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Systematic evaluation of tensile strength for natural and synthetic plant roots for soil reinforcement applications

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ABSTRACT: Plant roots contribute to improving the slope stability; however, their large variability affects how they interact mechanically with the surrounding soil. Additionally, their anatomical structure also influences their mechanical properties like tensile strength, a key parameter in rooted soil. In this study, the tensile strength of *Salix sp.* roots from 90-day indoor pot experiments were evaluated at four different dehydration periods. These results informed the selection of suitable synthetic materials, which included polylactic acid (PLA), and ultraviolet value tough (T) and flex (F) resins, varied into three resin matrices of 100 TF, 80/20 TF, and 50/50 TF. The tensile strength of natural roots increased from 8.6 MPa to 12.0 MPa with drying time, while mean stele strength increased from 21.3 MPa to 26.7 MPa. In comparison, the average tensile strengths of the respective synthetic resin blends were 44 MPa, 38 MPa, 34 MPa, and 21 MPa. The validation of the tensile strength for 50/50 TF using ASTM D 638-22 yielded 24.7 MPa which further closely mimicked the stele strength properties. This study provided insights into designing synthetic root to effectively replicate natural roots for various geotechnical tests.

Keywords: 3D printing synthetic materials; variability; rooted soil; tensile strength; Young's modulus

1 INTRODUCTION

Vegetation through their root systems are essential for soil stability and erosion prevention especially on slopes (Vergani et al., 2012). Natural roots exhibit bio-mechanical properties like tensile strength, influenced by species, age, and environmental conditions. Key factors influencing the tensile tests include the length of the specimens (Mickovski et al., 2009), strain rate, sample preparation for clamping the ends of the roots (Alam et al., 2018; Chen et al., 2022; Genet et al., 2005) and the initial root diameter at the beginning of tensile or end of the rupture (Mickovski et al., 2009).

Dehydration significantly affects root tensile strength, as moisture content changes with the seasons. Laboratory evaluations usually assess roots in fresh, dry, or saturated states (Zhang et al., 2019). In addition, Hales and Miniat, (2017), demonstrated that the tensile strength of fresh roots showed more pronounced effects compared to the laboratory hydrated ones. Studies by Hales and Miniat, (2017) indicate that tensile strength generally decreases with increased moisture content, though the precise relationship remains unclear, particularly regarding diameter reduction during desiccation (Boldrin et al., 2017). Additionally, Boldrin et al., (2017) and Zhang et al., (2019) found that root dehydration impacts the relationship between tensile strength and root diameter. Notably, there is no well known standardized method for preparing and dehydrating roots before tensile tests, indicating a need for further research.

The biomechanical properties of plant roots vary with anatomical structure, significantly influencing their tensile behavior. The stele and cortex (root diameter) exhibit different characteristics; a thicker cortex can reduce tensile strength because calculations consider the total root diameter, rather than focusing on the stele, which provides most tensile strength (Chimungu et al., 2015; Liu et al., 2023). Studies suggest that stele diameter is a more accurate predictor of root tensile strength than overall root diameter (Meijer et al., 2024).

Because natural variability among plants complicates findings (Vergani et al., 2012), synthetic roots by 3D printing that mimic natural counterparts have been suggested to address these challenges in root-soil reinforcement studies. This approach enables controlled experiments to systematically investigate how factors like root geometry, and stiffness impact root-soil interactions among others. Furthermore, synthetic roots facilitate repeatable experiments, reducing the variability often encountered with natural roots (Arrieta-Escobar et al., 2020). Most existing research has concentrated on understanding how root analogues influence soil behavior, and by broadening the scope of these investigations, we can gain deeper insights into the complexities of root-soil relationships.

This study evaluated the tensile strength of natural plant roots from indoor-grown willows (*Salix sp.*) at 90

days subjected to different dehydration periods, and the results obtained were used as a baseline to idenitfy resin mixs that best mimick the natural roots.

2 METHODOLOGY

Salix sp. was cultivated for 90 days using the method described by Otim et al., (2025). After the growth period, two replica pots were disassembled, and the sand was washed out. Primary roots from the stake were cut into 100 mm sections, and plastic glue was applied to both ends, creating a 50 mm effective length. Plastic glue was adopted as the most suitable approach based on pre-trials with different other methods. About 160 roots were divided into four dehydration groups: 0 (saturated), 1.5, 3.0, and 5.0 hours. Dehydration occurred within a humidity chamber at 20°C and 60% relative humidity. Measurements for both the root and stele diameter were taken at least twenty times along each root using a Nikon digital microscope. Tensile tests were performed with an Instron 5965 universal tensile strength machine at a strain rate of 10 mm/min, screening the results to those failing in the middle third (Otim et al., 2025b).

3D printing of synthetic roots effectively utilized Fused Deposition Modelling (FDM) and Stereolithography (SLA) methods. FDM extrudes materials like polylactic acid (PLA), while SLA uses ultraviolet (UV) light to cure liquid resin layer by layer. Two resins were chosen: UV Value Tough (T) and UV Value Flex (F). UV Value Tough (T) has an elongation strain at break of 11 % to 21 %, whereas UV Value Flex (F) is more ductile and has elongation up to 130 % (PrimaCreator, n.d.). By combining these properties in resin matrix composites of 100 % TF, 80/20 TF, and 50/50 TF, we were able to investigate the material which aligned more closely with natural roots. Because of limitations in the minium size, the specimen diameter was restricted to 1 mm. Therefore, all 3D specimens had uniform diameter of 1 mm, except for specimen TFA for the most suitable resin matrix validated according to ASTM D638 (2022) for type I specimens, which was also created through the SLA method. The tensile test for the synthetic specimen was identical to those of the natural roots with the exception of end preparation.

Tensile strength was calculated as the ratio of force to average cross sectional area of the stele or root diameter or 3D material, while the Young‘s modulus was determined within the initial linear part of the stress-strain curve.

3 RESULTS AND DISCUSSION

3.1 Stress-strain curves

The 90-day mean root and stele diameters were 0.6 mm and 0.4 mm, categorizing these as being fine roots. After 1.5 hours of dehydration, mean root and stele diameters decreased by 31% and 32%, respectively. Beyond this period, further dehydration was not statistically significant on the respective diameters. Additionally, the mean tensile stress-strain curve for natural roots displayed large variability under saturated conditions, which decreased with longer dehydration times, as shown in Figure 1.

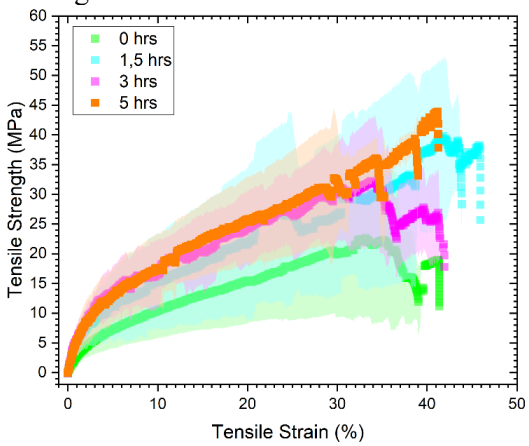


Figure 1. Tensile stress-strain curves for natural roots

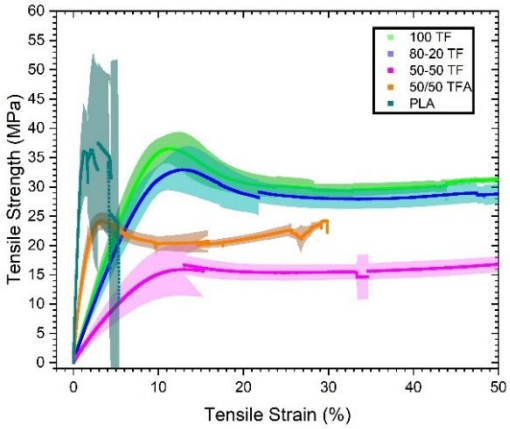


Figure 2. Tensile stress-strain curves for synthetic roots

The mean stress-strain curves for natural roots showed elasticity up to the yield point, followed by plastic strain hardening until rupture, with elongation reaching up to 42% across all dehydration periods. In contrast, synthetic roots demonstrated better repeatability, as shown in Figure 2, with stress-strain curves typically exhibiting elasticity followed by plastic strain softening. Notably, the 50/50 TFA sample showed a combination of plastic softening followed by plastic hardening, while PLA experienced catastrophic failure due to consecutive cylindrical-ring ruptures along its length since it was more rigid and brittle. Synthetic roots often displayed significant necking beyond the yield point, whereas natural roots fractured at multiple locations within the root-cortex before rupture of the stele occurred. The ultimate tensile strength of natural roots was generally higher than their yield strength, while synthetic roots showed equivalent yield and ultimate strengths, highlighting distinct stress-strain curves between the two types of roots.

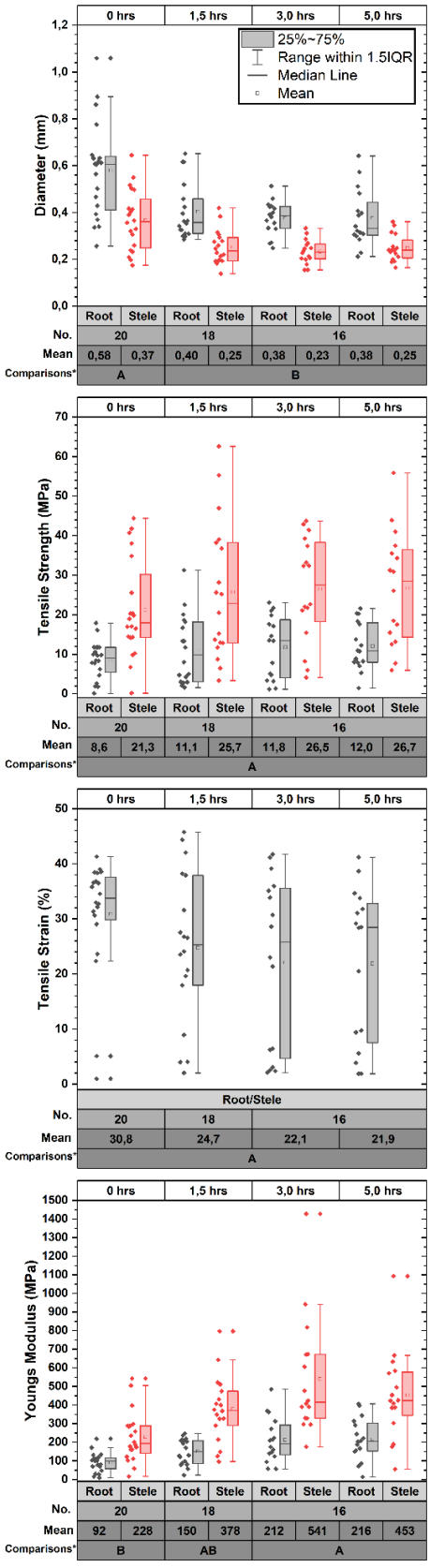


Figure 3. Biomechanical properties for natural roots, the letter comparisons of the mean indicate that means denoted by different letters are statistically different p ≤ 0.05 (Tukey's test)*

The mean tensile strength at saturation was 8.6 MPa for roots and 21.3 MPa for steles, with both values increasing with dehydration time, although these changes were not statistically significant (stele: F = 0.59, p = 0.624; root: F = 0.996, p = 0.400). This implies that the dehydration did not significantly impact the relationship between the tensile strength and root diameter.

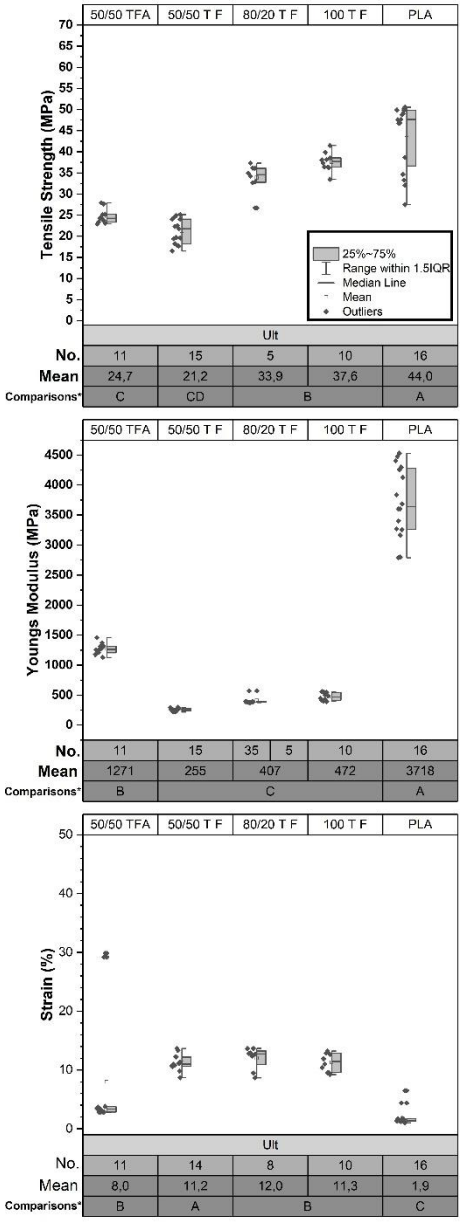


Figure 4. Mechanical properties for 3D root analogues; the letter comparisons of the mean indicate that means denoted by different letters are statistically different p ≤ 0.05 (Tukey's test)*

Furthermore, the mean tensile strain at rupture decreased from 30.8 %, in saturated conditions to 21.9 % after 5 hours, but this effect was not statisticaly significant (F = 1.76, p = 0.163). In contrast, dehydration had a statistically significant effect on Young's modulus going from 92 MPa to 216 MPa for stele (F = 6.48, p = 0.00065) and root (F = 7.68, p = 0.000178) indicating that the roots exhibited increased stiffness. Importantly, both the stele tensile strength and Young's modulus were higher than those of the roots due to the smaller diameter of the stele (Chimungu et al., 2015; Liu et al., 2023;

Meijer et al., 2024). It is important to note that the roots in this study were grown in a controlled environment and this might have influenced their biomechanical properties representing a limitation of the study.

The PLA samples showed the highest ultimate tensile strength (44 MPa), followed by 100 TF (38 MPa), 80/20 TF (34 MPa), and 50/50 TF (21 MPa). PLA specimens exhibited the highest Young's modulus with 3718 MPa, followed by 100 TF at 472 MPa, 80/20 TF at 407 MPa, and 50/50 TF at 255 MPa. These results highlight the significant influence of preparation methods and resin matrices on tensile properties (tensile strength: $F = 57.2$, $p < 0.0001$; tensile strain: $F = 10.6$, $p < 0.0001$; Young's modulus: $F = 321.1$, $p < 0.0001$). Validation tensile tests on the 50/50 TF resin matrix, following ASTM D638 (2022), showed a mean tensile strength of 25 MPa for the 50/50 TFA, closely matching its resin matrix strength. However, as ASTM D638 (2022) focuses on tensile strength, and Young's modulus and strain at failure are dependent on the material shape, the validity of these properties could not be validated, and the standard could be improved to cover these aspects.

4 CONCLUSIONS

The tensile strength test for natural roots has yet to be standardized internationally, presenting challenges due to the significant variability in methods and results. This research shows that dehydration does not influence tensile strength and strain at failure in a statistically significant manner and for these variables the stele diameter is a more reliable predictor, but not for the Young modulus. The synthetic roots created using a 50/50 TF resin matrix closely replicate the tensile strength of natural roots in saturated conditions using the stele diameter. This resin formulation also met tensile validation tests per ASTM D638-22. Despite dimensional differences between 50/50 TF and 50/50 TFA specimens, the tensile strength of this resin remains consistent, indicating its potential as a reliable synthetic alternative that mimic natural root properties with less variability.

5 ACKNOWLEDGEMENTS

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