Soil reinforcement capability of two legume species from plant morphological traits and mechanical properties

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Vegetation is an essential tool to reinforce soil and improve slope stability. Two legume species, lead tree (*Leucaena leucocephala*) and copperpod (*Peltophorum pterocarpum*), were tested in terms of their capacity for soil reinforcement using a modified laboratory shear box. In addition, morphological parameters of the plant and root tensile strength were measured, while root composition also was analysed. Root system significantly contributed to increase the shear strength and residual strength of soil. The soil–root matrix of both species significantly affected the cohesion but not the angle of friction. Overall effects varied with soil depth and plant species. Lead tree showed higher soil shear strength and residual strength compared to copperpod. It also exhibited higher root biomass, root length, fine roots, root tensile strength and concentration of cellulosic components in root than copperpod, indicating a higher contribution to soil–root matrix, soil shear strength and soil reinforcement. A positive correlation (*r* = 0.99) was observed between root biomass and soil shear strength of the species studied. Likewise, root cellulosic components and soil shear strength were positively correlated. Overall, lead tree exhibited exceptional root profiles and mechanical properties and can be the best suited plant for soil reinforcement.

Keywords: Cellulosic components, root biomass, soil reinforcement, shear strength, tensile strength.

SOIL reinforcement is one of the major ways in which vegetation influences slope stability. The degree of soil reinforcement depends on the engineering properties of plants, which in turn are combined functions of morphological and mechanical characteristics of the root system such as length, tensile strength, cellulose content, length/diameter ratio and orientation[1–4]. However, root strength and distribution within the soil are major variables for assessing the magnitude of soil reinforcement[5]. Vegetation increases slope stability by providing soil shear strength via soil–root interaction. In the presence of a root matrix, the shear strength of the soil mass is enhanced due to increased cohesion and intertwining of root–soil particles[6,7]. If the non-rooted (bare) soils expand their volumes, both the density of soil particles and the shear strength will tend to decrease. In addition, the rooted soil can provide substantial increment in shear strength via root distribution within the soil[8]. Therefore, vegetated soil is more capable of resisting continuous deformation without loss of residual strength than the bare soil. Shear strength of rooted soil depends on the tensile strength and morphological characteristics of plant root system, which strongly vary with plant species and have been demonstrated to be influenced by environmental conditions and the cellulose concentration per unit mass.

The root biomass of plant consists mainly of cellulosic compounds (holocellulose and alpha-cellulose), lignin and extractives[9–12]. The structure of cellulose has been found to be optimal for resisting failure induced by tension[10,13]. When shear force occurs, the root-penetrated soil and root system are deformed. This deformation causes the root system to elongate, provided there is sufficient interface friction and confining stress to lock the root in place. Additionally, high cellulose content in the root will enable the plant to keep attached in the soil and prevent slippage[13]. Field and laboratory studies have shown that plant roots, especially fine roots efficiently penetrate the soil and improved soil–root interaction[14]. The impacts of fine roots on soil shear strength are higher than those of thick roots and potential plants should be selected considering their root profiles such as root biomass, quantity of fine roots, root length and root cellulosic composition[14,15]. Different plant species can perform various functional roles on slope, but certain types of plants are better than others in terms of their engineering properties, assessed by morphological and mechanical characteristics[1,3,16,17]. Therefore, selection of suitable plant species in terms of morphological and mechanical characteristics has become crucial. Lead tree is one of the most productive fast-growing and nitrogen-fixing legume plants, which has been introduced to Malaysia since long. An invasive root system of lead tree helps break up compacted subsoil layers, improving the penetration of moisture into the soil and decreasing surface run-off[3].

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Copperpod is a native plant in Malaysia that is planted in roadsides, gardens and parks as a woody ornamental plant. It has a huge root system and high atmospheric nitrogen-fixing potentiality. However, insufficient information is available on morphological and mechanical characteristics of both species. Therefore, detailed investigations are required in order to utilize their potentiality as a slope plants. An experiment was designed to assess the morphological and mechanical characteristics of two selected legume plants and to deduce some correlations amongst the parameters studied.

Materials and methods

Two wooden boxes, each (of dimensions 30 cm × 30 cm × 15 cm), were stacked to shape a box of 30 cm height (Figure 1). The customized boxes were filled with 15 kg sandy loam soil at moisture content ($cm^3/100\ cm^3$) of 15%. The soil was collected from the slope; its physical properties and grain size distribution are shown in Table 1. The soil was pressed by a rammer consisting of 2.5 kg mass falling freely through 30 cm for 40 blows. The soil was compressed steadily to prevent the boxes from being damaged and the soil-filling process was continued until the soil filled the wooded box of 30 cm height and soil volume was 27,000 cm^3.

An experiment was conducted under glasshouse conditions at the Institute of Biological Sciences, University of Malaya, Malaysia during May–December 2012. Lead tree and copperpod seedlings were grown in the customized (30 cm × 30 cm × 30 cm) wooden shear boxes (Figure 1). A seedling was planted at the centre of each shear box. Planted as well as the control (bare soil) boxes were arranged in a completely randomized design (CRD) with three replications under prevailing conditions (temperature 21–32°C, average 12 h photoperiod, maximum PAR 2100 $\mu E\ m^{-2}\ s^{-1}$ and relative humidity 60–80%). Box row spacing was 1 m throughout the experiment. The plants were irrigated every two days to avoid water stress. Physiological parameters of plants were observed at eight months after planting and thereafter each plant was cut-off near the base of the stem. The shear box test was performed in the laboratory.

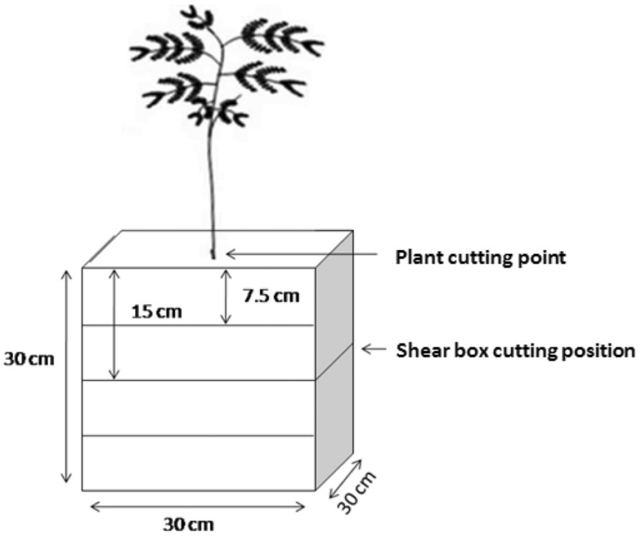

Figure 1. Seedlings grown in a customized wooden box.

The plant height and stem diameter were measured after eight months of plant growth using a measuring tape and vernier slide calipers respectively. The root biomass was determined using a balance (Model-PJ3000, Mettler Toledo, Japan) after eight months of plant growth, by oven-drying at 80°C for 72 h.

The root length of both plant species was determined by scanning and using the WinRHIZO Pro Software (WinRHIZO Version 2008a, Regent Instruments Inc, Canada). The software was also used to assess root length, volume and tips.

For root chemical analysis, after removing the bark, root samples (at eight months of growth) of plant species were ground into fine powder. The holocellulose content was measured based on the procedure developed by Wise *et al.*[18]. Alpha-cellulose was determined by TAPPI 203 os-74 method[10,13].

Root tensile test was conducted using Universal Testing Machine (Model 5582, Instron, United Kingdom) and ASTM[19] standard was followed to determine the root tensile strength. Roots were cut into pieces 15 cm in length and the two ends of the roots were clamped with sand paper to avoid slippage during testing. The root tensile tests were performed using an initial load of 0.5 N and a constant crosshead speed of 5 mm/min (ref. 13). During the test, the data on force and extension at failure were generated automatically by the software which was connected to the Universal Testing Machine. The applied force required to break the root was taken as the measure of root strength. Tensile strength was calculated by dividing the applied force by the cross-sectional area of the root at its rupture point[4].

Table 1. Properties of sandy loam soil used in this study

Soil properties	Sandy loam
Specific gravity	2.62
Dry unit weight (kN/m^3)	13.1
Moisture content (%)	13.5
Soil field capacity (%)	20.3
pH	4.45
Colour	6/8/hue 10 (Bright yellowish-brown)
Type	Size distribution (%)
Coarse sand (500–1.0 mm)	12.165
Medium sand (250–500 mic.)	29.45
Fine sand (100–250 mic.)	38.58
Very fine sand (50–100 mic.)	13.14
Silt and clay (<2–50 mic.)	6.64

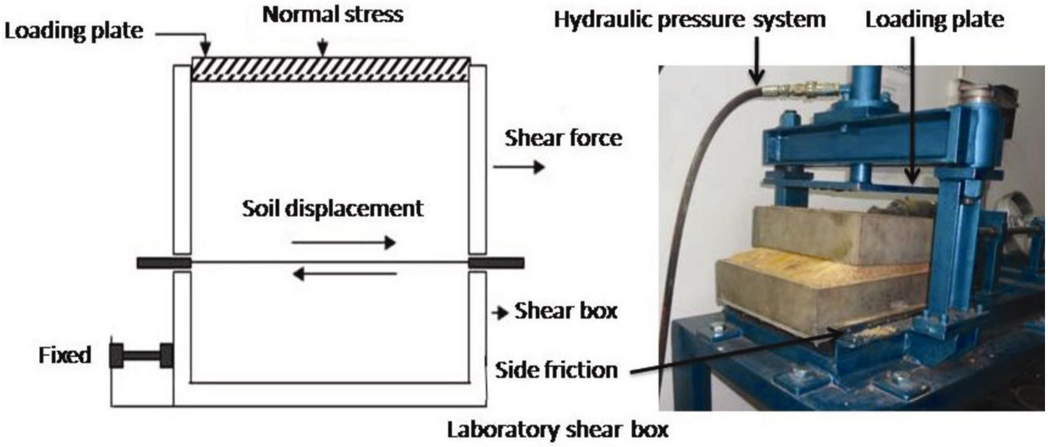

Figure 2. Laboratory shear box (300 mm × 300 mm × 150 mm) machine.

The soil shear strength was determined by carrying out laboratory shear box tests. The dimension of each planted box was identical to the laboratory shear box (Figure 2); so the root-penetrated soil sample blocks can be placed in a shear box apparatus by gradually pushing the sample downward. Different normal stresses – 10, 20 and 30 kPa – were applied vertically on the soil sample from the top plate of the shear box by hydraulic pressure system. The horizontal displacement was applied by pushing the lower half of the shear box at a speed of 3 mm $\min^{-1}$ until shear failure occurred or the peak shear force was recorded. The side friction was minimized by applying lubricated silicon grease to the side walls of the testing box. The cohesion and angle of friction of treated, untreated and control soils were calculated from the Mohr–Coulumb's equation

$$\tau = \sigma \tan\varphi + c, \tag{1}$$

where τ is the soil shear strength (kPa), σ the normal load, φ the angle of friction (°) and c is the cohesion.

Statistical analysis was carried out using SPSS software (Version 16). One-way ANOVA was applied to evaluate significant differences among means. Differences among treatment means ($P < 0.05$) were compared by the Fisher's least significant difference (LSD). Microsoft Excel was used for regression analysis and graphical presentation.

Results

Plant height of lead tree was 168% greater than that of copperpod (Table 2). Similarly, root diameter and root biomass were found to be significantly higher in lead tree than copperpod. Thus, higher root biomass presumably anchored huge amount of soil which ultimately can improve soil–root interaction. Root profiles differed significantly among species. At 7.5 cm soil depth, lead tree had 66% higher root length than copperpod (Table 3). At 22.5 cm soil depth, lead tree had greater root length than copperpod. In terms of root volume, lead tree also showed a higher value than copperpod at 7.5 cm soil depth. At 7.5 and 22.5 cm soil depth, lead tree had a higher number of root tips than copperpod. The quantity of fine (0–2.0 mm) and thin (2–4.5 mm) roots at 7.5 and 22.5 cm soil depth is shown in Tables 4 and 5 respectively. Generally, lead tree showed 35–42% higher root length in the root diameter range 0.0–0.5 mm at both soil depths. Whereas copperpod recorded lower root length (0.0–0.5 mm) at both soil depths. A higher number of fine roots was found at 22.5 cm soil depth than 7.5 cm soil depth. In case of thin (4.5 mm) roots, 22.5 cm of soil depth possessed a lower percentage (0.03) of root length than 7.5 cm soil depth. The results indicated that the type of root varied with soil depth. At 7.5 cm soil depth, lead tree exhibited higher root length which was almost 29% more than copperpod. A positive relationship was observed between root biomass and root tips (Figure 3 *a*), implying that the root tips would be higher if the root biomass was higher. Moreover, root length and root volume were positively correlated, implying that increasing root length would increase root volume (Figure 3 *b*). As a result, slopes that had high root length and volume were less likely to undergo failure[14].

In terms of root chemical compositions, the holocellulose content was significantly higher in lead tree than in copperpod. The holocellulose content was 70.6 ± 1.1% in lead tree and 56.7 ± 0.5% in copperpod (Table 6). A significant difference in root alpha-cellulose content was observed between the studied species. The alpha-cellulose content in lead tree and copperpod roots was observed to be 44.5 ± 0.4% and 31.3 ± 0.2% respectively.

Root tensile strength is used to assess plant potentiality for soil reinforcement. The results showed that lead tree exhibited a higher root tensile strength than copperpod. The root tensile strength was 98 and 61.5 MPa in lead

Table 2. Plant height and root diameter (close to the stem base) of plant species

Plant species	Plant height (cm)	Root diameter (mm)	Root biomass (g)
Lead tree	193 ± 4.4a	10.5 ± 0.2a	44.3 ± 6a
Copperpod	72 ± 3.9b	6.6 ± 0.2b	25.7 ± 8b

Means (± standard error) with different letters within the same column are significantly different ($P < 0.05$).

Table 3. Root profile at 7.5 cm and 22.5 cm soil depth

Plant species	Root length (cm)	Root volume (cm^3)	Root tips (no.)
Soil depth = 7.5 cm			
Lead tree	1543 ± 37a	12.5 ± 0.4a	1449 ± 32a
Copperpod	926 ± 15b	7.9 ± 0.4b	918 ± 25b
Soil depth = 22.5 cm			
Lead tree	1265 ± 47a	10 ± 0.52a	1165 ± 49a
Copperpod	678 ± 13b	6.1 ± 0.6b	869 ± 72b

Means (± standard error) with different letters within the same column are significantly different ($P < 0.05$).

Table 4. Root length and root percentage under different root diameters at 7.5 cm soil depth

	Root length (cm) *(%)	
Root diameter (mm)	Lead tree	Copperpod
$0.0 < x \leq 0.5$	553.21 (35.84)	251.46 (27.7)
$0.5 < x \leq 1.0$	477.25 (30.92)	223.61 (24.53)
$1.0 < x \leq 1.5$	242.66 (15.72)	106.77 (11.35)
$1.5 < x \leq 2.0$	122.94 (7.96)	93.13 (7.51)
$2.0 < x \leq 2.5$	54.77 (3.54)	68.28 (7.5)
$2.5 < x \leq 3.0$	27.30 (1.76)	35.06 (3.82)
$3.0 < x \leq 3.5$	16.56 (1.07)	22.72 (2.5)
$3.5 < x \leq 4.0$	9.75 (0.63)	23.61 (2.6)
$4.0 < x \leq 4.5$	16.66 (1.08)	35.83 (3.9)
$x > 4.5$	22.18 (1.43)	46.49 (5.1)

*Percentage of root length given in parenthesis.

Table 5. Root length and root percentage under different root diameters at 22.5 cm soil depth

	Root length (cm) *(%)	
Root diameter (mm)	Lead tree	Copperpod
$0.0 < x \leq 0.5$	538.67 (42.26)	187.74 (26.91)
$0.5 < x \leq 1.0$	393.72 (30.89)	233.86 (34.07)
$1.0 < x \leq 1.5$	149.86 (11.75)	138.96 (20.24)
$1.5 < x \leq 2.0$	95.34 (7.48)	63.51 (9.25)
$2.0 < x \leq 2.5$	44.74 (3.51)	29.28 (4.26)
$2.5 < x \leq 3.0$	26.76 (2.10)	15.60 (2.27)
$3.0 < x \leq 3.5$	14.54 (1.14)	9.43 (1.37)
$3.5 < x \leq 4.0$	8.016 (0.62)	7.51 (1.09)
$4.0 < x \leq 4.5$	2.36 (0.18)	2.53 (0.36)
$x > 4.5$	0.48 (0.03)	0.95 (0.13)

*Percentage of root length given in parenthesis.

Table 6. Holocellulose and alpha-cellulose in plant root

Treatment	Holocellulose (%)	Alpha-cellulose (%)
Lead tree	70.6 ± 1.1a	44.5 ± 0.4a
Copperpod	56.7 ± 0.5b	31.3 ± 0.2b

Means (± standard error) with different letters within the same column are significantly different ($P < 0.05$).

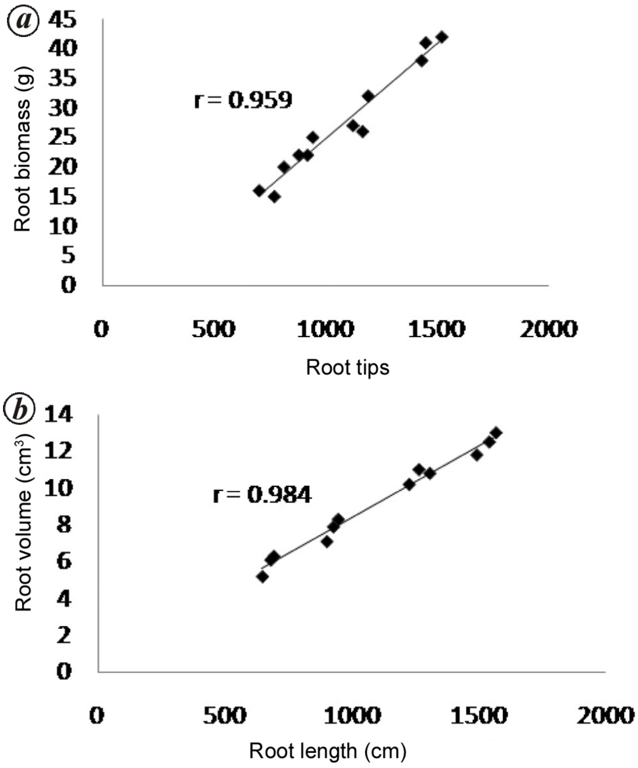

Figure 3. Relationship between (***a***) root biomass and root tips and (***b***) root length and root volume.

tree and copperpod respectively (Figure 4). Additionally, root tensile strength was observed to decrease with increasing root diameter, implying that large root diameter reduced tensile strength.

After eight months of plant growth, the root permeated soils of both species showed a higher soil shear strength than root-free (control) soil (Table 7). Amongst the treatments, lead tree exhibited the highest soil shear strength at both soil depths (7.5 and 22.5 cm). At 7.5 cm soil depth with the normal pressure of 10 kPa, the shear strength of lead tree increased by 27% and 256% compared to copperpod and control soil respectively. Additionally, at 7.5 cm soil depth with the normal pressure of 20 kPa, the shear strength of lead tree increased by 17% and 144% compared to copperpod and control soil respectively. The results showed that the root system of lead tree enhanced soil shear strength, which can improve soil–root interaction and hold soil particles together in the soil mass. On the other hand, residual strength was considered as the shear resistance of soil after the peak resistance has been achieved. Higher residual shear strength was observed in root-penetrated soils than control soils. This increment was due to the high root length density in soils, which in turn resulted in an increase in residual strength. Amongst the treatments, lead tree showed the highest residual strength, implying that its roots can maintain the highest soil–root interaction. Under normal pressure of 10 kPa, the soil residual strength of lead tree increased by 26% compared to copperpod at the 7.5 soil depth. Therefore, a higher residual shear strength of lead tree soils ultimately improved of soil shear strength and soil–root interaction. The soil shear strength and residual strength increased with the increase in normal load for both species and control soil.

The results implied that root-penetrated soils had higher cohesion than the root-free (control) soil (Figures 5 and 6). Additionally, lead tree exhibited a higher cohesion than copperpod. At 7.5 cm soil depth, the cohesion of lead tree was enhanced by 580% than control soil. Similarly, at 7.5 cm soil depth, the cohesion was enhanced by 411% in copperpod than control soil. On the

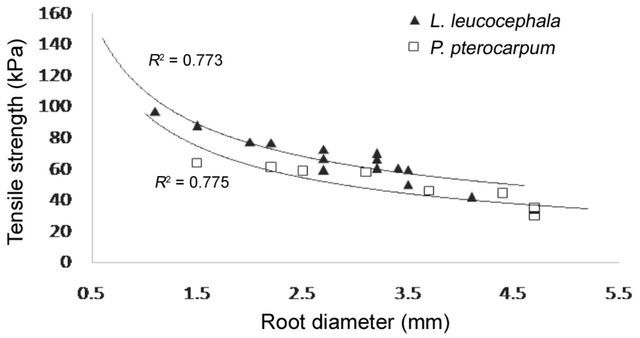

Figure 4. Relationship between root tensile strength and root diameter.

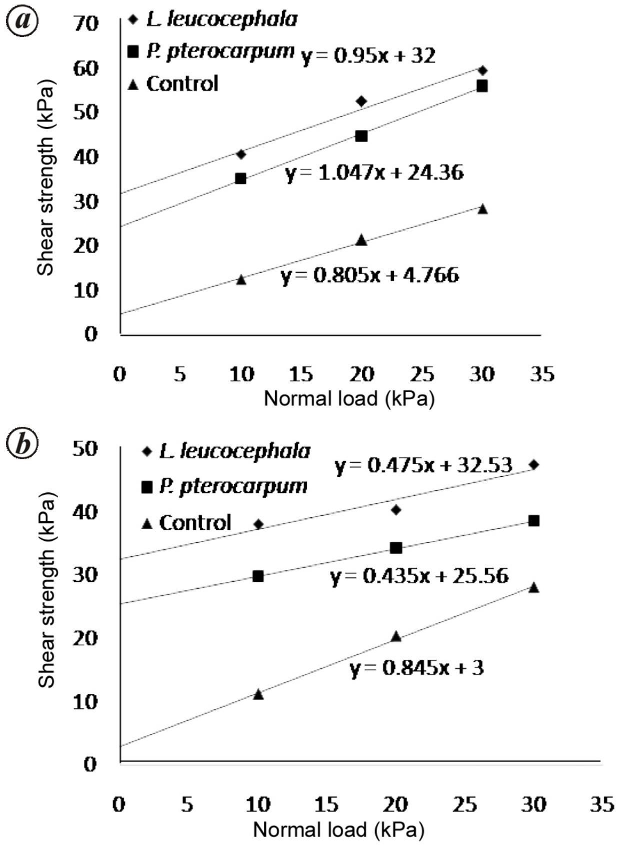

Figure 5. Relationship between shear strength and normal load of control (bare soil) and root-penetrated soil after eight months of growth. ***a***, Soil depth = 7.5 cm; ***b***, Soil depth = 22.5 cm.

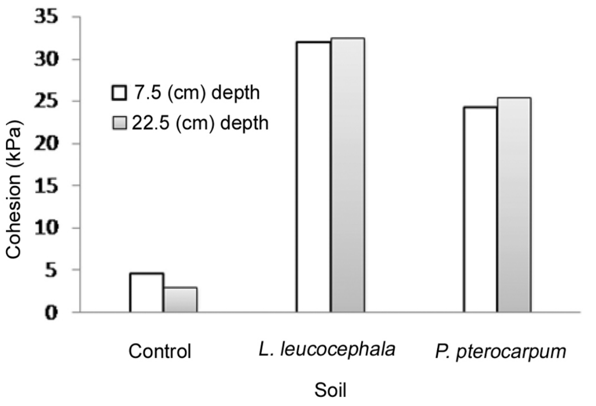

Figure 6. Cohesion of plant species at 7.5 and 22.5 cm soil depth.

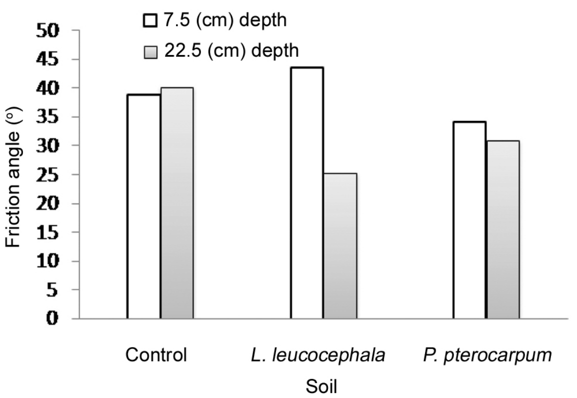

Figure 7. Angle of friction of plant species at 7.5 and 22.5 cm soil depth.

Table 7. Shear strength and residual strength of different planted soils at different values of normal pressure and soil depth

Species studied	Soil depth (cm)	Normal pressure (kPa)	Shear strength (kPa)	Residual strength (kPa)
Control	7.5	10	12.5	5.6
		20	21.5	10.5
		30	28.6	21.7
Control	22.5	10	11.2	5.1
		20	20.4	10.5
		30	28.1	19.6
Lead tree	7.5	10	44.6	18.4
		20	52.6	22
		30	59.7	28
	22.5	10	38.1	16.1
		20	40.4	18.5
		30	47.6	21.4
Copperpod	7.5	10	35.1	14.6
		20	44.8	17
		30	56	20
	22.5	10	29.9	12.4
		20	34.3	14
		30	38.6	18

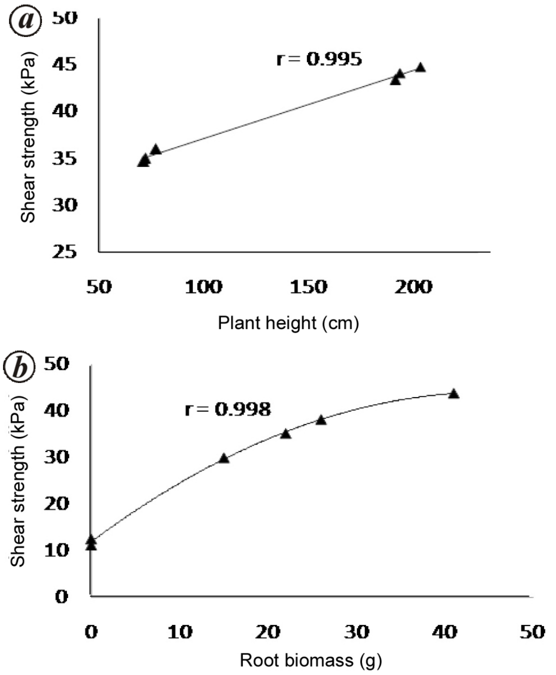

Figure 8. Relationship between (***a***) soil shear strength and plant height and (***b***) soil shear strength and root biomass.

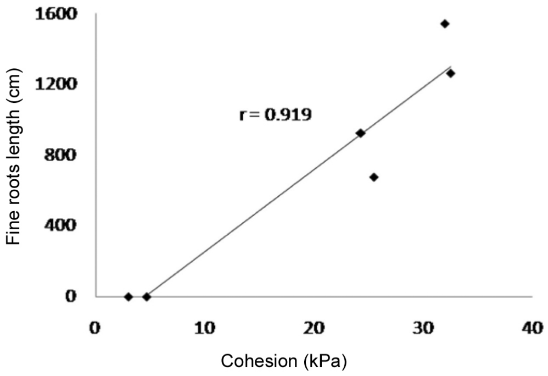

Figure 9. Relationship between fine roots length and cohesion.

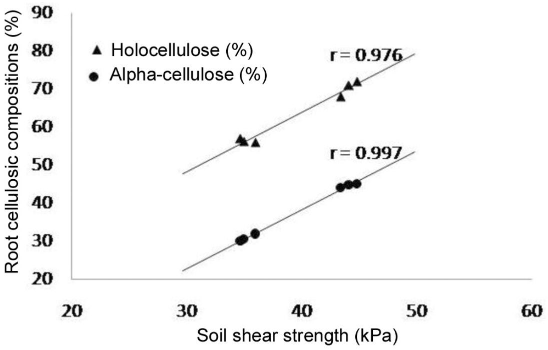

Figure 10. Relationship between shear strength and root cellulosic compositions.

other hand, angle of friction was lower in root-penetrated soil (22.5 cm soil depth) than control soil (Figure 7). This implies that the presence of root or root system does not have positive effects on the angle of friction. However, root system of both species significantly affected cohesion, which was the result of interaction between soil and root, whereas the frictional factor was the result of interaction among soil particles in tension.

A positive relationship ($r = 0.99$) was observed between soil shear strength and plant height, implying that greater plant height assists in strengthening the soil by improving the soil shear strength (Figure 8 *a*). Similarly, soil shear strength and root biomass were positively correlated ($r = 0.99$), implying that an increase of belowground biomass would increase the soil shear strength (Figure 8 *b*). This result was similar to the findings of Normaniza *et al.*[3]. This root-penetrated soil would also be helpful in reducing soil erosion due to the increased shear strength of soil caused by a greater shear force due to which soil particles can be separated. It was observed that fine root length was positively correlated with cohesion, implying that fine root length would enhance cohesion (Figure 9). Therefore, root profiles were important characteristic of plants to predict a reinforced soil. A positive correlation ($r = 0.97$) was observed between root holocellulose content and soil shear strength of the species studied, implying that a high holocellulose content of roots improved soil shear strength (Figure 10). Likewise, root alpha-cellulose content and soil shear strength were positively correlated ($r = 0.99$), indicating that an increase in root alpha-cellulose content would increase soil shear strength. As a result, roots which have high holocellulose and alpha-cellulose content were less likely to undergo failure. It has been reported that high cellulose content of roots improved the mechanical effects on soil, thus enhancing the soil shear strength and soil reinforcement capacity of the plant[13,14].

Discussion

In this study, lead tree exhibited comparatively better morphological characteristics such as plant height, stem diameter and root biomass than copperpod. A significant increase in root length, volume and tips was also observed in lead tree, implying that higher root profiles could be involved in greater soil–root interaction. The higher root profiles are attributed to the high soil–root matrix, which resulted in greater soil reinforcement[20]. An increase in root biomass and root length would significantly reduce the soil water, thus improving the soil shear strength and reducing slope failure[3]. To evaluate the influence of plant roots on soil reinforcement, it is required to quantify the mechanical properties of plants. Root tensile strength is the single most important mechanical property of plants[15,16,21]. Root tensile strength also contributed to tree anchorage; a tree that possesses high root tensile strength will be more resistant to overturning[16,21]. The higher tensile strength was attributed to the thinner roots of lead tree, which ultimately increased soil–root interaction and soil shear strength[21]. Thus, lead tree roots have a higher capacity to serve as soil–root composite material and will exhibit better resistance to slope failure during tension compared to copperpod roots. Another mechanical contribution of plants is its root cellulosic composition. The resistance of a root to failure in displacement or stress is controlled by root chemical composition, especially cellulosic molecules[10]. Higher holocellulose and alpha-cellulose content results in higher tensile strength property of roots[11]. Thus, the roots of lead tree showed higher soil shear strength than copperpod when horizontal displacement or stress was applied on the soil. However, if root length and biomass are equal in different species, the increase in root holocellulose and alpha-cellulose content would involve improving the tensile strength or soil reinforcement[10,13]. Thus, root chemical compositions are important parameters to consider when selecting suitable plants to reinforce the soil.

Likewise, reinforcement capacity of the species studied, as measured by its soil shear strength was observed to be the highest in root-penetrated soil of lead tree followed by the root-penetrated soil of copperpod and control soil. The extensive root system of lead tree provided greater soil–root interaction, which in turn increased the soil shear strength. Both species also showed higher shear strength at 7.5 soil depth than 22.5 cm soil depth. This was possibly due to the presence of high root biomass and length at 7.5 cm soil depth. Moreover, the number of fine roots and root biomass was higher in lead tree than copperpod, which in turn improved the soil shear strength and soil–root interaction. The soil anchoring capability of plants was strongly influenced by the individual root properties and quantity of fine roots[22].

Cohesion of root-penetrated soil showed variation between the studied plants. Results indicated that lead tree had higher cohesion than copperpod. Additionally, root-penetrated soil of the species studied had higher cohesion than control soil. However, no differences were seen in the angle of friction of the treated, untreated and control soils. Therefore, friction angle did not play substantial role in the stability of slope[23]. The total amount of cohesion component within a soil mass is associated with the root biomass and length within soil volume[24].

The shear strength of the tested species showed positive correlation with the morphological characteristics such as plant height and root biomass. This indicates that the increment of soil shear strength is mainly due to plant growth and root profiles[25–27]. The results also showed that the shear strength was higher in root-penetrated soils than root-free or control soils. The higher root length occupied large volume of soil which penetrated through the failure zone and improved soil shear strength[3]. A number of studies have documented that fine roots improved cohesion and soil shear strength[3,6]. This was consistent with the correlation studies where cohesion was strongly correlated with the fine root length. The fine roots of the species studied might be attributed to cover a large area of the soil, which ultimately improves soil cohesion and shear strength[1,6]. With regard to root chemical composition, cellulose is the main structural component of the primary and secondary cell walls in green plants[10]. It has been found that the cellulosic composition of the root is highly resistant to tension. Thus, root chemical composition (i.e. hollocellulose and alpha-cellulose) influence root tensile strength and soil shear strength[28]. Root cellulosic composition and soil shear strength were positively correlated, indicating that high cellulosic composition in roots increased soil shear strength. As a result, roots with high cellulose content can improve the capability of a plant to reinforce the soil. Thus, root chemical composition is also an important factor for enhancing the soil reinforcement capacity of plants and should be considered when selecting suitable plants for soil reinforcement[29,30]. The outstanding morphological and mechanical properties of lead tree attributed to the high soil shear strength and soil–root interaction, resulted in greater soil reinforcement.

The reinforcement capacity of lead tree and copperpod was characterized by their morphological and mechanical properties. Lead tree achieved relatively high root reinforcement potentiality through the increment of root profiles, tensile strength, cellulosic composition and cohesion compared to copperpod. The soil shear strength and soil–root matrix of root-penetrated soil were controlled by the individual root tensile strength, amount of fine roots and cellulosic composition of roots. Overall results suggest that lead tree possesses excellent morphological and mechanical properties and can be a suitable plant for soil reinforcement.

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