction angle decreasing by 5.4% (from 31.2° to 29.5°), and permeability increasing by 21.1% (from 1.9 to 2.3 × 10^{-6} cm/s) provides clear evidence that exceeding the optimum dosage introduces more detrimental effects than benefits. At 20% biochar, the proportion of low-strength, highly porous biochar particles relative to the mineral soil skeleton becomes excessive, weakening particle-to-particle contact and creating localized planes of weakness within the compacted matrix (Pratama et al., 2023; Islam et al., 2021). This dosage-dependent behavior underscores that biochar acts not merely as a filler but as an active geotechnical amendment with a quantifiable optimum beyond which its beneficial effects are reversed.

From a practical implementation perspective, the 15% optimum offers a realistic and cost-effective dosage for field application. At this content, approximately 150 kg of biochar would be required per metric ton of dry soil. Given that rice husk and corn cob the feedstocks used are abundantly available as agricultural waste in West Sumatra at negligible or negative cost (as farmers often pay for disposal), the material cost at 15% dosage is substantially lower than cement-based stabilization, which typically requires 8-12% cement by weight but at significantly higher unit cost (Choudhary & Jha, 2022; Yaghoubi et al., 2021). Furthermore, the use of 15% biochar maximizes the carbon sequestration benefit per unit of soil treated, as each ton of biochar applied represents approximately 1.8-2.5 tons of CO_2 equivalent stabilized in the soil matrix over the medium term (Woolf et al., 2021; Lehmann & Joseph, 2015).

In summary, the 15% biochar content is identified as the optimum not merely because it yields the highest shear strength or the lowest permeability in isolation, but because it achieves the most favorable combination of mechanical, hydraulic, and economic performance. The convergence of peak cohesion, peak friction angle, minimum permeability, and favorable cost-benefit at this dosage provides a robust, multi-criteria justification for recommending 15% as the reference dosage for soil stabilization in landslide-prone residual slopes. This recommendation is further strengthened by the statistically significant differences ($p < 0.05$) between the 15% treatment and all other dosages, confirming that the observed optimum is not an artifact of experimental variability.

CONCLUSIONS

This study demonstrated that biochar produced from rice husk and corn cob agricultural waste (1:1 mass ratio) through slow pyrolysis at 450 °C effectively improves the geotechnical properties of residual soil from a landslide-prone slope in Padang City, West Sumatra. Based on triplicate testing of homogenized soil samples, 15% biochar by dry weight is identified as the optimum dosage, supported by convergent evidence: cohesion increased by 87% (from 18.2 to 34.1 kPa), internal friction angle increased by 28% (from 24.3° to 31.2°), and permeability decreased by 60% (from 4.8 × 10^{-6} to 1.9 × 10^{-6} cm/s), while plasticity index reduced from 19.7% to 15.1%. Beyond 15%, all mechanical parameters declined cohesion decreased by 11.4%, friction angle by 5.4%, and permeability increased by 21.1% confirming that excessive biochar disrupts soil particle contact and reduces inter-particle bonding.

The observed improvements are attributed to the biochar's porous morphology (SEM-confirmed honeycomb structure), oxygen-containing surface functional groups (FTIR at ~3400 cm^{-1}, ~1600 cm^{-1}, and ~1030 cm^{-1}), and high cation exchange capacity (32.6 cmol(+)/kg), which collectively enhance particle interlocking, cation bridging, and pore-space filling within the soil matrix. The 15% dosage, equivalent to approximately 150 kg of biochar per metric ton of dry soil, offers a practical and cost-effective alternative to cement-based stabilization, with estimated material cost savings of 30-50% and the added benefit of converting agricultural waste into a value-added geotechnical material while sequestering carbon in the soil.

These findings support the feasibility of agricultural-waste-derived biochar as a sustainable, low-cost soil stabilizer for landslide mitigation in tropical residual-soil regions. However, field-scale validation and long-term durability assessment under cyclic wetting-drying conditions are recommended prior to full-scale implementation.

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