Postprint: Study on Mechanical Properties of Amorpha fruticosa Taproot

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Abstract

To investigate the differences in mechanical properties of plant root materials under axial and radial loads, taproots of Amorpha fruticosa—a common plant species in soil erosion areas—within the 1–5 mm diameter range were studied using a TY8000 servo-controlled testing machine to examine root strength characteristics, constitutive characteristics, and elastic deformation properties under the two loading conditions. The results showed that: (1) Under both axial and radial loads, the ultimate force of taproots exhibited a positive power function correlation with root diameter, while ultimate strength exhibited a negative power function correlation with root diameter; (2) The constitutive curves of taproots under both axial and radial loads demonstrated a transition from elastic deformation to plastic deformation, with no significant difference in ultimate stress or elastic stress; however, the ultimate strain (15.04%) and elastic strain (2.71%) under axial load were significantly smaller than those under radial load (20.39% and 4.19%, respectively); (3) Both the tensile elastic modulus and flexural elastic modulus of taproots exhibited a negative power function correlation with root diameter, while tensile stiffness and flexural stiffness exhibited a positive power function correlation with root diameter. The average percentage of elastic stress to ultimate stress under axial load (50.45%) was significantly greater than that under radial load (34.08%). Overall, Amorpha fruticosa roots exhibited superior elastic performance under axial load, and Amorpha fruticosa is more suitable for planting in wind and water erosion areas where the primary load type is axial.

Full Text

Preamble

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Mechanical Properties of *Amorpha fruticosa* Straight Roots

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Abstract

To investigate the differences in mechanical properties of plant root materials under axial and radial loads, we examined the straight roots of *Amorpha fruticosa*—a common species in soil erosion regions—using a TY8000 servo-controlled testing machine. Roots with diameters ranging from 1–5 mm were tested to characterize their strength, constitutive behavior, and elastic deformation under both loading conditions. The results demonstrated that: (1) Under both axial and radial loads, the ultimate force of straight roots showed a positive power-function correlation with root diameter, while ultimate strength exhibited a negative power-function correlation with diameter. (2) The constitutive curves transitioned from elastic to plastic deformation under both loading types, with no significant differences in ultimate stress or elastic stress between axial and radial loading. However, the ultimate strain (15.04%) and elastic strain (2.71%) under axial loading were significantly smaller than those under radial loading (20.39% and 4.19%, respectively). (3) Both tensile elastic modulus and bending elastic modulus were negatively correlated with root diameter via power functions, whereas tensile stiffness and bending stiffness were positively correlated with root diameter via power functions. The percentage of average elastic stress relative to ultimate stress under axial loading (50.45%) was significantly greater than under radial loading (34.08%). Overall, *A. fruticosa* root systems exhibited superior elastic performance under axial loading, making this species particularly suitable for planting in wind- and water-eroded areas where axial loads dominate.

Keywords: axial load; radial load; strength; deformation; *Amorpha fruticosa*

Introduction

The role of plant roots in enhancing soil stability is widely recognized. Roots interweave with soil to form root-soil composites that not only meet plant water and nutrient demands but also strengthen soil mass. The strength of these composites depends on individual root mechanical properties and root-soil interface friction characteristics. When soil mass moves, most roots experience axial tension due to friction constraints at the root-soil interface, while roots crossing shear failure planes undergo radial loading from soil displacement. Current research on root mechanical properties under axial loading is well-established, showing that root strength characteristics are influenced by species, diameter class, and cultivation method, and that elastic deformation properties are critical factors affecting soil reinforcement. Roots are elastoplastic materials, and their elastic behavior significantly influences anchorage effectiveness. However, studies on root mechanical properties under radial loading remain limited, with only a few reports on ultimate force and strength for species such as *Salix psammophila*, *Caragana microphylla*, and *Hippophae rhamnoides* in the Shaanxi-Inner Mongolia border region, without addressing elastic deformation under radial stress. Moreover, while previous work has compared mechanical property differences between load types, these studies have focused primarily on force and strength, neglecting deformation characteristics. Therefore, systematic investigation of both strength and deformation properties of the same plant species under axial versus radial loads holds substantial practical significance.

Amorpha fruticosa is a widely distributed deciduous shrub valued for its cold and drought tolerance and soil improvement capabilities, commonly planted in arid northwestern China. This study examined straight roots of *A. fruticosa* from the Shaanxi-Inner Mongolia border region to investigate strength and deformation characteristics under both axial and radial loading, thereby improving our understanding of the mechanical mechanisms of shrub root reinforcement in arid zones and providing a theoretical basis for afforestation species selection.

1.1 Experimental Design

The study area was located in the Daliuta Experimental Zone, Shenmu City, Shaanxi Province, a region severely affected by wind and gravitational erosion. Previous research on soil-root friction characteristics in this area indicated that the soil is silty sand, and frictional properties at the root-soil interface enable straight roots to remain stable under external forces. External loads on roots are categorized as either axial or radial (Fig. 1). Under axial loading, straight roots experience only axial strain; under radial loading, root segments crossing the shear plane experience shear deformation, while more distant segments undergo tension and bending deformation. Following Wang et al., this combined tension-shear loading condition is defined as a tension-shear composite force, with corresponding strength, elastic modulus, and stiffness termed tension-shear composite strength, bending elastic modulus, and bending stiffness, respectively.

1.2 Material Collection and Preparation

Roots were collected in October from a soil and water conservation demonstration park in the Daliuta Experimental Zone. On a sample plot of *A. fruticosa*, eight healthy shrubs were randomly selected to measure plant height, crown width, and ground diameter, with average values used as standard plant data to determine plant age. Standard plant measurements were: height 150.25 ± 33.20 cm, crown width 156 ± 33.67 cm, and ground diameter 8.59 ± 1.02 cm. Based on these standards, test plants were selected and excavated using a partial excavation method on one side of each plant to ensure survival. Straight roots with uniform diameter and intact epidermis were selected as test specimens. In the laboratory, roots were screened and processed to a total length of 10 cm, with 2 cm reserved at each end for clamping (Fig. 3). The root cross-section was treated as circular (Fig. 2). Root diameter was measured using the cross method at three points (root middle, and 1 cm from each end), with the average taken as the root diameter. Roots were stored in a constant-temperature refrigerator at 4°C, with a one-week testing period.

1.3 Test Methods

1.3.1 Testing Equipment The testing equipment consisted of a TY8000 servo-controlled testing machine with matching fixtures.

1.3.2 Tensile Test Method Following established root tensile testing methods, root ends were fixed in the machine clamps and subjected to constant-rate axial loading at 10 $\mathrm{mm \cdot min^{-1}}$. The machine automatically generated load-displacement (F-ΔL) curves, with tensile force defined as the axial load at fracture. Tensile strength was calculated as:

$$\sigma = 4F/(\pi D^2)$$

where σ is tensile strength (MPa), F is tensile force (N), and D is root diameter (mm). Preliminary tests showed that roots >5 mm often failed at the clamps, while roots <1 mm could not be securely gripped; thus, the test diameter range was set at 1-5 mm. Previous studies typically use 1 mm intervals, but since *A. fruticosa* root strength and deformation patterns across diameters were unknown, we used 0.5 mm intervals, creating eight diameter classes with 16 roots per class.

1.3.3 Tension-Shear Test Method Following three-point bending test methods, roots were fixed at both ends in a statically indeterminate state, with constant-rate radial loading applied at the center point at 10 $\mathrm{mm \cdot min^{-1}}$. This created shear at the center and tension at both ends. The machine recorded load-displacement (F-ΔS) curves, with ultimate tension-shear composite force defined as the radial load at fracture. Ultimate tension-shear strength was calculated as:

$$\tau = 4F/(\pi D^2)$$

where τ is tension-shear strength (MPa) and F is tension-shear composite force (N).

1.3.4 Constitutive Test Method From the ultimate force tests, stress-strain (σ-ε) curves were derived for constitutive analysis. Stress was calculated as:

$\sigma = 4F/(\pi D^2)$

Strain was calculated as:

$\varepsilon = \Delta L/L$

where ΔL is axial elongation (mm) and L is the length of the loaded root segment (mm).

1.3.5 Elastic Modulus and Stiffness Calculation Methods Tensile elastic modulus was calculated as the slope at the inflection point of the σ-ε curve:

$E = \Delta\sigma/\Delta\varepsilon$

where $\Delta\sigma$ is the stress at the inflection point and $\Delta\varepsilon$ is the strain at the inflection point.

Bending elastic modulus was calculated from the F-ΔS curve slope change point using three-point bending theory:

$E_b = (FL^3)/(48I\Delta S)$

where ΔS is radial displacement (mm), I is the moment of inertia about the neutral axis (mm^4), calculated as $I = \pi D^4/64$.

Stiffness was calculated following *Mechanics of Materials*: tensile stiffness = EA, and bending stiffness = E_{bI}, where A is cross-sectional area.

1.4 Data Processing and Statistics

Data processing and statistical analysis were performed using Excel 2010, SPSS 20.0, and Origin 9.5 software. Significance testing employed the least significant difference (LSD) method.

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2 Results

2.1 Ultimate Force and Ultimate Strength of *A. fruticosa* Straight Roots

Invalid data from failures at clamping points were excluded. Under axial loading, ultimate tensile force and strength were determined at root fracture (Figs. 4–5). Across the 1–5 mm diameter range, as average diameter increased from 1.26 ± 0.15 mm to 4.80 ± 0.22 mm, ultimate tensile force increased from 208.93 ± 73.23 N to 262.92 ± 119.9 N, showing a positive power-function correlation with diameter. Conversely, tensile strength decreased from 47.98 ± 40.43 MPa to 12.91 ± 3.15 MPa, showing a negative power-function correlation. This indicates that larger-diameter roots can resist greater forces, but their stress-bearing capacity per unit area is lower than that of smaller-diameter roots.

Under radial loading, ultimate force and strength showed similar patterns (Figs. 6-7). As diameter increased from 1.26 ± 0.15 mm to 4.80 ± 0.22 mm, tension-shear composite force increased from 40.90 ± 22.70 N to 31.88 ± 14.91 N (positive power-function correlation), while tension-shear strength decreased from 40.43 ± 16.24 MPa to 11.65 ± 4.81 MPa (negative power-function correlation), mirroring the axial loading results.

2.2 Constitutive Properties of *A. fruticosa* Straight Roots

Material constitutive behavior reflects the deformation process under load. From the ultimate force tests, σ-ε curves were derived for each root. Table 1 shows that ultimate stress was negatively correlated with root diameter under both loading types, decreasing from 47.98 MPa to 12.91 MPa under axial load and from 40.43 MPa to 11.65 MPa under radial load, with no significant difference between loading types. Ultimate strain under radial loading (13.38%-16.53%) was significantly greater than under axial loading (16.58%-22.73%), and was independent of diameter.

To facilitate comparison, representative σ-ε curves were selected for each diameter class based on proximity to average ultimate stress (Figs. 8-9). Under axial loading, the stress required per unit strain remained initially constant then gradually decreased, producing a convex σ-ε curve. Roots first underwent elastic deformation, then plastic deformation, with a clear transition point. Under radial loading, stress per unit strain increased slowly at first then rapidly until fracture, producing a concave σ-ε curve. Variation among diameters (1-5 mm) showed that smaller-diameter roots had steeper curve slopes, requiring greater stress per unit strain and exhibiting higher ultimate stress (greater strength).

2.3 Elastic Limit and Elastic Mechanical Indices of *A. fruticosa* Straight Roots

The deformation process of *A. fruticosa* roots under both loading types can be divided into elastic and plastic stages. The elastic limit corresponds to the inflection point on the σ-ε curve. Statistical analysis of stress and strain values at elastic limits (Table 2) revealed:

Under axial loading, elastic limit stress was negatively correlated with diameter, decreasing from 17.24 MPa to 5.53 MPa, representing 41.63%-67.86% of ultimate stress (increasing with diameter). Elastic limit strain ranged from 2.08% to 3.45%, representing 13.38%-25.78% of ultimate strain, and was independent of diameter.

Under radial loading, elastic limit stress also showed negative correlation with diameter, decreasing from 13.38 MPa to 5.53 MPa, representing 24.10%-44.63% of ultimate stress. Elastic limit strain ranged from 2.08% to 5.69%, representing

10.46%-34.32% of ultimate strain. Both stress and strain percentages at the elastic limit increased with diameter.

Both tensile and bending elastic moduli were negatively correlated with root diameter via power functions (Figs. 10-11). Smaller-diameter roots exhibited higher moduli, which decreased rapidly as diameter increased, slowing when diameter exceeded 2 mm. Average tensile and bending elastic moduli in the 2-5 mm range were only 10.60% and 54.78% of values in the 1-2 mm range, indicating that finer roots can bear more stress at the same strain.

Stiffness calculations (Figs. 12-13) showed that both tensile stiffness and bending stiffness were positively correlated with root diameter via power functions. As diameter increased from 1.26 ± 0.15 mm to 4.80 ± 0.22 mm, average tensile stiffness increased from 956.44 ± 571.77 N to 25938.65 ± 8528.47 N, and average bending stiffness increased from 4251.68 ± 2013.11 $\mathrm{N \cdot mm^2}$ to 4167.53 ± 2013.11 $\mathrm{N \cdot mm^2}$.

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3 Discussion

As biological materials, the heterogeneous structure of root systems causes their mechanical properties to vary with species and diameter. Under axial loading, *A. fruticosa* root tensile force and strength showed power-function relationships with diameter (positive and negative correlations, respectively), consistent with most plants such as *Cynodon dactylon*, *Populus davidiana*, *Pinus tabuliformis*, and *Agropyron trachycaulum*. These relationships depend on microstructural differences; Zhang et al. found that root cross-section vessel diameter increases with root diameter, increasing absolute but decreasing relative effective load-bearing area, creating stress concentration. Complex vessel arrangement patterns and changing xylem-to-bark ratios contribute to the negative correlation between strength and diameter.

Different diameter classes contribute differently to soil reinforcement. Fine roots (1-2 mm) significantly enhance residual strength of root-soil composites, while anchorage is primarily provided by thicker roots. Our results explain this from an elastic modulus perspective: modulus decreases with increasing diameter, so finer roots bear more stress at equal strain. Conversely, coarser roots with greater stiffness resist deformation under external forces, better maintaining soil stability. Microstructural studies show that as diameter increases, phloem percentage decreases while xylem percentage increases. Phloem fibers (long, flexible cells) provide elasticity, while xylem fibers (short, thick-walled, highly lignified cells) provide mechanical anchorage but lower toughness.

Traditional root reinforcement models (e.g., Wu & Waldron model, Fiber Bundle Model) assume all roots experience axial tension, but actual root systems encounter multi-directional forces. Comparative studies of axial versus radial loading are scarce and focus on strength rather than deformation. For *A. fruti-*

cosa, constitutive curves under both loading types transitioned from elastic to plastic deformation, but ultimate strain under axial loading (15.04%) was significantly smaller than under radial loading (20.39%). The average percentage of elastic stress to ultimate stress under axial loading (50.45%) significantly exceeded that under radial loading (34.08%). Thus, *A. fruticosa* roots demonstrate superior elastic performance under axial loading, with greater elastic limits and smaller displacements, making them more effective for long-term soil reinforcement in axial-load-dominated erosion environments.

While ultimate force and strength showed no significant differences between loading types, the higher elastic limit percentage and smaller displacements under axial loading indicate more favorable mechanical performance for sustained function. Considering long-term reinforcement, *A. fruticosa* is better suited for wind- and water-eroded areas where axial loads predominate.

4 Conclusions

For *A. fruticosa* straight roots (1–5 mm diameter) under axial and radial loading:

1. Ultimate force was positively correlated with root diameter via power functions, while ultimate strength was negatively correlated. As diameter increased, average ultimate force increased from 208.93 ± 73.23 N to 262.92 ± 119.9 N under axial load and from 40.90 ± 22.70 N to 31.88 ± 14.91 N under radial load. Average ultimate strength decreased from 47.98 ± 40.43 MPa to 12.91 ± 3.15 MPa under axial load and from 40.43 ± 16.24 MPa to 11.65 ± 4.81 MPa under radial load.
2. Constitutive curves transitioned from elastic to plastic deformation under both loading types. No significant differences existed in ultimate stress between loading conditions, but ultimate strain (15.04%) and elastic strain (2.71%) under axial loading were significantly smaller than under radial loading (20.39% and 4.19%, respectively).
3. Both tensile and bending elastic moduli were negatively correlated with root diameter via power functions, while tensile and bending stiffness were positively correlated. The percentage of average elastic stress to ultimate stress under axial loading (50.45%) significantly exceeded that under radial loading (34.08%).

Overall, *A. fruticosa* root systems exhibit superior elastic properties under axial loading, making this species particularly suitable for planting in wind- and water-eroded areas where axial loads are predominant.

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