Evaluation of hydro-mechanical properties and root architecture of plants for soil reinforcement

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Plant helps to stabilize the masses of soil via hydrological and mechanical means. The effects of vegetation on soil depend on the overall root growth, architecture and its hydro-mechanical functions. Three leguminous plants, *Leucaena leucocephala*, *Pterocarpus indicus* and *Peltophorum pterocarpum* were evaluated in terms of their hydro-mechanical characteristics and root architecture for soil reinforcement. The results show that *L. leucocephala* exhibited the highest hydrological properties such as diurnal transpiration, water absorption capacity and soil matric suction (SMS). Regarding mechanical characteristics, *L. leucocephala* exhibited the highest root tensile strength and cellulosic components in the root. Interestingly, *L. leucocephala* also showed a higher root length, volume and tips than *Pterocarpus indicus* and *Peltophorum pterocarpum*. The SMS was strongly ($r = 0.79$) correlated with leaf area index (LAI), indicating that high LAI improved SMS. In conjunction with the cellulosic composition, root tensile strength of the species studied was highly correlated with the alpha-cellulose content ($r = 0.9$) and showed that high alpha-cellulose content of roots improved mechanical properties of plants to provide reinforcement in the soil. The high-root tensile strength, root cellulosic composition and VH-type root of *L. leucocephala* make the species special for growing as a soil reinforcing plant. In conclusion, *L. leucocephala* properties revealed that it possessed excellent hydro-mechanical properties and root architecture and can be planted on slopes for soil reinforcement.

Keywords: Cellulosic composition, mechanical characteristics, root length, tensile strength, soil reinforcement.

VEGETATION refers to the ground cover provided by plant communities. The development of vegetation cover for stabilization of slopes has been practised for many centuries[1]. The growth of vegetation is extremely beneficial as it is environment-friendly and helps in the development of sustainable ecosystem. The vegetation cover and slope stability are interrelated by the ability of the plant growing on slopes and the interaction of root and soil. But the interaction of vegetation cover and soil is complex as it is involved with, inter alia, the combination of soil type and plant coverage[2].

The contribution of vegetation cover to soil reinforcement or slope stability can be divided into two parts, viz. hydrological and mechanical[3,4]. Concerning the hydrological aspect, the presence of aboveground biomass or plant canopy reduces soil erosion rate through interception of raindrops, enhancing infiltration rate and extraction of soil water via canopy transpiration. The relation between soil water content and vegetation depends on the interaction between water uptake through plant roots and water loss through canopy transpiration. Therefore, root-penetrated soil removes soil water by lowering pore water pressure and increased soil matric suction[5]. The second property concerns with the mechanical aspect of the root system, which reinforces the soil by transforming shear stress in the soil to tensile resistance in the roots[6]. When plant roots are grown in the soil, the root-penetrated soil functions as a composite material, which can hold the soil particles tightly in place between the roots. The main root penetrates vertically and crosses the shear plane, which provides high resistance to the soil for arresting soil movement[7].

Total anchorage or reinforcement by plant roots is related to individual root tensile strength and root architecture. The root tensile strength varies with plant species, diameter, age, soil nutrients, soil moisture and chemical composition of roots[8,9]. The influence of vegetation cover and stability of slope depends on the type of plant species, their root system and tensile strength[10,11]. Genet *et al.*[12] showed that the main structural elements of cell wall of plant roots consist of cellulosic component. The cellulosic composition has been found to be highly resistant in the development of tension. Thus, plant roots that possess a higher tensile strength and cellulosic composition can contribute more to the enhancement of soil strength, thereby reducing slope failure. Therefore, plant selections with suitable plant hydro-mechanical properties and root architecture are essential to protect slopes against failure.

Leucaena leucocephala, *Pterocarpus indicus* and *Peltophorum pterocarpum* are abundant in Malaysia. These legume plants are fast-growing varieties and are also planted as ornamental plants along the streets and in the gardens[13]. However, we have a limited understanding

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about the hydro-mechanical and root architectural impacts of these tropical legume plants on soil behaviour. Therefore, screening of plant species in terms of potential slope control plant characteristics (i.e. root architecture and hydro-mechanical) have become crucial[2]. An experiment was designed to assess hydro-mechanical properties and root architecture of the three tropical legume plants for soil reinforcement.

Materials and methods

Experimental site, soil properties and plants

Three native legume plant species, *Leucaena leucocephala*, *Pterocarpus indicus* and *Peltophorum pterocarpum* were selected for the study[11,13]. Seedlings with an average age of half month were grown in PVC pots (30 cm diameter and 70 cm height) filled with 0.197 m^3 of soil collected from slope terrain with six replications (Table 1). The seedlings were grown without fertilization and the experiment was spread over 12 months under the prevailing condition with relative humidity (RH) (70–90%), PAR (maximum 2200 $\mu E\ m^{-2}\ s^{-1}$), temperature (32–38°C) and rainfall of 225 and 232 mm/month during 2011 and 2012 respectively. The experimental site was located in the Physiology Garden, Institute of Biological Science, University of Malaya (3°07′51″N and 101°39′25.9″E). The pots were arranged in a completely randomized design keeping a distance of 3 m between plants (Figure 1).

Leaf area index and soil matric suction

The leaf area index (LAI) and soil matric suction (SMC) were measured at 6-months interval by a leaf area measuring instrument (AccuPAR-LP80, UK) and soil moisture tensiometers (Model 2100F, Soil Moisture Equipment Corp.) respectively.

Diurnal transpiration rate and water absorption rate

Diurnal transpiration rate was measured by Portable Photosynthesis Equipment (Model LI-6400XT, USA). The data were collected during 12 months under natural environmental conditions. The diurnal measurements were made during 0700 and 1900 h. During the measurement, youngest, fully expanded leaves with three independent replications (separate plants) were selected. The water absorption capacity (WAC) of the root was computed using the Baker's theory[14]. According to this theory, 98% of the water absorbed by the roots transpired into the atmosphere. This statement leads to the following:

WAR is the water absorption rate of the root/day
($L\ H_2O$/plant/day) = $E^{\theta} \times 100/98$,

where E^{θ} is the diurnal transpiration rate ($L\ H_2O$/plant/day)

$= Y \times A \times$ molecule weight of water $\times$ time
$= \Sigma E$ (mmol $m^{-2}\ s^{-1}$) $\times$ leaf area (m^2) $\times$ 0.000018 kg $\times$ 60 $\times$ 60 sec

WAC ($L\ H_2O$/cm root/day) = WAR/total root biomass.

Biomass

The root biomass (oven-dried at 80°C for 72 h) was determined using a balance (Model-Mettle PJ3000, Japan) at the end of experiment.

Assessment of root architecture and profiles

Root samples were washed manually to remove soil. The root growth pattern of the two species studied was determined by examining the branching patterns or architecture described by Yen[15]. A WinRHIZO Pro 2008a (WinRHIZO Version 2008a, Regent Instruments Inc., Canada) system was used, connected to a Epson XL 10000 professional scanner equipped with an additional light unit (TPU). A 400 (dpi) resolution was used for measuring root morphology. The analyses were performed immediately after the images were acquired and the files were saved in TIFF format so that they could later be accessed from an Excel spreadsheet with integrated XLRhizo system. The following root characteristics were determined: total root length (cm), root volume (cm^3), mean root diameter (mm), and root length per diameter class (cm).

Assessment of root diameter and tensile strength

Root diameter was measured using a vernier caliper. The root tensile strength was measured by Universal Testing

Table 1. Physical properties of the soils in the study area

Property of soil on slope	
Specific gravity	2.62
Dry unit weight (kN/m^3)	13.1
Soil field capacity	20.3%
pH	4.45
Colour	6/8/hue 10 (bright yellowish-brown)
Type	**Size distribution (%)**
500–1.0 mm	12.16
250–500 μm	29.45
100–250 μm	38.58
50–100 μm	13.14
<2–50 μm	6.64

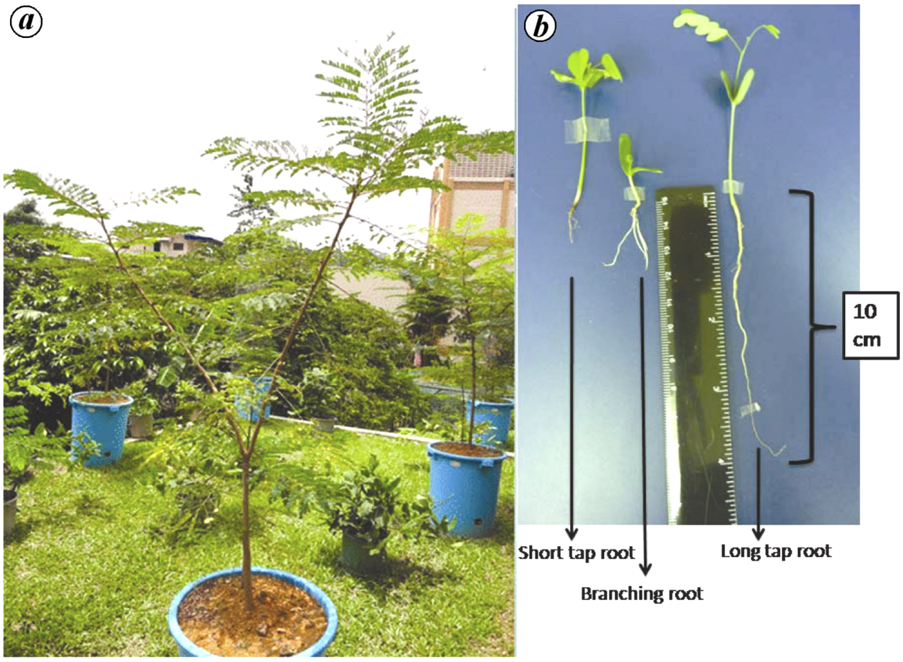


Figure 1. A PVC pot for seedling plantation. ***a***, 12 month seedlings; ***b***, Half month seedlings.

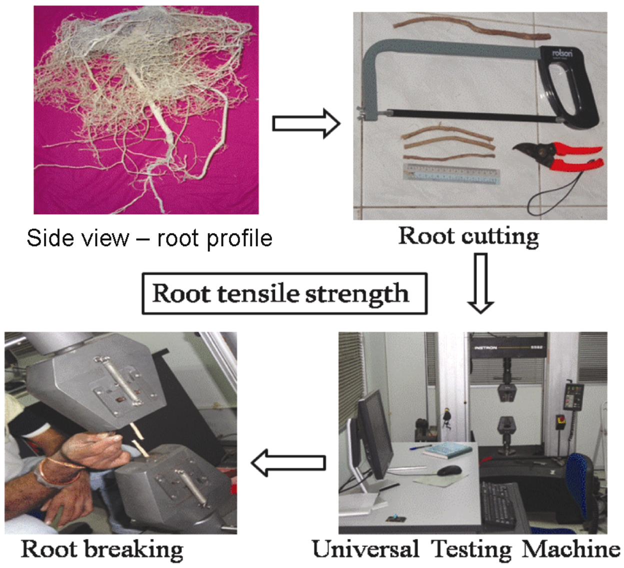


Figure 2. Assessment of root tensile strength using Universal Testing Machine.

Machine (Instron, Model 5582, United Kingdom). The root sample of species studied was cut into pieces of 10 cm length and clamped in the testing machine. The roots were pulled up vertically at 5 mm/min. The graph loads (kN) versus extension (mm) were measured from the testing machine. The value of tensile strength was derived as maximum force/cross-sectional area of the root (N/mm^2), due to the force direction and root alignment were correspond to each other (Figure 2).

Root chemical analysis

After removing the bark, root samples of species of equal root diameter ranging from 2.0 to 3.0 mm studied were ground into fine powder. The method applied to measure total holocellulose content was based on that developed by Wise *et al.*[16]. Alpha-cellulose was determined by TAPPI 203 os-74 method[11]. The acid-insoluble lignin content was determined in accordance with TAPPI 222 om-02 method[12,17].

Statistical analysis

Statistical analysis of the studied parameters was carried out using SPSS software (version 16). One-way analysis of variance (ANOVA) was applied to evaluate the significant ($P < 0.05$) difference among means. Microsoft Excel was used for regression analysis and graphical presentation.

Results and discussion

Table 2 shows LAI and SMS at six and twelve months of the species studied. At the 12th month of plant growth, LAI in *L. leucocephala* was found to be significantly higher than *Pterocarpus indicus* and *Peltophorum pterocarpum*. Additionally, higher SMS was observed in *L. leucocephala* than *Pterocarpus indicus* and *Peltophorum pterocarpum*. It was observed that *L. leucocephala* was more effective in enhancing SMS than

Table 2. Leaf area index (LAI) and soil matric suction (SMS) during 6th and 12th month of plant growth

	LAI		SMS (MPa)	
Plant species	6th month	12th month	6th month	12th month
Leucaena leucocephala	1.5 ± 0.05[a]	2.7 ± 0.15[a]	26 ± 0.5[a]	28.7 ± 0.3[a]
Peltophorum pterocarpum	1.1 ± 0.08[b]	2.1 ± 0.12[b]	25 ± 0.5[b]	27.3 ± 0.2[b]
Pterocarpus indicus	0.8 ± 0.04[bc]	1.8 ± 0.17[c]	20.5 ± 0.2[c]	22.6 ± 0.5[c]

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

Table 3. Water absorption capacity (WAC) of species studied along with related data

Plant species	Diurnal transpiration (E) (mmol H_2O m^{-2} s^{-1})	WAC	m = root biomass (kg)
Leucaena leucocephala	27.44[a]	28.1	0.994[a]
Pterocarpus indicus	16.1[b]	18.4	0.767[cb]
Peltophorum pterocarpum	16.67[b]	19.8	0.857[b]

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

Table 4. Root length, root volume and root tip number of species

Plant species	Root length (cm)	Root volume (cm^3)	Root tip number
Leucaena leucocephala	18,520 ± 196[a]	21 ± 0.17[a]	1,169 ± 72[a]
Pterocarpus indicus	1,380 ± 52[c]	12.9 ± 0.5[c]	958 ± 86[c]
Peltophorum pterocarpum	1,675 ± 77[b]	16.9 ± 0.8[b]	1,023 ± 63[ab]

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

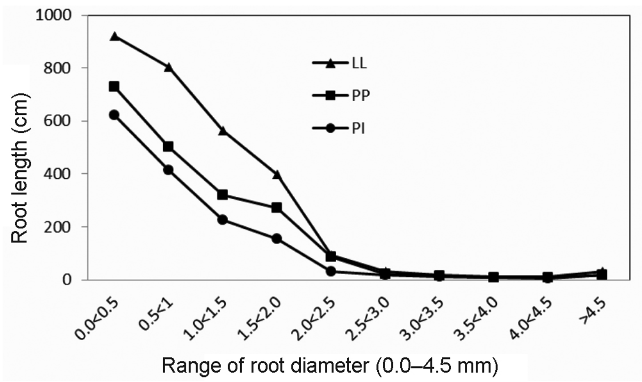


Figure 3. Root length of different species based on various diameters: fine roots (>0.0–2.0 mm) and thin roots (>2.0–4.5 mm).

Pterocarpus indicus and *Peltophorum pterocarpum*. Moreover, *L. leucocephala* had a higher transpiration rate than *Pterocarpus indicus* and *Peltophorum pterocarpum*. In terms of WAC, *L. leucocephala* also showed a higher value than *Pterocarpus indicus* and *Peltophorum pterocarpum* (Table 3). The results showed that *L. leucocephala* had a higher root biomass than *Pterocarpus indicus* and *Peltophorum pterocarpum*. High transpiration rate would demand huge amount of water for suction which can be fulfilled by the extensive root system and biomass of the plant. This high WAC may be due to the increment of physiological factors such as high transpiration rate, root biomass and LAI of *L. leucocephala*[13]. Normaniza and Barakbah[18] documented that high root biomass of the plant presumably resulted in the suction of a huge amount of water from the soil, which ultimately reduced soil water content. With the high water suction rate, *L. leucocephala*-grown soil exhibited a lower moisture content and higher SMS value than *Pterocarpus indicus* and *Peltophorum pterocarpum*-grown soils.

The root length and volume were extensively ($P < 0.05$) greater in *L. leucocephala* followed by *Peltophorum pterocarpum* and *Pterocarpus indicus* (Table 4). Additionally, a higher root tip was observed in *L. leucocephala* than *Pterocarpus indicus* and *Peltophorum pterocarpum*. Thus, the high root length and volume were presumably associated with high root tips number and biomass. A larger fine roots length was observed in *L. leucocephala* than *Pterocarpus indicus* and *Peltophorum pterocarpum* (Figure 3). Therefore, it can be assumed that large fine roots improved the root–soil interaction, which considerably improved soil reinforcement and WAC. Tensile strength of species was determined on roots of 1.0–7.0 mm diameter to observe the relationship between root diameter and tensile strength. The results revealed that in three species, a significant correlation exists between root diameter and tensile strength. Root tensile strength was observed to increase with decreasing root diameter (Figure 4).

With regard to the root chemical composition, the holocellulose content was found to be 75%, 62% and

66% in *L. leucocephala*, *Pterocarpus indicus* and *Peltophorum pterocarpum* respectively (Table 5). Additionally, the alpha-cellulose content in *L. leucocephala*, *Pterocarpus indicus* and *Peltophorum pterocarpum* roots was observed to be 53%, 31% and 35% respectively. Results show that *L. leucocephala* has significantly ($P < 0.05$) higher holocellulose and alpha-cellulose content than *Pterocarpus indicus* and *Peltophorum pterocarpum*.

The root growth patterns of the three species were determined by examining the root growth and branching patterns described by Yen[15]. By assessing the growth of the taproot and the lateral roots as well as the overall root architecture at 12th month, it can be concluded that *L. leucocephala* has a long taproot and lateral roots grow horizontally and profusely. Therefore, the root system of *L. leucocephala* was more similar to the VH-type (Table 6). However, the root architecture of *Peltophorum pterocarpum* was more similar to the R-type because it had many lateral roots that were initiated and extended obliquely from the main vertical taproot. *Pterocarpus indicus* also exhibited VH-type root system. The taproot of *Peltophorum pterocarpum* was shorter than that of *L. leucocephala*, and a larger number of lateral roots grew in various orientations.

At the 12th month age, there was a significant difference in LAI among the species studied. LAI of *L. leucocephala* was larger than *Pterocarpus indicus* and *Peltophorum pterocarpum* by 50% and 28% respectively. In addition, there was considerable variation in SMS and root biomass among the species studied. Higher SMS and root biomass were observed in *L. leucocephala* than *Pterocarpus indicus* and *Peltophorum pterocarpum*. High plant canopy or LAI of *L. leucocephala* can contribute to enhanced water uptake and SMS. This was verified by correlation studies of LAI and SMS (Figure 5). LAI was positively correlated ($r = 0.79$) with SMS, implying that a higher plant canopy cover would enhance the SMS. The high LAI of species studied may be attributed to the large amount of belowground biomass, which is similar to the findings of other studies[19,20]. Stokes *et al.*[2], and Saifuddin and Normaniza[13] indicated that high plant canopy or LAI could improve water uptake and these parameters are important factors in selecting potential plants to reinforce the soil. In addition, the enhancement of hydrological characteristics of *L. leucocephala* was due to high diurnal transpiration. In canopy transpiration, soil water content was reduced or escaped from a leaf surface, which must have increased with increasing LAI[21]. In the presence of high root biomass and LAI, the consequence will be more effective in absorbing soil water via additional roots and evaporating water through additional plant canopy. Similar findings were documented by Shaozhong *et al.*[22] and Saifuddin *et al.*[23], who showed that the decrease in soil water content was due to extensive root length and plant canopy. Tognetti *et al.*[24] also documented that larger root system such as root length and volume improved water absorption. Similarly, Cairns *et al.*[25] showed that large root system enhanced water uptake and improved the soil–plant–atmosphere continuum (SPAC). Moreover, large root system was effective for better root–soil water interaction, soil reinforcement and soil anchorage. Thus, the hydrological role of a plant was found to be a significant factor as it can potentially help in strengthening the soil via its water matric suction capacity, in turn reducing slope failure and soil erosion[18]. With the high WAC, soil needs less watering, resulting in high matric suction from the soil. Mafian *et al.*[26] documented that the root–soil water interaction was found lower when the matric suction was lower. The WAC and matric suction were most likely to be low when the soil was saturated with water. An analysis of these characteristics indicated that *L. leucocephala* and *Peltophorum pterocarpum* possess greater hydrological performance than *Pterocarpus indicus*. It was found that *L. leucocephala* possesses relatively large root system with dense fine roots. The extensive root growth and WAC of *L. leucocephala* were considered to be the cause of enhancement of hydrological impact on soil matrix suction. Therefore, better hydrological properties of plants such as LAI and WAC are regarded as essential parameters to consider when selecting suitable plants for reinforcement of soils.

The differences in root length, volume and root tips among the species studied are presented in Table 4. Large

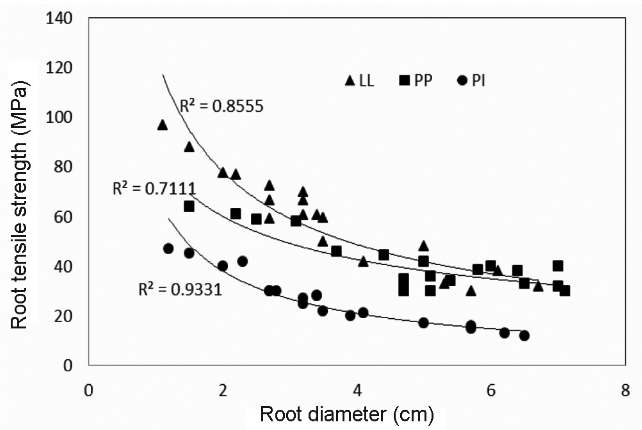


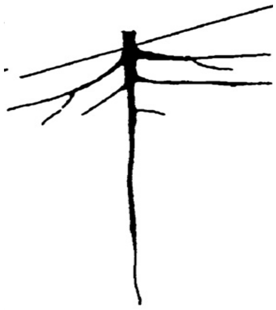
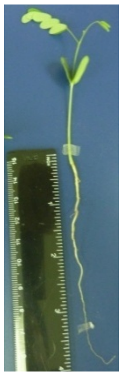
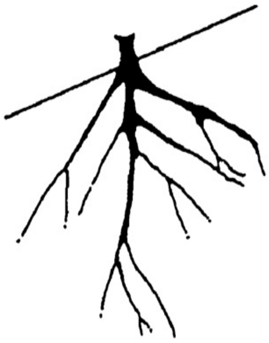
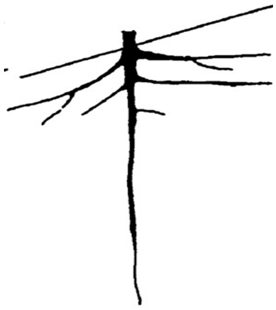
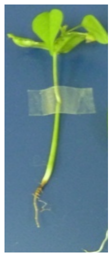
Figure 4. Root tensile strength (MPa) decreases with improving root diameter of species studied.

Table 5. Holocellulose and alpha-cellulose (equal root diameter: 2.0–3.0 mm) composition

Plant species	Holocellulose (%)	Alpha-cellulose (%)
Leucaena leucocephala	75 ± 1a	53 ± 0.7a
Pterocarpus indicus	62 ± 0.2c	31 ± 0.14c
Peltophorum pterocarpum	66 ± 0.4b	35 ± 0.22bc

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

Table 6. Classification of the root systems of *Leucaena leucocephala* (LL), *Peltophorum pterocarpum* (PP) and *Pterocarpus indicus* (PI)

Plant species	Root system description	Classification according to Yen[15]	Photograph of root after 12 months	Photograph of root after half a month
LL	There is a strong tap root. The lateral roots extend in a low orientation with respect to the horizontal plane. There are well-grown near-vertical roots.	VH-type 		
PP	Most of the main roots grow obliquely. Lateral roots are initiated and extend widely from the main root.	R-type 		
PI	There is a short tap root. The lateral roots extend in a low orientation with respect to the horizontal plane.	VH-type 		

root length, volume and tips were observed in *L. leucocephala* followed by *Peltophorum pterocarpum* and *Pterocarpus indicus*. It was reported that extensive root growth allowed in nailing a larger volume of soil matrix[27]. Additionally, *L. leucocephala* possessed more fine roots than *Pterocarpus indicus* and *Peltophorum pterocarpum*. It has been well documented that fine roots improve root–soil matrix, which in turn helps improve soil cohesion[2,27]. The presence of fine roots enhances soil nailing capacity and improves soil adhesion among soil particles[2]. Moreover, increased number of fine roots and root length would enhance water suction and thereby help in the reduction of soil water content. Similar findings have been reported by Saifuddin and Normaniza[13]. Thus it can be confirmed that the presence of fine roots in large numbers improves the water absorption capacity of plants[23], which is a required characteristic for reducing soil water content that controls the occurrence of landslides.

Root tensile strength is a prominent characteristic of plants for assessment of their potential for soil reinforcement[27]. In plants, most of the anchorage was controlled by the presence of a large number of structural roots. A higher root tensile strength is required for tree anchoring. The results indicate that *L. leucocephala* possessed a higher tensile strength than the other two species. Further, the root tensile strength of all species reduced with increasing root diameter. Fan and Chen[6] showed that high root tensile strength provides better anchorage to a plant in the soil matrix and enhances resistance to vertical uprooting. Stokes *et al*.[2] showed that plants which possessed high root tensile strength would ultimately improve the soil shear strength and thereby the soil reinforcement capacity. Thus, the root system of *L. leucocephala* is found to be more prominent to reinforce soil than *Peltophorum pterocarpum* and *Pterocarpus indicus*.

The structure of cellulose composition of root has been found highly resistant to soil tension. Genet *et al*.[12] showed that in green plants, cellulose was the main component in the cell wall. Genet *et al.*[17] also showed that cellulose was a polymeric compound connected with hemicelluloses matrix linked by hydrogen bonds, which makes it highly resistant to soil tension. Other components of soil matrix also influence tensile strength of roots, such as percentage of ash. However, this phenomenon is not well documented[12]. Stokes *et al*.[2] and Genet *et al*.[17] showed that root chemical composition controls the tensile strength of roots and plant anchorage in the soil matrix. The holocellulose and alpha-cellulose percentage in the roots was found extensively higher in *L. leucocephala* followed by *Peltophorum pterocarpum* and *Pterocarpus indicus*. Thus, the root of *L. leucocephala* has been found extremely resistant to soil tension.

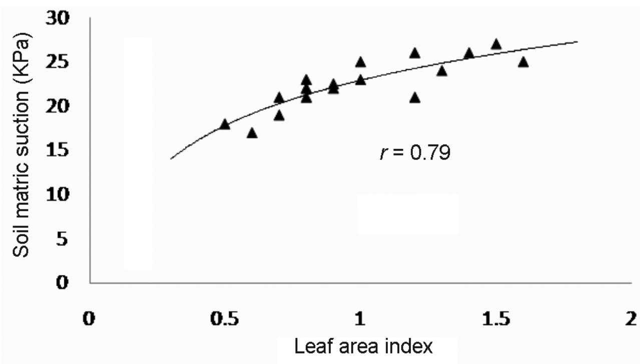


Figure 5. Positive correlation between soil matric suction (kPa) and leaf area index.

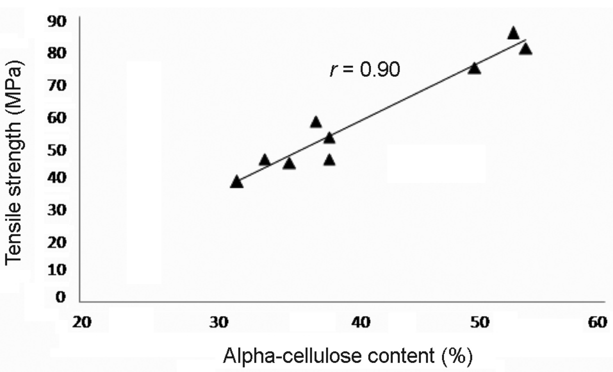


Figure 6. Correlation between root alpha-cellulose content (%) and root tensile strength (MPa).

A strong positive correlation ($r = 0.9$) was observed between tensile strength and alpha-cellulose content in roots, implying that a high alpha-cellulose content improved root tensile strength (Figure 6). As a result, soils penetrated by high root tensile strength and alpha-cellulose content are less likely to undergo failure. So high root tensile strength and cellulose composition were found essential as soil reinforcement and shear strength are mainly controlled by these two mechanical properties. Thus, root tensile strength and chemical composition are important parameters to consider when selecting suitable plants for reinforcement of soils.

The root architecture of the species studied was classified according to Yen[15] (Table 6). The typical distribution of a root system provides a general idea of how roots grow and indicates the localization of lateral and fine roots within the root system. *L. leucocephala* exhibits taproot system. Few lateral roots are oriented horizontally to the main taproot and most of the fine roots are surrounded by lateral roots. However, in the *Peltophorum pterocarpum* rooting system, lateral roots dominate over the total root structure. Most of the lateral roots emerge and extend obliquely from the main vertical roots. The lateral roots are also found widely spread in various orientations. Additionally, the lateral roots of *Peltophorum pterocarpum* are found longer than those of *L. leucocephala*. *Pterocarpus indicus* exhibits VH-type roots and its emergence of lateral roots was lower than *L. leucocephala*. Therefore, according to the root architecture of Yen[15], root systems of *L. leucocephala*, *Peltophorum pterocarpum* and *Pterocarpus indicus* were classified into VH-, R- and VH-type respectively. The VH-type roots are proposed to be beneficial for slope stabilization and wind resistance, whereas the R-type root architecture is considered to be the most effective root system for increasing shear strength[6].

The hydro-mechanical characteristics and root architecture of plants have been assessed to identify plant potentiality for reinforcement of soil. In this study, three tropical plant species were evaluated based on their hydro-mechanical characteristics and root architecture. Based on the observations, *L. leucocephala* showed a better hydro-mechanical characteristics than *Peltophorum pterocarpum* and *Pterocarpus indicus*. The SMS was positively correlated with LAI and root tensile strength was positively correlated with alpha-cellulose content (%). Extensive hydro-mechanical characteristics and VH-type roots were observed in *Leucaena leucocephala*, which shows that this is the most effective plant for soil reinforcement.

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