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Soil-root Shear Strength Properties of Some Slope Plants

(Sifat Kekuatan Ricih Tanah-Berakar Beberapa Tumbuhan Cerun)

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ABSTRACT

Rapid development in hilly areas in Malaysia has become a trend that put a stress to the sloping area. It reduces the factor of safety by reducing the resistant force and therefore leads to slope failure. Vegetation plays a big role in reinforcement functions via *anchoring the soils and forms a binding network within the soil layer that tied the soil masses together. In this research, three plant species namely* Acacia mangium, Dillenia suffruticosa *and* Leucaena leucocephala *were assessed in term of their soil-root shear strength properties. Our results showed that* Acacia mangium *had the highest shear strength values, 30.4 kPa and 50.2 kPa at loads 13.3 kPa and 24.3 kPa, respectively.* Leucaena leucocephala *showed the highest in cohesion factor, which was almost double the value in those of* Dillenia suffruticosa *and* Acacia mangium. *The root profile analysis indicated* Dillenia suffruticosa *exhibited the highest values in both root length density and root volume, whilst* Leucaena leucocephala *had the highest average of root diameter.*

Keywords: Angle of friction; cohesion factor; factor of safety; root length; shear strength

ABSTRAK

Pembangunan pesat di kawasan berbukit di Malaysia menjadi satu trend dan ini memberi tekanan kepada kawasan cerun. Ianya mengurangkan faktor keselamatan dengan pengurangan daya tahan yang boleh menyebabkan ketidakstabilan cerun. Vegetasi memainkan peranan penting dalam fungsi penguatan dengan membentuk rangkaian ikatan pada lapisan tanah. Berlandaskan kepada kepentingan terhadap penguatan tanah-akar ini, kajian telah dijalankan ke atas tiga spesies tumbuhan iaitu Acacia mangium, Dillenia suffruticosa *dan* Leuceana leucocephala *dan pokok-pokok ini diuji daripada segi ciri-ciri kekuatan ricih tanah-akarnya. Keputusan menunjukkan* Acacia mangium *mempunyai kekuatan ricih yang tinggi iaitu 30.4 kPa dan 50.2 kPa pada beban 13.3 kPa dan 24.3 kPa, secara berturutan.* Leucaena leucocephala *menunjukkan nilai faktor kohesi yang paling tinggi iaitu hampir dua kali ganda berbanding* Dillenia suffruticosa *dan* Acacia mangium. *Daripada segi analisis profil akar,* Dillenia suffruticosa *menunjukkan nilai yang tinggi bagi kedua-dua ketumpatan akar dan juga isipadu akar manakala* Leucaena leucocephala *mempunyai nilai purata diameter akar yang paling tinggi.*

Kata kunci: Faktor kohesi; faktor keselamatan; kekuatan ricih; panjang akar; sudut geseran

INTRODUCTION

The use of vegetation in restoring the stability of slopes becomes highly demanded especially to solve the problem of shallow slope failure in both natural and man-made slopes (Petrone & Preti 2010). With variation in plant species that may be established on severe slopes condition, variation reinforcing trend can be observed. Several key factors have been identified that determine slope stability. The vegetation arguably affects the slope by increasing the Factor of Safety (FOS) (Genet et al. 2010; Schwarz et al. 2010), the term generally used to express the stability of slopes, where the main beneficial effects towards slope stability can be classified into root reinforcement, soil moisture depletion, buttressing and arching also surcharge (Fan & Su 2008). Although the use of conventional technique in retaining the slope stability has become a major interest for engineers, the application of engineering in tandem with bio-engineering is proven to be more cost-effective and effective approach (Devkota et al. 2006; Petrone & Preti 2010).

However, certain factors may limit the application of bio-engineering techniques such as the establishment of plant on slope that is affected by climate; in consequence of that, plant establishment varies between different geographical areas (Alday et al. 2010; Burylo et al. 2007; Florineth et al. 2002). Climate influences the physiological development of the plant species such as the roots (Zhong et al. 2009) that reinforced the soil through mechanical and hydrological mechanism. Through hydrological mechanism, root functions by controlling the soil water content from exceeding the field capacity (Normaniza & Barakbah 2006). Root absorbs and circulates the water to atmosphere rather than letting all infiltrates deep into the soil. Rainfall water infiltrates on slopes lead to an increase in soil moisture content especially in the near-surface (Fan & Su 2008). Through mechanical mechanism, it forms a web of network with the soil where the root is the key for this mechanism to operate and has become the main elements which related to shear strength (Huat et al. 2005). As a result, root types and properties are crucial in determining the reinforcing effect on slope. Different kind of plants exhibit different root properties and ways they perform the function. These properties can be observed through the structure of the root that can be classified into three major systems namely sinkers, heart and taproot (Stokes & Mattheck 1996).

Hence, the objective of this study was to observe the reinforcing trend of three tropical plant species namely *Acacia mangium, Dillenia suffruticosa* and *Leucaena leucocephala* that have the potential as slope plants. In order to achieve that, field shear box tests were carried out on different ranges of stem diameter.

MATERIALS AND METHODS

SITE INVESTIGATION

The site selected was situated within the University of Malaya campus near the Institute of Mathematical Sciences, 03°07'27.9" N, 101°39'16.7" E. The area chosen, 3500 m^2, was based on the abundant numbers of plant species required that establish naturally in the field. The site is in the area of tropical climate with heavy rains occurring throughout the year and daily temperature that can reach around 35°C.

PLANT MATERIALS

Three plant species namely *Acacia mangium, Dillenia suffruticosa* and *Leucaena leucocephala* were chosen based on their prominent and physiological characteristic. These species are known to be resistant towards the poor and eroded condition of the slope (Normaniza et al. 2008). The total of three stem ranges 0.00 mm – 20.0 mm, 20.0 mm – 40.0 mm and 40.0 mm – 60.0 mm, in four replications, were sampled. In each species, two samples in the stem diameter ranged of 20.0 mm – 40.0 mm, were applied with different loads, 13.3 and 24.3 kPa. Two bare samples were also used as control in this test.

FIELD SHEAR BOX TEST

In order to achieve the actual result, customized field shear box test was used to assess the shear strength of root-reinforced soil block. A model of shear box was specifically designed to fit the field shear box test (Figure 1). It comprised several components that need to be set up on site and has the maximum capacity up to 5 ton. Preparation of soil blocks was done by cutting the plant shoot and stem and also clearance of area around it (Figure 1). Soil block with the size of 300 mm × 300 mm and depth of 160 mm were made to fit the steel-made shear box. Flat base trench was prepared to place the metal frame that attached the components. Each block contained a single plant species selected. Normal load of 13.3 kPa were applied to the blocks during the shear box test in order to compare the shear strength in ranging diameter and various species. Shear box test were carried out with a shearing rate of 1.5 mm/minute.

ROOT PROFILE STUDIES

The roots were washed, cleaned and kept in a plastic container sized 90 cm × 60 cm. The structure and types of

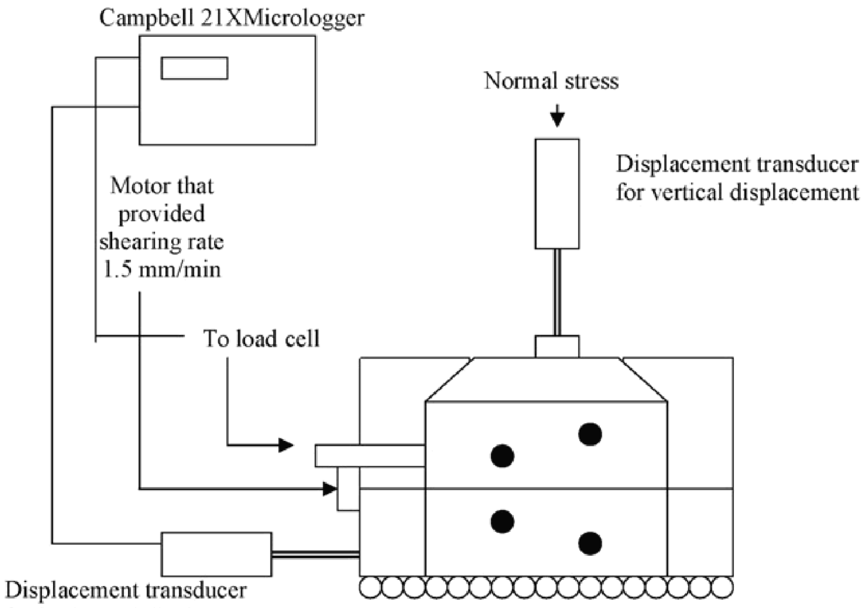


FIGURE 1. Model of shear box with the soil block installed to the metal frame before the tests get started. The shoot was cut off and left the basal stem behind

root were observed. Root profile studies were conducted using 'WinRHIZO' (Pro v. 2008a. 32 bits version) software accompanied by Epson perfection V700 scanner. The roots were measured in terms of a) root length, b) root volume and c) root diameter. The relationships between the shear strength of the species with the root profile were also determined.

RESULTS AND DISCUSSION

SHEAR STRENGTH OF THE SPECIES

The results showed that the shear strength of all species studied increased steadily with increasing displacement and gradually fell down when the maximum strength achieved (Figure 2). Moreover, it was observed that the samples studied increased in the value of shear strength as the stem diameter increasing. However, there was a slight different condition occurred in *L. leucocephala*, with the stem diameter of 2.5 cm. An abrupt increment occurred in this sample as compared to the sample with 4.3 cm of stem diameter. A different trend was observed where it achieved a higher shear strength and displacement.

The increase in shear strength was due to the presence of long vertical tap root (3(c)) of *L. leucocephala* compared to the other samples within the species. The root identification showed that both *A. mangium* (Figure 3(b)) and *L. leucocephala* (Figure 3(c)) have a tap root system whilst *D. suffruticosa* has a heart-root system (Figure 3(a)). Although, both *A. mangium* and *L. leucocephala* has a tap root system, lateral roots were bare minimum in *L. leucocephala*. Generally, a tap root system is characterized by a large central vertical root accompanied by small lateral roots (Stokes & Mattheck 1996). Previous studies indicated that vertical root helps in plant establishment on slopes as it increases the pullout resistance where surface movement are frequent and it also anchored the soil to improve the resistance (Anisuzzaman et al. 2002; Schroeder 1985). Thus, the plant could enhance the resistance towards other forces like wind and surface runoff that can cause slope erosion or landslide. In terms of the maximum shear strength, the samples with lower stem diameter achieved the maximum shear strength earlier compared to those samples with higher stem diameter.

It was observed that the shear strength values differ between species even within the same range of stem

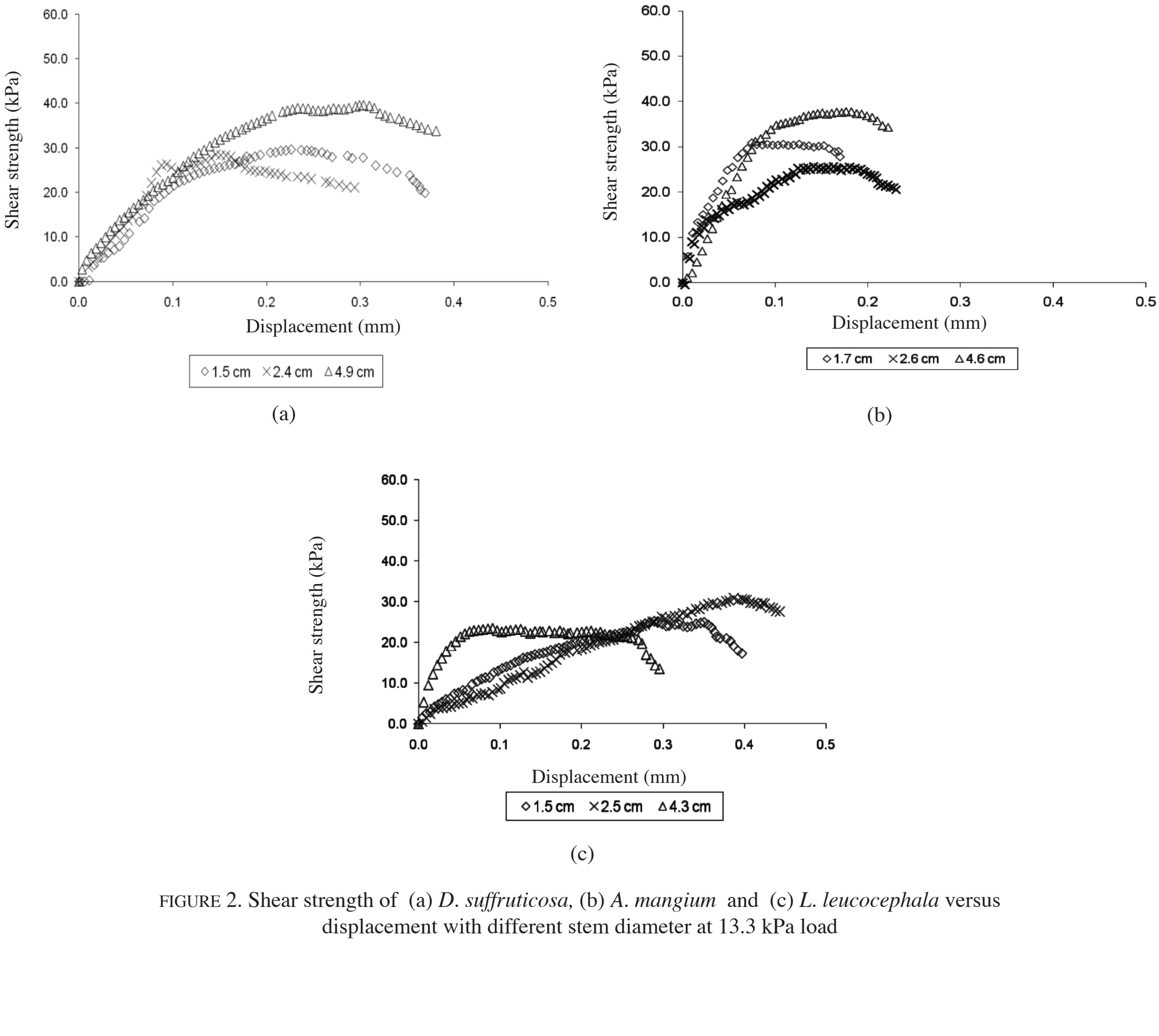
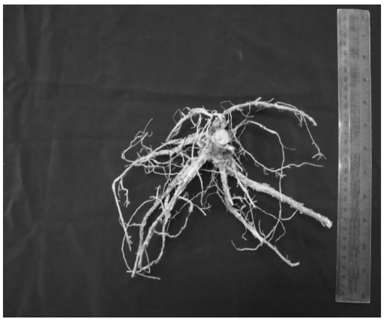


FIGURE 2. Shear strength of (a) *D. suffruticosa,* (b) *A. mangium* and (c) *L. leucocephala* versus displacement with different stem diameter at 13.3 kPa load



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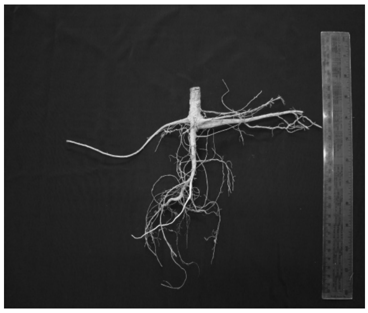

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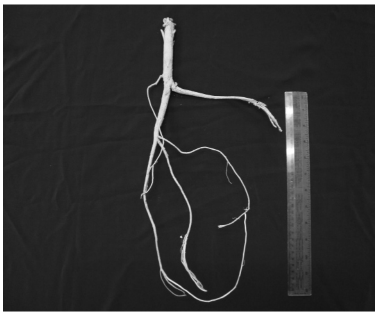
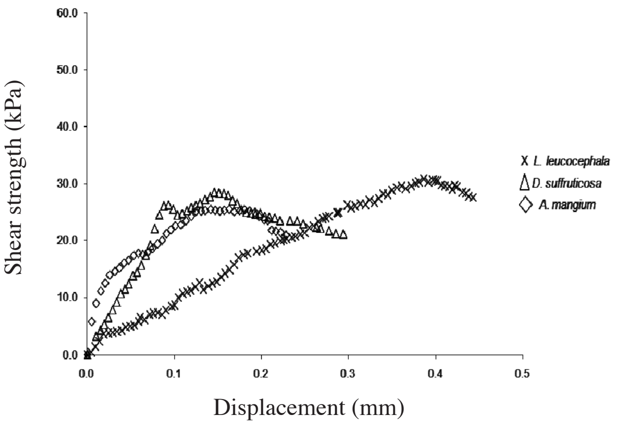


(c)

FIGURE 3. Root profiles of (a) *Dillenia suffruticosa* with a heart-root system, (b) *Acacia mangium* with a tap-root system and (c) *Leucaena leucocephala* with a tap-root system

diameter. The results on the average shear strength versus displacement showed that *L. leucocephala* had the highest shear strength value in the category of 20.0 mm – 40.0 mm of stem diameter and 13.3 kPa loads (Figure 4(a)). It was followed by *D. suffruticosa* and *A. mangium*. Whilst *A. mangium* had the highest shear strength, 50.2 kPa, at the double load of 24.3 kPa (Figure 4(b)). This variation occurred due to the difference in the root system between species. The outstanding shear strength performance of both *L. leucocephala* and *A. mangium* was due to the role of their larger tap root diameter. The morphology and architecture of the root influence the way root reinforced the soil. Despite the differences, root-reinforced soil still has a greater shear strength compared to bare soil (Figure 5). It was observed that *L. leucocephala* in both categories of load had higher displacements before it achieved the maximum shear strength, indicating high resistance towards the force applied before it losses the strength. In terms of loads, the value of shear strength was higher when 24.3 kPa loads was applied compared to those with 13.3 kPa load (Figure 5(a), (b) and (c)). These loads resembled the load provided by the stem and shoot of the plant in natural



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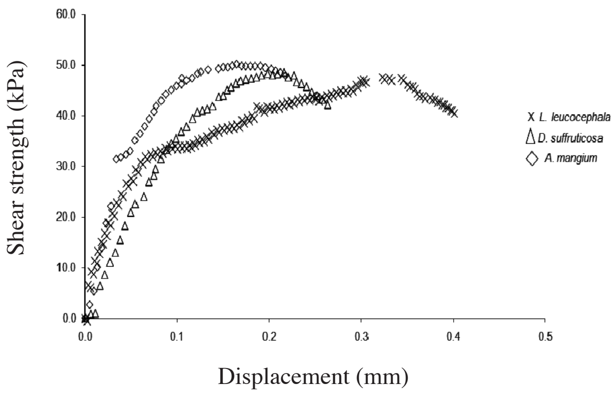


(b)

FIGURE 4. Comparison of shear strength in the three species (20.0-40.0 mm) at (a) 13.3 kPa and (b) 24.3 kPa

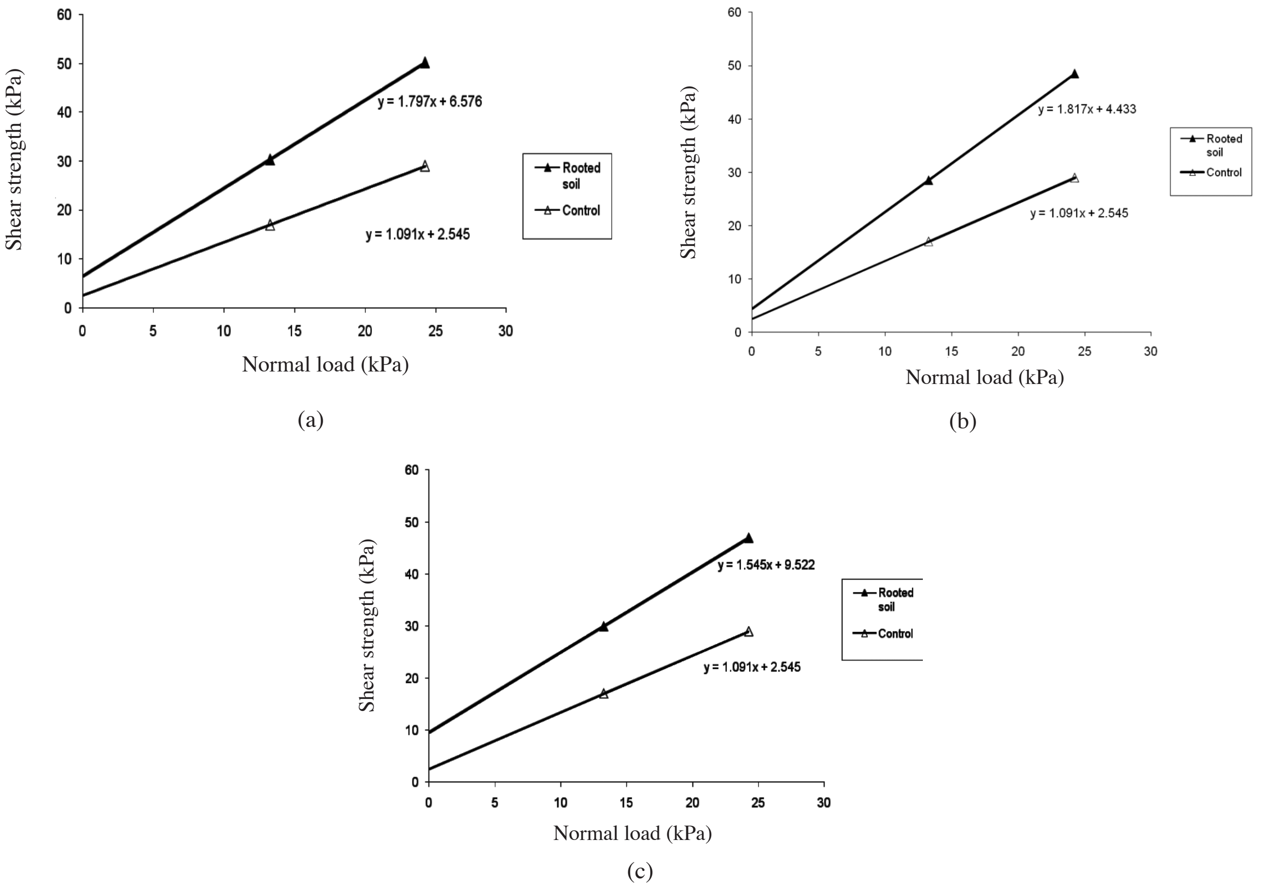


FIGURE 5. Shear stregth versus normal load of (a) *A.mangium,*(b), *D. suffruticosa* and (c) *L. leucocephala*

condition. Researchers also discovered that increase in load had increased the shear strength (Abe & Iwamoto 1986; Docker & Hubble 2008), implying, the additional load by vegetation contributed in improving the slope stability. It is undeniable that the load available had increased with the presence of the vegetation but the resistance provided by the root system is greater and reliable to support the load. Therefore, clearance of vegetation on slope by removing the trees, shrubs or grasses is not practically helping in maintaining the slope stability.

The cohesion factor determined from the graph of shear strength versus normal load based Figure 5 on Coulumb's equation (O'Loughlin 1974);

$$T = \sigma \tan \theta + c,$$

where T is the shear strength (kPa), σ is the normal stress, θ is the angle of friction (°) and c is the cohesion.

Amongst the three species studied, *L. leucocephala* had the highest value, 9.52 kPa, almost double the value of *D. suffruticosa* due to a long vertical tap root that intersect the shear plane which contributes most to soil reinforcement Figure 6(a). *D. suffruticosa*, as expected had the lowest value due to the heart root system. It consists mainly fibrous root which concentrate on the shallow depth (Devkota et al. 2006). Shrub and grass root with the heart system such as in *D. suffruticosa* commonly provide a greater increase in soil cohesion compared to taproot system (Baets et al. 2009). It contributes more root covers for wider area on the top soil reducing shallow landslide (van Beek et al. 2005). The roots anchored to the soil mantle and govern the stability of shallow thickness (Tosi 2007). Increase in the root numbers improves the cohesion (Huat et al. 2005) that reduces the detachment of soil particles. This explains how fine root content (root densities, root length and root volume per unit of soils) (Bankhead & Simon 2010) and types of vegetation has been the main important factors determining the reinforcement on top soil. However, in this experiment, the cohesion factor of *L. leucocephala* indicates a clear difference which is almost double of the other two plant species and five times of control although it consists most of taproot (Figure 6(a)). Soil cohesion is crucial in affecting soil detachment by runoff where it limits the soil detachment and in many cases it was recognized that the plant root had contributed the overall cohesion of the soil. Soil's condition, whether dry or wet does not affect the cohesion (Baets et al. 2009). In contrast, Zhang et al. (2010) come out with dissimilar findings where observation found that increase in soil water content favourably decline the soil cohesion. With the presence of root, evapotranspiration process occured and regulates the soil water content that improved the matric suction, thus contributing an increase in factor of safety especially on slope area (Bankhead & Simon 2010). In terms of the

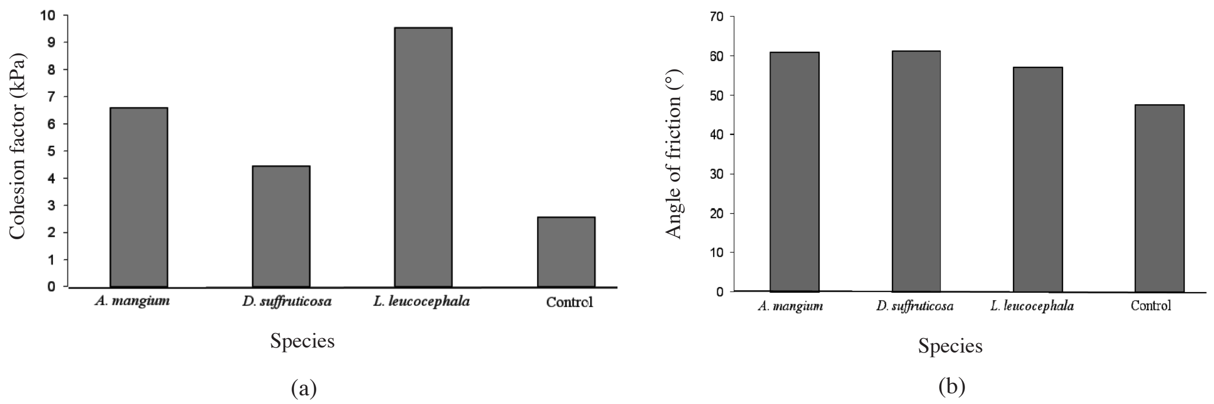


FIGURE 6. Comparison among the three species studied in (a) cohesion factor and (b) angle of friction

plant studied, the environmental conditions and water content did not vary. Thus, the similarity in the amount of percipitation received over the years and moisture content may not be the factor that may lead to the differences in cohesion between the samples studied.

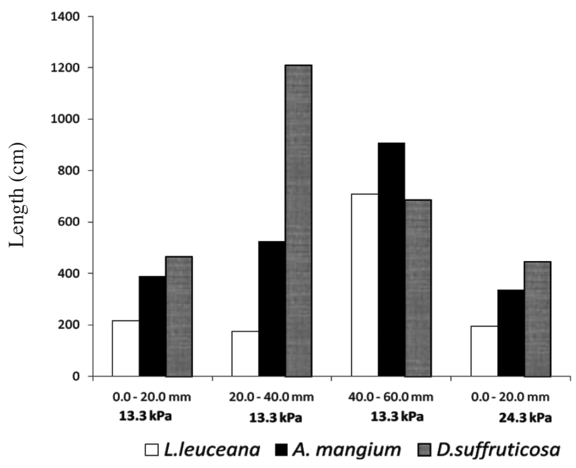
In this study, it is emphasized that the angle of friction does not significantly affect the shear strength. The presence of root had a little influence on the friction angle of root-reinforced soil with respect to that of root-free soil (Gray & Ohashi 1983). The differences in angle of friction between the three species were not significant. It was observed that the angle of friction for the species of *L. leucocephala* was the lowest compared to the other two species (Figure 6(b)). Research found that the angle of friction was influenced by the types and size of the soil (Dowell & Bolton 1998). Therefore, the differences of angle of friction between species observed may be affected by the density and architecture of the root presence where *L. leucocephala* has a low quantity of total root length Figure 7(a) and a large tap root system Figure 3(c).

ROOT PROFILE ANALYSIS

In terms of total root length, *D. suffruticosa* had the highest values amongst the species studied followed by *A. mangium* and *L. leucocephala* (Figure 7). This species was mainly built up of many long and fine fibrous roots Figure 3(a). High root length and fibrous type of root occupied large spaces in the soil especially at the topsoil, hence increases the density of root. In this way, more spaces were covered by the roots and this improved the cohesion by increasing the binding with the soil particles. Furthermore, it is also anticipated that dense root system would help to stabilize the slope by absorbing the water which infiltrates through the soil, thus improves the matric suction (Bankhead & Simon 2010). Generally most of the species consist of high quantity of root length in the interval of root diameter, 0.5-1.0 mm, which represented 27-38 percent of the total root length in each sample (Tables 1, 2 and 3). These roots were in the form of fine root with low diameters. Fine roots increased the efficiency of soil binding between the soil particles and improved the cohesion. Furthermore, studies have shown that root with diameter of 1.0 cm and less are directly affecting the slope stability positively (Abe & Ziemer 1990).

Resistance contributed by the root depends on the orientation and number of roots with respect of the shear plane (Loades et al. 2010; Wu et al. 1988). In the presence of root widening the shear zone, each soil particle is required to move less than when the shear zone is narrower. However, the amount of root deformed increases as the number of root decreases in the shearing soil (Abe & Ziemer 1991). High concentration of root crossing the shear plane helps in increasing shear resistance and reinforces slope against landslide (Abe & Iwamoto 1986; Abe & Ziemer 1991; Danjon et al. 2007). However, in this study, the number of dense fine root of *D. suffruticosa* located in the shear plane was less and the effects of root concentration towards shear resistance were not observed although this species has a high root length density. On the other hand, *A. mangium* and *L. leucocephala* with large root diameter had high shear strengths as their long vertical tap roots penetrate the shear plane. Fine roots have a higher tensile strength compared to a larger root. It provides the maximum tensile strength during soil displacement that leads to the increase of soil shear strength (Tosi 2007). These roots act as tensile elements within the soil matrix whereas large diameter roots can also act as tendon or anchors connecting planted surface layers to underlying or adjacent stable soil zones (Danjon & Reubens 2008).

Additional lateral root presence in *A. mangium* exerts the tractive resistance that contributed in increase of tensile strength of root at the upper surface (Zhou et al. 1998). In the average root diameter, the results indicated that *L. leucocephala* had the highest average value of stem diameter in both ranges, 0.0-20.0 mm and 20.0-40.0 mm (Figure 7(b)). From the root observations, this species mainly consisted of tap root with high diameter and can penetrate deep to the soil. This feature helps the root to intersect the slip plane and reduces the probability of movement than leads to landslide. The application of vegetation on slope is influenced by the location and height. Plant such as *D. suffruticosa* is suitable to be used as toe reinforcement at downslope where roots improve



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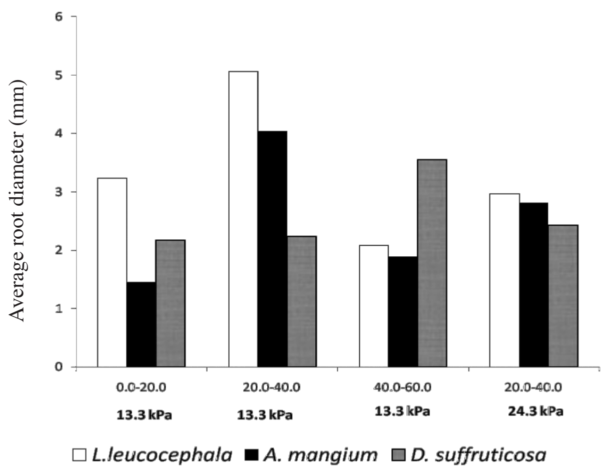

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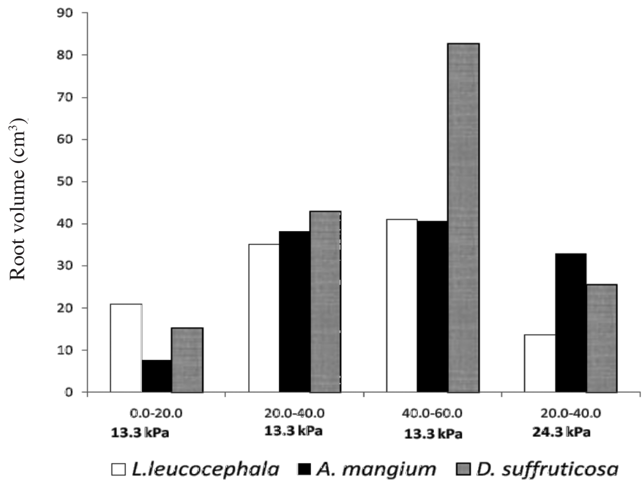

(c)

FIGURE 7. Comparison among the three species studied in (a) total root length, (b) average root diameter and (c) root volume

TABLE 1. Samples with stem diameter ranging at 0.0-2.0 cm (13.3 kPa load)

Root diameter (mm)	Root length (cm) *(%)		
	D. suffruticosa	*A. mangium*	*L. leucocephala*
0.0<x≤0.5	73.72 (15.85)	70.95 (18.25)	19.04 (8.83)
0.5<x≤1.0	129.11 (27.76)	151.44 (38.95)	18.56 (8.60)
1.0<x≤1.5	100.64 (21.64)	74.08 (19.05)	33.49 (15.53)
1.5<x≤2.0	43.49 (9.35)	32.93 (8.47)	39.79 (18.45)
2.0<x≤2.5	25.16 (5.40)	21.22 (5.46)	21.67 (10.05)
2.5<x≤3.0	19.39 (4.17)	5.58 (1.44)	21.94 (10.17)
3.0<x≤3.5	12.28 (2.64)	5.35 (1.38)	12.61 (5.85)
3.5<x≤4.0	12.07 (2.60)	6.21 (1.60)	8.34 (3.87)
4.0<x≤4.5	9.56 (2.06)	2.87 (0.74)	6.81 (3.16)
x>4.5	39.68 (8.53)	18.16 (4.66)	33.41 (15.49)

* Percentage of root length in bracket

TABLE 2. Samples with stem diameter ranging at 2.0-4.0 cm (13.3 kPa load)

Root diameter (mm)	Root length (cm) *(%)		
	D. suffruticosa	*A. mangium*	*L .leucocephala*
0.0<x≤0.5	162.92 (13.48)	94.69 (18.02)	15.28 (8.77)
0.5<x≤1.0	346.28 (28.62)	163.73 (31.15)	22.55 (12.94)
1.0<x≤1.5	202.58 (16.75)	83.69 (15.93)	36.79 (21.12)
1.5<x≤2.0	114.78 (9.49)	35.05 (6.66)	9.94 (5.71)
2.0<x≤2.5	107.34 (8.87)	31.57 (6.01)	8.51 (4.88)
2.5<x≤3.0	72.48 (5.99)	24.89 (4.74)	8.71 (5.00)
3.0<x≤3.5	44.14 (3.65)	11.65 (2.22)	9.81 (5.63)
3.5<x≤4.0	36.44 (3.02)	13.61 (2.59)	3.45 (1.98)
4.0<x≤4.5	31.19 (2.58)	9.88 (1.88)	4.38 (2.51)
x>4.5	91.78 (7.55)	56.75 (10.80)	54.81 (31.46)

* Percentage of root length in bracket

TABLE 3. Samples with stem diameter ranging at 4.0-6.0 cm (13.3 kPa load)

Root diameter (mm)	Root length (cm) *(%)		
	D. suffruticosa	*A. mangium*	*L. leucocephala*
0.0<x≤0.5	27.35 (3.98)	182.14 (20.07)	124.94 (17.61)
0.5<x≤1.0	89.96 (13.10)	268.44 (29.58)	216.49 (30.52)
1.0<x≤1.5	114.84 (16.72)	174.36 (19.22)	92.64 (13.06)
1.5<x≤2.0	59.59 (8.68)	82.44 (9.08)	49.19 (6.93)
2.0<x≤2.5	46.93 (6.83)	47.76 (5.25)	37.04 (5.22)
2.5<x≤3.0	55.93 (8.14)	34.83 (3.84)	28.74 (4.05)
3.0<x≤3.5	43.41 (6.32)	20.10 (2.22)	25.67 (3.62)
3.5<x≤4.0	38.34 (5.58)	9.49 (1.05)	16.65 (2.35)
4.0<x≤4.5	53.74 (7.83)	9.32 (1.03)	14.31 (2.02)
x>4.5	156.66 (22.82)	78.51 (8.66)	103.66 (14.62)

* Percentage of root length in bracket

the cohesion at the end of shear plane whilst *A. mangium* and *L. leucocephala* will fit soil better in the middle of the slope where the deep penetration of tap root intersect the shear plane and reduces the shear plane movement. It may also help to displace the shear surface either deep beneath the soil surface or high at the slope (Collison et al. 1995; Danjon et al. 2007).

CONCLUSION

The results gathered from the field shear box test indicate that the shear strength of most samples increased gradually with increasing of stem diameter. *Acacia mangium* had the highest shear strength at the higher load (24.3 kPa) compared to the other species. In terms of cohesion factor and average root diameter, *Leucaena leucocephala* had the highest value. Whilst, the highest percentage of root volume and root length density can be observed in *Dillenia suffruticosa*, criteria as surface erosion plant. Thus, overall results showed that all the species studied have good potential as slope plants based on their pertaining root and shear strength properties.

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