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Why fine tree roots are stronger than thicker roots: The role of cellulose and lignin in relation to slope stability

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ABSTRACT

Plant roots help to reinforce the soil, increase slope stability and decrease water erosion. Root tensile strength plays an important role in soil reinforcement and slope stabilization. The relationship between tensile strength and internal chemical composition of roots is unknown due to limited studies. Thus, it is difficult to determine why root tensile strength tends to decrease with increasing root diameter. In this study, biomechanical and biochemical tests were performed on the roots of Chinese pine (*Pinus tabulaeformis*) to determine the relationships among tensile strength and the contents of the main chemical composition: cellulose, alpha-cellulose and lignin in the roots with different diameters. Our results confirmed that the tensile strength of Chinese pine roots decreased with increasing root diameter, and this relationship might be a power function. The chemical contents of the roots and root diameter were also related to each other with significant power regression. With increasing root diameter, the cellulose content and alpha-cellulose content increased, but the lignin content decreased. In addition, the lignin content exhibited a significantly positive relationship with tensile strength. Furthermore, the ratios of lignin/cellulose and lignin/alpha-cellulose decreased with increasing root diameter following significant power regressions, and they also demonstrated a positive relationship with tensile strength. Taken together, these results may be useful for studies on root tensile strength, soil reinforcement and slope stability.

1. Introduction

There have been several geomorphological studies performed of the earth's landscape and the processes responsible for its formation. Vegetation plays an important role in altering its landscape. Water from rain and floods is a significant driving force for soil erosion and landslides. To help stabilize slopes and mitigate landslides, vegetation is a relatively effective and inexpensive measure (Docker and Hubble, 2008; Kazmierczak and Carter, 2010), and the removal of vegetation may increase the frequency of soil erosion and slope failure (Gray and Sotir, 1996). In landslide activity, vegetation is a decisive factor in addition to hydrological, geological and geotechnical parameters (Rickli et al., 2001). Studies in the Northern Italian Apennines demonstrate that shrub species can stabilize debris measuring up to 0.6 m in thickness and with a topographical gradient of up to 45° (Tosi, 2007). For displacement values exceeding 1–5 cm, plants are the primary lateral stabilization mechanism on scarps (Schwarz et al., 2010).

It is well established that plants can exert hydrological and mechanical effects (Greenway, 1987; Gray and Sotir, 1996). The root is the main organ of a plant to exert the mechanical effects by holding the soil and reducing the soil water content (Stokes et al., 2008). Plant roots can reinforce the soil by providing apparent cohesion to soil shear strength (Fan and Su, 2008; Zhang et al., 2010). The cohesion due to root presence (root cohesion; e.g., Waldron and Dakessian, 1981; Abe and Ziemer, 1991; Abernethy and Rutherfurd, 2001; Pollen and Simon, 2005) is a product of the root cross-section area per unit area of soil and root tensile strength (Waldron, 1977; Wu et al., 1979).

Root tensile strength governs not only soil stabilization and strength but also plant anchorage (Ennos and Fitter, 1992), particularly tree anchorage against the uprooting force of the wind (Coutts, 1986). Approximately 75% of anchorage during uprooting is provided by roots held in tension (Crook and Ennos, 1996). Root tensile strength, an important index of soil reinforcement and plant anchorage, is affected by root diameter, species, root length (Zhang et al., 2012), seasons (Wästerlund, 1989; Makarova et al., 1998), test speed (Cofie and Koolen, 2001), living or decaying of roots (Watson et al., 1999; Schmidt et al., 2001), and environmental conditions (Sun et al., 2008). Among these factors, root diameter is the most important due to its power relationship with tensile strength (e.g., Bischetti et al., 2005; Mattia et al., 2005). Small roots demonstrate greater strength per unit area compared to large roots, and differences in root chemical composition may explain this phenomenon.

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Cellulose is a linear polymer of glucose, which generally has a flat, ribbon-like structure (O'Neill and York, 2003), and is the most abundant polysaccharide in plant cells. Hemicellulose exhibits a random, amorphous structure with small strength. Lignin, the most abundant chemical composition in cell walls except for cellulose, binds to cell wall polysaccharides via covalent and non-covalent interactions to form a lignin–polysaccharide complex, and provides the structural integrity of cell walls, which is crucial for woody plants with a high requirement for structural support and stem rigidity (Tiimonen, 2007). Cell walls define the morphology and size of individual cells and ultimately its root morphology (O'Neill and York, 2003), and provide resistance to tension (Obembe, 2006). Lignin fills the spaces in the cell wall between cellulose, hemicellulose and pectin composition, and increases the mechanical strength of the cell wall (Janssen, 2000). However, very few studies have investigated the relationship between the lignin content and root tensile strength, and studies on root cellulose content and tensile strength have been limited. To the best of our knowledge, only Hathaway and Penny (1975) have investigated the root tensile strength of *Polulus* and *Salix*, and its relationship to their anatomy and chemical composition, including cellulose, hemicellulose and lignin. Furthermore, Genet et al. (2005) reported on the effect of cellulose content on root tensile strength. However, the relationship between root tensile strength and chemical composition still remains unclear. Alpha-cellulose, which consists of mainly of β-1, 4 glucopyranose chains, is an insoluble fibrous residue extracted from wood and straw pulps under strong alkali conditions. Alpha-cellulose exhibits the natural structure of cellulose fibers with a high degree of polymerization and is a major index for the synthesis of fibers (Jäger et al., 2010). Thus, the alpha-cellulose content should also be considered as a factor of root tensile strength.

In this study, the relationship between tensile strength and the contents of cellulose, alpha-cellulose and lignin were investigated. Genet et al. (2005) reported that the lignin/cellulose ratio should be considered to confirm the effect of the chemical composition of roots on their mechanical properties. Thus, root tensile strength was also examined in relationship to the lignin/cellulose ratio.

2. Materials and methods

2.1. Root sampling

Root sampling was performed in the Beigou forest field (41°50′ to 41°54′N, 117°29′ to 117°34′E, mean altitude 1500 m), which is located approximately 20 km southwest of Weichang Town in Hebei Province, North China. This mountainous area has an altitude ranging from 700 to 2000 m. The climate is semiarid to semihumid, with very cold and dry winters, windy springs, and warm summers. The mean annual temperature is 1.3 °C, with a minimum record of −29.1 °C in January 2010, and a maximum of 39.4 °C in July 2000. The annual precipitation is 380–560 mm, with 70% in July to September. The major soil type is aeolian sandy soil. The general soil thickness is 0.5–1.5 m, with a humus layer of 0.15–0.50 m and a litter of 0.10–0.50 m. The soil pH varies from 7.3 to 7.4 (Xu, 2007).

Chinese pine (*Pinus tabulaeformis*), a very common species for plantation in the Loess Plateau and North China (Zhang, 2004), was selected as the study species. Roots of Chinese pine (23–28 years old) were sampled to investigate tensile strength. To avoid any root damage or stress during the sampling and for safe and convenient root excavation, the trees were cut before the root system was excavated (Böhm, 1979). Subsequently, intact roots were cut using sharp scissors to avoid the effects of pre-stress. The roots were then placed into plastic bags, and these bags were sealed and transported to the laboratory in a refrigerated box at a temperature of 4 °C to maintain root freshness (Bischetti et al., 2009). In the laboratory, the roots were evenly divided into two halves. One half of the roots were used for tensile tests and the other half were used for composition tests.

2.2. Root tensile tests

Root tensile tests were performed according to the previously described methods of Cofie and Koolen (2001) and De Baets et al. (2008). These tests were performed using a computer-controlled electronic universal testing machine (UTM, Jinan Shijin Group Corporation, Shandong, China; Fig. 1). This instrument was able to generate tensile force to measure load and displacement. A load cell with a maximal capacity (F_N) of 10.0 kN and a resolution of 0.001% F_N was used. Strain rates from 0.001 to 500 mm min^{-1} were applicable, and the resolution of the displacement measurement was 0.001 mm. A crosshead speed of 10 mm min^{-1} was selected for the tests (Bischetti et al., 2009; Zhang et al., 2012). The over-bark diameter of the roots tested varied between 0.50 and 7.75 mm. These tests were interpreted invalid when the roots were broken near or at the position of clamping, and when root breakage was due to stress concentration proximal to the clamps and not induced by the tensile force. The clamp used as a fastening device consisted of a pair of steel blocks. To increase the friction between the blocks and roots, each block was provided with a groove that had an arc cross-section and ridge strips in the groove vertical to the axial direction of the clamped roots. When the blocks were positioned in the jaws of the testing machine, the grooves formed a cylinder-like hole where a tested root sample was fixed. The testing machine had two clamps in the vertical direction, which fastened the two ends of the root during the tests.

Before the tests, the root samples were carefully checked to avoid any apparent breakage and peelings. Subsequently, the samples were cut into sections of 100 cm in length. The tensile strength (T_s) was calculated by dividing the maximal force required for failure (F_{max}) by the cross-sectional area of the root.

$$T_s = \frac{F_{max}}{\pi\left(\frac{D^2}{4}\right)} \quad (1)$$

where D is the mean root diameter (mm) with the bark near the point of rupture after stretching. The root diameter was measured using a slide gauge with 0.02 mm accuracy. After root breakage, the largest and smallest diameters were measured on the longer section of the two remaining sections at approximately 10 mm away from the breakage point. This procedure was necessary because preliminary tests had shown that some diameter reduction occurred close to the breakage point due to plastic deformation. The potential to over-estimate the load per unit area was reduced by measuring the failure diameters at a point sufficiently distant from the failure (Parr and Cameron, 2004).

2.3. Cellulose, alpha-cellulose and lignin contents

In general, roots that were approximately 1 mm diameter and 100 cm in length were light, particularly when their bark was removed. For such roots, the quantity of the individual root was usually insufficient to test for chemical composition. Thus, for our tests, all of the roots were divided into eight groups (1–8). Their diameters (D_i, where i is the group number) were as follows: $D_1 = 0.5$–1.5 mm, $D_2 = 1.5$–2.5 mm, $D_3 = 2.5$–3.5 mm, $D_4 = 3.5$–4.5 mm, $D_5 = 4.5$–5.5 mm, $D_6 = 5.5$–6.5 mm, $D_7 = 6.5$–7.5 mm, and $D_8 = 7.5$–8.5 mm (similar to Osman et al., 2011). The cellulose, alpha-cellulose and lignin contents of each group were analyzed.

2.3.1. Determination of cellulose content

The methods used to evaluate the cellulose content were similar to that of ASTM (1978), and analysis of the cellulose content was performed according to Genet et al. (2005). First, the bark was removed from each root using a scalpel. Each root was then air dried at 60 °C for