

Research Article

Root Tensile Resistance of Selected *Pennisetum* Species and Shear Strength of Root-Permeated Soil

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Received 5 August 2019; Revised 16 December 2019; Accepted 23 January 2020; Published 10 March 2020

Academic Editor: Davey Jones

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It is widely recognized that vegetation plays a significant role in contrasting slope instability through the root reinforcement. The main objectives of this paper are to evaluate the root tensile of selected *Pennisetum* species, namely, *P. pedicellatum* (PPd) and *P. polystachion* (PPI), and to determine the soil shear strength of root-permeated soil from these species. The selected species were initially planted in the polybags using the hydroseeding technique. A mineral fertilizer of NPK ratio 10 : 8 : 10 was adopted in the hydroseeding mixture. Routine watering program was applied twice a day throughout growth observation for six months. Four replications were prepared for each species including a set of control polybags, which contained only soil for reference and comparison. The results of root tensile tests revealed the significant relationships between root diameter and tensile force. In comparison, the PPI was still indicated by higher values of root tensile force than PPd. The presence of roots clearly has contributed to the shear stress of root-permeated soils. The root density based on root biomass measurement attributed to the higher value of peak shear stress as achieved by PPI than PPd. The combined effects of root tensile and the soil shear strengths of this selected species can be used as biological materials in slope protection against erosion.

1. Introduction

Plants can play a vital role in controlling the soil erosion through their canopy and root networking. Soil erosion can happen at a very gentle slope and caused by erosion agents of water, wind, and others. In tropic regions, water is the main erosion agent that is responsible in extreme gully type of erosion up to soil landslides. These features are commonly associated with highly weathered barren soil and steep slopes with high annual rainfall [1]. High-intensity rainfall coupled with highly weathered soil may speed up soil saturation that leads to the loss of shear strength. Apart from that, removal or change in slope vegetation is among the control factors that also contribute to slope instability [2].

Soil-root interaction via vegetation can substantially improve slope stability as plants provide canopy (ground surface) and binding (subsurface) effects that contribute to soil shear strength. Many researchers reported that vegetation can play an important role in slope stabilization by strengthening of soil structure [2, 3]. It is obviously a complex relationship between vegetation and soil reinforcement as they attribute to factors such as soil types, plant species and coverage, and soil moisture condition [1, 4]. Past experiences show that slopes covered by vegetation pose less tendency of soil erosion due to water and wind actions [2, 5–7]. Vegetation contributes to slope stabilization through two different types of mechanisms: mechanical and hydrological mechanisms. From the mechanical point of

view, plants can contrast soil instabilities by increasing soil shear strength through friction between root and soil particles as well as soil cohesiveness [8–10] (Rey et al., 2019; Stokes et al., 2007). Hydrologically, vegetation stimulates soil suction with evaporation, thus reducing soil moisture, which in turn delays the soil saturation time, limits the water leakage in the soil, and retains the soil dry [11]. A considerable improvement on soil shear strength of root-permeated soil has been linked to the distribution of root within the soil and the root tensile strength of particular root [12–15]. The relationship between root diameter and tensile strength is negatively correlated whilst root diameter is positively correlated with tensile resistance [16, 17]. Mattia et al. [18] applied Wu [19] and Waldron [20] models to calculate the reinforcing effect in terms of increased shear strength of the soil. Later, Mao et al. [21] studied the root systems (root density, root orientation, and root tensile strength) and discussed the result in different models (Wu and Waldron's Model (WWM) and Fiber Bundle Model (FBM)). De Baets et al. [22] examined the influences of root tensile strength and root distribution of some typical Mediterranean plant species on soil shear strength. They found that smaller diameter root has higher tensile strength and root from grass species can increase soil strength at topsoil but with the combination of shrub species, the soil can be improved up to the greater depth up to 0.5 m. Fan and Chen [23] examined the effect of difference in root architecture on shear strength increment provided by plant roots in the soil. They found that plants with conspicuous oblique and vertical roots provide larger shear strength increment than that of root structures with copious lateral root system.

Various plant species have been studied for biological material in slope erosion control and slope stability [24–28]. Grasses have been a prevalent selection for slope erosion control as they can effectively offer surface coverage against rainfall impact and subsurface offer soil interparticle binding by plant root networking to increase the soil shear strength. Vetiver (*Chrysopogon zizanioides*) and signal grass (*Brachiaria decumbens*) are two common species used in slope management for improving the eroded slope areas. Vetiver has a unit long fibrous root networking that can reach up to 1 m deep into the soil profile. However, there are plenty of native plant species that can be highlighted due to their wide distribution and well adapted with local climate environment [29, 30]. Plant species can be found locally which offer cheaper maintenance cost and can definitely tolerate local environments [31–33]. Besides that, the use of local species as biological materials in soil bioengineering applications can be added-value and economic in terms of cost reduction and compete with other products available in the market. There are still “unknown” herbs in terms of their biotechnological properties which can contribute to soil bioengineering and assess their potential impact on ecosystems to produce seed mixes, which, together with their usefulness in stabilizing the soil, can accelerate the plant dynamics [34].

Pennisetum spp. consists of more than a hundred species, belonging to the family Poaceae, fast-growing, perennial weed, and is widespread throughout Australia and the tropical mainland of Africa and Asia, including Malaysia

[35]. It has been regarded as an enemy to agricultural plants and uneconomically useful. The abundant presence of *Pennisetum* spp. reflects their successful adaption in local tropical environments and can be potentially adopted as biological materials in slope bioengineering approach. Hence, the main aims of this work are (i) to examine the effect of root tensile force of selected *Pennisetum* spp. (*P. polystachion* and *P. pedicellatum*) and (ii) to determine the shear strength of root-permeated soil. For the shear strength tests, control samples were also examined for reference purpose.

2. Materials and Methods

2.1. Plant Species and Soil. Two localized grass species were selected, namely, *Pennisetum polystachion* (PPI) and *Pennisetum pedicellatum* (PPd), in this study. Mature seeds of species were initially collected from the various sites in Universiti Kebangsaan Malaysia (UKM). The soil medium was obtained from a slope adjacent to the plot study site. The properties of soil are shown in Table 1. It can be characterized as sandy clay loam (32.6% clay 16.3% silt and 51% sand) with a highly acidic pH. Meanwhile, the moisture and organic contents were 21% and 3.2%, respectively.

Germination of each species was performed through hydroseeding technique in a polybag with a diameter of 22 cm and 24 cm in height. It contains a mixture of soil tackifier, seed, water, fertilizer, and paper mulch. The amount of each component is calculated according to the standard proposed by Hydroturf Services (M) Sdn. Bhd (Table 2). The fertilizer used in hydroseeding was a mineral fertilizer with NPK ratio of 10:8:10. This ratio was used based on the growth performance of signal grass (*Brachiaria decumbens*) in preliminary study [36]. The results indicated that the signal grass showed successful growth in comparison with the NPK ratio of 5:5:7.

In order to germinate the species, the hydroseeding slurry was manually and evenly sprayed on the soil surface of each polybag. Four replications were prepared for each species (PPI₁, PPI₄ and PPd₁, PPd₄) including a set of control polybags, which contained only soil (C₁, . . . , C₄). This study was monitored for six months; both species were watered twice a day and left under glasshouse conditions with temperatures between 21°C and 32°C, an average 12 h photoperiod, and relative humidity ranging between 60% and 90%. Root and soil samples were then collected after six months of observation for further root characterization, tensile test, and determination of the soil shear strength.

2.2. Root Characteristics. Sampling of roots from both species was carried out after six months for root characterization. The parameters of root consisted of measurement of root diameter, length, and biomass. The polybags were torn out and the soil samples were carefully washed with tap water to remove all soil particles. Several root samples were selected for length measurement and the length of root was measured using universal tape meter. A vernier caliper was used to measure the diameters of the root at three different

TABLE 1: Properties of the soils used in this study.

Parameters	Results
pH H ₂ O (1 : 2.5; w/v)	4.1 ± 0.19
Soil organic matter (%)	3.2 ± 0.08
Soil water content (%)	20.8 ± 0.51
Sand (%)	51 ± 2.94
Clay (%)	33 ± 1.24
Silt (%)	16 ± 3.09
Soil texture	Sandy clay loam
K (mg/kg)	26.76 ± 1.45
P (mg/g)	0.032 ± 0.004
Total nitrogen (%)	0.4 ± 0.2

*Replicate soil samples of three are required for each test.

TABLE 2: Proportion amount of hydroseeding mixture.

Materials	Amounts
Seed (g/m ²)	27.5
Paper mulch (g/m ²)	125.0
Soil tackifier (ml)	3.0
Fertilizer (g/m ²)	31.25
Distilled water (ml)	300.0
Average pH	5.48

points. Then, the root sample was placed into the oven for 48 hours at temperature of 60°C. Then, the dried samples were weighted several times until the weight becomes constant with a balance (Model Mettler PJ3000, made in Japan). The root samples were then kept in a plastic bag for future reference.

2.3. Root Tensile Test. The tensile strength of the root can be expressed in terms of resistance or stress as the ratio of resistance and root area [37]. Many studies have provided data on the relationship between the tensile stress and root diameter which can be presented by an inverse power law equation [18, 22, 37, 38]. Tensile stress is the ratio of maximum force to the cross-sectional area which derived from the root diameter at the rupture point as follows:

$$T_r = \frac{4F}{\pi d^2}, \quad (1)$$

where T_r is tensile strength (MPa), F is the maximum load at the rupture point (N), and d is the average root diameter (mm).

Meanwhile, other authors preferred to express the tensile resistance-diameter relationship in terms of force unit [39–41]. Vergani et al. [37] stated that although there was no unique equation proposed, the commonly adopted form of a power law equation to represent the relationship between tensile force and diameter is as follows:

$$T_f = \alpha \cdot d^\beta, \quad (2)$$

where T_f is tensile force (N) and d is the average root diameter (mm).

The tensile stress value is calculated by dividing the applied force by the cross-sectional area of the root at its rupture point [42]. However, the use of tensile force is probably preferable than tensile stress as the accurate

measurement is difficult to be accurately determined for the root diameter at breaking force. In addition, the exact point of rupture also cannot be certain before the test especially for the fine and very fine roots. Generally, the point of rupture is established after the test and the diameter is reduced as a result of tensile strain and the rupture process is associated with a small proportion of the root rather than to a single infinitesimal section [37]. Therefore, the acceptable method for estimating the diameter is to measure the diameters at three different points along the root and then take average measurements [37, 41–45].

Root samples were taken from the polybags, which followed the same procedures for root biomass determination. In order to investigate the effect of different ages of the root on tensile resistance, root sampling was carried out after two and six months of growth period. Tensile test for individual root was carried out using the Universal Testing Machine (UTM) with the capacity of 50 N (Instron, Model 5566, USA). The samples were cut into lengths of 10 cm before being weighed. The diameter of the root was recorded according to the method of root characteristics procedures. The two ends of the root were carefully wrapped using sand paper in accordance with ASTM D 3379-75 [46]. In order to achieve a superior grip with little risk of slippage during testing, the root was clamped into the entire wedge grip length. The root was pulled vertically up at a rate of 5 mm/min. The occurrence of extension until failure and reading of the force (F) were recorded and generated automatically using the software that is linked to the UTM. The tensile force at the point of rupture was taken as the peak load (F_{Max}) [37, 41, 42]. The tensile force unit was recorded in Newton (N). The relationship between tensile force and root diameter is expressed as shown in (1).

2.4. Direct Shear Test. The presence of plants on slope provides shelter to the soil surface against rainwater erosion while at subsurface level, slope can benefit from soil reinforcement through plant root. The impact of vegetation roots on the shear strength of soil can be considered as part of the cohesive strength aspect of the soil-root system [47]. Ideally, the shear strength of root-permeated soil creates surplus strength to the soil compared to a condition without the root.

The collection of soil sample applied a metal mould with sharp edges and pressed vertically into the soil surface. The mould was dug out carefully and was wrapped with plastic film in order to preserve the soil moisture content prior to laboratory tests. The sample was then trimmed carefully and fixed into brass box of shear box test (60 mm × 60 mm × 25 mm). This test follows the standards of British Standard Institution 1377 [48]. Each soil sample was applied with normal loads of 10 kPa, 20 kPa, and 30 kPa based on the values applied by previous researchers [4, 49, 50]. The samples were sheared horizontally at a strain rate of 1.2 mm/min. Mohr Coulomb's shear strength equation was used to calculate the cohesion and angle of friction of treated and control soils. In the presence of roots, the failure of soil should also take into account the failure of roots in the soil.

Therefore, in this case the root is considered as reinforcement that increases the shear strength by c_r [38, 51–53] as follows:

$$\tau = c_s + c_r + \sigma \tan \theta, \quad (3)$$

where c_s is the soil cohesion, c_r is the root reinforcement, θ is the angle of friction, σ is the normal load, and τ is the soil shear strength.

After the completion of the shearing, the moisture content and root biomass were determined for each sample. The sheared sample was weighed and transferred into the oven at 105°C for an overnight. Then, the sample w was weighed again to measure the moisture content. The sample was gently washed to remove all the soil and the roots were put in a petri dish before being allowed to dry in the oven overnight at a temperature of 60°C.

3. Results and Discussion

3.1. Root Characteristics. The root characteristics of both species are shown in Table 3. There was a very slim difference in terms of diameter between PPl and PPd species. However, the root length for PPl species was higher than PPd species. A similar trend was also found for the root biomass of the PPl species (50.28 ± 9.39 g). A significant increase in root length and root biomass that were observed in PPl species can contribute to a higher soil-root interaction. Subsequently, a great soil-root interaction will result in higher soil reinforcement that increases the shear strength of soil slope [2, 54]. Root biomass increases the preferential path for the subsurface runoff, thus improving the soil shear strength and reducing slope failure [4]. On the other hand, preferential flow in the meadows promotes the accumulation of nutrients and can prevent the loss of organic matter. Previous studies reported that the preferential flow can prevent the absorption of water by the roots under low rainfall conditions and reduce runoff before the soil is saturated under high rainfall conditions [55–57]. Moreover, previous studies also showed that the vegetation recovery can highly increase the soil stability by accelerating plant growth and promoting soil formation processes such as fine soil particle collection, organic matter, and dispersal of mycorrhizas [58, 59].

3.2. Root Tensile Resistance

3.2.1. Tensile Force-Root Diameter Relationship. A total of thirty-two root samples from both species were collected after six months and were analyzed for the tensile strength test. The root diameters of the PPl and PPd species range from 0.21 mm to 1.1 mm and 0.25 mm to 1.2 mm, respectively. The results of tensile force of the studied species are shown in Table 4. The mean, maximum, and minimum values recorded for PPl species were 4.88, 9.33, and 1.06 N, respectively. Meanwhile, for the PPd species, the mean, maximum, and minimum values recorded were 4.57, 8.51, and 1.14 N, respectively. The PPl species exhibited a higher root tensile force if compared to that of the PPd species. The tensile force increased with increasing root diameter following a power function as shown in Figure 1.

TABLE 3: Root characteristics of the selected species.

Plant species	Root diameter (mm)	Root length (cm)	Root biomass (g)
PPl	0.82 ± 0.05	42.67 ± 2.05	50.28 ± 9.39
PPd	0.84 ± 0.06	21.33 ± 0.94	28.50 ± 2.96

TABLE 4: Tensile forces of the studied species.

Plant species	Tensile force, T_f (N)		
	Minimum	Maximum	Mean
PPl	1.06	9.33	4.88
PPd	1.14	8.51	4.57

The relationship between the tensile force and root diameter for both species is shown in Figure 1. The scattered values of tensile force against root diameter for PPl species can best be represented by a power law equation:

$$T_f = 7.762d^{1.1233}, \quad (4)$$

$$R^2 = 0.893.$$

Meanwhile, the PPd species is represented by the following equation:

$$T_f = 7.0713d^{1.489}, \quad (5)$$

$$R^2 = 0.8611,$$

where T_f is in N and d is in mm.

Based on these results, the root tensile force values showed an increasing trend with increasing values in diameter of root. The relationship can be represented by both power law equation [60] and second-order polynomials [39]. The power law equation was applied since this equation represents the best fit line for the data and has been widely reported by many previous researches [18, 54, 61]. As shown in Figure 1, the relationship represented by the power law equation for both of the studied species was very closely presented due to the small variation in diameter of root. Higher tensile strength capacity of root exhibits better resistance to tensional force that develops during slope failure [31]. Plant roots intercept the potential failure plane by binding ground/soil surface and failure plane together [62]. Root density, network, and types can further enhance the existing stability throughout root anchorage of the particular soil slope [63, 64]. In addition, the presence of higher root tensile resistance can contribute to the increased density of grass on the slope and more resistance toward overturning [1, 6]. Teerawattanasuk et al. [54] also mentioned the contribution of fiber on tensile strength for the tested root which varied in different species and growing period. The influence of cellulose and lignin contents on tensile strength has been comprehensively studied by Genet et al. [16] and Zhang et al. [17]. They found that the thinner root diameter attributed to stronger tensile strength as a result of the cellulose and lignin contents which subsequently add to slope stability. The effect of moisture content on tensile strength of root was also discussed by Zhang et al. [61] and Noorasyikin and Zainab [65].

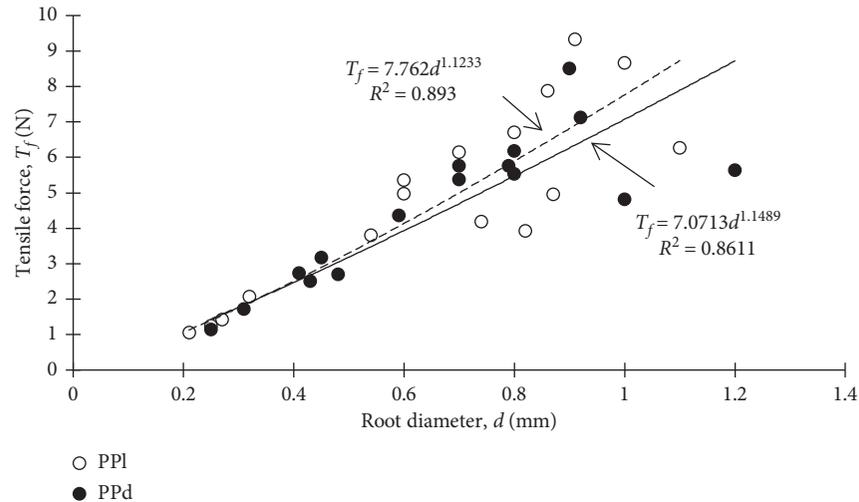


FIGURE 1: Relationships between root tensile force (N) and root diameter (mm). Black solid line = PPd; dashed line = PPI.

3.3. Direct Shear Box Test. The shear stress–displacement curves from the direct shear box test for both studied species are shown in Figure 2. Table 5 shows the summary of the shear strength parameters and available biomass of each test. Generally, the shear stresses increase linearly at early displacement (less than 1.0 mm) before achieving their maximum shear stresses. As the applied normal stress increases, the values of maximum strength also increase. At applied normal stress 10 kPa, the maximum shear stress was 8.40 kPa for the PPI species. The maximum shear stress at greater applied normal stresses at 20 kPa and 30 kPa increased to 11.30 kPa and 19.09 kPa, respectively (Figure 2).

The results showed that the root-permeated soil of both species displayed higher soil shear strength values than the root-free soil (control) (Figure 3). In comparison, the PPI species demonstrated higher value of soil shear strength than PPd species. The cohesion values for the PPI and PPd species were 7.5 kPa and 6.1 kPa, respectively. As expected, the cohesion value for control was lower than root-permeated soil sample (Table 5).

The contribution of root biomass to the maximum shear stress was clearly observed in PPI and PPd species. As shown in Table 5, PPI species presents higher value of average of biomass content (0.146 g) than PPd species (0.058 g). The internal friction angle θ for the root-permeated soil of PPI and PPd species showed higher values than the control sample. The friction angle θ for the PPI species was 21.3° while for the control it was 10.7°. The different values between PPI and PPd with the control were 10.6° and 1.8°, respectively.

The increase in the soil shear strength of root-permeated soil is clearly influenced by the presence of root biomass. In comparison, the average biomass for the PPI species is higher than PPd species which corresponds to the higher shear strength. However, the increase in shear strength of soil can also be associated with the matric suction and root-shoot ratio [66]. They found that the plant induced suction can be enhanced with increasing root biomass (plant maturity or biodiversity).

The increase in shear strength is due to the presence of roots, which interact with soil that occurred at relatively balanced increases in cohesion values and internal friction angles. However, the cohesion parameter was mostly influenced by the presence of roots [67]. A higher root biomass of root-permeated soil can improve the cohesion and friction values which overall increase the shear strength of the soil. Meanwhile, lower biomass content is associated with low cohesion and friction. These reflect how the root content is one of the main important factors in reinforcement of soil [68, 69]. The presence of roots has an effect on the internal friction angle value between two selected species (Table 3). As stated early, the change in internal friction can be explained in terms of the root biomass. Both species exhibited different amount of biomass that significantly resulted with friction angle. The friction angle value of PPI species is approximately 70% higher than PPd species. The frictional angle values in this present study were smaller than the value for sandy soil (Table 5). Similarly, Maffra et al. [67] performed a study on the effect of root on sandy soil shear strength using *Phyllanthus sellowianus*. They found the friction angle was 29.01° for root-permeated soil and 27.4° for soil without root (control). On the other hand, internal friction angle of the root-soil composite system for *Artemisia ordosica* (*Artemisia ordosica* Krasch.) is higher than the angle of the soil without *Artemisia ordosica* Krasch roots, 10.26° and 8.95°, respectively [70]. According to Veylon et al. [71], this could be due to several factors such as type of soil, sample size, and methods of sample preparation. It has also been reported that there is a link between the small amount of roots and insignificant effect on internal friction [67, 71].

Studies have shown that the mean values of root per unit area of soil at shallow layers are lower than 1% [72, 73]. This small proportion of roots over the soil block seems to justify why few roots have experienced little change in their particle arrangement, thus subsequently having minor effect on the internal friction angle [67]. The influence of root on internal friction angle was also performed by Graf et al. [74]. They found that planted soil exhibited a higher internal friction

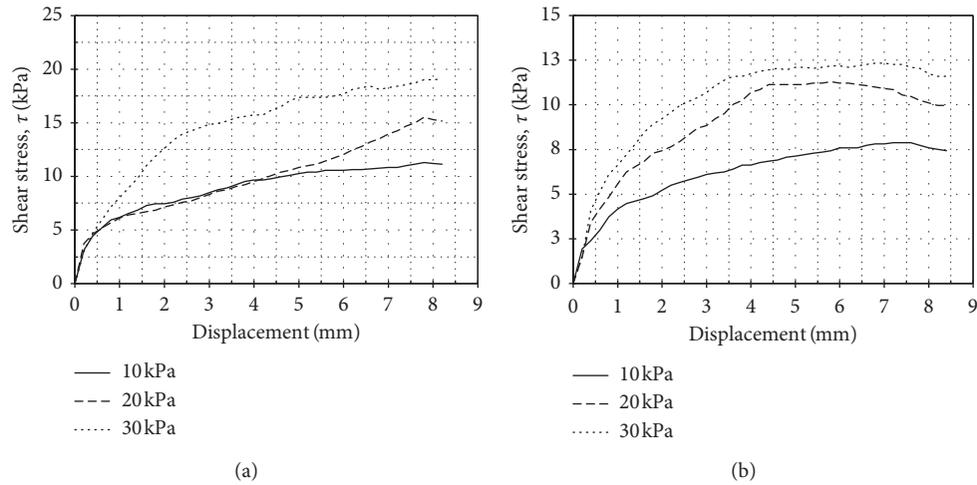


FIGURE 2: Shear stress against displacement curves for direct shear tests on three different normal loads of (a) PPI and (b) PPD species.

TABLE 5: Summary of the shear strength parameters and biomass of different planted soils at different values of normal pressure.

Species studied	Normal pressure (kPa)	Max. shear stress (kPa)	Average biomass (g)	Cohesive value c (kPa)	Friction angle θ ($^{\circ}$)
PPI	10	11.3	0.146	7.5	21.3
	20	15.5			
	30	19.0			
PPd	10	7.8	0.058	6.1	12.5
	20	11.2			
	30	12.3			
Control	10	6.4	NA*	4.2	10.7
	20	8.4			
	30	11.5			

*NA = not available (no plant).

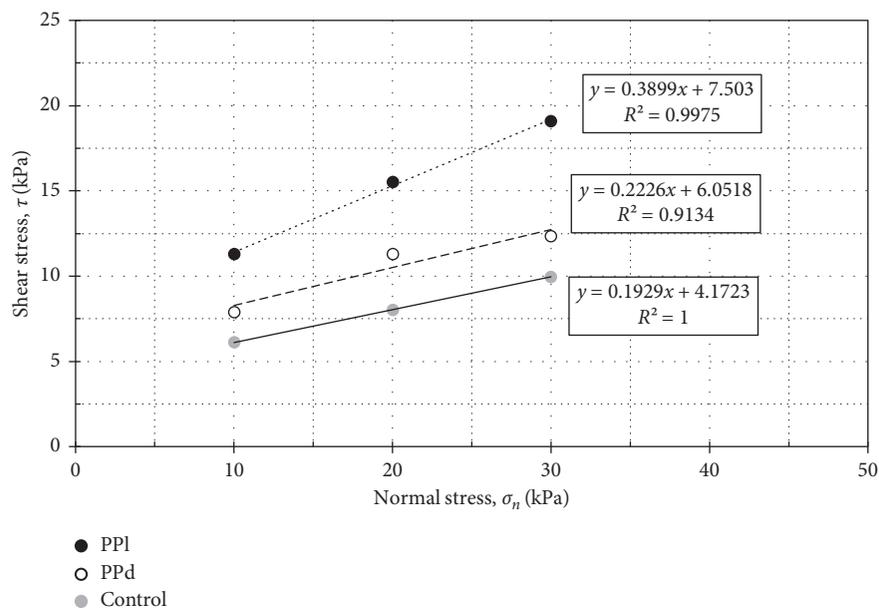


FIGURE 3: Relationship between shear strength and normal stress of control (bare soil) and root-penetrated soil after 6 months of growth.

value ($\theta = 39.4^{\circ}$, unit weight, $\gamma = 15.5 \text{ kN/m}^3$) than untreated soil at the same unit weight ($\theta = 34.3^{\circ}$). By increasing the unit weight γ , from 15.5 kN/m^3 to 19 kN/m^3 , the internal friction

angle for untreated soil rose up to 40.1° . Similarly, synthetic fibers were used to mimic the function of root in soils apparently showing higher shear strength than bare soil

[75, 76]. Small amount of root can greatly influence the value of soil cohesion. The soil cohesion increases as the roots intercept the potential failure surface, which can result in rupture or slip of the fibers when the roots are subjected to further shear force [2, 77].

4. Conclusions

This study investigated the effects of the grass species, namely, *P. polystachion* and *P. pedicellatum*, on the root tensile resistance and soil shear strength of root-permeated soils. The results of root tensile force increased with increasing the root diameter for both studied species of *Pennisetum*. The relationship between root tensile force and root diameter was slightly different for both species, which could be due to small variation in root diameter. It was found that PPl showed higher root tensile force compared to PPd. This study showed that roots can significantly contribute to the soil shear strength. The root-permeated soils showed higher shear strength than control samples, which were zero plants. In comparison, again PPl exhibited higher values of shear strength than PPd. The results from this study were in agreement with the presence of root systems that can mechanically reinforce soil slope. Therefore, with the combined mechanical characteristics of root tensile and the influence of these selected plant species on soil shear strength, the stability of particular slope can be successfully improved. It is expected that the improvement of bioengineered slope gradually increases with the plant age. The use of selected *Pennisetum* spp. has never been adopted as a biological material for soil bioengineering approach as these species have several advantages due to their widely distribution, easily adaptation, and soil strength improvement.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

Acknowledgments

The authors would like to thank UKM for the financial support through research Grant no. GUP-2016-068. The authors also thank the laboratory assistant staff of Civil Engineering School of Faculty of Engineering and FORCE, UKM, for assisting the mechanical testing of root tensile and direct shear box tests.

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