Tensile strength and cellulose content of Persian ironwood (*Parrotia persica*) roots as bioengineering material

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ABSTRACT: Unstable slopes create numerous problems for forest management and may destroy the road network and disturb access to forest. Soil bioengineering is a solution that can prevent these problems and reinforce the hillslope. Persian ironwood is considered as a good protective species for hillslope stability in Iran with an extensive lack of information about biotechnical properties. In this research the root strength of this species and also the relation between root diameter and cellulose content were investigated. The results showed that the mean tensile force and tensile strength were 99.70 ± 2.01 N and 173.23 ± 4.94 MPa, respectively, for the root diameter range between 0.22 and 3.78 mm. The results of ANOVA showed that the power models between root diameter and tensile force and tensile strength were statistically significant and the results of t-test showed that coefficients and constants of the models are also significant. The values of the parameters of the power law (α and β) obtained for Persian ironwood do not fall in the range that has already been suggested for hardwood roots, which may be due to a narrow diameter range. The mean cellulose content was 56.87 ± 5.79% and the relationship between root diameter and cellulose content was not statistically significant. The data presented in this study expand the knowledge of biotechnical properties of Persian ironwood and support the idea that there is still an extensive lack of information about plant roots as a bioengineering material.

Keywords*:* biotechnical

Natural slopes (like mountain forests) are usually formed over a long period of time and any changes including the road construction and slope modification can fail them (Genet et al. 2005). Unstable slopes usually cause various problems for forest management through destroying road networks and disturbing access to forest. One known solution to this problem is soil bioengineering techniques, i.e. the use of plant (grass, shrub or tree) materials to perform some engineering functions like soil reinforcement and prevent instability. Vegetation reduces water-caused erosion by intercepting rainfall, increasing water infiltration, intercepting runoff at the soil surface level and stabilizing the soil (De Baets et al. 2007). Among different parts of a plant, roots have a significant effect on soil properties (Genet et al. 2005). The main concern of most previous bioengineering techniques was mainly limited to the aboveground biomass and less attention has been paid to the role of the belowground biomass, i.e. the root system (De Baets et al. 2007). Many studies have been conducted on root growth, phenology and function but fewer studies have focused on the engineering aspects of a root (Cazzuffi et al. 2006). Roots affect soil properties including infiltration rate, stability, moisture content, compaction rate, shear strength and its organic matter content (De Baets et al. 2007). However, the correct choice of material (plants) for soil bioengineering requires knowledge concerning the efficiency of the plant (Stokes et al. 2008). The major factors contributing to the efficiency of the root system in soil reinforcing include the

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quantity of roots and their directional distribution as well as their tensile strength, soil shear strength and soil-root interaction (Bischetti et al. 2005; De Baets et al. 2007). Tensile strength is one of the most important factors in soil stabilization and has been considered as a main focus of many studies (Bischetti et al. 2005; Genet et al. 2005; Pollen 2007). Roots produce a reinforced matrix in the soil whose stress is transferred to the roots during the loading of the soil in a way similar to the reinforcement of concrete structures with steel (Pollen 2007). Wide variations in root tensile strength have been reported in the literature, depending on species and site factors such as the local environment, season, root diameter, and orientation (Bischetti et al. 2005; Genet et al. 2005). These studies have shown that tensile strength usually decreases while the root size increases. This phenomenon is attributed to the differences in root structure, as smaller roots possess more cellulose per dry mass than larger ones (the structure of cellulose is optimal for resisting failure in tension) and ensure most the reinforcement effect (Genet et al. 2005; Hales 2009).

Few studies in literature have been focused on the influence of Hyrcanian plant roots on soil strength (Bibalani, Majnounian 2007; Abdi et al. 2009, 2010). Therefore, the available information on Hyrcanian plant root characteristics and their use for soil erosion control are still very limited. The main objectives of this work were (1) to assess strength properties of Persian ironwood roots as a typical species of Hyrcanian forest and (2) to investigate root strength and its relation to cellulose content.

MATERIAL AND METHODS

The Hyrcanian forest is located in the north of Iran northward to the southern shore of the Caspian Sea. The study was conducted in the first district of an educational and experimental forest of University of Tehran (Kheirud Forest). The district of Patom is the lowest district of the forest that is about 900 ha and extends from 40 to 900 m a.s.l. The system of management is a selection system which is followed to ensure sustainable development and yield. Some areas of this forest are characterized by the presence of shallow translational slides and gullies alongside forest roads. These slides contain superficial layers of the slopes, which are in many cases less than 1 m deep and extend to the bedrock, where vegetation exerts a beneficial effect on stability as a result of lateral root reinforcement. The site has a relatively thin soil mantle, underlaid by the calcareous bedrock (Jura, Cretaceous) that contains discontinuities and cracks penetrable by roots (Majnounian, Etter 1993). Therefore, roots can act in the same way as toe piles (Tsukamoto, Kusakaba 1984). The main tree species of this forest are *Fagus orientalis*, *Carpinus betulus, Parrotia persica, Acer cappadocicum*, *Ulmus glabra*, *Cerasus avium.* Among these species *Parrotia persica* as an endemic species has a low commercial value and is therefore considered as a protective species for the hillslope stability. This 7-m to 15-m high deciduous tree is low-branched, 7 m to 12 m wide. Persian ironwood has a reputation for its hardness and dense wood.

Tensile strength tests. Roots for experiments were collected from a forest stand in July 2012. Five different trees were selected randomly from the stand, live roots were collected randomly from the soil by excavating pits or trenches beside trees at a depth of about 30 cm below the soil surface (Cofie et al. 2001; Abdi et al. 2010). In order to prevent prestress effects, none of the roots were pulled; they were instead cut with sharp scissors, put in plastic bags and loosely sealed (Bischetti et al. 2005). We preserved the roots for a few days using a 15% alcohol solution, which has definitely no influence on the measured parameters (Bischetti et al. 2005). Tensile tests were then carried out on fresh roots within 1 week from the sampling date (Bischetti et al. 2005; Abdi et al. 2010). In the laboratory, the roots were thoroughly inspected for any possible breakage. Afterward root hairs were carefully dismembered and suitable root samples with lengths of about 150 mm were cut (Cofie, Koolen 2001). Before each experiment began, root diameter was found by measuring diameters at about 3 different positions along the length of the root.

Tensile strength testing was carried out using a computer-controlled Instron Universal Testing Machine (Model 4486) (TestResources Inc., Shakopee, USA), equipped with a 10 kN maximum-capacity load cell. By visual inspection, root samples were positioned as vertical as possible with their axis coinciding with the load cell axis. The root ends were clamped and a strain rate of 10 $mm \cdot min^{-1}$ (Bischetti et al. 2005; Mattia et al. 2005; Pollen 2007) was applied until rupture occurred. 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 required to break the root by the cross-section area of the root at its rupture point. Tests subjected to slippage, or those roots that broke because of crushing at the jaw faces, were disregarded (Cofie et al. 2001; Bischetti et al. 2005; Mattia et al. 2005).

Cellulose content. All root samples were grouped into eight diameter classes and the middle of each diameter range was selected for tests. The selected diameters were: 0.47, 0.92, 1.36, 1.81, 2.25, 2.70, 3.14 and 3.59 mm. The isolation procedure was carried out according to the method described by LEAVITT and DANZER (1993) to extract root holocellulose with small modifications. Briefly, the waxes were extracted to remove the low molecular weight hydrophilic compounds and delignification. Samples were then dewaxed in a Soxhlet extractor with acetone for 24 hours. We added 80 ml of hot distilled water, 0.5 ml of acetic acid, and 1 g of sodium chlorite to 2.5 g of extractive free sample, in a 250-ml Erlenmeyer flask. The mixture was heated in a water bath at 70°C. After 60 min, 0.5 ml of acetic acid and 1 g of sodium chlorite were added. After each succeeding hour, fresh portions of 0.5 ml acetic acid and 1 g sodium chlorite were added with continued shaking. The addition of 0.5 ml acetic acid and 1 g of sodium chlorite was repeated until the root samples were completely separated from lignin. The complete delignification procedure took 6 to 8 hours and the sample was left without further addition of acetic acid and sodium chlorite in the water bath for overnight. At the end of 24 h of reaction, the sample was filtered on a tarred fritted disc glass thimble, washed with acetone, and vacuum oven dried at 105°C for 24 h (ROWELL et al. 2012).

Data analysis. In order to test the significance of fitting regression models and the coefficient and constant of the models, ANOVA and *t*-test were used respectively. To select the best regression model fitting tensile strength data (based on higher R square and lower standard error of the estimation) the Curve Estimation function was used. Pearson correlation test was used to assess the correlation between root diameter and cellulose content. All statistical analyses were conducted in SPSS v.16, (SPSS, Tulsa, USA) and the graphs were plotted using Microsoft Excel 2007 and R 2.13.0 and Excel were used for fitting the power curve to plotted data.

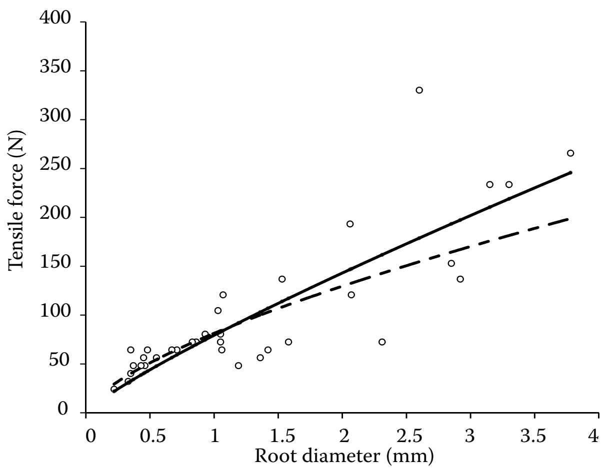

Fig. 1. Tensile force at failure versus root diameter (the curves show the power law fitted to the data by R and Excel)

RESULTS

Tensile strength tests

A number of trial experiments were first conducted to develop an appropriate clamping force to prevent slippage. Thirty-six root specimens were analyzed for strength characteristics. Tensile force (TF) increases as diameter (D) increases in tensile tests. The diameter of roots analysed varies between 0.22 and 3.78 mm (the relatively narrow range of root diameter is due to the limitation of clamping device); the mean tensile force was 99.70 ± 2.01 N and the maximum and minimum recorded values were 24.20 and 335.20 N, respectively. Data with the corresponding fitting curve (power) for tensile force is shown in Fig. 1.

When tensile strength is concerned, the mean strength value was 173.23 ± 4.94 MPa and the maximum and minimum recorded values were 17.30 and 669.69 MPa, respectively. The results of ANOVA showed that the model for tensile force was statistically significant ($F_{1,33}$= 86.27, *P* = 0.000) and the results of *t*-test showed that the coefficient and constant of the model are also significant (*t* = 9.28, *P* = 0.000 for coefficient and *t* = 18.03, *P* = 0.000 for constant). HALES et al. (2009) presented tensile force curves versus root area instead of diameter because of autocorrelation, but our results showed that it did not have any positive effect on R square.

The relation between tensile strength and diameter was tested using several regression models whose power was the best based on higher R square and lower standard error of the estimation simultaneously (Table 1).

The results of ANOVA showed that the model was statistically significant ($F_{1.3}$ = 337.105, *P* = 0.000) and *t*-test also showed that the coefficient and constant of the model are significant (*t* = –18.36, *P* = 0.000 for coefficient and *t* = 18.03, *P* = 0.000 for constant).

Cellulose content

The mean cellulose content was 56.87 ± 5.79% for samples. The relation between cellulose content and root diameter is shown in Fig. 2.

Table 1. Model summary and parameter estimates

Equation	Model summary				Parameter estimates			
	R square	F	SE	sig.	constant	b_1	b_2	b_3
Linear	0.49	30.81	128.91	0.00	341.01	–125.72		
Logarithmic	0.77	109.45	85.913	0.00	175.49	–201.12		
Inverse	0.91	328.79	53.79	0.00	–45.96	166.93		
Quadratic	0.78	56.51	85.14	0.00	561.24	–509.15	106.60	
Cubic	0.89	84.45	60.70	0.00	754.76	–1.05	467.87	–64.70
Power	<u>0.91</u>	337.10	<u>0.32</u>	0.00	103.61	–1.32		
Exponential	0.75	98.86	0.54	0.00	361.86	–0.94		

b_1–b_3 means coefficients, underlined – power law

As Fig. 2 shows there is not any relationship between tensile strength and cellulose content. The Pearson correlation coefficient was 0.53 ($P > 0.05$) and also the results of ANOVA showed that the model ($y = 2.85x + 51.07$) was not statistically significant ($F_{1, 7} = 2.44$, $P = 0.169$). Therefore a significant relation between root diameter and cellulose content was not observed in this set of analyses.

DISCUSSION

Tensile strength

Root tensile strength is an important factor influencing slope reinforcement (Greenwood 2006) and tree anchorage (Genet et al. 2005). Variations in root tensile strength are high between species and environments and even within a species (intraspecies variations) (Abdi et al. 2010). For example Abdi et al. (2010) measured the root tensile strength of Persian ironwood in *Hyrcanian* forest (with the same diameter range as in this study) and found the values of the power law (α and β) as 29.27 and 0.365 which are different from this study (α = 103.61 and β = 1.32).

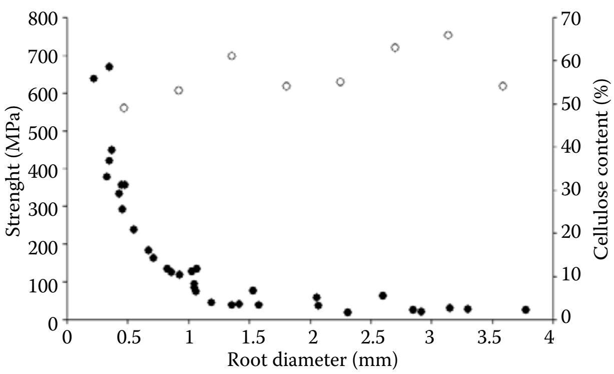

Fig. 2. Relation between root diameter (○) and tensile strength (●) and cellulose content

The different predicted root tensile strength values could be due to variations in root age (Genet et al. 2005), growth rate, soil moisture content, soil texture (Bischetti et al. 2005), nutrient status and precipitation history (Hales et al. 2009). The root tensile strength values showed that the smallest roots were the most resistant ones. Root strength decreases sharply as diameter increases, following the power law (regarding R square and standard error of estimation, Table 1.) as found by many other studies (Bischetti et al. 2005; Genet et al. 2005; De Baets et al. 2007). Compared to De Baets et al. (2007) and Hales et al. (2009), R square of power regression was high ($R^2 = 0.91$) in our study. De Baets et al. (2007) found a poor correlation between tensile strength and root diameter due to the inclusion of root bark while our results showed high R square despite the inclusion of root bark in tensile tests. This may be attributed to not considerable thickness of root bark in this species. Bischetti et al. (2005) suggested that the exponent of the power law equation (β) controls the rate of strength decay with diameter, whereas α can be considered as a scale factor. Therefore a low scale factor (α) and a high exponent (β) mean a less resistant species. Based on our results the value of β is relatively high, suggesting strength decay should be high in this species. The number and morphology of root branches are reported to influence the stress-strain relationship, ultimate resistance to failure (Tosi 2007) and magnitude of root reinforcement (De Baets et al. 2007). Many branches of the ironwood root system and usual failure at branch points in larger roots may justify a high strength decay rate.

A diameter-force curve was fitted using two types of software (Excel and R) and the results showed that the power equation parameters are different in the two curves ($y = 81.33x^{0.67}$ in Excel and $y = 79.35x^{0.85}$ in R). This is consistent with the results of Schwarz et al. (2013), who indicated that different algorithms (Excel or R) lead to quite different values of the equation parameters and small changes in the fitting of the root diameter–force curve lead to changes in RBMw model. They stated that power fitting curves in Excel are not correct.

In addition to tensile strength, root distribution influences the efficiency of the root system in soil reinforcement. Although we did not assess root distribution in the present study, previous experiences in the same study area using a profile trench method (Abdi et al. 2010) showed that the average root area ratio (RAR) values decrease generally with depth following an exponential law. Their minimum and maximum values along the profiles were 0.001% and 1.39%. Detailed information about the root distribution of Persian ironwood can be found in Abdi et al (2010).

Cellulose content

The mean cellulose content of ironwood was determined as 56.87 ± 5.79%, which is less than those previously reported by Genet et al. (2005) for Sweet chestnut and Maritime pine roots (60.0 ± 2.2% and 69.9 ± 2.3%, respectively). As the cellulose content variation of roots could be dependent on topographical features as reported by Hales et al. (2009), the relatively flat terrain of our study area might be responsible for the lower cellulose content. The decrease in root tensile strength as root diameter increases is a function of cellulose content (Genet et al. 2005; Hales et al. 2009). Cellulose content is also reduced as the root grows up (De Baets et al. 2007). Differences in cellulose content have been proposed to be the main parameter governing the root tensile strength (Genet et al. 2005). Detailed root chemical and mechanical analysis indicated that there is no definite trend between the cellulose content and root diameter as shown in Fig. 2. The unclassified age and bulk analysis of the roots might be possibly responsible for these results (Stokes 2008). Because very fine roots were analyzed in this study, it was not possible to determine individual root cellulose content. Roots were mixed up and diameter classes were analysed. Hales et al. (2009) stated that in hardwood species, the xylem tissue under greater mechanical stress has a lower lignin to cellulose ratio compared to the non-stressed xylem, which results in localized accumulation of cellulose and higher tensile strength. Relatively flat terrain and lack of slope stress can contribute to the obtained results. Special attributes of ironwood as an endemic species combined with the lack of adequate biotechnical information may be other possible factors.

CONCLUSION

The purpose of this study was to determine biotechnical properties of Persian ironwood. The findings showed both positive and negative relation between the tensile force and strength with root diameter. It also suggests the power equation as the best regression model statistically. The results of tensile strength combined with root distribution information can be used to evaluate the effect of root reinforcement using Wu et al. (1979). It is worth mentioning that different methods have been developed to quantify root reinforcement: Wu et al. (1979), RipRoot model (Pollen, Simon 2005) and Root Bundle Model (e.g. RBM and RBMw) (Schwarz et al. 2013). Among these, Wu et al. (1979) model is the simplest and requires minimal parameters (only root tensile strength and the cross-section area of fibres) but with overestimation in reinforcement. Pollen and Simon (2005) stated that the assumptions made by Wu et al. (1979) that all of the roots break at the same time, and that their full tensile strength is mobilized at breaking point is the source of reinforcement overestimation. Pollen and Simon (2005) developed a FBM theory based model, RipRoot with progressive breaking of roots and therefore improved the accuracy of estimates of root reinforcement. The latest model is RBMw, which considers variability of mechanical properties of each root diameter class and implemented it to reinforcement model (Schwarz et al. 2013). Schwarz et al. (2013) noted the applications of RBMw as: prediction of the pull-out of riparian plants due to drag forces of water flow, study of tree stability during wind storms or rock fall impacts and slope stability modelling at large temporal and spatial scales. Although the model needs more parameters (such as: root size distribution, root tensile force, secant Young's modulus, length, tortuosity and field pull-out tests), it allows a more complete force-displacement characterization of root reinforcement for a bundle of roots compared to simpler models such as Wu et al. (1979) (Schwarz et al. 2013).

The changes in the factor of safety (FS) due to root reinforcement can be then used in hillslope stability mapping and analyses for road construction and logging planning in forested areas. Surprisingly, no significant relation was found between root diameter and cellulose content. This might be through either unclassified age or bulk analysis of the roots or the studied species attribution. The results of this research support the idea that there is an extensive lack of information about plant roots as a bioengineering material.

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