

Research Article

Root Tensile Behaviour and Soil Shear Reinforcement of an Amended Residual-Soil Medium by Tropical Shrubs for Soil Bioengineering Applications

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ABSTRACT

The use of tropical shrub species in soil bioengineering has gained increasing attention for slope stabilisation; however, information on their biomechanical contribution to an amended tropical residual soil medium remains limited. This study evaluated the root tensile behaviour, soil shear reinforcement of planting substrate, and root–substrate micromorphology of *Strobilanthes crispata* (SC) and *Pseuderanthemum carruthersii* (PC) cultivated for six months in a modified residual-soil planting substrate. Root tensile tests were conducted across diameter classes, while unconsolidated-undrained (UU) triaxial tests on reconstructed specimens reinforced with manually inserted vertical roots and Field Emission Scanning Electron Microscopy (FESEM) were used to assess soil reinforcement mechanisms and root–soil interactions. Root tensile strength followed an inverse power-law relationship, ranging from 0.72–9.79 MPa for PC and 0.51–21.67 MPa for SC, highlighting the importance of fine roots. In triaxial testing, artificially root-reinforced soil specimens exhibited significantly higher maximum shear stress ($\tau_{\max}$) than non-vegetated soil. At 200 kPa confining pressure, SC recorded the highest $\tau_{\max}$ (248.9 ± 16.67 kPa), followed by PC (231.1 ± 0.01 kPa), and control soil (214.8 ± 2.30 kPa). Strong linear relationships between $\tau_{\max}$ and confining pressure were observed ($R^2 = 0.9689 - 0.9943$), accompanied by slight reductions in apparent cohesion (100.30 kPa in the control soil, 91.80 kPa in SC & 90.05 kPa in PC) and substantial increases in internal friction angle (29.52° , 39.87° , and 38.24° , respectively). FESEM analysis revealed denser aggregate packing, finer root fibrils ($232.9 \mu\text{m}$) and stronger root-soil interlocking in SC than in PC, with larger fibrils ($251.9 \mu\text{m}$). These findings demonstrate that both species, particularly *Strobilanthes crispata*, possess favourable biomechanical characteristics for sustainable shallow slope stabilisation when utilised within modified residual-soil planting substrates.

Key words: FESEM microstructural analysis; *Pseuderanthemum carruthersii*; root tensile strength; *Strobilanthes crispata*; triaxial shear test; modified planting substrate.

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INTRODUCTION

Soil erosion and shallow slope instability are among the major environmental problems affecting tropical regions due to high rainfall intensity, highly weathered residual soils, and increasing land disturbance activities associated with urbanisation and infrastructure development (Morgan, 2005; Osman & Barakbah, 2011). In Malaysia, annual rainfall exceeding 2000 mm contributes to rapid surface runoff generation and sediment transport, particularly on exposed slopes lacking sufficient vegetation cover. Under intense rainfall conditions, the direct impact of raindrops on bare soil surfaces accelerates splash erosion, soil

particle detachment, and shallow slope failure processes (De Baets *et al.*, 2007). These conditions frequently occur along roadside embankments, construction slopes, and degraded tropical landscapes, resulting in severe environmental and infrastructural impacts.

Conventional slope stabilisation methods such as concrete retaining systems and synthetic reinforcements are widely used to reduce slope instability. However, these approaches are often expensive, environmentally disruptive, and less sustainable under tropical ecological conditions (Gray & Sotir, 1996). Consequently,

soil bioengineering has gained increasing attention as an environmentally sustainable alternative that integrates vegetation with engineering principles for slope stabilisation and erosion control (Stokes *et al.*, 2014). Vegetation contributes to slope stability through hydrological effects such as rainfall interception and evapotranspiration, as well as mechanical reinforcement provided by root systems within soil matrices (Mickovski & Van Beek, 2009; Gonzalez-Ollauri & Mickovski, 2017; Tang *et al.*, 2018).

Among these hydrological and mechanical slope stabilisation mechanisms, root reinforcement plays an important role in improving the mechanical stability of shallow soils. Plant roots function as natural tensile reinforcements that bind soil particles, increase apparent cohesion, and improve stress redistribution during shear deformation (Wu *et al.*, 1979; Docker & Hubble, 2008). Root systems also enhance soil structure and interparticle bonding, thereby increasing resistance against shallow soil displacement and erosion processes (Loades *et al.*, 2010). The reinforcing effect of roots is strongly influenced by root architecture, root density, root orientation, and root tensile behaviour within soil systems (Hales *et al.*, 2009; Mao *et al.*, 2012).

Root tensile strength is widely recognised as a key biomechanical parameter for evaluating vegetation reinforcement capacity. In many plant species, tensile strength decreases with increasing root diameter following an inverse power-law relationship (Burylo *et al.*, 2011; Hales *et al.*, 2013). Fine roots generally exhibit greater tensile resistance due to denser fibre arrangement and higher cellulose organisation compared with thicker roots (Genet *et al.*, 2005). These properties directly influence the ability of roots to improve soil shear resistance and reinforce shallow soil layers under loading conditions. Recent reviews have further highlighted the importance of root mechanical properties in improving soil stability and erosion resistance under varying environmental conditions (Bordoloi & Ng, 2020; Masi *et al.*, 2021).

Previous studies on vegetation reinforcement have primarily focused on grasses and tree species for slope stabilisation applications (Reubens *et al.*, 2007; Bordoloi & Ng, 2020). Although grasses provide rapid surface protection and trees offer deeper anchorage systems, shrub species may provide more effective shallow reinforcement through dense root networks and rapid canopy establishment under tropical conditions. Shrub vegetation also possesses advantages including adaptability to disturbed soils, lower maintenance requirements, and continuous surface coverage suitable for tropical slope rehabilitation (Stokes *et al.*, 2009). Root networks increase soil shear resistance by mitigating shearing deformation through tensile reinforcement and improved particle bonding (Docker & Hubble, 2008; Li *et al.*, 2022). Consequently, variations in root morphology, diameter, orientation, and distribution directly dictate how root inclusion alters the soil's apparent cohesion and internal friction angle (Mickovski & Van Beek, 2009; Mao *et al.*, 2012).

Despite these advantages, information regarding the combined tensile behaviour, shear reinforcement mechanisms, and root-soil micromorphological interactions of tropical shrub species remains scarce. Furthermore, studies integrating macroscale root tensile testing, unconsolidated-undrained (UU) triaxial shear assessment, and microscale FESEM-based evaluation within a single experimental framework are still severely limited, particularly under tropical conditions. The microscale mechanisms governing root-soil interaction and how root inclusion alters soil failure boundaries, improves post-peak deformation behaviour, and enhances stress redistribution remain insufficiently understood in tropical artificially root-reinforced soil systems.

Therefore, this study provides a comprehensive assessment of the biomechanical and microstructural performance of two tropical shrub species, *Strobilanthes crispata* (SC) and *Pseuderanthemum carruthersii* (PC), cultivated in a modified soil medium under controlled conditions. These shrubs were selected due to their high adaptability to tropical environments, rapid growth characteristics, and well-developed root systems, which are highly expected to contribute to effective soil reinforcement (Osman & Barakbah, 2011; Masi *et al.*, 2021). Specifically, this study investigated the relationship between root diameter and tensile strength, determined the influence of artificially root-reinforced soil on shear behaviour under UU triaxial conditions, and elucidated the underlying microstructural parameters governing the root-soil interface. It was hypothesised that artificially root-reinforced soils would exhibit greater shear resistance than non-vegetated soils due to root-induced reinforcement, with differences in species-specific root tensile characteristics uniquely influencing soil failure pathways and stress redistribution during loading (Stokes *et al.*, 2009). The conceptual mechanisms of root reinforcement in tropical root-reinforced soil, including rainfall interception, runoff reduction, root-soil interlocking, and shallow shear resistance, are illustrated in Figure 1.

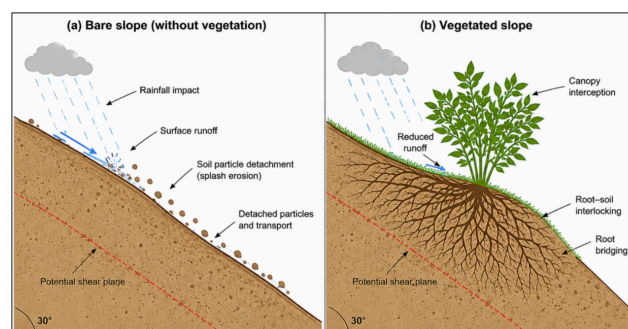


Fig. 1. Schematic illustration of root reinforcement mechanisms in tropical root-reinforced soil, showing rainfall interception, runoff reduction, root-soil interlocking, and shallow shear resistance. Both slopes are presented at the same inclination (30°) for accurate comparison.

MATERIALS AND METHODS

Study area and plant materials

This study was conducted at Taman Botani Bangi (TBB), Universiti Kebangsaan Malaysia (UKM), Bangi, Selangor, Malaysia. The study area is located within a tropical humid climatic region characterised by high annual rainfall and highly weathered residual soils. The geological formation of the area mainly consists of meta-sedimentary materials associated with the Kajang Formation, which is commonly exposed to erosion and shallow slope instability under tropical environmental conditions (Rahman & Mapjabil, 2017; Ghani *et al.*, 2020).

Two tropical shrub species, *Strobilanthes crispata* (SC) and *Pseuderanthemum carruthersii* (PC), were selected based on their adaptability to tropical environments, dense root systems, and potential suitability for slope bioengineering applications (Abdi, 2018; Masi *et al.*, 2021). Stem cuttings approximately 15 cm in length were obtained from healthy mother plants and propagated in a nursery before transplantation into polybags containing a modified soil medium. The modified soil medium consisted of slope soil, organic matter, sand, and chicken manure at a ratio of 3:1:1:1 by volume (soil: organic matter: sand: chicken manure). This formulation aimed to enhance soil fertility, water retention, and root development under controlled planting conditions. Similar soil amendment approaches have been widely used to improve vegetation establishment and root growth in slope bioengineering

studies (Bordoloi & Ng, 2020; Osman & Barakbah, 2011). The transplanted shrubs were cultivated in this medium under shaded conditions at Taman Botani Bangi, Universiti Kebangsaan Malaysia, for six months prior to root tensile and shear strength testing to ensure sufficient root establishment and biomechanical development within the soil medium.

It is important to note that the substrate used in this study represents an amended residual-soil planting medium, not unamended natural tropical residual soil. The addition of sand, organic matter, and chicken manure altered the baseline geotechnical and microstructural properties of the original slope soil. Specifically, increased sand content may reduce cohesion associated with clay while enhancing frictional interlocking. Meanwhile, the organic amendments promote a more porous structure, which facilitates root penetration and may reduce dry bulk density (Kim *et al.*, 2018). Consequently, the apparent cohesion, internal friction angle, shear behaviour, and FESEM microstructural characteristics reported here should be interpreted as properties of this modified planting substrate and its interaction with roots. Direct extrapolation to natural in-situ tropical residual soils should therefore be made with caution, as field soils can differ significantly in clay content, organic matter, density, weathering structure, and other factors governing root–soil interaction (Chok *et al.*, 2015; DiBiagio *et al.*, 2024).

Root tensile strength test

Root tensile strength testing was conducted after six months of planting to evaluate the biomechanical properties of the studied shrub species. Healthy roots were carefully excavated from the soil medium and washed gently using distilled water to remove adhered soil particles without damaging the root structure. Root samples represented a range of diameter classes, including fine (< 2 mm), medium (2–5 mm), and coarse (> 5 mm) roots. A total of 40 root samples were tested for each species (SC & PC), covering a wide range of root diameters to capture variability in root tensile behaviour.

Root diameter (d) was measured at three points along each root segment: the midpoint and both ends. The average of these three measurements was calculated and utilised as the representative root diameter to account for natural variations in root taper and morphology. All measurements were conducted using a digital calliper with an accuracy of 0.01 mm. Root tensile testing was performed using a universal testing machine following procedures commonly applied in root biomechanics studies (Genet *et al.*, 2005; Loades *et al.*, 2010). Root samples were trimmed to a gauge length of 10 cm prior to testing. The root ends were secured using sandpaper to minimise slippage during loading following ASTM D3379-75 (1989). Uniaxial tensile force was applied at a constant displacement rate of 5 mm min⁻¹ until failure (Table 1).

The maximum tensile force ($F_{\max}$) at root failure was recorded, and the corresponding maximum root tensile strength ($T_{\max}$) was calculated based on the cross-sectional area of the root using Equation 1:

$$T_{\max} = \frac{4F_{\max}}{\pi d^2}$$

where $T_{\max}$ is the maximum root tensile strength (MPa), $F_{\max}$ is the maximum tensile force (N), and d is the average root diameter (mm). The relationship between root diameter and tensile strength was analysed using a power-law regression model widely reported in vegetation biomechanics studies (Burylo *et al.*, 2011; Hales *et al.*, 2013).

Preparation of artificially root-reinforced soil specimens

The fabrication of artificially root-reinforced soil specimens was carried out following a six-month cultivation period to evaluate the mechanical influence of root inclusion on soil shear behaviour (Li *et al.*, 2022). Roots from both SC and PC were carefully retrieved and manually inserted vertically within the remoulded soil matrices prior to triaxial shear testing (Fan & Su, 2008). Control specimens without manually inserted roots were also prepared for comparison. A standardised composite soil medium consisting of slope soil, organic matter, sand, and chicken manure at a volumetric ratio of 3:1:1:1 was utilised to prepare the remoulded specimens to minimise baseline heterogeneity across replicates (Osman & Barakbah, 2011). During specimen fabrication, the gravimetric moisture content was strictly maintained at approximately 20% to achieve consistent compaction density and structural stability during subsequent loading (Fan & Su, 2008).

An estimated degree of saturation (S_r) of 0.56 was determined based on this target water content, confirming that the remoulded soil samples remained in a moderately unsaturated condition throughout the unconsolidated-undrained (UU) triaxial procedures. Following the initial mixing phase, the moistened soil mass was sealed and allowed to equilibrate for 30 min to facilitate homogeneous moisture distribution. The baseline physico-chemical characteristics of the original slope soil used in the preparation of the amended planting substrate are presented in Table 2.

Cylindrical soil specimens, approximately 45 mm in diameter and 90 mm in height, were prepared for unconsolidated-undrained (UU) triaxial shear testing in accordance with ASTM D2850-15. To ensure consistent root density across treatments and simulate the dominant structural root fraction after six months of growth, five roots (1.5–2.0 mm in diameter) were vertically arranged within each specimen. This configuration, which utilised species-specific root diameters as detailed in Table 1, resulted in a Root Area Ratio (RAR) of approximately 0.71% for SC and 0.95% for PC. These RAR values align with the low root densities reported for naturally rooted tropical shrub and woody vegetation (Avani *et al.*, 2013; Stokes *et al.*, 2014; Lee *et al.*, 2020). This five-root arrangement also balanced the objective of achieving measurable root reinforcement with the necessity of preserving specimen integrity. A greater number of manually inserted roots could have led to excessive soil disturbance, localised void formation, and inconsistent compaction in the remoulded specimens. The vertical root orientation was chosen to simulate shallow root reinforcement common in tropical shrub vegetation systems (Docker & Hubble, 2008; Fan & Su,

Table 1. Quantitative root network parameters within the artificially root-reinforced specimens.

Species	Number of roots crossing failure plane (N)	Total root cross-sectional area (A_r , mm ²)	Root Area Ratio (RAR, %)	Root Volume Ratio (RVR, %)	Average root spacing (S , mm)
SC	5	11.23	0.71	0.79	15.20
PC	5	15.10	0.95	1.06	15.20

Note: PC - *Pseuderanthemum carruthersii*, SC - *Strobilanthes crispus*. Calculations are based on a specimen diameter of 45 mm ($A = 1590.43$ mm²) and average root diameters of 1.70 mm for SC and 1.96 mm for PC.

2008). Control specimens without roots were also prepared for comparison.

UU triaxial shear test

Unconsolidated-undrained (UU) triaxial shear tests were conducted to evaluate the influence of root reinforcement on the shear behaviour of artificially root-reinforced soil specimens. The tests were performed using a standard triaxial testing apparatus following ASTM D2850-15 procedures for cohesive soils under unconsolidated-undrained conditions. Artificially root-reinforced and non-vegetated control soil specimens were subjected to confining pressures of 50, 100, and 200 kPa to simulate different loading conditions commonly associated with shallow slope environments. Axial loading was continuously applied until specimen failure occurred, and the corresponding stress-strain responses were recorded throughout the testing process.

A total of 18 artificially root-reinforced specimens and 9 control specimens without roots were prepared. Each treatment consisted of three replicate specimens for each confining pressure condition (50, 100 & 200 kPa). Soil shear strength parameters, including apparent cohesion (c) and internal friction angle (φ), were determined using the Mohr-Coulomb failure criterion. The shear strength of artificially root-reinforced soil was expressed as:

$$\tau = c_s + c_r + \sigma_n \tan \varphi$$

where τ is the soil shear strength, c_s is the soil cohesion component, c_r is the root-associated apparent cohesion component, φ is the internal friction angle, and σ_n is the applied normal stress. In artificially root-reinforced soil specimens, the inclusion of plant roots is conventionally assumed in the theoretical models (such as the Wu-Waldron model) to contribute an additional shear strength component primarily in the form of root-associated cohesion, c_r (Wu, 1979; Ghestem *et al.*, 2011). However, to maintain experimental objectivity and account for potential physical variations induced during specimen preparation, this study evaluated the overall alterations to both the apparent cohesion (c) and the internal

friction angle (φ) parameters, rather than assuming a unilateral cohesion enhancement.

Statistical analysis

Experimental data were analysed using descriptive statistics and regression analysis. A one-way Analysis of Variance (ANOVA) was performed to compare the mean maximum shear stress ($\tau_{\max}$) among treatments (soil reinforced with *Strobilanthes crispata* (SC), soil reinforced with *Pseuderanthemum carruthersii* (PC), and non-vegetated control soil) to evaluate the biomechanical contribution of root inclusions under shear deformation at confining pressure levels of 50, 100, and 200 kPa. This analysis assessed the influence of different root inclusions. Where significant differences were indicated by the ANOVA, Tukey's Honestly Significant Difference (HSD) post-hoc test was applied for multiple pairwise comparisons of means at a significance level of $p < 0.05$. Regression analysis was conducted to evaluate the relationship between root diameter and tensile strength using a power-law model commonly applied in root biomechanics studies (Genet *et al.*, 2005; Burylo *et al.*, 2011). The relationships between maximum shear stress ($\tau_{\max}$) and confining pressure (σ_3) were also evaluated using linear regression analysis. Coefficients of determination (R^2) were used to assess the strength of the regression relationships. All statistical analyses were performed using IBM SPSS Statistics software.

RESULTS AND DISCUSSION

Root tensile strength characteristics

Table 3 summarises the root tensile properties and power-law regression relationships of PC and SC, while Figure 2 illustrates the relationship between maximum root tensile strength ($T_{\max}$) and root diameter (d). The analysis was based on 40 root samples for each species (SC and PC), providing sufficient representation of root diameter variability and tensile response patterns. Both species exhibited the expected inverse power-law trend ($T_{\max} = \alpha d^{-\beta}$), indicating the important reinforcing role of fine roots in soil stabilisation (Genet *et al.*, 2005; Hales *et al.*, 2013).

Table 2. Summary of the physico-chemical characteristics of the original slope soil

Parameter	Soil
Physical properties	
Soil texture	Clay loam
Bulk density, g cm ⁻³	1.08 ± 0.05
Specific gravity, G_s	2.96 ± 0.06
Moisture content, %	29.21 ± 12.56
Particle size distribution, %	
Clay	31.29 ± 9.65
Silt	30.43 ± 15.19
Sand	38.28 ± 7.75
Hydraulic property	
Hydraulic conductivity, cm hr ⁻¹	1.71 ± 0.80
Chemical properties	
pH	4.62 ± 0.33
Organic content, %	6.14 ± 1.01
Consistency limits	
Liquid limit (LL), %	32.52 ± 2.32
Plastic limit (PL), %	27.31 ± 2.32
Plasticity index (PI)	5.21 ± 2.22

Table 3. Root tensile properties and regression relationships of SC and PC after six months of planting.

Species	Root diameter range (mm)	Tensile strength range (MPa)	Regression equation	R ²
SC	0.30-6.68	0.51-21.67	$T_{\max} = 2.8496d^{-0.437}$	0.0831
PC	0.43-4.66	0.72-9.79	$T_{\max} = 3.0067d^{-0.34}$	0.1259

Note: PC - *Pseuderanthemum carruthersii*, SC - *Strobilanthes crispus*, $T_{\max}$ = maximum root tensile strength; d = root diameter.

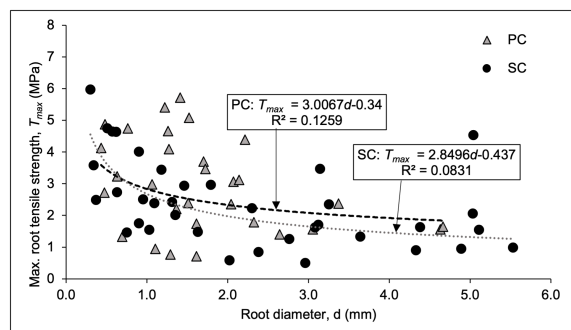


Fig. 2. Relationship between root tensile strength ($T_{\max}$) and root diameter for PC and SC after six months of planting.

The calculated regression equations revealed distinct biomechanical behaviours between the two species. PC exhibited a tensile strength range of 0.72 to 9.79 MPa across a root diameter range of 0.43 to 4.66 mm, governed by the power-law equation $T_{\max} = 3.0067d^{-0.34}$ ($R^2 = 0.1259$). In contrast, SC demonstrated a substantially wider tensile strength range from 0.51 to 21.67 MPa across a wider diameter spectrum of 0.30 to 6.68 mm, adhering to the relationship $T_{\max} = 2.8496d^{-0.437}$ ($R^2 = 0.0831$). The low R^2 ($R^2 = 0.0831 - 0.1259$) values indicate substantial natural variability among root samples, which may be influenced by differences in root age, anatomy, moisture content, and developmental heterogeneity (Genet *et al.*, 2005; Hales *et al.*, 2013).

The fundamental phenomenon where $T_{\max}$ decreased with increasing root diameter indicates that the finer root fractions of both tropical shrubs contribute with more efficiently to tensile reinforcement within shallow soil layers. Biochemically and anatomically, this behaviour is largely attributed to the fact that fine roots inherently possess a denser fibre arrangement, higher cellular organisation, and a greater proportion of alpha-cellulose content per unit area compared to their thicker, more lignified counterparts (Genet *et al.*, 2005). Thicker roots often undergo secondary growth, leading to an increased ratio of mechanical cortex or pith tissue relative to structural xylem vessels, which subsequently lowers the overall tensile stress resistance. Although SC exhibited a markedly broader tensile strength distribution and a higher maximum peak value (21.67 MPa) than PC (9.79 MPa), the persistent inverse power-law signature in both profiles reflects a shared biomechanical adaptation strategy (Burylo *et al.*, 2011; Loades *et al.*, 2010). Fine roots from both species likely play an important role in reinforcing shallow amended tropical residual soil medium.

Stress-strain behaviour of artificially root-reinforced soil

The deviatoric stress-strain responses of the non-vegetated control and artificially root-reinforced soil specimens under varying confining pressures ($\sigma_3 = 50, 100$ and 200 kPa) are presented in Figure 3. Across all applied confining pressures, the artificially root-reinforced soil specimens consistently exhibited higher maximum shear stress ($\tau_{\max}$) thresholds compared to the non-vegetated control soil, directly implying an enhanced structural resistance to baseline shear deformation. As expected under the Mohr-Coulomb framework, increasing the confining pressure led to a corresponding increase in mobilised shear resistance for all

treatments, primarily because greater confinement intensifies particle-to-particle contact and frictional interlocking within the compacted soil matrix. However, the net magnitude of stress mobilisation was markedly and consistently higher in the vegetated specimens, verifying that the presence of shrub roots remains mechanically active and effective across different engineering confinement states.

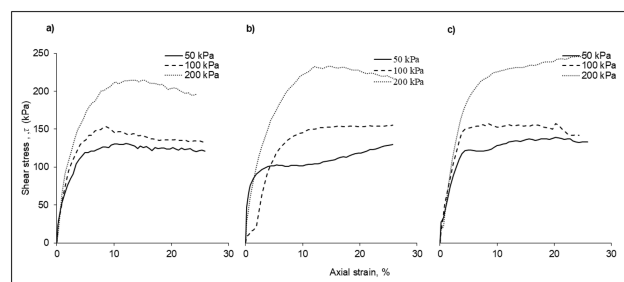


Fig. 3. Stress-strain behaviour of (a) non-vegetated soil, (b) PC-reinforced soil, and (c) SC-reinforced soil under different confining pressures.

A distinct divergence in the post-peak failure mechanics was observed between the bare and artificially root-reinforced soils. The non-vegetated control soil displayed a relatively sharp, abrupt reduction in shear stress immediately after reaching its peak strength, which is a classic manifestation of brittle shear failure modes. In stark contrast, the soil specimens integrated with plant roots displayed a more gradual, controlled post-peak stress reduction and significantly improved deformation stability throughout the shearing process. This transition from brittle to highly ductile failure behaviour is directly credited to the spatial reinforcing role of the root networks. The roots function effectively as flexible tensile inclusions that bridge emerging shear planes, thereby actively redistributing shear loads and resisting progressive lateral soil displacement under continuous axial loading conditions (Wu *et al.*, 1979; Docker & Hubble, 2008).

Comparatively, *Strobilanthes crispus* (SC) demonstrated a more stable stress-strain response and improved post-peak behaviour compared to *Pseuderanthemum carruthersii* (PC). Although the natural macro-architecture, such as branching patterns and spatial network distribution, was not preserved in these reconstructed, vertically reinforced laboratory specimens, the superior shear resistance of SC-reinforced specimens reflects the higher intrinsic material and biomechanical qualities of its individual root fibres. Consequently, even when arranged as individual vertical inclusions, SC roots mobilised higher interface frictional resistance than PC roots. In real-world, in-situ slope applications, the dense, highly branched shallow root architecture characteristic of SC would provide an additional structural advantage. This intact branching network would naturally increase volumetric root density and offer a compounding spatial reinforcement effect, potentially yielding even greater soil reinforcement than observed under these controlled, single-fibre laboratory triaxial conditions.

Table 4. Shear strength parameters of artificially root-reinforced soil specimens under UU triaxial shear testing.

Treatment	Confining pressure, σ_3 (kPa)	Maximum shear stress, τ_{max} (kPa)	Apparent cohesion, c (kPa)	Internal friction angle, φ (°)
SC	50	138.0 ± 4.94 ^a	91.8 ± 25.77	39.87 ± 8.00
	100	156.5 ± 0.88 ^a		
	200	248.9 ± 16.67 ^a		
PC	50	128.0 ± 0.95 ^b	90.1 ± 54.06	38.24 ± 7.22
	100	154.4 ± 4.19 ^a		
	200	231.1 ± 0.01 ^{ab}		
C	50	111.1 ± 0.66 ^c	100.3 ± 19.13	29.52 ± 0.68
	100	153.2 ± 1.52 ^a		
	200	214.8 ± 2.30 ^b		

Note: Values are presented as mean ± standard deviation ($n = 3$). SC = soil specimens reinforced with *Strobilanthes crisper* roots; PC = soil specimens reinforced with *Pseuderanthemum carruthersii* roots; C = unreinforced control soil specimens. Different lowercase superscript letters within the same confining pressure indicate significant differences among treatments based on one-way ANOVA followed by Tukey's HSD test ($p < 0.05$).

Shear strength parameters of artificially root-reinforced soil

The shear strength parameters obtained from the UU triaxial shear tests are summarised in Table 4, while the corresponding Mohr–Coulomb failure envelopes are presented in Figure 4. Artificially root-reinforced soil specimens exhibited clear improvements in shear resistance compared with the non-vegetated control soil.

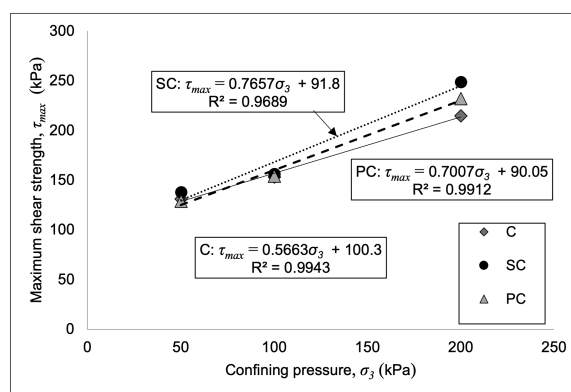


Fig. 4. Mohr–Coulomb shear strength envelopes of artificially root-reinforced soil specimens containing tropical shrub roots under UU triaxial shear testing.

The maximum shear stress, τ_{max} , of soil specimens artificially reinforced with *S. crisper* (SC) roots was significantly greater than that of both the *P. carruthersii* (PC) artificially reinforced and non-vegetated control specimens ($p < 0.05$) at 50 kPa. The differences were not statistically significant ($p = 0.3602$) at 100 kPa. At 200 kPa, the SC root-reinforced specimens recorded a significantly higher maximum shear stress than the non-vegetated control specimens ($p < 0.05$), while the PC root-reinforced specimens showed intermediate performance. The slight reduction in apparent cohesion (c) from 100.30 kPa (Control) to 91.80 kPa (SC) and 90.05 kPa (PC) is attributed to the localised structural disturbance and micro-void formation during the vertical insertion of roots into the remoulded soil matrix (Fan & Su, 2008; Ghestem *et al.*, 2011). However, this reduction was substantially compensated for by an increase in the internal friction angle (φ), which rose from 29.52° to 39.87° (SC) and 38.24° (PC). This response indicates a transition from cohesion-dominated behaviour to friction-dominated mechanical reinforcement, whereby root systems enhanced soil strength through particle interlocking, tensile bridging, and more efficient

stress transfer during shear deformation (Docker & Hubble, 2008; Mickovski & Van Beek, 2009).

Theoretical models, such as the Wu-Waldron model, typically assume that plant roots enhance soil shear strength by increasing root-associated apparent cohesion (c_r). However, our experimental results contradict this assumption, showing a slight decrease in the apparent cohesion (c) of artificially root-reinforced specimens. Specifically, apparent cohesion dropped from 100.30 kPa in the non-vegetated control to 91.80 kPa for SC and 90.05 kPa for PC. This contradiction arises from the specimen fabrication method. Manually inserting roots vertically into the remoulded soil matrix inevitably caused localised structural disturbances, macro-shearing, and micro-voids along the root-soil interface. This physical disruption partially compromised the soil's native cohesive structure (c_s), leading to a net reduction in the overall measured apparent cohesion. Therefore, the reinforcement provided by the roots in these specimens is not reflected as an increase in cohesion (c_r). Instead, it manifests as a substantial increase in the internal friction angle (φ). This increase is driven by root-soil particle interlocking, tensile bridging, and frictional transfer along the fibrils, as observed in FESEM analysis. This suggests that for artificially root-reinforced specimens, root reinforcement primarily operates through a friction-dominated mechanism rather than enhanced cohesion.

Furthermore, it must be noted that the classical Wu-Waldron model operates under the simplifying assumption of simultaneous root tensile mobilisation, which often overpredicts root reinforcement in the field. Natural root failure along a shear plane is progressive, with roots rupturing sequentially. This process is influenced by the balance between root pull-out resistance and tensile rupture, as well as by root spatial orientation. However, our laboratory specimens used manually inserted vertical roots, which did not replicate the complex natural root architecture and its progressive failure modes. This is a key limitation of our laboratory-scale assessment. Upon post-test specimen analysis, we observed distinct failure mechanisms for integrated roots. Thicker root segments (diameters > 1.8 mm) primarily failed due to interface slippage and pull-out. This is likely because their limited anchorage length within the triaxial specimen dimensions prevented full tensile mobilization. In contrast, finer roots (diameters < 1.2 mm) predominantly experienced tensile rupture near the shear failure plane, indicating they mobilised their full tensile capacity during shear. This mechanistic interpretation is further supported by the

FESEM observations, which revealed denser aggregate packing, reduced pore spaces, and stronger root–soil interaction, particularly in the SC-reinforced soil. Similar reinforcement mechanisms have been reported in previous studies, where root networks have been shown to enhance soil shear resistance through physical binding and frictional transfer along the root–soil boundary (Docker & Hubble, 2008; Mickovski & Van Beek, 2009). Furthermore, strong positive relationships between maximum shear stress and confining pressure (σ_3) were observed for both species, with R^2 values ranging from 0.9689 to 0.9943. These statistical and experimental outcomes clearly demonstrate that the inclusion of shrub roots significantly improved the ability of the amended residual soil–medium to resist shear deformation under increasing loading conditions.

Overall, the shear strength results demonstrate that both tropical shrub species contributed significantly to shallow soil reinforcement under UU triaxial conditions. These findings strongly support the suitability of utilising tropical shrub vegetation as an effective biological reinforcement material for sustainable slope stabilisation and erosion mitigation in tropical environments.

Micromorphology and root–soil interaction

The FESEM micrographs revealed distinct differences in soil microstructure between the control and artificially root-reinforced soil specimens (Figure 5). The micromorphological characteristics observed from the FESEM analysis are summarised in Table 5.

The control soil exhibited a loose aggregate structure with large pore spaces, whereas the artificially root-reinforced soils showed improved aggregate stability and distinct root–soil interaction features. The absence of root fibrils in the control specimens resulted in limited particle binding and reduced aggregate stability, making the soil matrix more susceptible to structural degradation and subsequent shear deformation. Similar observations have been reported in soils lacking biological reinforcement, where poor aggregate stability is closely associated with higher erosion susceptibility and lower mechanical resistance (Bronick & Lal, 2005; Le Bissonnais *et al.*, 2007).

In contrast, soil reinforced by SC exhibited a dense and stable microstructure, with soil particles tightly bound to a network of fine root fibrils approximately 232.9 μm in diameter. Soil aggregates ranging from 50 to 330 μm were closely packed with limited pore spaces, indicating enhanced aggregate stability and improved root–soil interaction. This dense fibril network likely increased particle interlocking and the overall contact area between the roots and soil particles, thereby contributing to greater resistance against soil displacement. The enhanced aggregate packing observed in the SC-reinforced soil is highly consistent with its higher internal friction angle (39.87°) and greater maximum shear stress under increasing confining pressures. The dense root fibril network effectively increased particle contacts and mechanical interlocking within the soil matrix, thereby improving frictional resistance

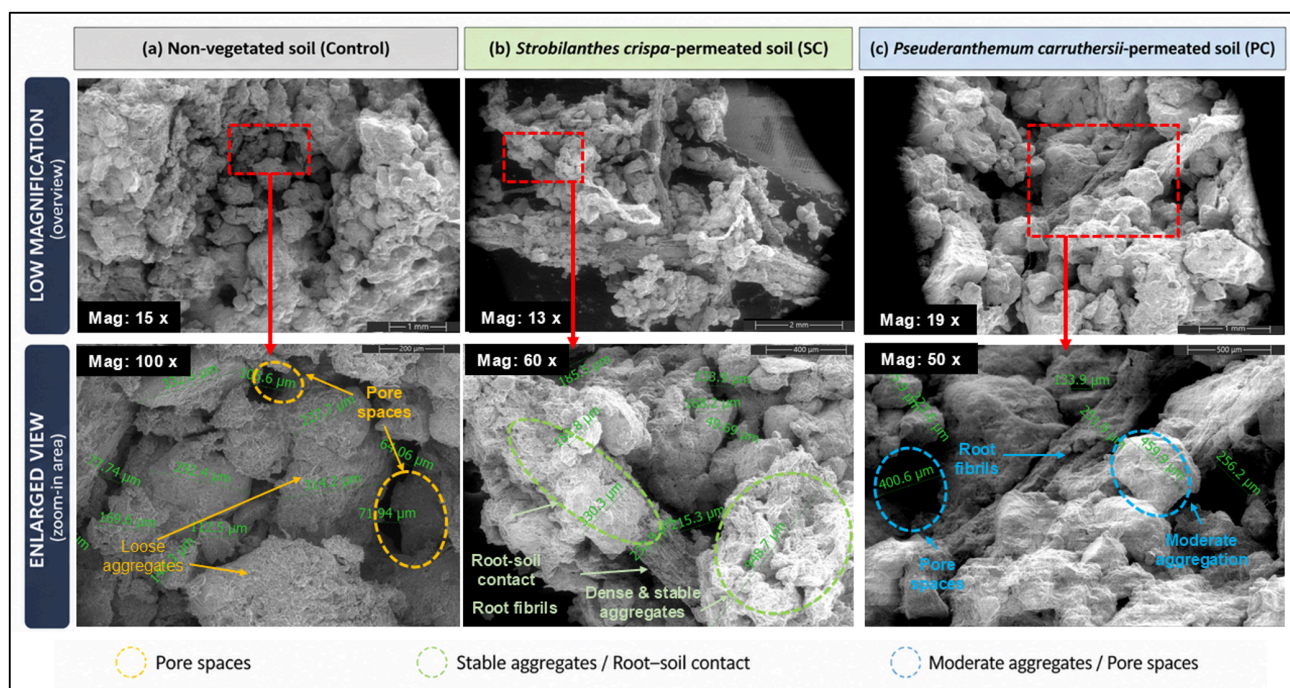


Fig. 5. FESEM micrographs showing root–soil interaction in (a) non-vegetated soil, (b) SC-reinforced soil, and (c) PC-reinforced soil.

Table 5. Comparison of micromorphological characteristics between non-vegetated soil and artificially root-reinforced soils of SC and PC.

Parameter	C	SC	PC
Aggregate structure	Loose	Dense and stable	Moderately stable
Root fibrils	Absent	Present (232.9 μm)	Present (251.9 μm)
Aggregate size	Random	50–330 μm	100–500 μm
Pore spaces	Large and abundant	Limited	More apparent
Root–soil interlocking	Absent	Strong	Moderate

Note: PC - *Pseuderanthemum carruthersii*, SC - *Strobilanthes crisper*, C - Control

during shear deformation. This microstructural behaviour directly supports the interpretation that root reinforcement contributed primarily through friction-dominated mechanisms rather than cohesion enhancement alone. Similar mechanisms have been reported in root-reinforced soils where fine roots improve aggregate stabilisation and mechanical reinforcement through physical binding effects (Ghestem *et al.*, 2011; Vergani *et al.*, 2016).

The microstructure of the PC-reinforced soil was generally stable but appeared less compact than that observed in the SC specimens. Root fibrils with diameters of approximately 251.9 µm were associated with moderately aggregated soil particles and more pronounced pore spaces. Although root–soil interaction was clear, the larger pore spaces suggest a lower aggregate packing efficiency compared with SC. The presence of root fibrils and aggregated soil particles nevertheless confirmed that PC contributed positively to soil reinforcement through root–soil bonding and tensile bridging mechanisms. Although the aggregate packing appeared less dense than in SC, the observed microstructural interaction was sufficient to improve soil shear resistance relative to the non-vegetated control. This observation is consistent with the macroscale stress–strain behaviour, where PC showed improved strength relative to the control, even though SC exhibited more stable post-peak deformation behaviour and superior stress redistribution under loading conditions.

Overall, the FESEM observations provide direct microstructural evidence supporting the macroscale tensile and triaxial shear test results. The presence of root fibrils, denser aggregate arrangements, and enhanced root–soil interlocking clearly demonstrates how shrub root systems improve soil mechanical stability. These observations successfully establish a mechanistic link between microscale root–soil interactions and macroscale improvements in shear resistance, highlighting the vital role of root architecture in tropical soil bioengineering applications.

CONCLUSION

Both *Strobilanthes crisper* and *Pseuderanthemum carruthersii* demonstrated favourable biomechanical characteristics for tropical soil bioengineering applications. Root tensile strength in both species followed an inverse power-law relationship with root diameter, highlighting the important reinforcing role of fine roots. Under UU triaxial shear conditions, artificially root-reinforced soils exhibited higher shear resistance than non-vegetated soil, accompanied by increased internal friction angles and improved post-peak deformation behaviour.

Among the two species, *Strobilanthes crisper* exhibited greater reinforcement potential, as reflected by its higher maximum shear stress, stronger root–soil interlocking, denser aggregate packing, and more stable stress–strain response. FESEM observations further demonstrated that root inclusion enhanced aggregate stability and promoted stronger root–soil interactions, providing microstructural evidence for the observed improvements in soil mechanical behaviour. The integration of root tensile testing, UU triaxial shear assessment, and FESEM analysis provides a useful framework for evaluating vegetation-based reinforcement mechanisms in an amended tropical residual-soil medium. Overall, the findings support the use of shrub-based vegetation systems, particularly *Strobilanthes crisper*, as a sustainable nature-based approach for shallow slope stabilisation and soil erosion control using modified residual-soil planting substrates.

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ETHICAL STATEMENT

This study did not involve human subjects, animal experimentation, or sensitive biological materials. All plant materials were sourced locally and handled in accordance with institutional guidelines.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

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